ANL/EVS/TM/11-2

Examination of Technetium-99 Dose Assessment Modeling with RESRAD (onsite) and RESRAD-OFFSITE

Environmental Science Division

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NOTATION

GENERAL ACRONYMS AND ABBREVIATIONS

DOE	U.S. Department of Energy
DSR	dose-to-source ratio
EPA	U.S. Environmental Protection Agency
IAEA	International Atomic Energy Agency
Kd	soil-to-water distribution coefficient
NDD	normalized dose difference
PCC	partial correlation coefficient
PRCC	partial rank correlation coefficient
SRC	standardized regression coefficient
SRRC	standardized rank regression coefficient
Tc-99	technetium-99

UNITS OF MEASURE

cal	calorie(s)
cm^3	cubic meter(s)
d	day(s)
g	gram(s)
K	Kelvin
kg	kilogram(s)
L	liter(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
mol	mole(s)
mrem	millirem(s)
pCi	picocurie(s)
s	second(s)
yr	year(s)

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1 INTRODUCTION

Technetium-99 (Tc-99) is a common contaminant of concern at many U.S. Department of Energy (DOE) sites. Because of its potential of high mobility in the environment, dose assessment modeling of soil contamination with Tc-99 would yield high-radiation-dose results if conservative generic (non-site-specific) parameter values were used. The high-radiation-dose results indicate either a low soil cleanup level that might require intensive remediation to attain, or a low waste acceptance criterion that would restrict the disposal of Tc-99-contaminated material in soil. As a result, to demonstrate compliance with regulatory requirements, realistic dose assessments involving the use of site-specific parameter values are needed. To select parameter values representative of site-specific conditions, it is essential to understand how the parameters are used in the modeling and how they affect the dose results.

The objectives of this report are to (1) examine the modeling of Tc-99 transport and exposure resulting from soil contamination in general, in order to identify critical parameters that strongly influence the dose assessment results, and (2) provide explanations of the use of these parameters to facilitate the understanding of their influence, which would then support the selection of appropriate parameter values. In addition, this report provides suggestions/guidance on determining the appropriate parameter values by presenting literature data associated with different environmental conditions and by discussing the general rules for determining parameter values.

This dose modeling examination project was started by reviewing the Tc-99 dose modeling results for various exposure scenarios concerning pre- and post-closure of the Paducah, Kentucky, on-site landfill disposal facility. On the basis of the dose modeling results, waste acceptance criteria for the landfill were developed and proposed to DOE. The review comments on dose modeling (Cheng 2010a,b) were communicated to the Paducah dose assessment team and resulted in the revisions of several key input parameters. The revised dose results and waste acceptance criteria are considered to be more realistic for the Paducah site. Some of the suggestions provided to correct inconsistencies observed during the dose modeling review are thought to be applicable to other sites as well; therefore, they are included in this report as part of the general discussions on several critical parameters in Section 3.

The examination of Tc-99 dose assessments focused on RESRAD (onsite) modeling (Yu et al. 2001) for on-site exposures and RESRAD-OFFSITE modeling (Yu et al. 2007) for off-site exposures. The input files (Volpe 2010a,b) developed by the Oak Ridge Institute for Science and Education (ORISE) for the Paducah site and forwarded to Argonne National Laboratory (Argonne) were modified slightly and used as the starting points for this study, in which sensitivity analyses were conducted on input parameters by considering their possible ranges in nature that were not specific to the Paducah site. As such, the sensitivity analysis results and pertaining discussions presented in this report are expected to be applicable to any site with Tc-99 contamination. Note that the Paducah input files do not account for the liners that would be installed to reduce water infiltration to the waste disposal area, which would greatly reduce potential leaching of Tc-99 to groundwater. However, cover materials with a total thickness of 1.52 m were employed in the input files for the resident farmer scenario; therefore, only exposures from the water-dependent pathways would be manifested. To examine potential exposures from the water-independent pathways, a hypothetical variation case was created by removing the cover materials. In reality, the Kentucky state regulation requires perpetual ownership and maintenance of the closed landfill, which would keep the cover materials in place for a long period of time.

Section 2 of this report discusses the resident farmer scenario considered in the dose assessment and presents the RESRAD (onsite) and RESRAD-OFFSITE input parameter values. Section 3 discusses deterministic sensitivity analyses conducted for the base and variation cases, respectively; identifies the critical parameters; and discusses the use of these critical parameters in the modeling and general rules for determining their values. Section 4 presents the latest data compiled by the U.S. Environmental Protection Agency (EPA) and the International Atomic Energy Agency (IAEA) for two critical parameters, as well as literature sources containing statistical distribution information for other important parameters. On the basis of the ranges of parameter values used in the deterministic sensitivity analysis, hypothetical distribution functions were assigned to the input parameters for the conduction of probabilistic analyses, which are presented in Section 5. The probabilistic analyses demonstrate a different approach that can also be utilized to study the sensitivities of input parameters and evaluate the distributions of potential radiation doses associated with various exposure scenarios.

2 ON-SITE AND OFF-SITE EXPOSURE SCENARIOS

To examine the dose assessment modeling for soil contamination with Tc-99, a hypothetical source containing Tc-99 in a large on-site landfill at Paducah was considered. Although multiple radionuclides could be disposed of at the Paducah landfill, all other radionuclides, except for Tc-99, were deleted from the RESRAD (onsite) input file (Volpe 2010a) provided to Argonne, so that the examination could focus on Tc-99. The landfill spans an area of 89,436 m^2 (299 m × 299 m), with a contamination depth of 13.4 m. In the base case of this study, a 1.52-m-thick cover layer was assumed to be placed on top of the disposal area before the landfill is closed permanently. Below the disposal area are five unsaturated zones with different physical and hydrogeological properties. A fast-flowing groundwater aquifer underlies the landfill facility and crosses the disposal area almost diagonally.

To examine the modeling of most exposure pathways, a resident farmer was assumed to intrude on the landfill facility after its closure and to establish a subsistence living on top of the waste disposal area. In reality, this is a very unlikely scenario given that various protection measures would be implemented to prevent the intrusion and access to the waste disposal area after the landfill is closed. Relevant exposure pathways for the resident farmer include external radiation; inhalation of resuspended dust particles; incidental ingestion of soil particles; and ingestion of plant foods, meat, and milk products that are grown or obtained from livestock assumed to be raised in the disposal area. A groundwater well located at the edge of the waste disposal area was assumed to provide water for drinking, household activities, and feeding of livestock. The site receives enough precipitation annually that irrigation of the farmland established on top of the disposal area is not necessary. Table 1 lists the input parameter values used for modeling potential radiation exposures of the resident farmer.

In the base case, a thick cover layer would provide shielding against external radiation, inhibit resuspension of contaminated soil particles, and prevent plant roots from reaching the contaminated zone where Tc-99 exists, thereby reducing or completely eliminating potential radiation exposures associated with the water-independent components of various exposure pathways. To examine modeling of the water-independent components, a variation case was created in this study by removing the cover material used in the base case, although it is doubtful that plants would grow out of the debris in the waste disposal area when cover material is removed.

