Uncertainty and Sensitivity Analysis of Food Pathway Results with the MACCS Reactor Accident Consequence Model

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Abstract

Uncertainty and sensitivity analysis techniques based on Latin hypercube sampling, partial correlation analysis and stepwise regression analysis are used in an investigation with the MACCS model of the food pathways associated with a severe accident at a nuclear power station. The primary purpose of this study is to provide guidance on the variables to be considered in future review work to reduce the uncertainty in the important variables used in the calculation of reactor accident consequences. The effects of 87 imprecisely-known input variables on the following reactor accident consequences are studied: crop growing season dose, crop long-term dose, milk growing season dose, total food pathways dose, total ingestion pathways dose, total long-term pathways dose, area dependent cost, crop disposal cost, milk disposal cost, condemnation area, crop disposal area and milk disposal area. When the predicted variables are considered collectively, the following input variables were found to be the dominant contributors to uncertainty: fraction of cesium deposition on grain fields that is retained on plant surfaces and transferred directly to grain, maximum allowable ground concentrations of Cs-137 and Sr-90 for production of crops, ground concentrations of Cs-134, Cs-137 and I-131 at which the disposal of milk will be initiated due to accidents that occur during the growing season, ground concentrations of Cs-134, I-131 and Sr-90 at which the disposal of crops will be initiated due to accidents that occur during the growing season, rate of depletion of Cs-137 and Sr-90 from the root zone, transfer of Sr-90 from soil to legumes, transfer of Cs-137 from soil to pasture, transfer of cesium from animal feed to meat, and the transfer of cesium, iodine and strontium from animal feed to milk.

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1. INTRODUCTION

In preparation for a joint study¹ with the Commission of European Communities (CEC) on the uncertainties associated with the input variables used in reactor accident consequence models, the U.S. Nuclear Regulatory Commission (NRC) is sponsoring a sequence of uncertainty and sensitivity analyses with the MACCS^{2,4} reactor accident consequence model. The primary purpose of these analyses is to identify the MACCS input variables that have the greatest effect on the uncertainty in MACCS predictions. The uncertainty in these variables will then be assessed as part of an expert-review process in the joint CEC/NRC study. Due to the large investments of resources (i.e., time, people, money) associated with an expert-review process, the number of variables that can be considered is limited. Thus, it is important to select variables for the review process that contribute substantially to the uncertainty in MACCS predictions.

A prior uncertainty and sensitivity analysis considered early exposure results calculated with MACCS.⁵ The present analysis considers the effects of uncertainty in the MACCS food pathway model. An additional analysis considers the effects of uncertainty in the MACCS chronic exposure model.⁶ All three analyses use the same source term (Ref. 5, Section 4.1) from the NUREG-1150 analysis⁷ for the Surry Nuclear Power Station.^{8,9}

In performing uncertainty and sensitivity studies, it is important to maintain a clear distinction between the different types of uncertainty involved.¹⁰⁻¹⁷ When viewed at a high level, there are two basic types of uncertainty associated with the calculation of reactor accident consequences: stochastic uncertainty, which results because the system under study can behave in many different ways (e.g., many different types of weather are possible at the time of a reactor accident), and subjective uncertainty, which results from the existing state of knowledge with respect to the correctness of the assumptions used in an analysis (e.g., what is the appropriate dry deposition velocity to use for a particular combination of release characteristics and weather). Thus, stochastic uncertainty is a property of the system under study, and subjective uncertainty is a property of the analysts performing the study (Ref. 5, Section 2). The primary focus of this study is subjective uncertainty.

The ordered triple representation for risk proposed by Kaplan and Garrick¹⁷ provides a useful framework with which to both describe the conceptual structure of a consequence calculation and distinguish between stochastic and subjective uncertainty. In this representation, risk is expressed as a set R of ordered triples of the form

$$R = \{ (S_i, pS_i, cS_i), i = 1, 2, \dots, nS \} , \quad (1)$$

where S_i is a set of similar occurrences (i.e., a scenario), pS_i is the probability (or frequency, as appropriate) for S_i , cS_i is a vector of consequences associated with S_i , nS is the number of sets selected for consideration, and the sets S_i have no occurrences in common (i.e., the S_i are disjoint). This representation formally decomposes risk into what can happen (the S_i), how likely things are to happen (the pS_i), and the consequences of what can happen (the cS_i). In the context of a typical reactor accident consequence model such as MACCS, the S_i are sets of similar weather conditions (Ref. 5, Section 3.1), the pS_i are probabilities for these sets of weather conditions (Ref. 5, Section 3.1), and the cS_i contain consequence values calculated for these sets of weather conditions (Ref. 5, Section 3.2). An overview of how cS_i is determined for the MACCS food pathways model is provided in Section 2. To facilitate

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visual examination, the information in pS_i and cS_i is usually summarized with complementary cumulative distribution functions (CCDFs) (Ref. 5, Figure 1).

The probabilities pS_i in Eq. (1) characterize stochastic uncertainty. Subjective uncertainty enters when the computational reality of evaluating the risk representation in Eq. (1) must be addressed. In practice, evaluation of the expression in Eq. (1) requires extensive computation and, in turn, this computation requires many inputs. If these inputs are represented by a vector

$$\mathbf{x} = [x_1, x_2, \dots, x_{nV}], \quad (2)$$

where nV is number of such inputs, the representation in Eq. (1) becomes

$$\mathbf{R}(\mathbf{x}) = \{(S_i(\mathbf{x}), pS_i(\mathbf{x}), cS_i(\mathbf{x})), i=1, 2, \dots, nS(\mathbf{x})\}. \quad (3)$$

If the vector $\mathbf{x}$ was known with complete certainty, then the expression in Eq. (3) could be evaluated and presented as the unambiguous outcome of the analysis. However, $\mathbf{x}$ is not known with certainty in most analyses, with the result that there is not a single CCDF for a particular consequence value that can be identified as the unambiguous outcome of evaluating the expression in Eq. (3). In particular, subjective uncertainty in $\mathbf{x}$ leads to a distribution of CCDFs, with the individual CCDFs displaying the effect of stochastic uncertainty conditional on a specific value of $\mathbf{x}$ and the distribution of CCDFs displaying the effect of subjective uncertainty in $\mathbf{x}$ (Ref. 5, Figure 2).

As previously indicated, the primary focus of this study is on the effect of subjective uncertainty in the MACCS food pathway model. Thus, the analysis objective is to determine the relationship between the uncertainty in a vector $\mathbf{x}$ of the form defined in Eq. (2) and the uncertainty in a risk representative $\mathbf{R}(\mathbf{x})$ of the form defined in Eq. (3). This relationship will be determined by characterizing the uncertainty in $\mathbf{x}$ with a sequence of distributions

$$D_1, D_2, \dots, D_{nV}, \quad (4)$$

where D_j describes a degree of belief as where the appropriate value to use for x_j is located given that the analysis has been structured so that only a single value of each variable x_j is required in the determination of the set $\mathbf{R}(\mathbf{x})$. Correlations and other restrictions between the x_j are also possible, which is equivalent to the specification of a joint probability distribution for the variables contained in $\mathbf{x}$. The distributions developed for the x_j are characterizing subjective uncertainty as they indicate the possible values of fixed, but unknown, quantities. The variables selected for consideration in this study and their assigned distributions are discussed in Section 3.

In practice, Monte Carlo techniques must be used to determine the distribution of CCDFs that results from the subjective uncertainty characterized by the distributions in Eq. (4). Specifically, a sample of the form

$$\mathbf{x}_k = [x_{1k}, x_{2k}, \dots, x_{nV,k}], k = 1, 2, \dots, nLHS, \quad (5)$$

is generated by Latin hypercube sampling¹⁸ or some other appropriate sampling procedure according to the distributions characterizing the subjective uncertainty in the individual elements x_j of $\mathbf{x}$, where $nLHS$ is the sample size. Evaluation of the MACCS model for each sample element $\mathbf{x}_k$ produces a sequence of results of the form

$$\mathbf{R}(\mathbf{x}_k) = \{(S_i, pS_i, cS_i(\mathbf{x}_k)), i = 1, 2, \dots, nS\} \quad (6)$$

for $k = 1, 2, \dots, nLHS$. Although the general representation for $\mathbf{R}(\mathbf{x})$ in Eq. (3) shows S_i , pS_i , cS_i and nS as functions of $\mathbf{x}$, only cS_i is a function of $\mathbf{x}$ in the present study. As each set $\mathbf{R}(\mathbf{x}_k)$ yields a CCDF for each consequence result under consideration, distributions of CCDFs are produced that characterize subjective uncertainty. Further, the sets $\mathbf{R}(\mathbf{x}_k)$ provide a mapping from analysis inputs to analysis results that can be explored with sensitivity analysis techniques based on regression analysis, partial correlation analysis and possibly other procedures.¹⁹⁻²⁴ The uncertainty analysis results obtained in this study and their subsequent exploration with regression-based sensitivity analysis techniques are presented in Sections 4 and 5.

Additional background on the uncertainties in reactor accident consequence calculations can be obtained from a number of studies.^{5,25-35}

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2. MODEL DESCRIPTION

Detailed descriptions of the models implemented in MACCS are available elsewhere.^{2-4,32} Further, an overview of the models in MACCS is provided in a preceding report (Ref. 5, Section 3). As the present report considers the effect of imprecisely-known variables in the MACCS food pathways model, this section provides a brief description of the MACCS food pathways model and associated models used in the calculation of the results under study.

2.1 Ingestion Dose

The basic relationship used in MACCS to determine the population dose D_{ijkl} (Sv) to organ k for radionuclide i and crop category j in spatial element l is

$$D_{ijkl} = DF_{ik} FC_j TF_{ij} FAC_{jl} FA_l GC_{il}, \quad (7)$$

where DF_{ik} is the ingestion dose conversion factor (Sv/Bq) for radionuclide i and organ k , FC_j is the fraction (dimensionless) of crop category j consumed by man, TF_{ij} is the transfer factor (dimensionless) from deposition to crop category j for radionuclide i (i.e., $TF_{ij} = AC_{ij}/AD_{ij}$, where AC_{ij} is the amount (Bq/m²) of radionuclide i transferred to crop category j over the time period under consideration and AD_{ij} is the initial deposition of radionuclide i (Bq/m²) onto land on which crop category j is being grown), FAC_{jl} is the fraction (dimensionless) of farmland in spatial element l devoted to crop category j , FA_l is the area (m²) in spatial element l devoted to farming, and GC_{il} is the initial ground concentration (Bq/m²) of radionuclide i in spatial element l .

The ground concentrations GC_{il} are calculated by MACCS with a Gaussian plume model as discussed in Refs. 2-3. The spatial elements and their associated areas FA_l used in this analysis for the Surry reactor site are given in Appendix A.3 of Ref. 32. In particular, spatial elements are defined on a polar coordinate grid centered at Surry with 16 angular 22.5° sectors and 26 radial intervals with outer radii of 0.1, 0.32, 0.75, 1, 1.5, 2, 2.5, 3, 3.5, 5, 7, 10, 13, 16, 20, 25, 30, 40, 50, 70, 100, 150, 200, 350, 500 and 1000 mi. The crop categories used in the Surry analysis are listed in Table 1, together with values for the consumption fractions FC_j and area fractions FAC_{jl} . The transfer factors TF_{ij} have a complex form and will be discussed in subsequent paragraphs. The ingestion dose factors DF_{ik} for the radionuclides included in the food pathways in this analysis are listed in Table 2.

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Table 1. Crop Categories and Associated Variables Used in MACCS Food Pathways Model in Analysis for Surry (Ref. 32, Table 4.1)

	Pasture	Stored Forage	Grain	Leafy Green Vegetables	Other Food	Legumes & Nuts	Roots & Tubers
	Various grasses	Alfalfa Clover Sorghum	Wheat Oats Barley Corn(incl. sweetcorn) Sorghum	Lettuce Cabbage Broccoli Spinach Celery Cauliflower Greens	Fruits: Apples Grapes Citrus: Oranges Grapefruit Lemons Vegetables: Tomatoes Cucumbers Peppers	Soybeans Peanuts Snap beans Dried beans Peas Nuts	Potatoes Carrots Beets Sugar Onion
FRCTCH ^a	0.0	0.0	0.35	1.0	1.0	0.24	1.0
FRCTCM ^b	0.1	0.13	0.04	0.0	0.0	0.046	0.0
FRCTCB ^c	0.9	0.87	0.61	0.0	0.0	0.714	0.0
FRCTTFL ^d	0.41	0.13	0.21	0.002	0.004	0.15	0.003
TGSBEG ^e	90	150	150	150	150	150	150
TGSEND ^f	270	240	240	240	240	240	240

^aFraction consumed by man (FC_j in Eq. 7); Ref. 32, Table 4.22.

^bFraction consumed by milk producing animals; Ref. 32, Table 4.22.

^cFraction consumed by meat producing animals; Ref. 32, Table 4.22.

^dFraction of crop land (FAC_{ji} in Eq. 7); Ref. 32, Table 4.22.

^eBeginning of growing season in days measured from beginning of year; Ref. 32, Table 4.2.

^fEnd of growing season in days measured from beginning of year; Ref. 32, Table 4.2.

Table 2. Dose Factors For Effective Whole Body Dose Equivalent³⁶ and Halfives for Radionuclides Used in MACCS Food Pathways Model (Ref. 32, Appendix A.4; Refs. 37, 38). As indicated in Ref. 32, Appendix A.4, a full MACCS calculation uses 60 radionuclides and dose factors for a variety of organs

Dose Factor	Sr-89	Sr-90	Cs-134	Cs-137	I-131	I-133
Cloudshine [(Sv/s)/(Bq/m ²)]	3.796×10^{-16}	9.537×10^{-17}	6.968×10^{-14}	2.526×10^{-14}	1.667×10^{-14}	2.685×10^{-14}
Groundshine [(Sv/s)/(Bq/m ²)]	5.069×10^{-17}	5.000×10^{-18}	1.377×10^{-15}	5.104×10^{-16}	3.553×10^{-16}	5.637×10^{-16}
Chronic Inhalation (Sv/Bq)	1.787×10^{-9}	5.919×10^{-8}	1.253×10^{-8}	8.628×10^{-9}	8.872×10^{-9}	1.583×10^{-9}
Ingestion (Sv/Bq)	2.503×10^{-9}	3.518×10^{-8}	1.975×10^{-8}	1.355×10^{-8}	1.434×10^{-8}	2.800×10^{-9}
Half-life	52.0 d	28.1 yr	2.06 yr	30.0 yr	8.04 d	0.87 d

When radioactive material is deposited onto farmland, an ingestion dose to the exposed population can result from two pathways: (1) a growing season pathway resulting from the direct deposition of radionuclides onto the growing crops, and (2) a long-term pathway resulting from root uptake, and possibly soil ingestion by animals, from contaminated soil. The growing season pathway can contaminate only those crops being grown at the time of the accident. The resulting dose to the population will depend on the day in the year when the accident occurs. The growing seasons for the individual crop categories are indicated in Table 1. If the accident occurs outside the growing season, there will be no dose from the growing season pathway. In contrast, the long-term root uptake of radioactive material into food products may span many successive growing seasons. The dose resulting from the long-term pathway is independent of the time of the year when the accident occurs. The manner in which the transfer factors TF_{ij} appearing in Eq. (7) are defined in the MACCS food pathways model for growing-season dose and soil-uptake dose are summarized in Table 3.

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Table 3. Transfer Factors (TF_{ij}) from Deposition to Crop Category j for Radionuclide i (adapted from Table 3.2 of Ref. 3)

Growing-Season Doses	
Crop-to-Man:	$TF_{ij} = FPLSCH_{ij} DCYPCH_{ij} CTD_{ij}$
Crop-to-Milk-to-Man:	$TF_{ij} = DCYPMH_i TFMLK_i DCYPCM_{ij} CTD_{ij}$
Crop-to-Meat-to-Man:	$TF_{ij} = DCYPBH_i TFBF_i DCYPCB_{ij} CTD_{ij}$
Soil-Uptake Doses	
Crop-to-Man:	$TF_{ij} = FPLSCH_{ij} DCYPCH_{ij} TCROOT_{ij}$
Crop-to-Milk-to-Man:	$TF_{ij} = DCYPMH_i TFMLK_i DCYPCM_{ij} TCROOT_{ij}$
Crop-to-Meat-to-Man:	$TF_{ij} = DCYPBH_i TFBF_i DCYPCB_{ij} TCROOT_{ij}$

Table 3 (concluded)

Definition of Terms			
Retention/ Transfer Factors*	Relevant Phenomena	Time Delay	
		From	To
<i>CTD</i>	weathering radioactive decay	deposition onto plants	harvest
<i>DCYPBH</i>	meat trimming radioactive decay	slaughter	consumption
<i>DCYPCB</i>	radioactive decay	harvest	consumption
<i>DCYPCM</i>	radioactive decay	harvest	consumption
<i>DCYPCH</i>	radioactive decay	harvest	consumption
<i>DCYPMH</i>	radioactive decay	production of milk	consumption
<i>FPLSCH</i>	food processing food preparation	harvest	consumption
<i>TCROOT</i>	radioactive decay percolation binding with soil	deposition onto soil	harvest
<i>TFBF</i>	biological filtration radioactive decay	feed consumption	slaughter
<i>TFMLK</i>	biological filtration radioactive decay	feed consumption	milk production
*All retention/transfer factors are dimensionless.			

All of the variables used in Table 3 in the definition of the transfer factor TF_{ij} are input variables to MACCS except for *CTD*; a summary of the values used for these variables in the Surry analysis is given in Table 4. The variable *CTD* is defined on the basis of the time of year at which an accident occurs and additional MACCS input variables that define interception fractions, weathering half-lives and growing seasons for different crop categories (Ref. 3, pp. 3-26 to 3-28; Ref. 32, Section 4.3.1). The

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values used for interception fractions and weathering half-lives are given in Table 5, and crop growing seasons are defined in Table 1.

**Table 4. Values for Retention/Transfer Factors Appearing in Table 3
Used in Analysis for Surry**

Retention and transfer factors involving milk and meat (Ref. 32, Tables 4.10, 4.17, 4.37, 4.42).				
Nuclide	Retention Factors Processing and Decay		Transfer Factors (Bq Transferred)/(Bq Ingested)	
	Milk/Man <i>DCYPMH</i>	Meat/Man <i>DCYPBH</i>	Milk <i>TFMLK</i>	Meat <i>TFBF</i>
Sr-89	0.66	0.77	0.022	0.00022
Sr-90	1.0	1.0	0.022	0.00022
Cs-134	1.0	1.0	0.11	0.023
Cs-137	1.0	1.0	0.11	0.024
I-131	0.28	0.18	0.13	0.0024
I-133	0.002	0.0	0.062	0.0011

Transfer factor from soil to plant by root-uptake (and by soil ingestion for grazing on pasture) integrated over all time [(Bq transferred)/(Bq deposited)] (Ref. 32, Tables 4.29, 4.30).							
Nuclide	Pasture <i>TCROOT</i>	Stored Forage <i>TCROOT</i>	Grains <i>TCROOT</i>	Green Leafy Vegetables <i>TCROOT</i>	Other Food Crops <i>TCROOT</i>	Legumes and Seeds <i>TCROOT</i>	Roots and Tubers <i>TCROOT</i>
Sr-89	4.1×10^{-4}	1.3×10^{-3}	4.3×10^{-5}	1.7×10^{-4}	8.6×10^{-6}	3.7×10^{-4}	1.1×10^{-4}
Sr-90	2.6×10^{-2}	9.0×10^{-2}	3.3×10^{-3}	1.3×10^{-2}	6.6×10^{-4}	2.8×10^{-2}	8.4×10^{-3}
Cs-134	1.3×10^{-3}	7.1×10^{-4}	3.5×10^{-5}	1.4×10^{-5}	1.1×10^{-4}	9.3×10^{-5}	5.6×10^{-5}
Cs-137	6.9×10^{-3}	1.5×10^{-3}	7.6×10^{-5}	3.0×10^{-5}	2.3×10^{-4}	2.0×10^{-4}	1.2×10^{-4}
I-131	1.6×10^{-4}	0.0	0.0	0.0	0.0	0.0	0.0
I-133	1.7×10^{-6}	0.0	0.0	0.0	0.0	0.0	0.0

Model Description

Table 4 (continued)

Radioactive decay retention factors (i.e., $1 - F$, where F = fraction of radioactivity lost by decay) for radionuclides in crops from time of harvest to time of consumption by humans (Ref. 32, Table 4.13).							
Nuclide	Pasture <i>DCYPCH</i>	Stored Forage <i>DCYPCH</i>	Grains <i>DCYPCH</i>	Green Leafy Vegetables <i>DCYPCH</i>	Other Food Crops <i>DCYPCH</i>	Legumes and Seeds <i>DCYPCH</i>	Roots and Tubers <i>DCYPCH</i>
Sr-89	NA ^a	NA	0.18	0.67	0.21	0.18	0.18
Sr-90	NA	NA	0.99	1.0	0.99	0.99	0.99
Cs-134	NA	NA	0.84	0.96	0.85	0.84	0.84
Cs-137	NA	NA	0.99	1.0	0.99	0.99	0.99
I-131	NA	NA	0.0099	0.21	0.024	0.0099	0.0099
I-133	NA	NA	0.0	0.0	0.0	0.0	0.0
Crop processing and preparation retention factors for radionuclides in food crops consumed by humans (Ref. 32, Table 4.20). Factors account for loss of radionuclides from foods due to processing (e.g., washing of fruit, peeling of potatoes, losses during canning) and food preparation (cooking) from the time of processing of the harvested crop to the time of consumption by humans. Factors do not reflect losses due to radioactive decay.							
Nuclide	Pasture <i>FPLSCH</i>	Stored Forage <i>FPLSCH</i>	Grains <i>FPLSCH</i>	Green Leafy Vegetables <i>FPLSCH</i>	Other Food Crops <i>FPLSCH</i>	Legumes and Seeds <i>FPLSCH</i>	Roots and Tubers <i>FPLSCH</i>
Sr-89	NA	NA	0.25	0.5	0.71	0.8	0.8
Sr-90	NA	NA	0.25	0.5	0.71	0.8	0.8
Cs-134	NA	NA	0.25	0.5	0.71	0.8	0.8
Cs-137	NA	NA	0.25	0.5	0.71	0.8	0.8
I-131	NA	NA	0.33	0.5	0.71	0.8	0.8
I-133	NA	NA	0.33	0.5	0.71	0.8	0.8

Table 4 (concluded)

Retention factors for radionuclides in crops from time of harvest to time of consumption by milk-producing and meat-producing animals (Ref. 32, Table 4.11). Factors account for losses due to radioactive decay.							
Nuclide	Pasture <i>DCYPCB</i> <i>DCYPCM</i>	Stored Forage <i>DCYPCB</i> <i>DCYPCM</i>	Grains <i>DCYPCB</i> <i>DCYPCM</i>	Green Leafy Vegetables <i>DCYPCB</i> <i>DCYPCM</i>	Other Food Crops <i>DCYPCB</i> <i>DCYPCM</i>	Legumes and Seeds <i>DCYPCB</i> <i>DCYPCM</i>	Roots and Tubers <i>DCYPCB</i> <i>DCYPCM</i>
Sr-89	1.0	0.37	0.20	NA	NA	0.20	NA
Sr-90	1.0	0.99	0.99	NA	NA	0.99	NA
Cs-134	1.0	0.92	0.85	NA	NA	0.85	NA
Cs-137	1.0	0.99	0.99	NA	NA	0.99	NA
I-131	1.0	0.063	0.032	NA	NA	0.032	NA
I-133	1.0	0.0068	0.0034	NA	NA	0.0034	NA

*Not applicable

Model Description

Table 5. Values Used in Definition of Transfer Factor *CTD* Appearing in Table 3 for Accidents Occurring During the Crop Growing Season in the Analysis for Surry

<p>Losses due to weathering from plant surfaces and during translocation from plant surfaces to interior edible portions of plants are modelled by</p> <p>Fraction Retained = $CTCOEF1 \exp(-\ln 2 \Delta t / CTHALF1) + CTCOEF2 \exp(-\ln 2 \Delta t / CTHALF2)$,</p> <p>where Δt is the time from the accident to the end of the growing season. Growing seasons are defined in Table 1. For pasture, stored forage, green leafy vegetables, and other food crops, this equation is used as a two term weathering equation. Time periods of 14 days (1.21×10^6 s) and 50 days (4.32×10^6 s) are used for weathering. For grains, legumes and seeds, and roots and tubers, where radionuclides are consumed only if translocated to edible portions of the plant, this equation is reduced to a translocation transfer factor by setting <i>CTCOEF2</i> to zero, <i>CTHALF2</i> to one second and <i>CTHALF1</i> to one million years (1×10^{13} s) and using <i>CTCOEF1</i> as a translocation factor.</p>								
Direct deposition transfer coefficients [(Bq intercepted)/(Bq deposited)] (Ref. 32, Tables 4.8, 4.9)								
	Nuclide	Pasture	Stored Forage	Grains	Green Leafy Vegetables	Other Food Crops	Legumes and Seeds	Roots and Tubers
<i>CTCOEF1</i>	Sr-89	0.3	0.2	0.01	0.24	0.2	0.005	0.0006
<i>CTCOEF1</i>	Sr-90	0.3	0.2	0.01	0.24	0.2	0.005	0.0006
<i>CTCOEF1</i>	Cs-134	0.3	0.2	0.05	0.24	0.2	0.01	0.025
<i>CTCOEF1</i>	Cs-137	0.3	0.2	0.05	0.24	0.2	0.01	0.025
<i>CTCOEF1</i>	I-131	0.3	0.2	0.0	0.24	0.2	0.0	0.0
<i>CTCOEF1</i>	I-133	0.3	0.2	0.0	0.24	0.2	0.0	0.0
<i>CTCOEF2</i>	Sr-89	0.076	0.05	0.0	0.06	0.05	0.0	0.0
<i>CTCOEF2</i>	Sr-90	0.076	0.05	0.0	0.06	0.05	0.0	0.0
<i>CTCOEF2</i>	Cs-134	0.076	0.05	0.0	0.06	0.05	0.0	0.0
<i>CTCOEF2</i>	Cs-137	0.076	0.05	0.0	0.06	0.05	0.0	0.0
<i>CTCOEF2</i>	I-131	0.076	0.05	0.0	0.06	0.05	0.0	0.0
<i>CTCOEF2</i>	I-133	0.076	0.05	0.0	0.06	0.05	0.0	0.0

Table 5 (concluded)

Crop transfer half-lives (s) (Ref. 32, Table 4.8)								
	Nuclide	Pasture	Stored Forage	Grains	Green Leafy Vegetables	Other Food Crops	Legumes and Seeds	Roots and Tubers
<i>CTHALF1</i>	Sr-89	1.21×10^6	1.21×10^6	1×10^{13}	1.21×10^6	1.21×10^6	1×10^{13}	1×10^{13}
<i>CTHALF1</i>	Sr-90	1.21×10^6	1.21×10^6	1×10^{13}	1.21×10^6	1.21×10^6	1×10^{13}	1×10^{13}
<i>CTHALF1</i>	Cs-134	1.21×10^6	1.21×10^6	1×10^{13}	1.21×10^6	1.21×10^6	1×10^{13}	1×10^{13}
<i>CTHALF1</i>	Cs-137	1.21×10^6	1.21×10^6	1×10^{13}	1.21×10^6	1.21×10^6	1×10^{13}	1×10^{13}
<i>CTHALF1</i>	I-131	1.21×10^6	1.21×10^6	1.0	1.21×10^6	1.21×10^6	1.0	1.0
<i>CTHALF1</i>	I-132	1.21×10^6	1.21×10^6	1.0	1.21×10^6	1.21×10^6	1.0	1.0
<i>CTHALF2</i>	Sr-89	4.32×10^6	4.32×10^6	1.0	4.32×10^6	4.32×10^6	1.0	1.0
<i>CTHALF2</i>	Sr-90	4.32×10^6	4.32×10^6	1.0	4.32×10^6	4.32×10^6	1.0	1.0
<i>CTHALF2</i>	Cs-134	4.32×10^6	4.32×10^6	1.0	4.32×10^6	4.32×10^6	1.0	1.0
<i>CTHALF2</i>	Cs-137	4.32×10^6	4.32×10^6	1.0	4.32×10^6	4.32×10^6	1.0	1.0
<i>CTHALF2</i>	I-131	4.32×10^6	4.32×10^6	1.0	4.32×10^6	4.32×10^6	1.0	1.0
<i>CTHALF2</i>	I-133	4.32×10^6	4.32×10^6	1.0	4.32×10^6	4.32×10^6	1.0	1.0

2.2 Interdiction

In addition to the transport of released radionuclides with a Gaussian plume model and the calculation of population exposure with the model indicated in Eq. (7), the MACCS food pathways model also implements interdiction criteria to mitigate population dose from both the growing season and long-term pathways. When an accident occurs within the growing season, the necessity for the disposal of milk within spatial element l is determined on the basis of a milk dose ratio MDR_l , defined by

$$MDR_l = \sum_i (GC_{il} / PCSMLK_i) \quad , \quad (8)$$

where $PCSMLK_i$ is a user-specified maximum permissible ground concentration (Bq/m²) of radionuclide i for milk production. Milk disposal occurs for three months in spatial element l when $MDR_l > 1$ (Ref. 3, p. 5-16). Similarly, the necessity for the disposal of crops within spatial element l is determined on the basis of a non-milk dose ratio $NMDR_l$, defined by

$$NMDR_l = \sum_i (GC_{il} / PSCOTH_i) \quad , \quad (9)$$

where $PSCOTH_i$ is a user-specified maximum permissible ground concentration (Bq/m²) of radionuclide i for crop production. Crop disposal occurs for one growing season in spatial element l if $NMDR_l > 1$ (Ref. 3, p. 5-16). Derivations for $PCSMLK_i$ and $PSCOTH_i$ are given in Appendix C of Ref. 3. The values for $PCSMLK$ and $PSCOTH$ used in the Surry analysis are summarized in Table 6.

Model Description

Table 6. Permissible Ground Concentrations (Bq/m²) and Soil Depletion Rates (yr⁻¹) Used in Surry Analysis to Evaluate Crop Disposal and Interdiction of Farmland

<p>Permissible ground concentrations (<i>PSCMLK</i>, <i>PSCOTH</i>, <i>GCMAXR</i>) were derived by inverting the food pathway model, thereby making the dose to an organ the independent variable and ground concentration the dependent variable (Ref. 32, Table 4.47). Permissible ground concentrations were calculated assuming (1) allowable first year (i.e., direct deposition) organ doses of 15 rem to thyroid and 5 rem to any other organ, and (2) allowable doses in subsequent years (i.e., root uptake) of 1.5 rem to thyroid and 0.5 rem to any other organ. Depletion rates (<i>QROOT</i>) were derived from processes involving radioactive decay, percolation and irreversible binding to soil (Ref. 32, Table 4.48).</p>				
Nuclide	Growing Season Milk <i>PSCMLK</i> (Bq/m ²)	Growing Season Other Crops <i>PSCOTH</i> (Bq/m ²)	Long Term All Crops <i>GCMAXR</i> (Bq/m ²)	Annual Depletion Rate <i>QROOT</i> (yr ⁻¹)
Sr-89	2.1×10^6	2.2×10^6	8.3×10^5	4.9
Sr-90	4.6×10^4	5.1×10^4	4.0×10^3	0.065
Cs-134	1.4×10^5	9.6×10^4	1.1×10^5	0.59
Cs-137	1.9×10^5	1.3×10^5	1.2×10^5	0.28
I-131	1.0×10^5	9.2×10^6	2.1×10^7	32.0
I-133	1.2×10^9	1.0×10^{20}	1.6×10^{12}	290.0

The interdiction of long-term food pathways is based on three criteria: habitability, maximum allowable ground concentrations for crop production, and cost effectiveness. Specifically, land is (1) temporarily removed from crop production if the projected long-term groundshine and inhalation doses to an individual living on the land would exceed a specified dose level (2 rem in first year and 0.5 rem/yr for years 2 through 5 for effective whole body dose equivalent in this analysis), (2) temporarily removed from crop production if maximum allowable ground concentrations (Bq/m²) for crop production are exceeded (MACCS variable *GCMAXR* defined in Table 6), and (3) permanently interdicted (i.e., condemned) if the cost of returning the land to agricultural production within eight years of the accident exceeds the value of the land and its associated investments. Each of these interdiction criteria are now discussed in more detail.

The decision on whether the people residing in a given spatial element are allowed to return after temporary relocation or evacuation depends on the habitability criterion indicated in the preceding paragraph and the cost effectiveness of protective actions such as decontamination and temporary interdiction. Two protective measures are considered to restore habitability: decontamination only and a combination of decontamination and temporary interdiction. The MACCS decontamination model assumes that several decontamination methods will be available for both farm and non-farm property. For each decontamination method, the model requires a cost per hectare for farm property (MACCS variable *CDFRM*) and per person for non-farm property (MACCS variable *CDNFRM*) and a decontamination factor F_D (MACCS variable *DSRFCT*), where

$$F_D = C_i / C_f \quad (10)$$

and C_i and C_f are the surface contamination levels before and after decontamination. These variables and other variables used in conjunction with the MACCS decontamination model in the Surry analysis are summarized in Table 7.

Based on a projection of exposures resulting from groundshine and inhalation of resuspended radionuclides (see Section 2.3) over a user-specified projection period (5 yr in the Surry analysis), MACCS determines if a given spatial element is immediately habitable. A spatial element is considered to be habitable if the projected dose commitment to the critical organ (effective whole body dose equivalent in the Surry analysis) does not exceed a user specified dose limit (2 rem in first year and 0.5 rem/yr for next four years in Surry analysis). If a spatial element is immediately habitable, the resident population is assumed to be present for the entire long-term period and no mitigative actions are taken to limit their exposure. If the evaluation of the long-term phase criterion indicates that the spatial element is not immediately habitable, mitigative actions are taken to assure that the criterion is not exceeded. The mitigative actions are evaluated in a predetermined sequence to select the least stringent action that will allow the dose criterion to be satisfied. The order of these actions is: (1) decontamination alone, (2) maximum level of decontamination followed by an interdiction period, and (3) permanent interdiction (condemnation) of the property. A given level of decontamination is considered to restore habitability if the projected dose over the projection period does not exceed the dose limit, with the projection period starting at the time of the prospective return of the resident population.