An on-site exposure scenario would yield greater dose results; however, an off-site exposure scenario, in many cases, is more realistic and more likely to occur. To examine off-site dose assessment modeling, the same resident farmer assumed for the on-site exposure scenario is utilized. The farmer is assumed to conduct the same daily activities at locations outside the boundary of the disposal area (i.e., the contaminated zone). Radiation exposures are assumed to occur at different off-site locations, taking advantage of the specific features incorporated into the RESRAD-OFFSITE code. For the most part, the input parameters used

TABLE 1 RESRAD (onsite) Input Parameter Values for the Base Case

Parameter	Value
Source	
Radionuclide concentration (pCi/g)	1 for Tc-99
Transport Factors	
Kd (distribution coefficient) of contaminated zone (cm^3/g)	1
Kd of unsaturated zones (cm^3/g)	0.2, 0.2, 20, 0.2, 20
Kd of saturated zone (cm^3/g)	0.2
Number of unsaturated zones	5
Time since placement of material (yr)	27
Groundwater concentration (pCi/L)	0
Leach rate (1/yr)	0
Solubility limit (mol/L)	0
Use plant/soil ratio (check box)	No
Calculation Parameters	
Basic radiation dose limit (mrem/yr)	25
Time for calculations (yr)	1, 50, 100, 500, 1,000, 2,000
Calculated Zone Parameters	
Area of contaminated zone (m^2)	89,436
Thickness of contaminated zone (m)	13.4
Length parallel to aquifer flow (m)	399
Cover and Contaminated Zone Hydrological Data	
Cover depth (m)	1.52
Density of cover material (g/cm^3)	1.5
Cover erosion rate (m/yr)	0.0006
Density of contaminated zone (g/cm^3)	1.89
Contaminated zone total porosity	0.17
Contaminated zone field capacity	0.07
Contaminated zone erosion rate (m/yr)	0.0006
Contaminated zone hydraulic conductivity (m/yr)	315.4
Contaminated zone b parameter	4.05
Evapotranspiration coefficient	0.83
Wind speed (m/s)	4.5
Precipitation rate (m/yr)	1.24
Irrigation rate (m/yr)	0
Irrigation mode	Overhead
Runoff coefficient	0.34
Watershed area for nearby stream or pond (m^2)	1,000,000
Accuracy for water soil computation	0.001
Saturated Zone Hydrological Data	
Density of saturated zone (g/cm^3)	1.67
Saturated zone total porosity	0.34

TABLE 1 (Cont.)

Parameter	Value
Saturated zone effective porosity	0.3
Saturated zone field capacity	0.04
Saturated zone hydraulic conductivity (m/yr)	55,630
Saturated zone hydraulic gradient	0.0011
Saturated zone b parameter	4.05
Water table drop rate (m/yr)	0.001
Well pump intake depth (below water table)	10
Model, nondispersion (ND) or mass-balance (MB)	ND
Well pumping rate (m^3/yr)	250
Uncontaminated Unsaturated Zone Parameters	
Unsaturated zone thickness (m)	0.3, 0.3, 0.9, 2.0, 8.4
Unsaturated zone density (g/cm^3)	1.2, 1.5, 1.8, 1.5, 1.76
Unsaturated zone total porosity	0.4, 0.45, 0.43, 0.4, 0.45
Unsaturated zone effective porosity	0.2, 0.2, 0.08, 0.2, 0.15
Unsaturated zone field capacity	0.25, 0.2, 0.35, 0.2, 0.3
Unsaturated zone soil b parameter	7.75, 7.75, 11.4, 7.75, 11.4
Unsaturated zone hydraulic conductivity (m/yr)	2.92, 9,460, 0.315, 2.92, 0.14
Occupancy, Inhalation, and External Gamma Parameters	
Inhalation rate (m^3/yr)	7,297
Mass loading for inhalation (g/m^3)	1.08E-06
Exposure duration (yr)	24
Indoor dust filtration factor	0.4
External gamma shielding factor	0.8
Indoor time fraction	0.64
Outdoor time fraction	0.32
Shape of the contaminated zone	Circular
Ingestion Pathway Dietary Data	
Fruit, vegetable, and grain consumption (kg/yr)	231.7
Leafy vegetable consumption (kg/yr)	20.3
Milk consumption (L/yr)	425
Meat and poultry consumption (kg/yr)	154
Fish consumption (kg/yr)	5.4
Other seafood consumption (kg/yr)	0.9
Soil ingestion rate (g/yr)	36.5
Drinking water intake (L/yr)	700
Drinking water contaminated fraction	1
Household water contaminated fraction	1
Livestock water contaminated fraction	1
Irrigation water contaminated fraction	1
Aquatic food contaminated fraction	0.5
Plant food contaminated fraction	−1
Meat contaminated fraction	−1
Milk contaminated fraction	−1

TABLE 1 (Cont.)

Parameter	Value
Ingestion Pathway, Nondietary Data	
Livestock fodder intake for meat (kg/d)	25
Livestock fodder intake for milk (kg/d)	25
Livestock water intake for meat (L/d)	50
Livestock water intake for milk (L/d)	160
Livestock intake of soil (kg/d)	1
Mass loading for foliar deposition (g/m^3)	1.00E-04
Depth of soil mixing layer (m)	0.15
Depth of roots (m)	0.9
Groundwater fraction usage for drinking water	1
Groundwater fraction usage for household water	1
Groundwater fraction usage for livestock water	1
Groundwater fraction usage for irrigation water	1
Plant Factors	
Wet-weight crop yields for nonleafy vegetables (kg/m^2)	0.7
Wet-weight crop yields for leafy vegetables (kg/m^2)	1.5
Wet-weight crop yields for fodder (kg/m^2)	1.1
Length of growing season for nonleafy vegetables (yr)	0.17
Length of growing season for leafy vegetables (yr)	0.25
Length of growing season for fodder (yr)	0.08
Translocation factor for nonleafy vegetables	0.1
Translocation factor for leafy vegetables	1
Translocation factor for fodder	1
Weathering removal constant (1/yr)	20
Wet foliar interception fraction for nonleafy vegetables	0.25
Wet foliar interception fraction for leafy vegetables	0.25
Wet foliar interception fraction for fodder	0.25
Dry foliar interception fraction for nonleafy vegetables	0.25
Dry foliar interception fraction for leafy vegetables	0.25
Dry foliar interception fraction for fodder	0.25
Storage-Times-before-Use Data	
Storage time for fruits, nonleafy vegetables, and grain (d)	14
Storage time for leafy vegetables (d)	1
Storage time for milk (d)	1
Storage time for meat (d)	20
Storage time for fish (d)	7
Storage time for crustacea and mollusks (d)	7
Storage time for well water (d)	1
Storage time for surface water (d)	1
Storage time for livestock fodder (d)	45
Dose Library	
External dose factors	Federal Guidance Report (FGR) 12

TABLE 1 (Cont.)

Parameter	Value
Internal dose factors	International Commission on Radiological Protection (ICRP) 72 adult
Storage time for well water (d)	1
Risk factors	FGR 13 morbidity
Cut-off half-life (d)	180
Number of graphic points	1024
Spacing of graphic points	Linear
Time integration, maximum number of points for dose	17
Time integration, maximum number of points for risk	1
Transfer Factors	
Plant transfer factor	5
Meat transfer factor (pCi/kg)/(pCi/d)	0.0001
Milk transfer factor (pCi/L)/(pCi/d)	0.001
Bioaccumulation factor for fish (pCi/kg)/(pCi/L)	20
Bioaccumulation factor for crustacea and mollusks (pCi/kg)/(pCi/L)	5

for RESRAD-OFFSITE modeling are consistent with those used for RESRAD (onsite) modeling. Additional parameters are used by RESRAD-OFFSITE to simulate environmental fate and transport of Tc-99 beyond the contaminated area. The values assumed for the additional parameters are listed in Table 2. Except for a few changes made to suit this study, most of the parameter values are consistent with those from the Paducah input file (Volpe 2010b).

Potential radiation exposures are modeled with RESRAD-OFFSITE for the base case, in which the contamination source lies beneath a 1.52-m-thick cover layer. The variation case with no cover material is not modeled, because the thickness of cover material would have little effect on the dose results. The long distance between the receptor and the contaminated zone would greatly reduce the radiation dose contributed by the water-independent components of various exposure pathways; as a result, the water-dependent components become dominant in terms of dose contribution.

A soil concentration of 1 pCi/g was assumed for Tc-99 in the contamination source, so that the total dose results obtained with RESRAD (onsite) and RESRAD-OFFSITE are dose-to-source ratios (DSRs), which can be used directly with a dose limit to derive soil cleanup guidelines.

According to the RESRAD (onsite) modeling results, ingestion of contaminated groundwater is the most critical exposure pathway for the base case (with cover), contributing 91% of the peak total dose. The remaining 9% of the peak total dose is contributed by the ingestion of contaminated milk, resulting from milk cows drinking contaminated groundwater. The peak total dose is 0.1795 mrem/yr, which would occur at

TABLE 2 Additional Input Parameters for RESRAD-OFFSITE Analysis

Parameter	Value
Site Layout	
X dimension of primary contamination (m)	299
Y dimension of primary contamination (m)	299
Smaller X coordinate of the fruit, grain, nonleafy vegetables plot (m)	34.375
Larger X coordinate of the fruit, grain, nonleafy vegetables plot (m)	65.625
Smaller Y coordinate of the fruit, grain, nonleafy vegetables plot (m)	806
Larger Y coordinate of the fruit, grain, nonleafy vegetables plot (m)	838
Smaller X coordinate of the leafy vegetables plot (m)	34.375
Larger X coordinate of the leafy vegetables plot (m)	65.625
Smaller Y coordinate of the leafy vegetables plot (m)	840
Larger Y coordinate of the leafy vegetables plot (m)	872
Smaller X coordinate of the pasture, silage growing area (m)	0
Larger X coordinate of the pasture, silage growing area (m)	100
Smaller Y coordinate of the pasture, silage growing area (m)	706
Larger Y coordinate of the pasture, silage growing area (m)	806
Smaller X coordinate of the grain fields (m)	192
Larger X coordinate of the grain fields (m)	292
Smaller Y coordinate of the grain fields (m)	700
Larger Y coordinate of the grain fields (m)	800
Smaller X coordinate of the dwelling site (m)	34.375
Larger X coordinate of the dwelling site (m)	65.625
Smaller Y coordinate of the dwelling site (m)	636
Larger Y coordinate of the dwelling site (m)	670
Smaller X coordinate of the surface-water body	−100
Larger X coordinate of the surface-water body	200
Smaller Y coordinate of the surface-water body	−850
Larger Y coordinate of the surface-water body	−550
Source Release and Deposition Velocity	
Deposition velocity (m/s)	0.001
Distribution Coefficients	
Sediment in surface-water body (cm^3/g)	0.2
Fruit, grain, nonleafy vegetable fields (cm^3/g)	0.2
Leafy vegetable fields (cm^3/g)	0.2
Pasture, silage growing areas (cm^3/g)	0.2
Livestock feed grain fields (cm^3/g)	0.2
Off-site dwelling site (cm^3/g)	0.2
Transfer Factors	
Fruit, grain, nonleafy vegetable transfer factor	5
Leafy vegetable transfer factor	5
Pasture and silage transfer factor	5
Livestock feed grain transfer factor	5

TABLE 2 (Cont.)

Parameter	Value
Storage Time	
Storage time for pasture and silage (d)	1
Storage time for livestock feed grain (d)	45
Primary Contamination	
Deposition velocity of dust (m/s)	0.001
Rainfall and runoff factor	250
Slope-length-steepness factor	0.4
Cover and management factor	0.2
Support practice factor	0.5
Contaminated Zone	
Soil erodibility factor of contaminated zone	0.37
Clean Cover	
Soil erodibility factor of clean cover	0.37
Volumetric water content of clean cover	0.347
Agriculture\Livestock Feed Growing\Off-Site Dwelling Area Parameters	
Fraction of area directly over primary contamination for all fields	0
Irrigation applied per year for all fields (m/yr)	0
Evapotranspiration coefficient for all fields	0.83
Runoff coefficient for all fields	0.34
Depth of soil mixing layer or plow layer for all fields (m)	0.15
Volumetric water content for all fields	0.347
Dry bulk density of soil for all fields (g/cm^3)	1.5
Soil erodibility factor for all fields	0.37
Slope-length-steepness factor for all fields	0.4
Cover and management factor for all fields	0.2
Support practice factor for all fields	0.5
Atmospheric Transport	
Release height (m)	0.1
Release heat flux (cal/s)	0
Anemometer height (m)	10
Ambient temperature (K)	285
AM atmospheric mixing height (m)	400
PM atmospheric mixing height (m)	1600
Dispersion model coefficients	Pasquill-Gifford
Wind speed terrain	Rural
Elevation of off-site location, relative to ground level at primary contamination, for all fields (m)	0
Grid spacing for areal integration (m)	10
Joint frequency of wind speed and stability class for a 16-sector wind rose	Actual values from Paducah, Kentucky

TABLE 2 (Cont.)

Parameter	Value
Unsaturated Zone Parameters	
Unsaturated zone longitudinal dispersivity (m)	15
Saturated Zone Hydrological Data	
Thickness of saturated zone (m)	1,000[a]
Saturated zone longitudinal dispersivity to well (m)	15
Saturated zone horizontal lateral dispersivity to well (m)	0.03
Saturated zone vertical lateral dispersivity to well (m)	1.5
Depth of aquifer contributing to well (m)	10[a]
Groundwater Transport Parameters	
Distance from downgradient edge of contamination to well in the direction parallel to aquifer flow (m)	407
Distance from downgradient edge of contamination to well in the direction perpendicular to aquifer flow (m)	0
Main subzones in saturated zone	1
Main subzones in each partially saturated zone	1
Nuclide-specific retardation in all subzones, longitudinal dispersion in all but the subzone of transformation?	Yes
Water Use	
Quantity of water consumed by an individual (L/yr)	700
Number of household individuals consuming and using water	4
Quantity of water for use indoors of dwelling per individual (L/d)	50[a]
Quantity of water for beef cattle (L/d)	50
Number of beef cattle	2
Quantity of water for dairy cows (L/d)	160
Number of dairy cows	2
Well pumping rate (m^3/yr)	250[a]
Ingestion Rates	
Fruit, grain, nonleafy vegetables consumption from affected area	0.5
Leafy vegetables consumption from affected area	0.5
Meat consumption from affected area	1
Milk consumption from affected area	1
Livestock Intake	
Pasture and silage intake for beef cattle (kg/d)	25
Grain intake for beef cattle (kg/d)	54
Soil from pasture and silage intake for beef cattle (kg/d)	0.2
Soil from grain intake for beef cattle (kg/d)	0.8
Pasture and silage intake for dairy cows (kg/d)	25
Grain intake for dairy cows (kg/d)	11
Soil from pasture and silage intake for dairy cows (kg/d)	0.8
Soil from grain intake for dairy cows (kg/d)	0.2

TABLE 2 (Cont.)

Parameter	Value
Livestock Feed Factors (for Pasture and Silage, Grain)	
Wet weight crop yield (kg/m^2)	1.1, 0.7
Duration of growing season (yr)	0.08, 0.17
Foliage to food transfer coefficient	1, 0.1
Weathering removal constant	20, 20
Foliar interception factor for irrigation	0.25, 0.25
Foliar interception factor for dust deposition	0.25, 0.25
Root depth (m)	0.9, 0.9
Occupancy Factors	
Indoor time fraction on primary contamination	0
Outdoor time fraction on primary contamination	0
Indoor time fraction on off-site dwelling site	0.64
Outdoor time fraction on off-site dwelling site	0.064
Time fraction in fruit, grain, and nonleafy vegetable fields	0.064
Time fraction in leafy vegetable fields	0.064
Time fraction in pasture and silage fields	0.064
Time fraction in livestock grain fields	0.064

[a] Parameter values were selected to match the assumptions used in RESRAD analysis. They are different from the values used for the Paducah site (Volpe 2010b).