Table 7. Variables Used in Conjunction with the Decontamination Model in MACCS in the Surry Analysis (Ref. 32, Appendix A.3; Ref. 39)

Description	MACCS Variable	Decontamination Level 1	Decontamination Level 2
Dose Reduction Factor	<i>DSRFCT</i>	3	15
Cost Farm Decontamination (\$/Ha)	<i>CDFRM</i>	562.5	1250.
Cost Nonfarm Decontamination (\$/Person)	<i>CDNFRM</i>	3000.	8000.
Decontamination Time (Days)	<i>TIMDEC</i>	60.	120.
Fraction Farm Cost Due to Labor	<i>FRFDL</i>	0.3	0.35
Fraction Nonfarm Cost Due to Labor	<i>FRNFDL</i>	0.7	0.5
Fraction Farm Labor Time in Decontamination Work	<i>TFWKF</i>	0.1	0.33
Fraction Nonfarm Labor Time in Decontamination Work	<i>TFWKNF</i>	0.33	0.33
Average Cost of Decontamination Labor (\$/man-yr)	<i>DLBCST</i>	35000	35000

To evaluate the cost effectiveness of decontamination or decontamination followed by temporary interdiction of nonfarm areas, the following criteria are used in MACCS: (1) If a spatial element cannot be

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restored to habitability by decontamination followed by temporary interdiction, then the spatial element is condemned permanently. (2) If a spatial element is not permanently condemned by the preceding criterion and the cost of decontamination and temporary interdiction of the property is less than the cost of condemning the property, then people residing in the spatial element are allowed to return after the interdiction period. (3) If a spatial element is not permanently condemned by the first criterion and the cost of decontamination and temporary interdiction of the property is greater than or equal to the value of the property, then the property is condemned permanently. The determination of costs in the MACCS economic model is discussed in Section 2.4.

When farmland is habitable, a need may still exist to restrict long-term crop production if radionuclide concentrations are too high (Ref. 3, Section 5.3.3.1). The allowable ground concentrations for long-term crop production are defined by the MACCS variable GC_{MAXR} as indicated in Table 6. A discussion on the derivation of GC_{MAXR} is given in Appendix C of Ref. 3. The determination of when the radionuclide concentrations in spatial element l are sufficiently low to permit crop production are made on the basis of the ratio

$$RS_l = \sum_i [GC_{ii} \exp(-YRS_l QROOT_i)] / GC_{MAXR_i} \quad , \quad (11)$$

where YRS_l is the time period (yr) over which crop production in spatial element l will be prohibited, GC_{MAXR_i} is the maximum allowable ground concentration (Bq/m^2) of radionuclide i for long-term crop production (see Table 6), $QROOT$ is the annual depletion rate (yr^{-1}) for loss of radionuclide i due to radioactive decay, percolation and irreversible binding to soil (see Table 6), and GC_{ii} has been defined previously. Crop production is assumed to resume in spatial element l for the smallest integer value of YRS_l for which $RS_l < 1$.

To evaluate the cost effectiveness of decontamination of farmland or decontamination followed by temporary interdiction of crop production, the following steps are used in MACCS (Ref. 3, Section 5.3.2.2): (1) If a spatial element is condemned permanently according to the habitability criterion or the restriction on crop production exceeds eight years, farmland is assumed to be permanently condemned. Cost effectiveness is not evaluated. (2) If the farmland in a spatial element is not permanently condemned and the cost of farmland decontamination and temporary interdiction is less than the value of the farmland and associated investments, then the farmland of that spatial element is allowed to return to production after a period of interdiction. The interdiction period ends at the larger of the two following times: (i) the time at which farmland meets the habitability criterion, and (ii) the time at which farmland can return to crop production. (3) If a spatial element is not permanently condemned but the cost of farmland decontamination and temporary interdiction is greater than or equal to the value of the farmland and associated investments, then the farmland is permanently condemned. The determination of costs in the MACCS economic model is described in Section 2.4.

2.3 Groundshine, Inhalation and Water Ingestion Doses

The groundshine dose $DG_k(t_1, t_2)$ (Sv) to organ k of an individual in spatial element l between times t_1 and t_2 is given by (Ref.3, Section 3.2.2)

$$DG_k(t_1, t_2) = \left[\sum_i GC_{ik} DFG_{ik}(t_1, t_2) \right] SFG, \quad (12)$$

where $DFG_{ik}(t_1, t_2)$ is the groundshine dose factor (Sv-m²/Bq) for organ k and radionuclide i for exposures incurred between time t_1 and t_2 , SFG is a groundshine shielding factor (dimensionless), and GC_{ik} has been defined previously. In the Surry analysis, the groundshine shielding factor for normal activity (MACCS variable $GSHFAC$) is 0.33 (Ref. 32, Appendix A.2; also see Ref. 32, Section 3.2). The dose factor $DFG_{ik}(t_1, t_2)$ is given by

$$DFG_{ik}(t_1, t_2) = DRFG_{ik} \int_{t_1}^{t_2} GW(t) \exp(-\lambda_i t) dt, \quad (13)$$

where $DRFG_{ik}$ is the groundshine dose rate conversion factor (Sv-m²/Bq-s) for organ k and radionuclide i (see Table 2), $GW(t)$ is Gale's weathering function as defined in Eq. (14), and λ_i is the decay constant for radionuclide i as previously defined. Gale's equation⁴⁰ for the attenuation of groundshine due to weathering is given by

$$GW(t) = \sum_{m=1}^2 GWCOEF_m \exp(-t \ln 2 / TGWHLF_m), \quad (14)$$

where $GWCOEF_m$ is a weathering coefficient (dimensionless), $TGWHLF_m$ is a weathering halflife(s) and t is the time (s) since the initial deposition. In the Surry analyses, $GWCOEF_m = 0.5$ for $m = 1$ and 2 , $TGWHLF_1 = 1.6 \times 10^7$ s (i.e., a weathering halflife of 0.5 yr) and $TGWHLF_2 = 2.8 \times 10^9$ s (i.e., a weathering halflife of 90 yr) (Ref. 32, Section 2.7).

The resuspension inhalation dose $DR_k(t_1, t_2)$ (Sv) to organ k of an individual in spatial element l between times t_1 and t_2 is given by (Ref. 3, Section 3.2.3)

$$DR_k(t_1, t_2) = \left[\sum_i GC_{ik} DFR_{ik}(t_1, t_2) \right] SFI, \quad (15)$$

where $DFR_{ik}(t_1, t_2)$ is the resuspension inhalation dose factor (Sv-m²/Bq) for organ k and radionuclide i for exposures incurred between times t_1 and t_2 , SFI is an inhalation shielding factor (dimensionless), and GC_{ik} has been defined previously. In the Surry analysis, the inhalation shielding factor for normal activity (MACCS variable $PROTIN$) is 0.41 (Ref. 32, Appendix A.2; also see Ref. 32, Section 3.2). The resuspension dose factor $DFR_{ik}(t_1, t_2)$ is given by

$$DFR_{ik}(t_1, t_2) = DFI_{ik} BR \int_{t_1}^{t_2} RW(t) \exp(-\lambda_i t) dt, \quad (16)$$

where DFI_{ik} is the inhalation dose conversion factor (Sv/Bq) for organ k and radionuclide i (see Table 2.2), BR is the breathing rate (m³/s), $RW(t)$ is the resuspension weathering function defined in Eq. (17),

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and λ_i is the decay constant for radionuclide i . The resuspension weathering function is similar to Gale's equation in Eq. (14) and is given by

$$RW(t) = \sum_{m=1}^3 RWCOEF_m \exp(-t \ln 2 / TRWHLF_m) , \quad (17)$$

where $RWCOEF_m$ is the resuspension coefficient (m^{-1}) for the m -th term, $TRWHLF_m$ is the resuspension half-life (s^{-1}) for the m -th term, and t is the time (s) since the initial deposition. The values used for $RWCOEF_m$ and $TRWHLF_m$ in the Surry analysis are given by $RWCOEF_1 = 1 \times 10^{-5} m^{-1}$, $RWCOEF_2 = 1 \times 10^{-7} m^{-1}$, $RWCOEF_3 = 1 \times 10^{-9} m^{-1}$, $TRWHLF_1 = 1.6 \times 10^7 s$ (6 mn), $TRWHLF_2 = 1.6 \times 10^8 s$ (5 yr) and $TRWHLF_3 = 1.6 \times 10^9 s$ (50 yr) (Ref. 32, Section 2.9).

Unlike the population dose given in Eq. (7), the groundshine and resuspension doses given in Eqs. (12) and (15) are individual doses. The actual population doses are determined in the following manner (Ref. 3, Section 5.3.1.3). If decontamination at level m (e.g., with a dose reduction factor of 3 ($m=1$) or 15 ($m=2$) in the Surry analysis as indicated in Table 7) is sufficient to meet the habitability criterion, people originally residing in a given spatial element are assumed to move back at the end of the decontamination period. Individual dose is obtained by adding the groundshine dose in Eq. (12) and the inhalation dose in Eq. (15), with the initial ground concentration GC_{il} in these equations reduced in accordance with the decontamination level used. The integration times in Eqs. (13) and (16) are defined with t_1 equaling the time at which people return after decontamination and t_2 equaling t_1 plus one million years. As all radionuclides typically considered in reactor accident consequence calculations with MACCS have half-lives that are short compared to one million years, the integration is effectively from t_1 to infinity. If the maximum decontamination effort fails to meet the dose criterion for immediate habitation and some temporary interdiction is cost effective to meet the habitability criterion, t_1 is the time at which the interdiction period ends. Population dose for a spatial element is then obtained by summing the individual doses.

The dose $DWNF_{kl}(t_1, t_2)$ (Sv) to organ k for decontamination workers engaged in the clean-up effort for nonfarm properties in spatial element l between times t_1 and t_2 is given by (Ref. 3, Section 5.3.2)

$$DWNF_{kl}(t_1, t_2) = FTIM \text{ NUMW}_l \text{ SFG} \sum_i GC_{il} DFG_{ik}(t_1, t_2) , \quad (18)$$

where $FTIM$ is the fraction of the decontamination period that workers actually spend in the area being decontaminated, NUMW_l is the number of workers required to perform decontamination in spatial element l , and the variables SFG , GC_{il} and $DFG_{ik}(t_1, t_2)$ have been defined previously. The time interval $[t_1, t_2]$ used in the definition of the groundshine dose factor $DFG_{ik}(t_1, t_2)$ in Eq. (13) is the time interval within which decontamination takes place and is defined by the MACCS variable $TIMDEC$ (see Table 7). The fraction $FTIM$ of the time interval $[t_1, t_2]$ that workers spend in the area being decontaminated is defined by the MACCS variable $TFWKNF$ (see Table 7). The number of workers NUMW_l is given by

$$NUMW_l = CSTDNF POPN_l FLBNF [LBCST TIMD]^{-1}, \quad (19)$$

where $CSTDNF$ is the decontamination cost (\$/person) for nonfarm property (MACCS variable $CDNFRM$ in Table 7), $POPN_l$ is the number of persons living in spatial element l (a MACCS input; see Ref. 32, Appendix A.3), $FLBNF$ is the fraction of nonfarm decontamination cost due to labor (MACCS variable $FRNFDL$ in Table 7), $LBCST$ labor cost (\$/worker-s) (MACCS variable $DLBCST$ in Table 7), and $TIMD$ is the time (s) required to perform decontamination (MACCS variable $TIMDEC$ in Table 7). The dose to workers engaged in the clean-up effort for farmland is determined in a similar manner (Ref. 3, Section 5.3.4).

The population dose D_{ikl} (Sv) to organ k due to water ingestion resulting from radionuclide i initially deposited in spatial element l is given by

$$D_{ikl} = DF_{ik} WINGF_{il} \left[\frac{\lambda_i WSHFRI_i + WSHRTA_i}{\lambda_i + WSHRTA_i} \right] TA_l GC_{il}, \quad (20)$$

where $WINGF_{il}$ is the fraction of radionuclide i entering surface water from spatial element l that will be consumed by man, $WSHFRI_i$ is the fraction of deposition of radionuclide i onto land surfaces that moves to surface-water bodies in a short period of time after deposition, $WSHRTA_i$ is the rate constant (s^{-1}) for the long-term movement of radionuclide i from land surfaces to surface-water bodies, TA_l is the area (m^2) of spatial element l , λ_i is the decay constant (s^{-1}) for radionuclide i , and the variables DF_{ik} and GC_{il} have been defined previously (Ref. 3, Section 3.2.5; Ref. 32, Section 2.8; Ref. 41). The preceding expression results from using the following differential equation to represent radionuclide movement from land surfaces to surface water bodies:

$$\frac{dx_{il}}{dt} = -(\lambda_i + WSHRTA_i) x_{il}, \quad x_{il}(0) = (1 - WSHFRI_i) TA_l GC_{il}, \quad (21)$$

where $x_{il}(t)$ is the amount of radionuclide i on land surfaces in spatial element l at time t . In the present analysis, $WINGF_{il}$ equals 5×10^{-6} or 0 depending on whether spatial element l is predominantly land or ocean; $WSHRTA_i$ equals $0.004 s^{-1}$ and $0.001 s^{-1}$ for strontium and cesium, respectively; and $WSHFRI_i$ equals 0.01 and 0.005 for strontium and cesium, respectively (Ref. 32, Section 2.8).

2.4 Interdiction Cost

The costs resulting from long-term protective actions have five sources (Ref. 3, Section 4.3): decontamination, decontamination followed by temporary interdiction of farm and urban areas, disposal of crops or products produced on farms, temporary prohibition of farm production, and condemnation of property. Long-term protective action costs are divided into two groups: farm costs and nonfarm costs. Specifically, the cost CL_l (\$) of long-term protective action in spatial element l is given by

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$$CL_i = CNF_i P_i + CF_i AF_i, \quad (22)$$

where CNF_i is the cost of long-term protective action for nonfarm property in spatial element i (\$/person), P_i is the population within spatial element i (persons), CF_i is the cost of long-term protective action for farm property in spatial element i (\$/Ha), and AF_i area of farmland within spatial element i (Ha). The population P_i is user-specified (Ref.32, Appendix A.3), and the farmland area AF_i is calculated by MACCS using site data (Ref. 32, Appendix A.3). The cost CNF_i of long-term protective action for nonfarm property is either the cost of restoring habitability or the cost of condemning the nonfarm property if it is not possible or cost effective to restore habitability. The cost CF_i of long-term protective action for farm property is the sum of (1) the cost of restoring habitability and farm production of the farm property or the cost of condemning the farm property and (2) the cost of crop disposal if the accident occurs during the growing season. The models used in MACCS in the estimation of these costs are now summarized.

A dose criterion for groundshine and inhalation exposure is used to determine if a spatial element is habitable. Decontamination without interdiction, decontamination with interdiction, or condemnation may be required for nonfarm property within any spatial element. The cost CNF_i (\$/person) of restoring habitability for nonfarm property in spatial element i is the sum of the costs for decontamination, relocation, and loss of usage of property. Specifically,

$$CNF_i = CDNFi + CR + CCNF_i, \quad (23)$$

where $CDNF_i$ is the cost of decontamination (\$/person) for nonfarm property (MACCS variable $CDNFRM$ in Table 7), CR is the relocation cost (\$/person) (MACCS variable $POPCST$, which equals \$5000/person in Surry analysis), and $CCNF_i$ is the cost for loss of usage of property (depreciation, deterioration, and losses) in spatial element i (\$/person) for nonfarm property. The cost $CCNF_i$ for loss of usage of nonfarm property is given by

$$CCNF_i = PVI_i + PVD_i, \quad (24)$$

where PVI_i is the present value (\$/person) of lost income due to interdiction of property in spatial element i and PVD_i is the present value (\$/person) of depreciation occurring due to interdiction of property in spatial element i . In turn, PVI_i and PVD_i are defined by

$$PVI_i = [VALW_i \exp(TH_i RIR) - VALW_i] \exp(-TH_i RIR) \quad (25)$$

and

$$PVD_i = [VALW_i FIM - VALW_i FIM \exp(-TH_i RDP)] \exp(-TH_i RIR), \quad (26)$$

where $VALW_i$ is the value of nonfarm wealth (\$/person) in spatial element i at the time of the accident, FIM is the fraction of nonfarm wealth resulting from improvements (i.e., $(1 - FIM) VALW_i$ is value of unimproved land in spatial element i), TH_i is the interdiction period (yr) in spatial element i , RIR is the inflation adjusted rate of investment return (yr^{-1}), and RDP is the depreciation rate during interdiction (yr^{-1}).

¹⁾. Values for $VALW_i$ are supplied through the MACCS input variable $VNFRM$ as indicated in Table 8. The variables FIM , RIR and RDP correspond to the MACCS input variables $FRNFIM$, $DSRATE$ and $DPRATE$ and are assigned values of 0.8, 0.12 yr^{-1} and 0.2 yr^{-1} , respectively, in the Surry analysis (Ref. 32, Sections 5.1, 5.2).

Model Description

Table 8. Regional Economic Data Used as Input to MACCS in Surry Analysis (Ref. 32, Appendix A.3)

Index ^a	Region ^b	FRMFRC ^c	DPF ^d	ASFP ^e (\$/Ha)	VFRM ^f (\$/Ha)	VNFRM ^g (\$/person)
1	ALA	.354	0.40	459.	1824.	62000.
2	ARIZ	.516	.104	110.	682.	74000.
3	ARK	.483	.041	466.	2049.	61000.
4	CALIF	.330	.144	1022.	4394.	93000.
5	COLO	.522	.048	211.	971.	83000.
6	CONN	.160	.294	1605.	4980.	107000.
7	DEL	.534	.042	1723.	3428.	82000.
8	FLA	.375	.080	832.	3341.	80000.
9	GA	.363	.060	613.	1885.	73000.
10	IDAHO	.270	.144	343.	1562.	61000.
11	ILL	.806	.044	709.	3900.	86000.
12	IND	.713	.079	611.	3283.	72000.
13	IOWA	.938	.060	695.	3133.	73000.
14	KANS	.917	.035	281.	1204.	81000.
15	KY	.571	.112	482.	1838	61000.
16	LA	.354	.074	459.	3284.	61000.
17	MAINE	.079	.260	662.	1133.	70000.
18	MD	.429	.216	956.	4489.	93000.
19	MASS	.136	.249	1349.	2563.	97000.
20	MICH	.313	.247	658.	2187.	81000.
21	MINN	.597	.223	516.	2111.	82000.
22	MISS	.470	.054	403.	2084.	53000.
23	MO	.703	.102	322.	1647.	76000.
24	MONT	.657	.030	61.	563.	65000.
25	NEBR	.962	.031	318.	1148.	75000.
26	NEV	.127	.139	63.	601.	84000.