746 years in the future. It should be noted that dose results presented in this report should not be used for comparison with or inference of potential exposures at the Paducah site, because some changes were made to the input files received for Paducah for the purpose of this study.

For the variation case (without cover), ingestion of contaminated plant foods is the most critical pathway, contributing 91% of the peak total dose. The ingestion of contaminated milk contributes 8% of the peak total dose; however, rather than resulting from livestock drinking contaminated groundwater, the contamination of milk results from livestock eating contaminated grass or fodder growing in the contaminated zone. The peak total dose is 1.62 mrem/yr at 0 year.

For the off-site exposure scenario, ingestion of contaminated groundwater is the most critical pathway, accounting for about 91% of the peak total dose. The remaining peak total dose is contributed by ingestion of contaminated milk. Although the contamination source is shielded by 1.52 m of cover material, the peak total dose would remain the same even if the cover material is removed. The peak total dose is calculated to be 0.0074 mrem/yr at 257 years by RESRAD-OFFSITE.

3 DETERMINISTIC SENSITIVITY ANALYSES AND RESULTS

Deterministic sensitivity analyses were performed for two on-site exposure cases (base case and variation case) and one off-site exposure case (base case). The analyses focus on physical parameters that could assume different values from site to site or could vary in value within the same site if they were measured at different locations. The analyses exclude the metabolic and behavioral parameters, because these parameters generally are scenario- and receptor-dependent rather than site-dependent, or because their values and distributions have been well studied and representative values have been established by regulatory agencies and used by the risk assessment community. Input parameters for sensitivity analyses were selected (1) on the basis of criticalness of each exposure pathway, so that input parameters relevant to an important pathway were studied, and (2) on the basis of previous sensitivity analysis results obtained for a generic site (Yu et al. 2000), so that important parameters identified previously were also selected for study.

Three parameters—area of contamination, thickness of contaminated zone, and density of contaminated zone—along with concentration in the contaminated zone determine the total activity of Tc-99 in the contamination source, which obviously directly affects potential radiation doses. In order to conduct sensitivity analyses with the same source inventory, these three parameters were kept at their baseline values throughout the analyses.

One input parameter is selected and studied in each sensitivity analysis; that is, the value of one parameter is varied while the values of the other parameters are held at their baseline value. When the value of a parameter is varied, the range of variation is purposely selected to be wide enough to cover possible values of that parameter at various sites. By so doing, the expectation is that even though the dose modeling is conducted with most of the baseline values specific to the Paducah site, the conclusions obtained from examining the sensitivity results are general enough that they are applicable to other sites as well.

The peak total dose and its occurrence time are used to gauge the influence of an input parameter on the dose results. If the peak total dose or its occurrence time changes substantially from the baseline values, the parameter under study is determined to be a sensitive parameter. By identifying the sensitive parameters, efforts can be prioritized to collect more representative site-specific values for a more realistic dose assessment. At the same time, the understanding of how the dose results are influenced by the sensitive parameters helps in assessing the level of uncertainty involved in the dose assessment.

3.1 ON-SITE BASE CASE

Table 3 lists the sensitivity analysis results for the on-site base case. Because of the existence of a thick cover layer on top of the contamination source, leaching of Tc-99 to the groundwater aquifer becomes the primary release mechanism for potential human radiation exposure. The sensitivity analyses were performed for the input parameters that determine

TABLE 3 Sensitivity Analysis Results for the On-Site Base Case with Cover Materials

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Thickness of cover (m)	1.52 (baseline)	746	0.1795	Yes	7.0167
	1	746	0.1917		
	0.5	0	0.7197		
	0.1	0	1.439		
Depth of roots (m)	0.9 (baseline)	746	0.1795	Yes	3.4524
	1.5	746	0.1886		
	2	0	0.3889		
	2.5	0	0.6351		
	3	0	0.7992		
Contaminated zone Kd (cm^3/g)	1 (baseline)	746	0.1795	Yes	42.7376
	0	746	7.688		
	5	746	0.0335		
	10	746	0.0166		
Contaminated zone total porosity	0.17 (baseline)	746	0.1795	No	0.0702
	0.1	746	0.1809		
	0.2	746	0.1778		
	0.3	746	0.1729		
	0.4	746	0.1683		
Contaminated zone field capacity	0.07 (baseline)	746	0.1795	No	0.0368
	0.05	746	0.1794		
	0.1	746	0.1778		
	0.15	748	0.1729		
Contaminated zone hydraulic conductivity (m/yr)	351.4 (baseline)	746	0.1795	No	0.0184
	10	746	0.1762		
	50	746	0.1778		
	100	746	0.1784		
Contaminated zone b parameter	4.05 (baseline)	746	0.1795	No	0.0318
	3	746	0.1808		
	6	746	0.1777		
	9	746	0.1761		
	12	746	0.1751		
Length parallel to aquifer flow (m)	399 (baseline)	746	0.1795	Yes	0.7978
	100	744	0.0451		
	200	744	0.0904		
	420	746	0.1883		

TABLE 3 (Cont.)

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Evapotranspiration coefficient	0.83 (baseline)	746	0.1795	Yes	3.8613
	0.4	194	0.8726		
	0.6	303	0.5009		
Density of saturated zone (g/cm^3)	1.67 (baseline)	746	0.1795	No	0.0033
	1.4	746	0.1791		
	1.6	746	0.1793		
	1.8	747	0.1789		
Saturated zone total porosity	0.34 (baseline)	746	0.1795	No	0.0033
	0.3	747	0.1791		
	0.4	746	0.1791		
	0.5	745	0.1797		
Saturated zone effective porosity	0.3 (baseline)	746	0.1795	No	0.0078
	0.1	742	0.1806		
	0.2	744	0.18		
	0.34	747	0.1792		
Saturated zone field capacity	0.04 (baseline)	746	0.1795	No	0.0017
	0.1	746	0.1794		
	0.2	747	0.1792		
	0.3	747	0.1792		
Saturated zone hydraulic conductivity (m/yr)	55,630 (baseline)	746	0.1795	Yes	8.9827
	10	785	0.1766		
	50	785	0.884		
	100	785	1.766		
	1,000	785	1.789		
	2,000	785	1.789		
	5,000	785	1.788		
	10,000	764	0.954		
	30,000	750	0.3289		
	40,000	748	0.248		
Saturated zone b parameter	4.05 (baseline)	746	0.1795	No	0.0022
	3	746	0.1794		
	6	746	0.1792		
	9	747	0.1791		
	12	747	0.1793		
Well pump intake depth (m)	10 (baseline)	746	0.1795	Yes	1.4999
	5	746	0.359		
	20	746	0.08976		

TABLE 3 (Cont.)

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Well pumping rate (m^3/yr)	250 (baseline)	746	0.1795	No	0
	500	746	0.1795		
	1,000	746	0.1795		
	5,000	746	0.1795		
	10,000	746	0.1795		
Saturated zone Kd (cm^3/g)	0.2 (baseline)	746	0.1795	Yes	0.2139
	0	743	0.18		
	1	761	0.1756		
	5	834	0.1594		
	10	938	0.1416		
Unsaturated zone thickness (m)	8.4 (baseline)	746	0.1795	Yes	1.0022
	1	112	0.1799		
	4	369	0.1796		
	10	883	0.1792		
	15	1,000 (1,312)[b]	0 (0.1793)[b]		
	20	1,000 (1,741)[b]	0 (0.1778)[b]		
Unsaturated zone total porosity	0.45 (baseline)	746	0.1795	Yes	1.0000
	0.15	1,000 (1,223)[b]	0 (0.0003)[b]		
	0.2	1,000 (1,635)[b]	0 (0.1783)[b]		
	0.3	1,000 (1,101)[b]	0 (0.1792)[b]		
	0.4	835	0.1792		
Unsaturated zone effective porosity	0.15 (baseline)	746	0.1795	Yes	1.0000
	0.1	506	0.1795		
	0.2	986	0.179		
	0.3	1,000 (1,466)[b]	0 (0.1787)[b]		
	0.4	1,000 (1,945)[b]	0 (0.1787)[b]		
Unsaturated zone density (m)	1.76 (baseline)	746	0.1795	No	0.0017
	1.4	601	0.1795		
	1.6	681	0.1792		
	1.8	763	0.1792		
Unsaturated zone field capacity	0.3 (baseline)	746	0.1795	No	0
	0.1	746	0.1795		
	0.2	746	0.1795		
	0.3	746	0.1795		
Unsaturated zone Kd (cm^3/g)	20 (baseline)	746	0.1795	Yes[c]	0.0022
	0	35.65	0.1799		
	5	213	0.1798		
	10	391	0.1796		

TABLE 3 (Cont.)

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Unsaturated zone hydraulic conductivity (m/yr)	0.14 (baseline)	746	0.1795	No	0.0039
	0.7	746	0.179		
	1.4	746	0.1788		
	5	745	0.1795		
	10	745	0.1793		
	20	745	0.1792		
Unsaturated zone b parameter	11.4 (baseline)	746	0.1795	No	0
	3	746	0.1795		
	6	746	0.1795		
	9	746	0.1795		
	12	746	0.1795		

[a] NDD (normalized dose difference) is calculated by dividing the difference between the maximum and minimum peak total dose associated with an input parameter by the baseline peak total dose. It is used to gauge the influence of the studied input parameter on the dose result.

[b] The values in parentheses are the results obtained by extending the time period of analysis beyond 1,000 years. For the calculation of NDD, the results obtained with a time period of 1,000 years are used.

[c] The unsaturated zone Kd parameter is designated as sensitive because it has considerable influence on the occurrence time of the peak total dose.

the leach rate of Tc-99 from the contamination source, the transport of Tc-99 in the unsaturated and saturated zones, as well as the dilution of the Tc-99 concentration in the well water. Because five unsaturated zones were considered in the modeling and each unsaturated zone is characterized by the same parameters, to avoid redundancy, only the parameters for unsaturated zone 5 were selected for the sensitivity study. Unsaturated zone 5 has the largest thickness and the smallest saturated hydraulic conductivity; it is the most crucial layer among the five unsaturated zones and requires the longest time for Tc-99 to travel through it. The chemical form with which Tc-99 exists in soil would vary with the geochemical conditions, which then would affect its mobility in soil. More detailed discussions on the possible chemical forms and their influence on Tc-99 mobility are provided in Section 4.

Four parameters—precipitation rate, irrigation rate, runoff coefficient, and evapotranspiration coefficient—are used together in RESRAD (onsite) modeling to determine the water infiltration rate to the contaminated zone. The precipitation rate can be determined quite accurately on the basis of meteorological data. The irrigation rate required to sustain the growth of plant foods depends on the precipitation rate and can be determined by referencing farming practices in the local or neighboring areas. Influence of the water infiltration rate on potential dose results was studied by varying only the value of the evapotranspiration coefficient, which was assigned values of 0.4, 0.6, and 0.83 (baseline value) in the analyses, resulting in infiltration rates of 0.490, 0.327, and 0.139 m/yr, respectively. No variation was made in the runoff coefficient value.

The dilution of the Tc-99 concentration in well water is modeled in RESRAD (onsite) by taking into account the groundwater flow rate and other input parameters. The groundwater flow rate can be calculated as the product of the saturated zone hydraulic conductivity and the saturated zone hydraulic gradient. To study the influence of the groundwater flow rate, the value of hydraulic gradient was kept at the baseline value, and only the value of hydraulic conductivity was varied. The value of hydraulic conductivity was changed from 10 to 55,630 m/yr (baseline value), producing a groundwater flow rate of 0.011 to 61.2 m/yr.

A variable named normalized dose difference (NDD) is used to quantify the influence of an input parameter on the peak total dose. The NDD is defined as the difference between the maximum peak total dose and the minimum peak total dose, obtained from the various calculations performed to study the sensitivity of a specific input parameter and normalized by the peak total dose obtained with the input parameters set at their baseline values. The NDD measures the potential range of the peak total dose associated with the variation of a single input parameter within the range of possible values. The normalization with the baseline peak total dose allows the comparison of NDD values from different input parameters and provides a quantitative basis for selecting sensitive input parameters. Judging by the NDD valued calculated, , a parameter with an NDD of greater than 0.2 is selected as a sensitive parameter. However, the influence on peak total dose is not the only consideration in selecting sensitive parameters; a parameter can still be sensitive if it has considerable influence on when the peak total dose occurs, even though the magnitude of the peak total dose does not change considerably at different times.

According to the results listed in Table 3, 12 parameters have a strong influence on the potential radiation exposures: (1) thickness of cover material, (2) depth of roots, (3) soil-to-water distribution coefficient (Kd) of the contaminated zone, (4) Kd of the saturated zone, (5) Kd of the unsaturated zone, (6) length parallel to aquifer flow, (7) evapotranspiration coefficient (i.e., water infiltration rate), (8) saturated zone hydraulic conductivity (i.e., groundwater flow rate), (9) well pump intake depth, (10) unsaturated zone thickness, (11) unsaturated zone total porosity, and (12) unsaturated zone effective porosity. Each of the sensitive parameters is discussed in the following sections.

3.1.1 Thickness of Cover Material and Depth of Roots

Thickness of cover material plays a significant role in determining the magnitude of the peak total dose and time at which the peak total dose occurs. As dose results of the base case (a peak total dose of 0.1795 mrem/yr at 746 years) and variation case (a peak total dose of 1.621 mrem/yr at 0 year) indicate, the plant ingestion–water-independent pathway and the water ingestion pathway are the two competing pathways that dominate the peak total dose of Tc-99. The plant ingestion–water-independent pathway would give a higher dose than the water ingestion pathway, if the root systems of food plants grow completely within the contaminated zone, taking up Tc-99 and resulting in a plant concentration that could be much higher than the soil concentration. The amount of uptake by roots can be reduced or eliminated by limiting the access of roots to the contaminated zone (i.e., by adding cover material on top of the contamination source). As the plant ingestion–water-independent pathway becomes less influential with an increasing thickness of cover material, the dose contribution from the water ingestion pathway becomes more important and eventually surpasses that from the plant ingestion–water-independent pathway. When that happens, the occurrence of the peak total dose shifts from 0 year to a later time, and the peak total dose is contributed mostly by the water ingestion pathway.

The thickness of cover material required to completely eliminate the uptake of Tc-99 by root systems depends on the depth the root systems can extend. If the cover thickness is less than the depth of the roots, then a fraction of the roots are located in the contaminated zone and still take up Tc-99, although in a fractional amount compared with the situation in which the root systems grow entirely within the contaminated zone. Therefore, the “depth of roots” parameter would be a sensitive parameter when its value is greater than the thickness of cover material.