Table 8 (continued)

Index ^a	Region ^b	FRMFRC ^c	DPF ^d	ASFP ^e (\$/Ha)	VFRM ^f (\$/Ha)	VNFRM ^g (\$/person)
27	N.H.	.096	.482	518.	2018.	87000.
28	N.J.	.203	.129	1399.	6477.	102000.
29	N.MEX	.590	.144	53.	473.	63000.
30	N.Y.	.310	.589	711.	1378.	94000.
31	N.C.	.352	.065	860.	2658	68000.
32	N.DAK	.924	.048	164.	948.	69000.
33	OHIO	.602	.175	581.	2686.	76000.
34	OKLA	.751	.060	204.	1508.	67000.
35	OREG	.292	.111	236.	1203.	73000.
36	PA	.303	.447	855.	2534.	78000.
37	R.I.	.108	.213	1062.	6438.	80000.
38	S.C.	.290	.084	472.	1843.	62000.
39	S.DAK	.915	.091	145.	587.	65000.
40	TENN	.509	.153	360.	1850.	66000.
41	TEX	.816	.064	164.	1492.	74000.
42	UTAH	.225	.259	123.	1286.	60000.
43	VT	.286	.789	628.	1472.	73000.
44	VA	.382	.198	371.	2075.	84000.
45	WASH	.377	.154	476.	1948.	82000.
46	W.VA	.246	.224	150.	1728.	58000.
47	WIS	.517	.591	723.	1751.	76000.
48	WYO	.561	.028	43.	380.	70000.
49	BRIT COL	.377	.154	476.	1948.	60000.
50	OCEAN	.000	.000	0.	0.	0.
51	SASKAT	.657	.030	61.	563.	60000.
52	MANITOBA	.924	.048	164.	948.	60000.

Model Description

Table 8 (concluded)

Index ^a	Region ^b	FRMFRC ^c	DPF ^d	ASFP ^e (\$/Ha)	VFRM ^f (\$/Ha)	VNFRM ^g (\$/person)
53	ONTARIO	.597	.223	516.	2111.	60000.
54	QUEBEC	.310	.589	711.	1378.	60000.
55	NOVA SCOT	.079	.260	662.	1133.	60000.
56	BAJA CAL	.330	.144	1022.	4394.	10000.
57	SONORA	.516	.104	110.	682.	10000.
58	CHIHUAHUA	.590	.144	53.	473.	10000.
59	COAHUILA	.816	.064	164.	1492.	10000.

^aIndex used to identify region in MACCS input.

^bName of Region.

^cFraction of land devoted to farming in region.

^dFraction of farm income in region resulting from dairy products.

^eAnnual farm income in region (\$/Ha).

^fValue of farm wealth in region (\$/Ha).

^gValue of non-farm wealth in region (\$/person).

The cost CF_i (\$) of restoring habitability and farm production for farm properties in spatial element i is determined in a manner similar to that used for non-farm properties. Specifically,

$$CF_i = CDF_i + CCF_i, \quad (27)$$

where CDF_i is the cost of decontamination for farm property in spatial element i (\$/Ha) and CCF_i is the cost for loss of usage of farm property (depreciation, deterioration, loss of income) (\$/Ha). The variable CDF_i is determined on the basis of the decontamination level used and the MACCS input variable $CDFRM$ (see Table 7). The variable CCF_i is determined in the same manner as $CCNF_i$ in Eqs. (24), (25) and (26) except that $VALW_i$ is value of farm wealth (\$/Ha) in spatial element i (MACCS variable $VFRM$ in Table 8) and FIM is the fraction of farm wealth resulting from improvements (MACCS variable $FRFIM$, which equals 0.25 in the Surry analysis). The variable TH_i is determined by MACCS and corresponds to the time at which farmland satisfies both the habitability criterion and the maximum allowable ground concentration criteria for farm production (Section 2.2). The value of TH_i used in the determination of CF_i may be different from the value of TH_i used in the determination CNF_i .

The model for growing season crop disposal estimates the costs of milk and other crop disposal for a reactor accident that occurs during the growing season. The cost of milk disposal CMD_i (\$) in spatial element i is given by

$$CMD_l = FP_l \cdot FDP_l \cdot FMD, \quad (28)$$

where FP_l is the value of annual farm production (\$/hectar) in spatial element l , FDP_l is the fraction of annual farm production value that comes from dairy products in spatial element l , and FMD is the fraction of the year over which milk disposal occurs (dimensionless). The variables FP_l and FDP_l are defined by the MACCS input variables $ASFP$ and DPF (see Table 8). The value of FMD is hard-wired in MACCS and equal to 0.25, which is equivalent to the assumption that milk disposal occurs for three months. Similarly, the expression

$$CNMD_l = FP_l (1 - FDP_l) \quad (29)$$

gives the cost $CNMD_l$ (\$/Ha) of the disposal of nondairy products in spatial element l .

The per person cost $CCNF_l$ (\$/person) to condemn nonfarm property in spatial element l is given by

$$CCNF_l = CR + VALW_l \quad (30)$$

where CR is the cost of relocating an individual (\$/person) and $VALW_l$ is the value of wealth for nonfarm property (\$/person) in spatial element l . The variables CR and $VALW_l$ have been discussed previously in conjunction with Eqs. (23), (25) and (26). The cost CCF_l (\$/Ha) to condemn farmland in spatial element l is the value of farm wealth in the spatial element, which is determined by the MACCS input variable $VFRM$ as indicated in Table 8.

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3 PROBLEM FOR ANALYSIS

To facilitate comparisons across analyses, this study and its two companion uncertainty/sensitivity studies^{5,6} use the same source term. In particular, the source term SUR-11-3 from the NUREG-1150 probabilistic risk assessment⁷ for the Surry Nuclear Power Station^{8,9} is used. This source term results from a steam generator tube rupture and is listed in Table 2 of Ref. 5. The following chemical group release fractions are associated with this source term: Noble gases ~ 1.0 , Iodine ~ 0.47 , Cesium ~ 0.45 , Tellurium ~ 0.25 , Strontium ~ 0.07 , Ruthenium ~ 0.002 , Lanthanum ~ 0.006 , Cerium ~ 0.008 , and Barium ~ 0.06 .

The performance of a MACCS calculation requires a large amount of input. The development of this input for use in the NUREG-1150 analyses is documented in Sprung et al.,³² with the actual MACCS input files used in the NUREG-1150 analyses for Surry appearing in Appendix A of the indicated report. The MACCS input for Surry described in Sprung et al.³² and summarized in Section 2 of this report is taken as the base-line description for the analysis problem considered in this study. Taken collectively, this input corresponds to the vector x shown in Eqs. (2) and (3). An overview of the analysis assumptions used in MACCS for the analyses contained in this presentation is given in Table 3 of Ref. 5.

After a review of the results in Sprung et al.³² and descriptions of the food pathways models in MACCS,^{2,3} the 87 variables listed in Table 9 were selected for consideration in this study. The distributions associated with the individual variables characterize subjective uncertainty and thus correspond to the distributions shown in Eq. (4). When done carefully, the development of such distributions is a very demanding task and requires detailed knowledge of the operation of the model under consideration, extensive literature review, and interaction with many individual investigators who are knowledgeable about the individual variables. The ranges in Table 9 were developed by the investigators in this study and are not the result of a comprehensive review process. In particular, ranges were obtained for each variable by applying a multiplicative scale factor to a central or "best-estimate" value. For example, the best-estimate value for AF (fraction of intercepted radionuclides undergoing rapid weathering from crop surfaces for pasture, forage, green leafy vegetables and "other" food) was assigned a best-estimate value of 0.2, with an uncertainty scale factor of 1.25. In turn, this produced an uncertainty range for AF from $0.2/1.25 = 0.16$ to $0.2(1.25) = 0.25$. All variables listed in Table 9 were assigned log uniform distributions, which assured both the full coverage of the range of each uncertain variable and an equal probability for values of a variable above and below the best-estimate value. The intent is for this preliminary assessment of subjective uncertainty to help identify the most important contributors to the (subjective) uncertainty in MACCS results. Then, efforts can be focused on characterizing the uncertainty in the inputs that have significant impacts on the uncertainty in predictions made by MACCS.

The correlations indicated in Table 9 are rank correlations, which provide a measure of the extent to which variables tend to move up and down together.^{42, 43} Rank correlations also have the desirable property that they are independent of the distributions assigned to the individual variables. The assigned correlations result from the belief that many MACCS input variables are not independent but are rather influenced by common underlying variables. The reactor accident consequences selected in this study are listed in Table 10. The predicted values for these consequences constitute the elements of the vector cS_i appearing in Eq. (1).

Problem for Analysis

Table 9. Imprecisely Known Variables Selected for Inclusion in an Uncertainty/Sensitivity Study of the MACCS Food Pathways Model

Variable	Description
AF	Fraction of intercepted radionuclides undergoing rapid weathering from crop surfaces for pasture, forage, green leafy vegetables and "other" food. Used in definition of MACCS variable CTCOE1 for weathering of radionuclides from pasture, forage, green leafy vegetables and "other" food; see IF1, IF2, IF5, IF7. Range: 0.16 - 0.25 (i.e., 0.2×1.25). Additional information: Sec. 4.3, Ref. 32; Sec. 3.2.4, Ref. 2.
C1GCS	Fraction of cesium deposition onto grain fields that is retained on plant surfaces and transferred directly to grain. Defines MACCS variable CTCOE1 for weathering of cesium from grain, which in conjunction with an infinite (i.e., 1×10^6 yr) weathering half-life produces a transfer factor rather than a weathering term. Range: 0.025 - 0.1 (i.e., 0.05×2). Additional information: p. A-25, Appendix A, Ref. 32.
C1GSR	Same as C1GCS but for strontium. Range: 0.005 - 0.02 (i.e., 0.01×2).
C1LCS	Same as C1GCS but for legumes. Range: 0.005 - 0.02 (i.e., 0.01×2).
C1LSR	Same as C1GSR but for legumes. Range: 0.0025 - 0.01 (i.e., 0.005×2).
C1RCS	Same as C1GCS but for roots and tubers. Range: 0.0125 - 0.05 (i.e., 0.025×2).
C1RSR	Same as C1GSR but for roots and tubers: Range: 0.0003 - 0.0012 (i.e., 0.006×2).
CDELAY	Time (days) from slaughter of animal to consumption of meat. Used in definition of MACCS variable DCYPBH. Range: 16 - 25 days (i.e., $20 \text{ days} \times 1.25$). Additional information: Sec. 4.3.2, Ref. 32; Sec. 3.2.4, Ref. 2.
CTHALF1	Half-life (days) for rapid weathering of deposited radionuclides from plant surfaces. Defines MACCS variable CTHALF for pasture, forage, grain, green leafy vegetables and "other" foods. Range: 11.2 - 17.5 days (i.e., $14 \text{ days} \times 1.25$). Additional information: Same as AF.
CTHALF2	Same as CTHALF1 but for slow weathering. Range: 40 - 62.5 days (i.e., $50 \text{ days} \times 1.25$).
FDELAY	Time (days) from harvest of forage to consumption by cattle. Used in definition of MACCS variables DCYPCB, DCYPCM. Range: 73.6 - 115 days (i.e., $92 \text{ days} \times 1.25$). Additional information: Sec. 4.3.3, Ref. 32; Sec. 3.2.4, Ref. 2.
FPLSCHG	Fraction of radionuclides present in grain at harvest that is retained until consumption by man. Does not account for losses due to radioactive decay. Defines MACCS variable FPLSCH for grains. Range: 0.2 - 0.31 (i.e., 0.25×1.25). Additional information: Sec. 4.3.6, Ref. 32; Sec. 3.2.4, Ref. 2.
FPLSCHL	Same as FPLSCHG but for legumes. Range: 0.64 - 1.0 (i.e., 0.8×1.25).
FPLSCHO	Same as FPLSCHG but for "other" foods. Range: 0.568 - 0.888 (i.e., 0.75×1.25).

Table 9 (continued)

Variable	Description
FPLSCHR	Same as FPLSCHG but for roots and tubers. Range: 0.64 - 1.0 (i.e., 0.8×1.25).
FPLSCHV	Same FPLSCHG but for green leafy vegetables. Range: 0.4 - 0.625 (i.e., 0.5×1.25).
FRCTCMF	Fraction of forage consumed by milk-producing animals. MACCS variables FRCTCM and FRCTCB for consumption of forage by milk- and meat-producing animals defined by FRCTCMF and 1-FRCTCMF, respectively. Range: 0.104 - 0.163 (i.e., 0.13×1.25). Additional information: Sec. 4.3.7, Ref. 32; Sec. 3.2.4, Ref. 2.
FRCTCMG	Fraction of grain consumed by milk-producing animals. MACCS variables FRCTCM and FRCTCB for consumption of grain by milk- and meat-producing animals defined by FRCTCMG and 1-FRCTCMG-FRCTCHG, respectively. Range: 0.032 - 0.05 (i.e., 0.04×1.25). Additional information: Same as FRCTCMF.
FRCTCML	Same as FRCTCMG but for legumes, with FRCTCHL used in the definition of MACCS variable FRCTCB for consumption of legumes by meat-producing animals. Range: 0.0368 - 0.0575 (i.e., 0.046×1.25).
FRCTCMP	Same as FRCTCMF but for pasture. Range: 0.08 - 0.125 (i.e., 0.01×1.25).
FRCTCHG	Fraction of grain consumed by humans. Defines MACCS variable FRCTCH for consumption of grain by humans. Range: 0.28 - 0.438 (i.e., 0.35×1.25). Additional information: Same as FRCTCMF.
FRCTCHL	Same as FRCTCHG but for legumes. Range: 0.192 - 0.3 (i.e., 0.24×1.25).
GCMSR89	Maximum allowable Sr89 ground concentration (Bq/m ²) for production of crops that assures the lifetime dose criteria will be met (i.e., the Federal Department of Agriculture protective action guide that the long-term doses to the thyroid and the whole body should be less than 0.015 Sv and 0.005 Sv, respectively ⁴⁴). Defines MACCS variable GCMAXR for Sr90. Range: 1.79×10^7 - 1.79×10^9 Bq/m ² (i.e., 1.79×10^8 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with GCMSR90; -0.5 rank correlation with TCPSR89, TCPSR90, TCFSR89, TCFSR90, TCGSR89, TCGSR90, TCLSR89, TCLSR90, TCVSR89, TCVSR90, TCRSR89, TCRSR90, TCOSR89, TCOSR90. Additional information: Sec. 4.4, Ref. 32; Appendix C, Ref. 2.
GCMSR90	Same as GCMSR89 but for Sr90. Range: 3.67×10^3 - 3.67×10^5 Bq/m ² (i.e., 3.67×10^4 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with GCMSR89; -0.5 rank correlation with TCPSR89, TCPSR90, TCFSR89, TCFSR90, TCGSR89, TCGSR90, TCLSR89, TCLSR90, TCVSR89, TCVSR90, TCRSR89, TCRSR90, TCOSR89, TCOSR90.
GCMCS134	Same as GCMSR89 but for Cs134. Range: 4.07×10^5 - 4.07×10^7 Bq/m ² (i.e., 4.07×10^6 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with GCMCS137; -0.5 rank correlation with TCPCS134, TCPCS137, TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCVCS134, TCVCS137, TCRCS134, TCRCS137, TCOC134, TCOC137.