3.1.2 Contaminated Zone Kd, Unsaturated Zone Kd, and Saturated Zone Kd

The Kd parameter plays an important role in the fate and transport modeling of potential groundwater contamination, as indicated by the sensitivity analysis results for the contaminated zone, unsaturated zone, and saturated zone Kds in Table 3. In general, the contaminated zone Kd parameter is used directly in determining the amount of radionuclides leaching out from the contaminated zone. A larger Kd value means there is more adsorption of Tc-99 nuclides to soil particles, and that results in a smaller amount of Tc-99 nuclides being released from the contaminated zone.

After the Tc-99 nuclides have been released from the contaminated zone, the unsaturated zone Kd value is used to determine the transport time required for them to pass the unsaturated zone to reach the groundwater table. Because the radioactive decay half-life of Tc-99 (2.13×10^5 year) is much longer than the transport time, little radioactive decay would occur in the unsaturated zone. As a result, the peak total doses associated with different unsaturated zone Kd values are basically the same, although the occurrence times are different.

Once the Tc-99 nuclides have reached the groundwater table, the saturated zone Kd is used to determine the transport time required for them to travel from the upgradient to the downgradient edge of the contaminated zone where a well is assumed to be located. In addition to affecting the transport time, the saturated zone Kd is used to determine the dissolved Tc-99 concentration in groundwater at the entry point. The integration of the dissolved concentration over the transport time, adjusted by radioactive ingrowth and decay, is then calculated and used with a dilution factor to determine Tc-99 concentration in well water that is pumped out for use. Increasing the Kd value increases the transport time but decreases the dissolved concentration. The net effect, as shown by the sensitivity analysis results, is a decrease in the peak total dose, which occurs at a later time.

On the basis of the sensitivity analysis results, the contaminated zone Kd has the greatest influence on the peak total dose, followed by the saturated zone Kd, and then the unsaturated zone Kd, if the time frame of analysis is long enough to allow the observation of the peak total dose caused by groundwater contamination. Because of the strong impact of Kd values on dose results, it is recommended that, whenever possible, site-specific Kds be measured and used in dose assessments.

3.1.3 Length Parallel to Aquifer Flow

The length parallel to aquifer flow is the distance between the upgradient and downgradient edges of the contaminated zone that Tc-99 nuclides would have to travel in the groundwater aquifer to reach the well. Increasing the distance would increase the transport time. As discussed previously, the peak total dose is obtained with the integration of the dissolved Tc-99 concentration in groundwater over the transport time; therefore, increasing the transport time increases the peak total dose proportionally. This is evidenced by the change in the peak total dose, as shown in Table 3.

Because of the increase in transport time with increasing distance, the peak total dose takes longer to appear. According to the baseline values of saturated zone hydraulic conductivity (55,630 m/yr) and hydraulic gradient (0.0011), the Paducah site has a fast-flowing groundwater aquifer, with a groundwater flow rate (i.e., Darcy velocity) of 61.2 m/yr. Therefore, even though the change in the length parallel to aquifer flow parameter spans 320 m in the sensitivity analyses, it results in only a slight shift in the occurrence time of the peak total dose.

Because of the strong influence of transport time on peak total dose, it is important to factor into consideration the actual location of a groundwater aquifer and its flow direction when an input value for the length parallel to aquifer flow parameter is being determined. The use of the square root of the contaminated area generally would result in conservative estimates (i.e., greater than what actually would occur) of potential groundwater contamination for most cases.

3.1.4 Evapotranspiration Coefficient (Water Infiltration Rate)

The amount of water infiltrating to the contaminated zone is determined by several parameters, including the precipitation rate, irrigation rate, evapotranspiration coefficient, and runoff coefficient. The relationship between the water infiltration rate and the four parameters is described by Equation E.4 of the RESRAD (onsite) user’s manual (Yu et al. 2001). While each of these four parameters can assume different values, it is the water infiltration rate that is used in modeling the leaching of radionuclides from the contaminated zone. To simplify the study of the influence of water infiltration rate on dose results, the values of precipitation rate, irrigation rate, and runoff coefficient were kept at their baseline values, and only the evapotranspiration coefficient was selected for sensitivity analysis.

The water infiltration rate affects several aspects in the modeling. First, it is used to determine the leach rate constant, which is used to determine the amount of radionuclides leaching out from the contaminated zone. Second, it is used to determine the saturation ratios in the unsaturated zones and affects the transport time of Tc-99 nuclides through the unsaturated zones. Last, it is used to determine the dilution of dissolved Tc-99 concentration in the saturated zone due to groundwater flow and well pumping.

The overall influence of the water infiltration rate on both the magnitude and the time of peak total dose is very significant. In Table 3, an evapotranspiration coefficient of 0.83 (the baseline value) yields a water infiltration rate of 0.139 m/yr and results in a peak total dose of 0.1795 mrem/yr at 746 years. Reducing the evapotranspiration coefficient to 0.4 increases the water infiltration rate to 0.49 m/yr and results in a peak total dose of 0.8726 mrem/yr at 194 years. Choosing a medium value of 0.6 for the evapotranspiration coefficient would yield a water infiltration rate of 0.327 m/yr and result in a peak total dose of 0.5009 mrem/yr at 303 years.

Although the water infiltration rate to the contaminated zone is calculated with four environmental parameters in RESRAD (onsite) modeling, nonenvironmental factors may affect its value. For example, if the contaminated zone is protected by synthetic cover materials, then the water infiltration rate to the contaminated zone can be greatly reduced. In such cases, using the runoff and evapotranspiration coefficients obtained for the background environment could produce a much higher water infiltration rate than would the actual situation; therefore, the background values would not be appropriate for use in RESRAD (onsite) modeling if more realistic dose results are desired. The values of these two coefficients can be thoughtfully selected to produce a water infiltration rate, in accordance with Equation E.4 of the RESRAD (onsite) user's manual (Yu et al. 2001), that is considered appropriate to represent the performance of the cover materials.

In addition to considering the performance of cover materials, it is also necessary to check the hydraulic conductivity of each of the unsaturated zones and ensure that their values are not less than the value of the water infiltration rate. If the hydraulic conductivity is less than the water infiltration rate, water would accumulate and backfill the soil layers above, which is a condition not modeled in the RESRAD (onsite) code.

3.1.5 Saturated Zone Hydraulic Conductivity (Groundwater Flow Rate)

The saturated zone hydraulic conductivity is used with the saturated zone hydraulic gradient parameter to determine the groundwater flow rate (Darcy velocity), which is used in determining (1) the transport time of nuclides from the upgradient to the downgradient edge of the contaminated zone, (2) the vertical displacement of nuclides below the groundwater table when they reach the downgradient edge of the contaminated zone, and (3) the dilution of dissolved nuclide concentration in well water. To study the influence of groundwater flow rate on dose results, the saturated zone hydraulic gradient was kept at its baseline value (0.0011), and only the value of the saturated zone hydraulic conductivity was changed in the sensitivity analyses. The value of saturated zone hydraulic conductivity can vary over a wide range at different sites and can be different at different locations within the same site. The value of hydraulic conductivity is varied from 10 to 55,630 m/yr (the baseline value) in the sensitivity analyses, yielding a groundwater flow rate of 0.011 to 61.2 m/yr.

The groundwater flow rate has great influence on the peak total dose, as indicated by the sensitivity analysis results for saturated zone hydraulic conductivity in Table 3; however, the influence is not monotonic. Its influence on the time of peak total dose is not observed until its value is greater than 5.5 m/yr (with a hydraulic conductivity of greater than 5,000 m/yr). When groundwater flows slowly, the transport time of radionuclides from the upgradient to downgradient edge of the contaminated zone increases. Therefore, according to the previous discussions, the peak total dose would increase proportionally, because it is obtained by using the integration of the dissolved water concentration over the transport time. However, during transport from the groundwater table entry point to the downgradient edge of the contaminated zone, the vertical displacement of radionuclides would increase with transport time because of the downward momentum caused by the entry of infiltration water. If the transport time is long, then by the time the dissolved radionuclides reach the downgradient edge, their vertical displacement could be greater than the screen depth of the well. As a result, these radionuclides would pass the downgradient edge without being screened into the well. As such, the integration used for calculating the peak total dose would need to be modified, so that rather than the dissolved nuclide concentration being integrated over the entire transport time from the upgradient to downgradient edge of the contaminated zone, the integration would be carried out only for a fraction of the entire transport time, and only those nuclides that would be screened to the well would be included in the calculation of peak total dose.

The groundwater flow rate would also affect the dilution factor, which is used in the calculation of peak total dose. In general, a slower groundwater flow rate results in greater dilution for the nuclide concentration in well water. The effective pumping width would increase with a decreased groundwater flow rate; as such, clean groundwater may be drawn to the well along with contaminated groundwater, depending on how much well water would be withdrawn for use.

Because the influence of the groundwater flow rate on the peak total dose and its occurrence time is not monotonic, it is suggested that a sensitivity analysis be conducted to gauge the potential change in the dose results by varying the groundwater flow rate within the possible range indicated by site-specific data. If, within the range of groundwater flow rate, the dose results show little change, then obtaining a more precise value for the groundwater flow rate would not be necessary.

3.1.6 Well Pump Intake Depth

The well pump intake depth parameter is used to determine the effective pumping width, which is used to determine the dilution of nuclide concentration in well water. In addition, it is used for comparison with the vertical displacement of nuclides in groundwater when they reach the downgradient edge of the contaminated zone. On the basis of the comparison, the integration of the dissolved nuclide concentration is performed over the entire or a fraction of the transport time, and the integration result is used in the calculation of the peak total dose. In general, increasing the well pump intake depth decreases nuclide concentration in the well water, as supported by the sensitivity analysis results.

In most cases, the RESRAD (onsite) default value of 10 m is used in dose assessments unless some site-specific conditions (e.g., a thickness of groundwater aquifer of less than 10 m) restrict its value.

3.1.7 Unsaturated Zone Thickness

Because the thickness of the unsaturated zone is the distance Tc-99 nuclides have to travel to get to the groundwater table, the time of peak total dose is influenced directly by its value. However, the magnitude of peak total dose shows little correlation with the thickness, mainly because Tc-99 has a long radioactive decay half-life; thus little radioactivity would be lost during the transport through the unsaturated zone.

In the sensitivity analyses, the time frame of analysis was increased from 1,000 to 2,000 years in order to observe the peak total dose caused by groundwater contamination. If the time frame of analysis was kept at 1,000 years, then when the thickness of the unsaturated zone was increased to 15 or 20 m, no groundwater contamination would be observed. In that case, the peak total dose within 1,000 years would be reduced to near zero.

For dose assessment modeling, the site-specific value for the unsaturated zone thickness should be used. At the same time, a longer time frame than is required for the modeling might be used to determine whether groundwater contamination is a potential concern for the site under consideration.

3.1.8 Unsaturated Zone Total Porosity and Effective Porosity

Although in RESRAD (onsite) modeling the unsaturated zone total porosity and effective porosity are treated as two independent parameters, in reality their values are closely related. A change in the value of one parameter affects the value of the other parameter. However, without knowing the exact relationship between them, in the sensitivity analyses these two parameters are studied independently of each other.

Similar to the results for the unsaturated zone thickness parameter, the sensitivity analysis results in Table 3 for the unsaturated zone total porosity and effective porosity show that both have a strong influence on the occurrence time of the peak total dose caused by groundwater contamination but have little impact on the associated peak total dose. The total porosity is used to calculate the retardation factor of Tc-99nuclides, whereas the effective porosity is used to calculate the average pore water velocity. Both the average pore water velocity and the retardation factor affect the transport time through the unsaturated zone. According to the occurrence times of the peak total dose listed in Table 3, the effects of these two porosities are opposite; increasing the total porosity (hence decreasing the retardation factor) reduces the peak total dose time, whereas increasing the effective porosity (hence decreasing the average pore water velocity) increases the peak total dose time. Because the values of total porosity and effective porosity are correlated, most likely positively, it is concluded that the actual influence of either parameter on the peak total dose time would be less than that indicated by the sensitivity analysis results.

The influence of total porosity and effective porosity is contingent on whether the groundwater contamination is an issue within the time frame of analysis. It is recommended that a time frame longer than that required for the modeling be used to determine whether groundwater contamination is a potential concern for the site under consideration.

3.2 ON-SITE VARIATION CASE

Table 4 lists the sensitivity analysis results obtained for the variation case with on-site exposures. The 1.52 m of cover material was removed, and the contamination source was exposed to the ground surface in the variation case. Because of the removal of cover material, non-zero radiation doses associated with the water-independent component of various exposure pathways were calculated. The most significant dose pathway is the one associated with plant ingestion, resulting primarily from uptake of Tc-99 nuclides by plant roots. The baseline peak total dose for the variation case was calculated to be 1.619 mrem/yr at time 0.

The number of physical parameters affecting the radiation dose resulting from root uptake of Tc-99 is limited. Table 4 lists five parameters selected for sensitivity analysis; two of them have no influence or little influence on the peak total dose. The parameters that show significant influence on the peak total dose are (1) contaminated zone Kd, (2) soil-to-plant transfer factor, and (3) milk transfer factor.

3.2.1 Contaminated Zone Kd

The influence of contaminated zone Kd was discussed in Section 3.1.2. It is used to determine the leach rate of Tc-99 nuclides from the contaminated zone. When the Kd value is 0 cm^3/g, all the Tc-99 nuclides in the contaminated zone would dissolve in soil water and be available for release from the contaminated zone. The high release rate would result in a maximum dose of 76.87 mrem/yr from the groundwater-related pathways at 746 years; this would greatly exceed the maximum dose of 1.531 mrem/yr from the water-independent pathways at time 0. Increasing the Kd value from 0 to 1 cm^3/g would result in longer retention of Tc-99 nuclides in the contaminated zone, thereby increasing the dose from the water-independent pathways slightly, but reducing the dose from the groundwater-related pathways greatly, to about 1.623 mrem/yr.

Because of the strong influence of the contaminated zone Kd parameter, the importance of using a representative (site-specific) Kd value for the contaminated zone cannot be overemphasized.

3.2.2 Soil-to-Plant Transfer Factor

The soil-to-plant transfer factor is an empirical parameter representing the ratio of the Tc-99 concentration in plant food due to root uptake to the Tc-99 concentration in soil. As shown by the sensitivity analysis results, the peak total dose is almost linearly proportional to

TABLE 4 Sensitivity Analysis Results for the On-Site Variation Case without Cover Material

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Contaminated zone Kd (cm^3/g)	1 (baseline)	0	1.619	Yes	46.4799
	0	746	76.87		
	5	0	1.623		
	10	0	1.623		
Length parallel to aquifer flow (m)	399 (baseline)	0	1.619	No	0.0000
	100	0	1.619		
	200	0	1.619		
	420	0	1.619		
Evapotranspiration coefficient	0.83 (baseline)	0	1.619	No	0.0056
	0.4	0	1.61		
	0.6	0	1.614		
Soil-to-plant transfer factor	5 (baseline)	0	1.619	Yes	3.7980
	1	0	0.325		
	10	0	3.238		
	20	0	6.474		
Milk transfer factor	0.001 (baseline)	0	1.619	Yes	0.7733
	0.0001	0	1.506		
	0.01	0	2.758		

[a] NDD is calculated by dividing the difference between the maximum and minimum peak total dose associated with an input parameter by the baseline peak total dose. It is used to gauge the influence of the studied input parameter on the dose result.

the value of the soil-to-plant transfer factor, indicating that the plant ingestion–water-independent pathway is the dominant pathway and that the root uptake component is the dominant component for plant contamination. Note that the other component of the water-independent plant ingestion pathway considered in RESRAD (onsite) modeling is the foliar deposition of resuspended dust particles.