Problem for Analysis

Table 9 (continued)

Variable	Description
GCMCS137	Same as GCMC89 but for Cs137. Range: 1.76×10^5 - 1.76×10^7 Bq/m ² (i.e., 1.76×10^6 Bq/m ² $\times$ 10). Correlation: 0.75 rank correlation with GCMCS134; -0.5 rank correlation with TCPCS134, TCPCS137, TCFCS134, TCFCS137, TCGS134, TCGCS137, TCLCS134, TCLCS137, TCVCS134, TCVCS137, TCRCS134, TCRCS137, TCOC134, TCOC137.
GDELAY	Time (days) from harvest of grain to consumption. Used in definition of MACCS variables DCYPCB, DCYPCM, DCYPCH for reduction of radioactivity in grain between harvest and consumption. Range: 148 - 231 days (i.e., 182 days $\times$ 1.25). Additional information: Same as FDELAY.
IF1	Fraction of initial radionuclide deposition onto pasture that is retained on plant surfaces. MACCS variables CTCOEF1 and CTCOEF2 for fraction of radionuclide deposition onto pasture that is retained on plant surfaces and undergoes rapid and slow weathering, respectively, are defined by $AF \cdot IF1$ and $(1 - AF) IF1$. Range: 0.304 - 0.475 (i.e., 0.38×1.25). Additional information: Same as AF.
IF2	Same as IF1 but for forage. Range: 0.2 - 0.313 (i.e., 0.25×1.25).
IF5	Same as IF1 but for green leafy vegetables. Range: 0.24 - 0.375 (i.e., 0.3×1.25).
IF7	Same as IF1 but for "other" foods. Range: 0.2 - 0.313 (i.e., 0.25×1.25).
LDELAY	Same as GDELAY but for legumes. Range: 148 - 231 days (i.e., 182 days $\times$ 1.25).
ODELAY	Same as GDELAY but for "other" foods. Range: 137 - 214 days (i.e., 171 days $\times$ 1.25).
MDELAY	Time (days) from production of milk to consumption. Used in definition of MACCS variable DCYPMH. Range: 16.8 - 26.2 days (i.e., 21 days $\times$ 1.25). Additional information: Sec. 4.3.5, Ref. 32; Sec. 3.2.4, Ref. 2.
PSMCS134	Ground concentration of Cs134 (Bq/m ²) at which disposal of milk products will be initiated to assure that emergency dose criteria will be met (i.e., the Federal Department of Agriculture emergency protective action guide that projected dose commitment to the thyroid and the whole body should be less than 0.15 Sv and 0.05 Sv, respectively ⁴⁴). Defines MACCS variable PSCMLK. Range: 2.18×10^4 - 2.18×10^6 Bq/m ² (i.e., 2.18×10^5 Bq/m ² $\times$ 10). Correlation: 0.75 rank correlation with PSMCS137; 0.5 rank correlation with PSMI131, PSMI133, PSMSR89, PSMSR90. Additional information: Sec. 4.4, Ref. 32; Appendix C, Ref. 2.
PSMCS137	Same as PSMCS134 but for Cs137. Range: 2.66×10^4 - 2.66×10^6 Bq/m ² (i.e., 2.66×10^5 Bq/m ² $\times$ 10). Correlation: 0.75 rank correlation with PSMCS134; 0.5 rank correlation with PSMI131, PSMI133, PSMSR89, PSMSR90.
PSMI131	Same as PSMCS134 but for I131. Range: 1.34×10^5 - 1.34×10^7 Bq/m ² (i.e., 1.34×10^6 Bq/m ² $\times$ 10). Correlation: 0.75 rank correlation with PSMI133; 0.5 rank correlation with PSMCS134, PSMCS137, PSMSR89, PSMSR90.

Table 9 (continued)

Variable	Description
PSMI133	Same as PSMCS134 but for I133. Range: $1.05 \times 10^9 - 1.05 \times 10^{11}$ Bq/m ² (i.e., 1.05×10^{10} Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSMI131; 0.5 rank correlation with PSMCS134, PSMCS137, PSMSR89, PSMSR90.
PSMSR89	Same as PSMCS134 but for Sr89. Range: $2.16 \times 10^6 - 2.16 \times 10^8$ Bq/m ² (i.e., 2.16×10^7 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSMSR90; 0.5 rank correlation with PSMCS134, PSMCS137, PSMI131, PSMI133.
PSMSR90	Same as PSMCS134 but for Sr90. Range: $2.41 \times 10^4 - 2.41 \times 10^6$ Bq/m ² (i.e., 2.41×10^5 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSMSR89; 0.5 rank correlation with PSMCS134, PSMCS137, PSMI131, PSMI133.
PSOCS134	Ground concentration of Cs134 (Bq/m ²) at which disposal of crops will be initiated to assure that emergency dose criteria are met (see PSMCS134). Defines MACCS variable PSCOTH. Range: $2.16 \times 10^6 - 2.16 \times 10^8$ Bq/m ² (i.e., 2.16×10^7 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSOCS137; 0.5 rank correlation with PSOI131, PSOI133, PSOSR89, PSOSR90. Additional information: Same as PSMCS134.
PSOCS137	Same as PSOCS134 but for Cs137. Range: $2.66 \times 10^9 - 2.66 \times 10^{11}$ Bq/m ² (i.e., 2.66×10^{10} Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSOCS134; 0.5 rank correlation with PSOI131, PSOI133, PSOSR89, PSOSR90.
PSOI131	Same as PSOCS134 but for I131. Range: $7.95 \times 10^5 - 7.95 \times 10^7$ Bq/m ² (i.e., 7.95×10^6 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSOI133; 0.5 rank correlation with PSOCS134, PSOCS137, PSOSR89, PSOSR90.
PSOI133	Same as PSOCS134 but for I133. Range: $1.02 \times 10^{10} - 1.02 \times 10^{12}$ Bq/m ² (i.e., 1.02×10^{11} Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSOI131; 0.5 rank correlation with PSOCS134, PSOCS137, PSOSR89, PSOSR90.
PSOSR89	Same as PSOCS134 but for Sr89. Range: $2.16 \times 10^6 - 2.16 \times 10^8$ Bq/m ² (i.e., 2.16×10^7 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSOSR90; 0.5 rank correlation with PSOCS134, PSOCS137, PSOI131, PSOI133.
PSOSR90	Same as PSOCS134 but for Sr90. Range: $2.41 \times 10^4 - 2.41 \times 10^6$ Bq/m ² (i.e., 2.41×10^5 Bq/m ² $\times 10$). Correlation: 0.75 rank correlation with PSOSR89; 0.5 rank correlation with PSOCS134, PSOCS137, PSOI131, PSOI133.
QRCS134	Rate of depletion (yr ⁻¹) of Cs134 from the root zone (includes radioactive decay, percolation into soil below root zone, irreversible binding with soil components). Used in determination of interdiction period for farmland before crops can be grown without violating the Federal Department of Agriculture lifetime dose criteria (see GCMSR89). Defines MACCS variable QROOT. Range: 0.059 - 5.9 yr ⁻¹ (i.e., $0.59 \text{ yr}^{-1} \times 10$). Correlation: 0.75 rank correlation with QRCS137; -0.5 rank correlation TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137. Additional information: Sec. 4.4.2, Ref. 32; Sec. 3.2.4, Ref. 2.

Problem for Analysis

Table 9 (continued)

Variable	Description
QRCS137	Same as QRCS134 but for Cs137. Range: $0.028 - 2.8 \text{ yr}^{-1}$ (i.e., $0.28 \text{ yr}^{-1} \times 10$). Correlation: 0.75 rank correlation with QRCS134; -0.5 rank correlation with same variables as QRCS134.
QSR90	Same as QRCS134 but for Sr90. Range: $0.0065 - 0.65 \text{ yr}^{-1}$ (i.e., $0.065 \text{ yr}^{-1} \times 10$). Correlation: -0.5 rank correlation with TCFSR89, TCFSR90, TCGSR89, TCGSR90, TCLSR89, TCLSR90, TCOSR89, TCOSR90, TCPSR89, TCPSR90, TCRSR89, TCRSR90, TCVSR89, TCVSR90.
RDELAY	Same as GDELAY but for roots and tubers. Range: 146 - 228 days (i.e., $182 \text{ days} \times 1.25$).
TCFCS134	Ratio Cs134 transferred to forage due to root uptake and resuspension and Cs134 deposition to soil surface (units: Bq/Bq). Numerator in ratio (i.e., Cs134 transferred to forage) is an integrated quantity in the sense that it equals the total transfer to forage over all years subsequent to the deposition and thus incorporates effects due to radioactive decay, percolation into soil below root zone, irreversible binding with soil, and efficiency of root uptake. Defines MACCS variable TCROOT. Range: $7.1 \times 10^{-3} - 7.1 \times 10^{-5}$ (i.e., $7.1 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137. Additional information: Sec. 4.3.8, Ref. 32; Sec. 3.2.4, Ref. 2.
TCFCS137	Same as TCFCS134 but for Cs137. Range: $1.5 \times 10^{-4} - 1.5 \times 10^{-2}$ (i.e., $1.5 \times 10^{-3} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCFSR89	Same as TCFCS134 but for Sr89. Range: $1.3 \times 10^{-4} - 1.3 \times 10^{-2}$ (i.e., $1.3 \times 10^{-3} \times 10$). Correlation: 0.75 rank correlation with TCFSR90; 0.5 rank correlation with TCGSR89, TCGSR90, TCLSR89, TCLSR90, TCOSR89, TCOSR90, TCPSR89, TCPSR90, TCRSR89, TCRSR90, TCVSR89, TCVSR90; -0.5 rank correlation with QRSR90.
TCFSR90	Same as TCFCS134 but for Sr90. Range: $9 \times 10^{-3} - 0.9 \times 10^{-1}$ (i.e., $9 \times 10^{-2} \times 10$). Correlation: 0.75 rank correlation with TCFSR89; 0.5 and -0.5 rank correlation with same variables as TCFSR89.
TCGCS134	Same as TCFCS134 but for grain. Range: $3.5 \times 10^{-6} - 3.5 \times 10^{-4}$ (i.e., $3.5 \times 10^{-5} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCGCS137	Same as TCFCS134 but for Cs137 and grain. Range: $7.6 \times 10^{-6} - 7.6 \times 10^{-4}$ (i.e., $7.6 \times 10^{-5} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.

Table 9 (continued)

Variable	Description
TCGSR89	Same as TCFCS134 but for Sr89 and grain. Range: 4.3×10^{-6} - 4.3×10^{-4} (i.e., $4.3 \times 10^{-5} \times 10$). Correlation: 0.75 rank correlation with TCGSR90; 0.5 rank correlation with TCFSR89, TCFSR90, TCLSR89, TCLSR90, TCOSR89, TCOSR90, TCPSR89, TCPSR90, TCRSR89, TCRSR90, TCVSR89, TCVSR90; -0.5 rank correlation with QRSR90.
TCGSR90	Same as TCFCS134 but for Sr90 and grain. Range: 3.3×10^{-4} - 3.3×10^{-2} (i.e., $3.3 \times 10^{-3} \times 10$). Correlation: 0.75 rank correlation with TCGSR89; 0.5 and -0.5 rank correlation with same variables as TCGSR89.
TCLCS134	Same as TCFCS134 but for legumes. Range: 9.3×10^{-4} - 9.3×10^{-6} (i.e., $9.3 \times 10^{-5} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS137, TCOCs134, TCOCs137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCLCS137	Same as TCFCS134 but for Cs137 and legumes. Range: 2×10^{-5} - 2×10^{-3} (i.e., $2 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCOCs134, TCOCs137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCLSR89	Same as TCFCS134 but for Sr89 and legumes. Range: 3.7×10^{-5} - 3.7×10^{-3} (i.e., $3.7 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCLSR90; 0.5 rank correlation with TCFSR89, TCFSR90, TCGSR89, TCGSR90, TCOSR89, TCOSR90, TCPSR89, TCPSR90, TCRSR89, TCRSR90, TCVSR89, TCVSR90; -0.5 rank correlation with QRSR90.
TCLSR90	Same as TCFCS134 but for Sr90 and legumes. Range: 2.8×10^{-3} - 2.8×10^{-1} (i.e., $2.8 \times 10^{-2} \times 10$). Correlation: 0.75 rank correlation with TCLSR89; 0.5 and -0.5 rank correlation with same variables as TCLSR89.
TCOCs134	Same as TCFCS134 but for "other" foods. Range: 1.1×10^{-5} - 1.1×10^{-3} (i.e., $1.1 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCs137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCOCs137	Same as TCFCS134 but for Cs137 and "other" foods. Range: 2.3×10^{-5} - 2.3×10^{-3} (i.e., $2.3 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCs134, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCOSR89	Same as TCFCS134 but for Sr89 and "other" foods. Range: 8×10^{-7} - 8×10^{-5} (i.e., $8 \times 10^{-6} \times 10$). Correlation: 0.75 rank correlation with TCOSR90; 0.5 rank correlation with TCFSR89, TCFSR90, TCGSR89, TCGSR90, TCLSR89, TCLSR90, TCPSR89, TCPSR90, TCRSR89, TCRSR90, TCVSR89, TCVSR90; -0.5 rank correlation with QRSR90.
TCOSR90	Same as TCFCS134 but for Sr90 and "other" foods. Range: 6.6×10^{-3} - 6.6×10^{-5} (i.e., $6.6 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCOSR89; 0.5 and -0.5 rank correlation with same variables as TCOSR89.

Problem for Analysis

Table 9 (continued)

Variable	Description
TCPCS134	Same as TCFCS134 but for pasture. Range: 1.3×10^{-4} - 1.3×10^{-2} (i.e., $1.3 \times 10^{-3} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS137, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCPCS137	Same as TCFCS134 but for Cs137 and pasture. Range: 6.9×10^{-4} - 6.9×10^{-2} (i.e., $6.9 \times 10^{-3} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCRCS134, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCPSR89	Same as TCFCS134 but for Sr89 and pasture. Range: 4.1×10^{-5} - 4.1×10^{-3} (i.e., $4.1 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCPSR90; 0.5 rank correlation with TCFSR89, TCFSR90, TCGSR89, TCGSR90, TCLSR89, TCLSR90, TCOSR89, TCOSR90, TCRSR89, TCRSR90, TCVSR89, TCVSR90; -0.5 rank correlation with QRSR90.
TCPSR90	Same as TCFCS134 but for Sr90 and pasture. Range: 2.6×10^{-3} - 2.6×10^{-1} (i.e., $2.6 \times 10^{-2} \times 10$). Correlation: 0.75 rank correlation with TCPSR89; 0.5 and -0.5 rank correlation with same variables as TCPSR89.
TCRCS134	Same as TCFCS134 but for roots and tubers. Range: 5.6×10^{-6} - 5.6×10^{-4} (i.e., $5.6 \times 10^{-5} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS137, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCRCS137	Same as TCFCS134 but for Cs137 and roots and tubers. Range: 1.2×10^{-5} - 1.2×10^{-3} (i.e., $1.2 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS134, TCVCS134, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.
TCRSR89	Same as TCFCS134 but for Sr89 and roots and tubers. Range: 1.1×10^{-5} - 1.1×10^{-3} (i.e., $1.1 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCRSR90; 0.5 rank correlation with TCFSR89, TCFSR90, TCGSR89, TCGSR90, TCLSR89, TCLSR90, TCOSR89, TCOSR90, TCPSR89, TCPSR90, TCVSR89, TCVSR90; -0.5 rank correlation with QRSR90.
TCRSR90	Same as TCFCS134 but for Sr90 and roots and tubers. Range: 8.4×10^{-4} - 8.2×10^{-2} (i.e., $8.2 \times 10^{-3} \times 10$). Correlation: 0.75 correlation with TCRSR89; 0.5 and -0.5 rank correlation with same variables as TCRSR89.
TCVCS134	Same as TCFCS134 but for green leafy vegetables. Range: 1.4×10^{-6} - 1.4×10^{-4} (i.e., $1.4 \times 10^{-5} \times 10$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS137; -0.5 rank correlation with QRCS134, QRCS137.

Variable	Description
TCVCS137	Same as TCFCS134 but for Cs137 and green leafy vegetables. Range: 3×10^{-6} - 3×10^{-4} (i.e., $3 \times 10^{-5} \times 5$). Correlation: 0.75 rank correlation with TCFCS134, TCFCS137, TCGCS134, TCGCS137, TCLCS134, TCLCS137, TCOCS134, TCOCS137, TCPCS134, TCPCS137, TCRCS134, TCRCS137, TCVCS134; -0.5 rank correlation with QRCS134, QRCS137.
TCVSR89	Same as TCFCS134 but for Sr89 and green leafy vegetables. Range: 1.7×10^{-5} - 1.7×10^{-3} (i.e., $1.7 \times 10^{-4} \times 10$). Correlation: 0.75 rank correlation with TCVSR90; 0.5 rank correlation TCFSR89, TCFSR90, TCGSR89, TCGSR90, TCLSR89, TCLSR90, TCOSR89, TCOSR90, TCPSR89, TCPSR90, TCRSR89, TCRSR90; -0.5 rank correlation with QRSR90.
TCVSR90	Same as TCFCS134 but for Sr90 and green leafy vegetables. Range: 1.3×10^{-3} - 1.3×10^{-1} (i.e., $1.3 \times 10^{-2} \times 10$). Correlation: 0.75 rank correlation with TCVSR89; 0.5 and -0.5 rank correlation with same variables as TCVSR89.
TFBCS	Ratio of amount of cesium in edible meat at time of slaughter to amount of cesium consumed by meat producing animals. Defines MACCS variable TFBF for Cs134 and Cs137. Range: 4.8×10^{-3} - 1.2×10^{-1} (i.e., $2.4 \times 10^{-2} \times 5$). Additional information: Sec. 4.3.9, Ref. 32; Sec. 3.2.4, Ref. 2.
TFBI131	Same as TFBCS but for I131. Defines MACCS variable TFBF for I131. Range: 4.8×10^{-4} - 1.2×10^{-2} (i.e., $2.4 \times 10^{-3} \times 5$). Correlation: 0.75 rank correlation with TFBI133.
TFBI133	Same as TFBCS for I133. Defines MACCS variable TFBF for I133. Range: 2.2×10^{-4} - 5.5×10^{-3} (i.e., $1.1 \times 10^{-3} \times 5$). Correlation: 0.75 rank correlation with TFBI131.
TFBSR	Same as TFBCS but for strontium. Defines MACCS variable TFBF for Sr89 and Sr90. Range: 4.4×10^{-5} - 1.1×10^{-3} (i.e., $2.2 \times 10^{-4} \times 5$).
TFMCS	Ratio of amount of cesium in milk to amount of cesium consumed by milk-producing animals. Defines MACCS variable TFMLK for Cs134 and Cs137. Range: 0.022 - 0.55 (i.e., 0.11×5). Additional information: Sec. 4.3.10, Ref. 32; Sec. 3.2.4, Ref. 2.
TFMI131	Same as TFMCS but for I131. Defines MACCS variable TFMLK for I131. Range: 0.026 - 0.65 (i.e., 0.13×5). Correlation: 0.75 rank correlation with TFMI133.
TFMI133	Same as TFMCS but for I133. Defines MACCS variable TFMLK for I133. Range: 0.0124 - 0.31 (i.e., 0.062×5). Correlation: 0.75 rank correlation with TFMI131.
TFMSR	Same as TFMCS but for strontium. Defines MACCS variable TFMLK for Sr89 and Sr90. Range: 0.0044 - 0.11 (i.e., 0.022×5).
VDELAY	Same as GDELAY but for green leafy vegetables. Range: 20.8 - 32.5 days (i.e., 26 days $\times 1.25$).

**Table 10. Predicted Variables Associated with the Food Pathways
Model in MACCS Selected for Analysis**

Population Dose
<u>Crop Growing Season Dose</u> --total population dose (Sv) resulting from consumption of nondairy food products contaminated as a result of deposition onto crops during the growing season.
<u>Crop Long-Term Dose</u> --total population dose (Sv) resulting from consumption of non-dairy food products contaminated by long-term uptake in the period following the accident.
<u>Milk Growing Season Dose</u> --total population dose (Sv) resulting from consumption of dairy products contaminated as a result of deposition onto crops during the growing season.
<u>Total Food Pathways Dose</u> --total population dose (Sv) from the consumption of contaminated dairy and nondairy products (excludes dose due to consumption of contaminated water).
<u>Total Ingestion Pathways Dose</u> --total population dose (Sv) from the consumption of contaminated dairy products, nondairy products, and water.
<u>Total Long-Term Pathways Dose</u> --total population dose (Sv) from groundshine, resuspension, consumption of contaminated food, ingestion of contaminated surface water, and decontamination work.
Economic Costs
<u>Area-Dependent Cost</u> --sum of area-dependent decontamination, interdiction, condemnation, milk disposal, and crop disposal costs (\$).
<u>Crop Disposal Cost</u> --compensation (\$) for lost crops.
<u>Milk Disposal Cost</u> --compensation (\$) for lost dairy product sales.
Impacted Area
<u>Condemnation Area</u> --area (Ha) within which farmland condemnation is required.
<u>Crop Disposal Area</u> --affected area (Ha) requiring the loss of nondairy food product sales for one year.
<u>Milk Disposal Area</u> --area (Ha) requiring the loss of dairy product sales for three months.

4. DETERMINATION OF DOMINANT VARIABLES

The purpose of the analyses presented in this section is to determine the effects of uncertainty in the MACCS input variables listed in Table 9 on the food pathway results indicated in Table 10. To accomplish this, the LHS program⁴⁵ was used to generate a Latin hypercube sample¹⁸ of size 120 from the 87 variables in Table 9, with the Iman/Conover restricted pairing technique⁴² being used to induce the indicated rank correlations. This produced a sample of the form shown in Eq. (5) with $nV = 87$ and $nLHS = 120$, which was then propagated through MACCS to produce the results shown in Eq. (6). As a reminder, the vector $cS_i(x_k)$ in Eq. (6) contains the values for the food pathway results in Table 10 obtained for scenario S_i , where S_i is the set of similar weather conditions defined in Eq. (13) of Ref. 5. The analyses for the individual food pathway results follow.

4.1 Population Dose

As described in Table 10, six predicted variables related to long-term population dose (Sv) are considered in this study: total long-term pathways dose, total ingestion pathways dose, milk growing season dose, crop growing season dose, crop long-term dose, and total food pathways dose. Mean and percentile curves for these variables are shown in Figure 1. As a reminder, each set of summary curves in Figure 1 is constructed from MACCS calculations performed for a Latin hypercube sample of size 120 from the 87 variables described in Table 9. Thus, each individual frame in Figure 1 summarizes a distribution of 120 CCDFs. For example, the mean and percentile curves for milk growing season dose are based on the distribution of CCDFs in Figure 2.

Determination of Dominant Variables

Figure 1 Mean and Percentile Curves for Population Dose.

Figure 2. Distribution of CCDFs for Milk Growing Season Dose.

Only food pathways variables are treated as being uncertain in this study. In particular, although the total long-term pathways dose and total ingestion pathways dose contain exposures in addition to those incurred through the food pathways, the uncertainty associated with these two doses in Figure 1 originates entirely from uncertainty in variables associated with the food pathways. The total ingestion pathways dose differs from the total food pathways dose in the inclusion of the dose that results from water ingestion. As comparison of the summary curves in Figure 1 for these two doses shows, exposure due to water ingestion is considerably smaller than the exposure due to the food pathways (i.e., the summary curves total ingestion pathways dose and total food pathways dose are essentially the same).

The total long-term pathways dose includes the doses from the ingestion pathways plus doses resulting from groundshine, inhalation of resuspended radionuclides and decontamination work. As comparison of the summary curves in Figure 1 for total long-term pathways dose and total food pathways dose shows, inclusion of the groundshine, resuspension and decontamination doses can cause an upward shift in total dose from the dose that results from ingestion (i.e., 5th percentile curve for total long-term pathways dose is considerably higher than the 5th percentile curve for total food pathways dose). However, the 95th percentile curves for total long-term pathways dose and total food pathways dose are similar. Thus, in this analysis in which only the uncertainty in the food pathways is under consideration, the more extreme values of the food pathways parameters produce doses that exceed those from groundshine, resuspension and decontamination work.

Summaries of the CCDFs for milk growing season dose, crop growing season dose and crop long-term dose are also presented in Figure 1. As examination of these summaries shows, crop long-term dose is the largest contributor to the probability of the total food pathways dose exceeding small doses and crop growing season dose is the largest contributor to the probability of the total food pathways dose exceeding large doses.

Determination of Dominant Variables

The primary purpose of the analyses presented in this report is to determine the importance of the individual variables in Table 9 in influencing results associated with the food pathways model in MACCS. One way to make such a determination is by using partial correlation analysis to determine the influence of the individual variables in Table 9 on the exceedance probabilities associated with the CCDFs summarized in Figure 1. For a distribution of CCDFs of the form shown in Figure 2, there are 120 exceedance probabilities (i.e., one for each sample element) for each dose on the abscissa. Partial correlation coefficients can be calculated between these probabilities and the variables in Table 9 and then plotted above the corresponding dose values on the abscissa. When the partial correlation values for individual variables from Table 9 are connected, plots of the form shown in Figure 3 are obtained. Due to the absence of any variables in the analysis that affect doses due to groundshine, resuspension, decontamination work and water ingestion, the partial correlation analyses for total long-term pathways dose and total ingestion pathways dose are the same as the analyses for total food pathways dose and thus are not presented in Figure 3.

To reduce the effects of nonlinear relationships, the analyses presented in Figure 3 and other similar figures in this report use partial rank correlation coefficients (PRCCs), which are correlation coefficients calculated with rank-transformed data. Further, to reduce clutter, the individual plot frames in Figure 3 only show PRCC plots for the four variables that have the largest PRCCs that exceed 0.6 in absolute value. The remaining variables that have PRCCs that exceed 0.6 in absolute value are listed in order of the absolute value of their PRCCs. Further, these variables are followed by a "+" or "-" to indicate whether the PRCC is positive (+) or negative (-) when it exceeds 0.6 in absolute value. The PRCCs in Figure 3 and other similar figures were calculated with the PCCSRC program.⁴⁶

The individual analyses presented in Figure 3 are now discussed briefly. The probability of exceeding individual values for the milk growing season dose is dominated by TFMCS (ratio of amount of cesium in milk to amount of cesium consumed by milk-producing animals), with the probability of exceeding a given dose value tending to increase as TFMCS increases. This effect results because increasing TFMCS increases the amount of cesium consumed by milk-producing animals that is transferred to milk. Also included in the top four variables are TFMSR (ratio of amount of strontium in milk to amount of strontium consumed by milk-producing animals), PSMI131 (ground concentration of I-131 at which disposal of milk will be initiated) and TFMI131 (ratio of amount of I-131 in milk to amount of I-131 consumed by milk-producing animals), with the probability of exceeding a given dose value tending to increase as each of these variables increases. As for TFMCS, the positive effects for TFMSR and TFMI131 result from increasing radionuclide transfer from animal feed to milk. The positive effect for PSMI131 results from reducing the amount of milk production that will be interdicted. In addition to TFMCS, TFMSR, PSMI131 and TFMI131, positive effects are also indicated for PSMCS134 (ground concentration of Cs-134 at which disposal of milk will be initiated), PSMCS137 (ground concentration of Cs-137 at which disposal of milk will be initiated), PSMSR90 (ground concentration of Sr-90 at which disposal of milk will be initiated) and IF1 (fraction of initial radionuclide deposition onto pasture that is retained on plant surfaces), and a negative effect is indicated for AF (fraction of intercepted radionuclides undergoing rapid weathering from crop surfaces for pasture, forage, green leafy vegetables and "other" food). The results of this analysis are dominated by two groups of

Figure 3 Partial Rank Correlation Coefficients for Exceedance Probabilities Associated with Individual Dose Values.

Determination of Dominant Variables

variables: variables that determine transfer of radionuclides from animal feed to milk (TFMCS, TFMSR, TFMI131) and variables that affect interdiction of milk production (PSMI131, PSMCS134, PSMCS137, PSMSR90). A third, but less important, group of variables affects the retention of radionuclides on crop surfaces (IF1, AF).

The probability of exceeding individual values for the crop growing season dose is dominated by TFBCS (ratio of amount of cesium in edible meat at time of slaughter to amount of cesium consumed by meat-producing animals), with the probability of exceeding a given dose value tending to increase as TFBCS increases. The positive effect for TFBCS results because increasing TFBCS increases the amount of cesium consumed by meat-producing animals that is transferred to edible meat. Additional positive effects are indicated for PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated), PSOC134 (ground concentration of Cs-134 at which disposal of crops will be initiated), C1GCS (fraction of cesium deposition onto grain fields that is retained on plant surfaces and transferred directly to grain) and PSOSR90 (ground concentration of Sr-90 at which disposal of crops will be initiated). The positive effects for PSOI131, PSOC134 and PSOSR90 result from decreasing the amount of land that undergoes crop interdiction, while the positive effect for C1GCS results from increasing the amount of cesium in grain used as animal feed.

The probability of exceeding individual values for the crop long-term dose is dominated by GCMSR90 (maximum allowable Sr-90 ground concentration for production of crops), TCLSR90 (ratio of amount of Sr-90 transferred to legumes due to root uptake and resuspension and amount of Sr-90 deposited on soil surfaces) and TFBCS (ratio of amount of cesium in edible meat at time of slaughter to amount of cesium consumed by meat-producing animals), with the probability of exceeding a given dose value tending to increase as each of these variables increases. These effects result because increasing GCMSR90 decreases the amount of farmland subject to interdiction, increasing TCLSR90 increases the amount of Sr-90 that will be transferred to legumes, and increasing TFBCS increases the amount of cesium that will be transferred from animal feed to edible meat. After GCMSR90, TCLSR90 and TFBCS, additional positive effects are indicated for QRSR90 (rate of depletion of Sr-90 from the root zone), FRCTCHL (fraction of legumes consumed by humans) and TCPCS137 (ratio of amount of Cs-137 transferred to pasture due to root uptake and resuspension and amount of Cs-137 deposition to soil surface), with the probability of exceeding individual dose values tending to increase as each of these variables increases. The positive effect for QRSR90 probably results from decreasing the time period over which farmland will be interdicted and also decreasing the amount of farmland that will undergo condemnation, which is assumed to remove it permanently from agricultural production. However, QRSR90 has no effect on the probability of exceeding the larger doses observed in this analysis. The positive effects indicated for FRCTCHL and TCPCS137 result because increasing FRCTCHL increases the amount of crop category (i.e., legumes) that will be consumed directly by humans and increasing TCPCS137 increases the amount of deposited cesium that will be transferred from soil to animal feed (i.e., pasture). The variables identified in this analysis can be divided into groups that determine interdiction (GCMSR90, QRSR90), root uptake (TCLSR90, TCPCS137) and transfer in the food chain to man after crop production (TFBCS, FRCTCHL).

The probability of exceeding individual values for total food-pathways dose is dominated by GCMSR90 (maximum allowable Sr-90 ground concentration for production of crops) and TCLSR90 (ratio of amount of Sr-90 transferred to legumes due to root uptake and resuspension and amount of Sr-90 deposited on soil surfaces) for doses less than approximately 5×10^4 Sv and by TFBCS (ratio of amount

of cesium consumed by meat-producing animals) for doses greater than 5×10^4 Sv, with the probability of exceeding a given dose value tending to increase as each of GCMSR90, TCLSR90 and TFBCS increases. As examination of Figure 3 shows, GCMSR90 and TCLSR90 are the dominant variables in the analysis for crop long-term dose, while TFBCS is the dominant variable in the analysis for crop growing season dose. After these three variables, additional positive effects are indicated for C1GCS (fraction of cesium deposition onto grain fields that is retained on plant surfaces and transferred directly to grain), PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated), TFMCS (ratio of amount of cesium in milk to amount of cesium consumed by milk-producing animals), TCPCS137 (ratio of amount of Cs-137 transferred to pasture due to root uptake and resuspension and amount of Cs-137 deposited on soil surfaces), QRSR90 (rate of depletion of Sr-90 from root zone), and FRCTCHL (fraction of legumes consumed by humans). Each of the variables G1GCS, PSOI131, TFMCS, TCPCS137, QRSR90 and FRCTCHL appears in, and has been discussed in conjunction with, one of the other analyses in Figure 3. In particular, C1GCS and PSOI131 appear in the analysis for crop growing season dose, TFMCS is the dominant variable in the analysis for milk growing season dose, and TCPCS137, QRSR90 and FRCTCHL appear in the analysis for crop long-term dose. Thus, as should be the case, the analysis for total food-pathways dose tends to identify the dominant variables that affect the individual doses from which the total food pathways dose is constructed. The variables affecting total food-pathways dose can be divided into two groups: variables that affect radionuclide transfer within the food chain (TFBCS, TCLSR90, C1GCS, TFMCS, TCPCS137, FRCTCHL) and variables that affect interdiction of food production (GCMSR90, PSOI131, QRSR90).

Distributions for mean population dose are shown in Figure 4. As discussed in conjunction with Eqs. (27) and (28) of Ref. 5, the mean doses summarized in Figure 4 are obtained by reducing the CCDFs associated with the risk representation in Eq. (6) to single numbers. For example, a single mean milk growing season dose is obtained from each of the 120 CCDFs in Figure 2; in turn, these 120 mean doses are summarized in the plot frame labeled "Milk Growing Season Dose" in Figure 4. Thus, the results summarized in Figure 4 are means over stochastic uncertainty; however, the distributions in Figure 4 are characterizing subjective uncertainty.

The uncertainty analysis results for mean population dose in Figure 4 can be investigated with sensitivity analysis techniques based on stepwise regression analysis. Variable importance is then indicated by the order in which variables enter the regression model, the changes in R^2 values with the entry of successive variables into the regression model, and the standardized regression coefficients in the final regression model constructed in the stepwise process, with all three ranking procedures producing the same ordering of variable importance for uncorrelated variables. When the variables are uncorrelated, the absolute values of the standardized regression coefficients and the differences between successive R^2 values will decrease monotonically as additional variables are added to the regression model.

The regression analyses contained in this presentation were performed with the STEP program.⁴⁷ Alpha values of 0.01 and 0.02 were required for variables to enter and remain in the regression models, respectively. Further, the PRESS criterion⁴⁸ was used to check for overfitting the data. The analyses were tried with raw (i.e., untransformed) data, rank-transformed data,⁴⁹ and logarithmically transformed data. The analyses with rank-transformed data and logarithmically transformed data produced similar

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Figure 4. Distributions of Mean Population Dose.

results and also considerably better results (e.g., higher R^2 values) than the analyses with raw data. As the logarithmic transformation has more intuitive appeal than the rank transformation and both transformations produced similar results, this study will use stepwise regression analyses with logarithmically-transformed data. In contrast, the logarithmic transformation is not particularly suitable for analyses of CCDFs of the form presented in Figure 2 due to the large number of zero exceedance probabilities that enter the analysis as the value of the consequence variable increases.

The stepwise regression analyses for milk growing season dose, crop growing season dose, crop long-term dose and total food pathways dose are presented in Table 11. As only variables affecting the food pathways model were sampled in this analysis, the regression analyses for total long-term pathways dose and total ingestion pathways dose are identical to the analysis for total food pathways dose and thus are not presented.

The mean milk-growing season dose is dominated by PSMCS134 (ground concentration of Cs-134 at which disposal of milk products will be initiated), TFMCS (ratio of amount of cesium in milk to amount of cesium consumed by milk-producing animals) and PSMI131 (ground concentration of I-131 at which disposal of milk products will be initiated), with dose tending to increase as each of PSMCS134, TFMCS and PSMI131 increases. Collectively, these three variables can account for 86% of the observed uncertainty in mean milk-growing season dose. After PSMCS134, TFMCS and PSMI131, the regression analysis identifies a number of additional variables that have small effects. In particular, small positive effects are indicated for PSMCS137 (ground concentration of Cs-137 at which the disposal of milk products will be initiated), TFMI131 (ratio of amount of I-131 in milk to amount of I-131 consumed by milk-producing animals), IF1 (fraction of initial radionuclide deposition onto pasture that is retained on plant surfaces), TFMSR (ratio of amount of Sr-90 in milk to amount of SR-90 consumed by milk-producing animals), FRCTCMP (fraction of pasture consumed by milk-producing animals) and PSMSR90 (ground concentration of Sr-90 at which disposal of milk products will be initiated), and a small negative effect is indicated for AF (fraction of intercepted radionuclides undergoing rapid weathering from crop surfaces for pasture, forage, green leafy vegetables and "other" food). The indicated effects are consistent with the use of the corresponding variables in MACCS. The regression model with all 10 variables can account for 94% of the observed uncertainty. Two dominant groups of variables appear in the analysis: variables that affect interdiction of milk production (PSMCS134, PSMI131, PSMCS137, PSMSR90) and variables that determine the transfer of radionuclides from animal feed to milk (TFMCS, TFMI131, TFMSR). The two remaining variables (IF1, AF) determine the retention of radionuclides on crop surfaces.

The mean crop growing season dose is dominated by TFBCS (ratio of amount of cesium in edible meat at time of slaughter to amount of cesium consumed by meat producing animals), PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated) and PSOCS134 (ground concentration of Cs-134 at which disposal of crops will be initiated), with dose tending to increase as each of TFBCS, PSOI131 and PSOCS134 increases. Together, these three variables can account for 86% of the observed uncertainty in crop growing season dose, with TFBCS accounting for 51% of the uncertainty. In addition, small positive effects are identified for C1GCS (fraction of cesium deposition onto grain fields that is retained on plant surfaces and transferred directly to grain), IF1 (fraction of initial radionuclide

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Table 11. Stepwise Regression Analyses with Logarithmically-Transformed Data for Mean Population Dose

Milk Growing Season Dose (Sv)				Crop Growing Season Dose (Sv)		
Step ^a	Variable ^b	SRC ^c	R ² ^d	Variable ^b	SRC ^c	R ² ^d
1	PSMCS134	0.27	0.38	TFBCS	0.74	0.51
2	TFMCS	0.62	0.78	PSOI131	0.41	0.80
3	PSMI131	0.32	0.86	PSOCS134	0.28	0.86
4	PSMCS137	0.19	0.89	CIGCS	0.20	0.90
5	TFMI131	0.13	0.90	IF1	0.13	0.91
6	IF1	0.11	0.92	AF	-0.09	0.92
7	AF	-0.10	0.92	CTHALF1	0.08	0.93
8	TFMSR	0.09	0.93			
9	FRCTCMP	0.09	0.94			
10	PSMSR90	0.09	0.94			

Crop Long-Term Dose (Sv)				Total Food Pathways Dose (Sv)		
Step ^a	Variable ^b	SRC ^c	R ² ^d	Variable ^b	SRC ^c	R ² ^d
1	TCLSR90	0.86	0.40	TFBCS	0.65	0.39
2	GCMSR90	0.47	0.54	PSOI131	0.35	0.61
3	TCPCS137	0.29	0.67	TCLSR90	0.40	0.68
4	TFBCS	0.33	0.77	GCMSR90	0.27	0.74
5	FRCTCHL	0.16	0.80	TCPCS137	0.20	0.78
6	GCMCS137	0.18	0.81	PSOCS134	0.21	0.81
7	TCPCS134	0.22	0.84	CIGCS	0.16	0.83
8	PSOI131	0.10	0.85	TFMCS	0.13	0.85
9				PSMI131	0.13	0.87
10				FRCTCHL	0.10	0.88
11				IF1	0.09	0.89

^aSteps in stepwise regression analysis.

^bVariables listed in order of selection in regression analysis.

^cStandardized regression coefficients in final regression model.

^dCumulative R² value with entry of each variable into regression model.

deposition onto pasture that is retained on plant surfaces) and CTHALF1 (half-life for rapid weathering of deposited radionuclides from plant surfaces), and a small negative effect is indicated for AF (fraction of intercepted radionuclides undergoing rapid weathering from crop surfaces for pasture, forage, green leafy vegetables and "other" food). The indicated effects are consistent with the use of the corresponding variables in MACCS, and the regression model with all seven variables can account for 93% of the observed uncertainty. The variables identified in this analysis are similar to those identified in the analysis for milk-growing season dose. In particular, the dominant variables define transfer from feed to meat (TFBCS) and interdiction criteria (PSOI131, PSOC134), while a less important set of variables determines retention on crop surfaces (CIGCS, IF1, AF, CTHALF1).

The mean crop long-term dose is dominated by TCLSR90 (ratio of amount of Sr-90 transferred to legumes due to root uptake and resuspension and amount of Sr-90 deposited on soil surfaces), GCMSR90 (maximum allowable Sr-90 ground concentration for production of crops), TCPCS137 (ratio of amount of Cs-137 transferred to pasture due to root uptake and resuspension and amount of Cs-137 deposited on soil surfaces) and TFBCS (ratio of amount of cesium in edible meat at time of slaughter to amount of cesium consumed by meat producing animals), with dose tending to increase as each of TCLSR90, GCMSR90, TCPCS137 and TFBCS increases. Together, these four variables can account for 77% of the observed uncertainty in crop long-term dose. Additional positive effects are indicated for FRCTCHL (fraction of legumes consumed by humans), GCMCS137 (maximum allowable Cs-137 ground concentration for production of crops), TCPCS134 (ratio of amount of Cs-134 transferred to pasture due to root uptake and resuspension and amount of Cs-134 deposited on soil surfaces) and PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated). The positive effects for TCLSR90, GCMSR90, TCPCS137, TFBCS, FRCTCHL, GCMCS137 and TCPCS134 are consistent with their usage in MACCS. The variable PSOI131 is not used in the determination of long-term doses, and so its appearance at the end of the regression analysis is probably spurious. With PSOI131 excluded, the remaining seven variables identified in the regression analysis can account for 84% of the observed uncertainty, and can be divided into groups that determine root uptake (TCLSR90, TCPCS137, TCPCS134), interdiction criteria (GCMSR90, GCMCS137), and transfer in the food chain to man after crop production (TFBCS, FRCTCHL).

The mean value for total food pathways dose is dominated by TFBCS (ratio of amount of cesium in edible meat at time of slaughter to amount of cesium consumed by meat producing animals), PSOI133 (ground concentration of I-131 at which disposal of crops will be initiated), TCLSR90 (ratio of amount of Sr-90 transferred to legumes due to root uptake and resuspension and amount of Sr-90 deposited on soil surfaces) and GCMSR90 (maximum allowable Sr-90 ground concentration for production of crops), with dose tending to increase as each of TFBCS, PSOI131, TCLSR90 and GCMSR90 increases. Collectively, these four variables can account for 74% of the observed uncertainty in total food pathways dose. After these variables, small positive effects are indicated for TCPCS137 (ratio of amount of Cs-137 transferred to pasture due to root uptake and resuspension and amount of Cs-137 deposited on soil surface), PSOC134 (ground concentration of Cs-134 at which disposal of crops will be initiated), CIGCS (fraction of cesium deposition onto grain fields that is retained on plant surfaces and transferred directly to grain), TFMCS (ratio of amount of cesium in milk to amount of cesium consumed by milk-producing animals), PSMI131 (ground concentration of I-131 at which disposal of milk products will be initiated), FRCTCHL (fraction of legumes consumed by humans) and IF1 (fraction of initial radionuclide deposition

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onto pasture that is retained on plant surfaces). The final regression model contains 11 variables and can account for 89% of the observed uncertainty in total food pathways dose. These variables can be divided into groups that affect the interdiction of food production (PSOI131, GCMSR90, PSOCS134, PSMI131) and radionuclide transfer within the food chain (TFBCS, TCLSR90, TCPCS137, CIGCS, TFMCS, FRCTCHL, IF1). However, 61% of the observed uncertainty was accounted for by only two variables: TFBCS (39%) and PSOI131 (22%).

4.2 Economic Cost

As described in Table 10, three predicted variables related to economic cost (\$) are considered in this study: area-dependent cost, crop disposal cost and milk disposal cost. Mean and percentile curves for these variables are presented in Figure 5. As discussed in conjunction with Figure 1, the mean and percentile curves in Figure 5 summarize the results of 120 MACCS calculations. The summary curves in Figure 5 indicate that area-dependent cost is approximately an order of magnitude above crop disposal cost, which in turn is approximately an order of magnitude above milk disposal cost.

The results of a sensitivity analysis with PRCCs for the CCDFs summarized in Figure 5 are presented in Figure 6. The probability of exceeding a given area-dependent cost is dominated by GCMSR90 (maximum allowable Sr-90 ground concentration for production of crops), QRSR90 (rate of depletion of Sr-90 from root zone) and GCMCS137 (maximum allowable Cs-137 ground concentration for production of crops). The probability of exceeding a given value of area-dependent cost tends to decrease as each of GCMSR90, QRSR90 and GCMCS137 increases due to reductions in the areas and time periods that require interdiction. In particular, increasing each of GCMSR90 and GCMCS137 tends to decrease the amount of farmland that will be interdicted, and increasing QRSR90 tends to decrease the duration of interdiction.

The probability of exceeding a given crop disposal cost is dominated by PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated), PSOSR90 (ground concentration of Sr-90 at which disposal of crops will be initiated) and PSOCS134 (ground concentration of Cs-137 at which disposal of crops will be initiated), with the probability tending to decrease as each of these variables increases. The negative effects for PSOI131, PSOSR90 and PSOCS134 result from reducing the area in which crop disposal is required. A negative effect is also indicated for TCPCS137 (ratio Cs-137 transferred to pasture due to root uptake and resuspension and Cs-137 deposition to soil surface). However, TCPCS137 does not effect the crop disposal model in MACCS and so its appearance in this analysis is spurious.

The probability of exceeding a given milk disposal cost is dominated by PSMI131 (ground concentration of I-131 at which disposal of milk products will be initiated), PSMCS134 (ground concentration of Cs-134 at which disposal of milk products will be initiated), PSMSR90 (ground concentration of Sr-90 at which disposal of milk products will be initiated) and PSMCS137 (ground concentration of Cs-137 at which disposal of milk products will be initiated). Thus, as for crop disposal cost, the uncertainty in exceeding individual milk disposal costs is dominated by the radionuclide concentration (i.e., PSMI131, PSMCS134, PSMSR90, PSMCS137) at which disposal will be initiated.

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The distributions for mean economic cost are shown in Figure 7. As with the CCDF summaries in Figure 5, the area dependent cost is about an order of magnitude above the crop disposal cost, which in turn is about an order of magnitude above the milk disposal cost. The regression analyses for the mean costs summarized in Figure 7 are presented in Table 12.

The mean area-dependent cost is dominated by GCMSR90 (maximum allowable Sr-90 ground concentration for production of crops), with this variable accounting for approximately 78% of the observed uncertainty. Mean area-dependent cost tends to decrease as GCMSR90 increases due to decreased interdiction and condemnation of farmland. After GCMSR90, the regression analysis indicates small negative effects for GCMCS137 (maximum allowable Cs-137 ground concentration for production of crops), QRSR90 (rate of depletion of Sr-90 from the root zone), PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated), FRCTCMG (fraction of grain consumed by milk-producing animals) and QRCS134 (rate of depletion of Cs-137 from the root zone). Collectively, the preceding six variables produce a regression model that can account for approximately 91% of the observed uncertainty in mean area-dependent dose. The variable FRCTCMG does not enter into the cost calculations performed in MACCS and thus its selection is spurious; however, it accounts for less than 1% of the observed uncertainty. The remaining five variables can be divided into two groups: variables that set interdiction criteria (GCMSR90, GCMCS137, PSOI131) and variables that determine the rate at which "effective" soil concentration decreases (QRS90, QRCS134).

The mean crop-disposal cost is dominated by variables that define the ground concentration at which crop disposal will be initiated. Specifically, the regression analysis selected PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated), PSOCS134 (ground concentration of Cs-134 at which disposal of crops will be initiated) and PSOSR90 (ground concentration of Sr-90 at which disposal of crops will be initiated), with these three variables producing a regression model that could account for 92% of the observed uncertainty. The dominant variable was PSOI131, which could account for 71% of the observed uncertainty.

The mean milk disposal cost is dominated by PSMCS134 (ground concentration of Cs-134 at which disposal of milk products will be initiated) and PSMI131 (ground concentration of I-131 at which disposal of milk products will be initiated), with an additional small contribution from PSMCS137 (ground concentration of Cs-137 at which disposal of milk products will be initiated). Mean milk disposal cost tends to decrease as each of PSMCS134, PSMI131 and PSMCS137 increases. The final regression model accounts for approximately 93% of the observed uncertainty, with PSMCS134, PSMI131 and PSMCS137 accounting for 72%, 17% and 4%, respectively, of the total uncertainty.

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Figure 5 Mean and Percentile Curves for Economic Costs.

Figure 6 Partial Rank Correlation Coefficients for Exceedance Probabilities Associated with Individual Cost Values.

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Figure 7 Distributions of Mean Economic Costs.

Table 12. Stepwise Regression Analyses with Logarithmically-Transformed Data for Mean Economic Cost

Step ^a	Area-Dependent Cost (\$)			Crop Disposal Cost			Milk Disposal Cost (\$)		
	Variable ^b	SRC ^c	R ² ^d	Variable ^b	SRC ^c	R ² ^d	Variable ^b	SRC ^c	R ² ^d
1	GCMSR90	-0.74	0.78	PSOI131	-0.53	0.71	PSMCS134	-0.44	0.72
2	GCMCS137	-0.24	0.85	PSOCS134	-0.35	0.86	PSMI131	-0.39	0.89
3	QRSR90	-0.16	0.88	PSOSR90	-0.29	0.92	PSMCS137	-0.26	0.93
4	PSOI131	-0.12	0.90						
5	FRCTCMG	-0.09	0.90						
6	QRCS134	-0.09	0.91						

^aSteps in stepwise regression analysis.

^bVariables listed in order of selection in regression analysis.

^cStandardized regression coefficients in final regression model.

^dCumulative R² value with entry of each variable into regression model.

4.3 Impacted Area

As described in Table 10, three predicted variables related to impacted area (Ha) are considered in this study: condemnation area, crop disposal area and milk disposal area. Mean and percentile curves for these variables are presented in Figure 8, with each plot frame summarizing the results of 120 MACCS calculations. As comparison of the summary curves for the three areas shows, there is considerably more uncertainty associated with the CCDFs for condemnation area than the CCDFs for crop disposal area and milk disposal area.

The results of a sensitivity analysis with PRCCs for the CCDFs summarized in Figure 8 are presented in Figure 9. Two variables are identified as affecting the probability that a given condemnation area will be exceeded: GCMSR90 (maximum allowable Sr-90 ground concentration for production of crops) and QRSR90 (rate of depletion of Sr-90 from root zone). The probability of exceeding a given condemnation area tends to decrease as GCMSR90 and QRSR90 increases. As a reminder, the MACCS food pathways model assumes that condemnation of farmland takes place if the time period over which the land must be removed from farm production exceeds 8 yr or if the cost of farmland decontamination and temporary interdiction exceeds the value of the farmland and associated investments (Section 2.4 of this report; Section 5.3.3.2, Ref. 3). The negative effect for GCMSR90 results from increasing the ground concentration of Sr-90 at which crop production will be interdicted, and the negative effect for QRSR90 results from reducing the time required for land with ground concentrations initially above GCMSR90 to reach concentrations that are below GCMSR90.

The probability that a given crop disposal area will be exceeded is dominated by PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated), PSOSR90 (ground concentration of Sr-90 at which disposal of crops will be initiated) and PSOCS134 (ground concentration of Cs-134 at which disposal of crops will be initiated). As discussed in conjunction with crop disposal

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cost, the appearance of TCPCS137 (ratio of amount of Cs-137 transferred to pasture due to root uptake and resuspension and amount of Cs-137 deposited on soil surfaces) is spurious. Thus, crop disposal area is dominated by the same three interdiction criteria that dominate crop disposal cost (i.e., PSOI131, PSOSR90, PSOCS134).

The probability of exceeding a given milk disposal area is dominated by PSMI131 (ground concentration of I-131 at which disposal of milk products will be initiated), PSMCS134 (ground concentration of Cs-134 at which disposal of milk products will be initiated), PSMSR90 (ground concentration of Sr-90 at which disposal of milk products will be initiated) and PSMCS137 (ground concentration of Cs-137 at which disposal of milk products will be initiated). Thus, as for milk disposal cost, the uncertainty in exceeding individual milk disposal areas is dominated by the radionuclide concentrations at milk which disposal will be initiated (i.e., PSMI131, PSMCS134, PSMSR90, PSMCS137).

The distributions for mean impacted area are shown in Figure 10, with most of these means falling between 1×10^5 and 1×10^6 Ha. Regression analyses for the mean areas summarized in Figure 10 are presented in Table 13.

The mean condemnation area is dominated by GCMSR90 (maximum allowable Sr-90 ground concentration for production of crops) and QRSR90 (rate of depletion of Sr-90 from the root zone). Together, GCMSR90 and QRSR90 can account for 74% of the observed uncertainty in mean condemnation area, with this area tending to decrease as each of these variables increases. After GCMSR90 and QRSR90, the regression analysis selects the corresponding two variables for Cs-137 (i.e., GCMCS137 and QRCS137). The final regression model with GCMSR90, QRSR90, GCMCS137 and QRCS137 can account for 83% of the observed uncertainty in mean condemnation area.

The mean crop disposal area is dominated by the same three variables as mean crop disposal cost: PSOI131 (ground concentration of I-131 at which disposal of crops will be initiated), PSOCS134 (ground concentration of Cs-134 at which disposal of crops will be initiated) and PSOSR90 (ground concentration of Sr-90 at which disposal of crops will be initiated). Collectively, these three variables can account for 92% of the observed uncertainty in mean crop disposal area, with PSOI131, PSOCS134 and PSOSR90 accounting for 71%, 15% and 6%, respectively, of the total uncertainty.

The analysis for mean milk disposal area is essentially the same as the analysis for mean milk disposal cost. In particular, the mean milk disposal area is dominated by PSMCS134, PSMI131, PSMCS137 and PSMSR90, which define the ground concentrations of Cs-134, I-131, Cs-137 and Sr-90, respectively, at which the disposal of milk products will be initiated. All four variables produce a regression model that can account for 94% of the observed uncertainty in mean milk disposal area. The dominant variable is PSMCS134, which can account for 72% of the uncertainty. In addition, PSMI131, PSMCS137 and PSMSR90 can account for 17%, 4%, and 1% of the uncertainty.

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Figure 8 Mean and Percentile Curves for Impacted Area.

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Figure 9 Partial Rank Correlation Coefficients for Exceedance Probabilities Associated with Individual Impacted Areas.

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Figure 10 Distributions of Mean Impacted Area.

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Table 13. Stepwise Regression Analyses with Logarithmically-Transformed Data for Mean Impacted Area

Step ^a	Condemnation Area (Ha)			Crop Disposal Area (Ha)			Milk Disposal Area (Ha)		
	Variable ^b	SRC ^c	R ² ^d	Variable ^b	SRC ^c	R ² ^d	Variable ^b	SRC ^c	R ² ^d
1	GCMR90	-0.56	0.59	PSOI131	-0.53	0.71	PSMCS134	-0.43	0.72
2	QRSR90	-0.43	0.74	PSOCS134	-0.36	0.86	PSMI131	-0.40	0.89
3	GCMCS137	-0.19	0.81	PSOSR90	-0.29	0.92	PSMCS137	-0.26	0.93
4	QRCS137	-0.17	0.83				PSMSR90	-0.09	0.94

^aSteps in stepwise regression analysis.

^bVariables listed in order of selection in regression analysis.

^cStandardized regression coefficients in final regression model.

^dCumulative R² value with entry of each variable into regression model.

5. EFFECT OF DOMINANT VARIABLES

The analyses presented in Section 4 identify the dominant MACCS input variables affecting the predicted variables listed in Table 10 conditional on the assumptions used in this analysis. Two questions naturally arise: (1) How much will the observed uncertainty in the variables in Table 10 be reduced if the uncertainty in the dominant variables identified in Section 4 can be reduced? (2) If the uncertainty in the dominant variables identified in Section 4 is reduced, which input variables in Table 9 will then emerge as the new dominant variables?^{50,51}

To answer these questions, the dominant variables identified in Section 4 were compiled. For the purposes of this investigation, a variable was included in the set of dominant variables if it was ranked among the top four variables on the basis of either PRCCs or stepwise regression analysis for one of the 12 predicted variables listed in Table 10. This produced the 18 variables listed in Table 14. As examination of Table 14 shows, selection based on either PRCCs and or stepwise regression analysis would have produced almost identical sets of variables. The MACCS calculations leading to the uncertainty and sensitivity analysis results presented in Section 4 were then repeated with the 18 variables listed in Table 14 set to their best-estimate values indicated in Table 9.

Setting the variables in Table 14 to their best-estimate values produced substantial reductions in the uncertainty in the predicted variables listed in Table 10. As an example, the spread between the percentile curves shown in Figure 11 for crop long-term dose obtained with the variables in Table 14 set to their best-estimate values can be compared with the corresponding spread shown in Figure 1 obtained with the variables in Table 14 allowed to vary. For the other variables in Table 10, the reduction in the spread in the CCDF distribution is greater than that indicated in the preceding comparison for crop long-term dose.

Table 14. Dominant Variables Identified in Uncertainty and Sensitivity Analyses Presented in Section 4

C1GCS (+ ^a , + ^b)	PSMSR90 (+, *)	TCLSR90 (+, +)
GCMCS137 (+, +)	PSOCS134 (+, +)	TCPCS137 (+, +)
GCMSR90 (+, +)	PSOI131 (+, +)	TFBCS (+, +)
PSMCS134 (+, +)	PSOSR90 (+, +)	TFMCS (+, +)
PSMCS137 (+, +)	QRCS137 (*, +)	TFMI131 (+, *)
PSMI131 (+, +)	QRSR90 (+, +)	TFMSR (+, *)

^a+/* indicates ranked (+) or not ranked (*) in top four variables on basis of PRCCS for at least one of the predicted variables in Table 10.

^b+/* indicates ranked (+) or not ranked (*) in top four variables on basis of order of selection in a stepwise regression analysis for at least one of the predicted variables in Table 10.

Effect of Dominant Variables

The effect of setting the variables in Table 14 to their best-estimate values can also be seen by comparing the means and standard deviations shown in Table 15. The means and standard deviations shown in Table 15 are calculated over the distributions shown in Figures 4, 7 and 10 for the case in which the variables in Table 14 are allowed to vary and over the corresponding distributions that are obtained for the case in which the variables in Table 14 are fixed at their best estimate values. For example, the distribution of mean crop long-term dose obtained with the variables in Table 14 fixed at their best-estimate values is shown in Figure 12; the corresponding mean and standard deviation shown in Table 15 for crop long-term dose are determined from this distribution. As comparison of the standard deviations obtained with and without the variables in Table 14 fixed at their best-estimate values shows, fixing the variables in Table 14 results in substantial reductions in the uncertainty in all the predicted variables under consideration in this study.

Figure 11 Mean and Percentile Curves for Crop Long-Term Dose with the Variables in Table 14 Set to Their Best-Estimate Values.

Table 15. Standard Deviations (SDs), Means, Medians and 95th Percentiles for Predicted Variables Obtained With and Without the Variables in Table 14 Set to Their Best-Estimate Values

Predicted Variable	All Variables in Table 9 Allowed to Vary				Variables in Table 14 Set to Best-Estimate Values			
	SD	Mean	Median	95th	SD	Mean	Median	95th
Total Long-Term Pathways Dose (Sv)	6.1×10^5	2.4×10^5	2.3×10^5	3.6×10^5	1.2×10^5	2.2×10^5	2.2×10^5	2.4×10^5
Total Ingestion Pathways Dose (Sv)	6.1×10^5	1.1×10^5	9.7×10^4	2.2×10^5	1.2×10^5	8.9×10^4	8.8×10^4	1.1×10^5
Milk Growing Season Dose (Sv)	1.1×10^5	9.4×10^3	5.8×10^3	3.0×10^4	1.8×10^4	7.5×10^3	7.3×10^3	9.9×10^3
Crop Growing Season Dose (Sv)	4.3×10^5	6.5×10^4	5.8×10^4	1.4×10^5	8.2×10^4	6.0×10^4	6.0×10^4	7.3×10^4
Crop Long-Term Dose (Sv)	2.6×10^5	2.6×10^4	2.0×10^4	7.7×10^4	4.8×10^4	1.7×10^4	1.6×10^4	2.5×10^4
Total Food Pathways Dose (Sv)	6.1×10^5	1.1×10^5	9.5×10^4	2.2×10^5	1.2×10^5	8.8×10^4	8.7×10^4	1.1×10^5
Area Dependent Cost (\$)	1.4×10^{10}	1.8×10^9	1.4×10^9	4.3×10^9	1.0×10^9	1.3×10^9	1.2×10^9	1.5×10^9
Milk Disposal Cost (\$)	2.3×10^8	3.2×10^7	3.0×10^7	7.0×10^7	3.4×10^6	1.8×10^7	1.8×10^7	1.8×10^7
Crop Disposal Cost (\$)	1.2×10^9	1.8×10^8	1.7×10^8	3.9×10^8	1.0×10^8	1.1×10^8	1.0×10^8	1.3×10^8
Condemnation Area (Ha)	5.9×10^6	5.2×10^5	3.1×10^5	1.5×10^6	2.2×10^5	3.3×10^5	3.2×10^5	3.7×10^5
Milk Disposal Area (Ha)	7.4×10^6	1.1×10^6	1.1×10^6	2.3×10^6	1.4×10^5	6.8×10^5	6.7×10^5	7.0×10^5
Crop Disposal Area (Ha)	2.3×10^6	3.4×10^5	3.3×10^5	7.4×10^5	1.8×10^5	2.0×10^5	2.0×10^5	2.4×10^5

Figure 12 Distribution of Mean Crop Long-Term Dose With the Variables In Table 14 Set to Their Best-Estimate Values.

Sensitivity analyses of the type previously presented in Section 4 can be used to determine which of the variables in Table 9 emerge as the new dominant variables after the variables in Table 14 have been set to their best-estimate values. The results of an analysis of this type with stepwise regression analysis with logarithmically-transformed data is presented in Table 16 for mean population dose; the corresponding analyses for variation of all variables in Table 9 appear in Table 11. As examination of Table 15 shows, there is little variation in the predicted variables for cost and area after the variables in Table 14 are set to their best-estimate values, and so analyses for these variables are not presented. Results based on stepwise regression rather than PRCCs were selected for presentation because of their compact form; as seen in Section 4, both analysis procedures yield similar sets of important variables.

Table 16. Stepwise Regression Analyses with Logarithmically-Transformed Data for Mean Population Dose With the Variables in Table 14 Set to Their Best-Estimate Values

Step ^a	Milk Growing Season Dose (Sv)		Crop Growing Season Dose (Sv)	
	Variable ^b	R ^{2c}	Variable ^b	R ^{2c}
1	FRCTCMP	0.31 (+)	AF	0.31 (-)
2	IF1	0.59 (+)	IF1	0.53 (+)
3	AF	0.86 (-)	CTHALF1	0.63 (+)
4	CTHALF1	0.94 (+)	C1LCS	0.72 (+)
5	CTHALF2	0.96 (+)	FPLSCHG	0.80 (+)
6	MDELAY	0.97 (-)	FRCTCHG	0.88 (+)
7	IF2	0.97 (+)	CTHALF2	0.90 (+)
8	FRCTCMG	0.98 (+)	FRCTCHL	0.92 (+)
9	FRCTCMF	0.98 (+)	FPLSCHL	0.94 (+)
10			PSOSR89	0.95 (+)
11			FPLSCHO	0.95 (+)
12			TFBI131	0.96 (+)

Effect of Dominant Variables

Table 16 (concluded)

Step ^a	Crop Long-Term Dose (Sv)		Total Food Pathways Dose (Sv)	
	Variable ^b	R ^{2c}	Variable ^b	R ^{2c}
1	TCPSC134	0.38 (+)	AF	0.24 (-)
2	TCGSR90	0.61 (+)	IF1	0.40 (+)
3	FPLSCHL	0.70 (+)	TCPSC134	0.54 (+)
4	FRCTCHL	0.78 (+)	FPLSCHG	0.60 (+)
5	TCRSR90	0.81 (+)	FRCTCHG	0.65 (+)
6	GCMCS134	0.83 (+)	FRCTCHL	0.70 (+)
7	TCFCS137	0.86 (+)	CTHALF1	0.75 (+)
8	TCLCS134	0.87 (+)	FPLSCHL	0.79 (+)
9	TCVSR90	0.88 (+)	TCRSR90	0.83 (+)
10			CTHALF2	0.86 (+)
11			C1LCS	0.89 (+)
12			TCVSR90	0.90 (+)
13			GCMCS134	0.91 (+)
14			FRCTCMP	0.92 (+)
15			TCFCS137	0.93 (+)
16			PSOSR89	0.94 (+)

^aSteps in stepwise regression analysis.

^bVariables listed in order of selection in regression analysis.

^cCumulative R² value with entry of each variable into regression model, with "+" and "-" indicating positive (+) and negative (-) regression coefficients, respectively.

6. DISCUSSION

The present analysis considered the effect of 87 imprecisely-known variables used in the MACCS food pathways model. Further, three groups of predicted variables were selected for study: population dose (crop growing season dose, crop long-term dose, milk growing season dose, total food pathways dose, total ingestion pathways dose, total long-term pathways dose), economic cost (area dependent cost, crop disposal cost, milk disposal cost), and impacted area (condemnation area, crop disposal area, milk disposal area).

Uncertainty/sensitivity analysis techniques based on Latin hypercube sampling, partial correlation analysis and stepwise regression analysis were used to determine the effect of the imprecisely-known variables on MACCS predictions. In performing this analysis, care was taken to maintain a distinction between stochastic uncertainty, which enters the analysis through the probability for different types of weather at the time of occurrence of a reactor accident, and subjective uncertainty, which enters the analysis due to a lack of knowledge about variables supplied as input to MACCS. In particular, the distributions assigned to the 87 variables under consideration characterize subjective uncertainty.

The uncertainty in milk growing season dose was dominated by the ground concentrations at which interdiction of milk production occurs (PSMCS134, PSMI131, PSMCS137) and by the transfer of cesium from animal feed to milk (TFMCS). Similarly, the crop growing season dose was dominated by the ground concentrations at which interdiction of farm production occurs (PSOI131, PSOC134) and by the transfer of cesium from animal feed to meat (TFBCS). The crop long-term dose is dominated by the transfer of Sr-90 from soil to legumes (TCLSR90), the ground concentration of Sr-90 at which crop production is prohibited (GCMSR90), and the transfer of cesium within the food chain (TCP137, TFBCS). The total food pathways dose is dominated by the crop growing season dose and the crop long-term dose. As a result, the dominant variables for total food pathways dose are the dominant variables for crop growing season dose (i.e., transfer of cesium from animal feed to meat, ground concentration of I-131 at which interdiction of farm production occurs) and crop long-term dose (i.e., transfer of Sr-90 from soil to legumes, ground concentration of Sr-90 at which crop production is prohibited). The total ingestion pathways dose differs from the total food pathways dose due to the inclusion of radiation exposures incurred through the consumption of water, and the total long-term pathways dose differs from the total food pathways dose due to the inclusion of radiation exposures incurred through groundshine, inhalation of resuspended material, decontamination work and consumption of water. As none of the MACCS inputs used in the calculation of the additional exposure modes associated with the total ingestion pathways and the total long-term pathways were treated as being uncertain in the analysis, the uncertainty in these variables for this analysis is controlled by the same variables as the uncertainty in the total food pathways dose. The effect of uncertainty in variables that affect groundshine, inhalation of resuspended material, decontamination work and water ingestion will be considered in a later study.⁶

The uncertainty in area-dependent cost (i.e., the sum of decontamination, interdiction, condemnation, milk disposal and crop disposal costs) is dominated by the uncertainty in the ground concentrations at which prohibition of crop production will occur (GCMSR90, GCMCS137). Similarly, crop disposal cost is dominated by the ground concentrations at which crop disposal will be initiated (PSOI131, PSOC134, PSOSR90), and milk disposal cost is dominated by the uncertainty in the ground concentrations at which milk disposal will be initiated (PSMCS134, PSMI131, PSMCS134). The sensitivity analyses for condemnation area, crop disposal area and milk disposal area produce results that

Discussion

are similar to those obtained for area-dependent cost, crop disposal cost and milk disposal cost, respectively.

After the dominant variables were determined, a second uncertainty/sensitivity analysis was performed to determine if reducing the uncertainty in the dominant variables would also substantially reduce the uncertainty in the predicted variables under consideration. In particular, the dominant variables from the first analysis were set to their best-estimate values, and then the uncertainty/sensitivity analysis was repeated with the remaining variables assigned the same distributions as before. The result was a substantial reduction in the uncertainty in the predicted variables. Further, the associated sensitivity analysis identified a new set of dominant variables conditional on the original set of dominant variables taking on their best-estimate values.

This analysis primarily considered variables that are actually used as input to MACCS. Many of these variables are not very natural as they are not quantities that are typically measured in studies of radionuclide movement through foodchains. For example, the variable TFMCS defines the ratio of amount of cesium in milk to amount of cesium consumed by milk-producing animals (units: Bq/Bq); a related and more natural variable is the ratio between the concentration of cesium in milk and the daily consumption of cesium by a milk-producing animal (units: (Bq/l)/(Bq/d)) (Table 5.36, Ref. 52). As another example, QRCS134 is the rate of depletion (yr^{-1}) of Cs-134 from the root zone due to radioactive decay, percolation into soil below the root zone and irreversible binding with soil components; a more informative analysis would result if QRCS134 and other similar variables were expressed as functions of variables more closely related to the individual processes that give rise to the overall depletion rate defined by QRCS134. The incorporation of such variables into the analysis requires either a preprocessor that maps from the sampled variables to the actual input variables used by MACCS or a change to MACCS.

The primary purpose of the analyses contained in this report is to identify the most important input variables used in the MACCS food pathways model. These variables can then be examined in more detail in future studies. As discussed in the introduction, these analyses help in the identification of variables for inclusion in a joint CEC/NRC review of the data used in reactor accident consequence calculations.¹ Further, the dominant variables identified in this analysis and a previous analysis of early health effects⁵ will be used together with additional variables in an uncertainty/sensitivity analysis of the chronic exposure model in MACCS.⁶

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Uncertainty and Sensitivity analysis techniques based on Latin hypercube sampling, partial correlation analysis and stepwise regression analysis are used in an investigation with the MACCS model of the food pathways associated with a severe accident at a nuclear power station. The primary purpose of this study is to provide guidance on the variables to be considered in future review work to reduce the uncertainty in the important variables used in the calculation of reactor accident consequences. The effects of 87 imprecisely known input variables on the following reactor accident consequences are studied: crop growing season dose, crop long-term dose, milk growing season dose, total food pathways dose, total ingestion pathways dose, total long-term pathways dose, area dependent cost, crop disposal cost, milk disposal cost, condemnation area, crop disposal area and milk disposal area.

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