The soil-to-plant transfer factor varies among different types of plants with different edible organs. Literature data on this parameter for different types of plants are available (see Section 4) and may be used to obtain better estimates of the potential radiation doses, if information on the types of plants consumed by the receptor is available.

3.2.3 Milk Transfer Factor

The total dose for the variation case at time 0 is contributed mostly by the plant ingestion–water-independent pathway, with a small fraction contributed by the milk ingestion–water-independent pathway. The milk product would become contaminated, because milk cows would consume contaminated fodder that would take up Tc-99 nuclidesfrom soil through the root system. The daily intake rate of Tc-99 nuclides by milk cows was multiplied by the milk transfer factor to give the Tc-99 concentration in milk, which was then used to determine the radiation dose associated with the milk ingestion pathway.

The milk transfer factor has some influence on the peak total dose, but its influence is not as significant as that of the plant transfer factor. Although site-specific values, whenever available, should be used for dose modeling, for most cases the RESRAD (onsite) default value is sufficient for dose assessments, because that value was determined after an intensive literature search and comparison.

3.3 OFF-SITE BASE CASE

Table 5 lists the sensitivity analysis results obtained for the base case with off-site exposures using RESRAD-OFFSITE. Because the exposures occur at off-site locations, Tc-99 would have to be carried either by wind or groundwater to reach the receptor exposure points. In general, the dilution of the nuclide concentration would be much greater in the air than in the groundwater; therefore, potential radiation exposures incurred by an off-site receptor would be dominated by the groundwater-related pathways. The potential dose associated with groundwater-related pathways would not be affected by the thickness of cover materials on top of the contaminated zone, as long as the amount of water infiltrating the contaminated zone remains the same. Because the groundwater concentration decreases with the travel distance, the radiation dose incurred at an off-site location is expected to be smaller than that incurred within the contaminated site boundary.

On the basis of the RESRAD-OFFSITE conceptual model, Tc-99 nuclides in the contaminated zone would travel vertically through the unsaturated zones to reach the groundwater table directly below the contaminated zone, and then travel horizontally in the groundwater aquifer to reach an off-site well location. The well water, in addition to being ingested, could be used to irrigate agricultural fields and livestock feed areas; thus Tc-99 nuclides could accumulate in soils at off-site locations and form secondary contamination sources. As a result, potential exposures incurred at off-site locations would be affected not only by parameters determining the release of Tc-99 nuclides from the contaminated zone and transport of the nuclides within the contaminated site boundary, but also by parameters determining the transport of Tc-99 nuclides from the contaminated site boundary to the off-site well location. In addition to the release and transport, parameters that determine the deposition of Tc-99 nuclides in the secondary contamination source and their transfer to plants and animal products from there could also affect the final radiation doses. As such, some of the input parameters studied in Sections 3.1 and 3.2 would continue to be sensitive parameters for RESRAD-OFFSITE dose modeling. In addition to those parameters, the irrigation rate applied to agricultural fields and livestock feed areas, dispersivities of unsaturated zones and the saturated zone, distance from the edge of the contaminated zone to the off-site well, and thickness of the saturated zone also have a significant influence on potential off-site doses. These additional parameters are discussed in detail in the following sections.

3.3.1 Irrigation Rate Applied to Agricultural Areas and Livestock Feed Areas

Tc-99 nuclides can accumulate in soil through long-term irrigation of contaminated groundwater. This accumulation forms a secondary contamination source and can result in radiation exposures in the same manner as those from the primary contamination source. As found in the variation case (without cover material) for on-site exposure in Section 3.2, the most significant pathway from the secondary contamination source would be the plant ingestion–water-independent pathway, primarily through the root uptake component.

The sensitivity analysis results show that without irrigation, the peak total dose is 0.0074 mrem/yr at 257 years, with 91% contributed by the water ingestion pathway and 9% contributed by the milk ingestion pathway, as a result of milk cows drinking contaminated groundwater. With irrigation being applied to either the agricultural areas or livestock feed areas, the peak total dose would increase. Table 5 shows the increase in peak total dose when irrigation is applied to a single area. The increase would be more substantial if more than one area is irrigated with contaminated groundwater. If 0.1 m/yr of groundwater is applied to all the agricultural areas and livestock feed areas, the peak total dose would increase to 0.0118 mrem/yr, with 57% contributed by the water ingestion pathway, 25% contributed by the plant ingestion pathway, and 17% contributed by the milk ingestion pathway. Increasing the irrigation rate to 0.2 m/yr would increase the peak total dose to 0.0159 mrem/yr, with 42% contributed by the water ingestion pathway, 36% by the plant ingestion pathway, and 21% by the milk ingestion pathway. When the irrigation rate is increased to 0.5 m/yr, the plant ingestion pathway would become the dominant pathway, contributing 47% of the peak

TABLE 5 Sensitivity Analysis Results for the Off-Site Base Case with Cover Material

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Thickness of cover (m)	1.52 (baseline)	257	0.0074	No	0
	1	257	0.0074		
	0.5	257	0.0074		
	0.1	257	0.0074		
Root depth of fruit, grain, and nonleafy vegetables (m)	0.9 (baseline)	257	0.0074	No	0
	1.5	257	0.0074		
	2	257	0.0074		
	2.5	257	0.0074		
	3	257	0.0074		
Root depth of leafy vegetables (m)	0.9 (baseline)	257	0.0074	No	0
	1.5	257	0.0074		
	2	257	0.0074		
	2.5	257	0.0074		
	3	257	0.0074		
Root depth of pasture and silage (m)	0.9 (baseline)	257	0.0074	No	0
	1.5	257	0.0074		
	2	257	0.0074		
	2.5	257	0.0074		
	3	257	0.0074		
Root depth of feed grain (m)	0.9 (baseline)	257	0.0074	No	0
	1.5	257	0.0074		
	2	257	0.0074		
	2.5	257	0.0074		
	3	257	0.0074		
Contaminated zone Kd (cm^3/g)	1 (baseline)	257	0.0074	Yes	1.6892
	0	99.5	0.0143		
	5	526	0.00295		
	10	736	0.0018		
Contaminated zone total porosity	0.17 (baseline)	257	0.0074	No	0.0270
	0.1	256	0.0074		
	0.2	258	0.0074		
	0.3	260	0.0073		
	0.4	263	0.0072		
Contaminated zone hydraulic conductivity (m/yr)	351.4 (baseline)	257	0.0074	No	0.0135
	10	258	0.0073		
	50	258	0.0074		
	100	257	0.0074		
	200	257	0.0074		

TABLE 5 (Cont.)

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Contaminated zone b parameter	4.05 (baseline)	257	0.0074	No	0.0135
	3	256	0.0074		
	6	258	0.0074		
	9	259	0.0073		
	12	259	0.0073		
Length of contamination parallel to aquifer flow (m)	399 (baseline)	257	0.0074	Yes	0.7432
	100	255	0.0022		
	200	256	0.0041		
	420	257	0.0077		
Evapotranspiration coefficient in area of primary contamination	0.83 (baseline)	257	0.0074	Yes	2.5000
	0.4[b]	77	0.0259		
	0.6[b]	113	0.0173		
Density of saturated zone (g/cm^3)	1.67 (baseline)	257	0.0074	No	0
	1.4	256	0.0074		
	1.6	257	0.0074		
	1.8	257	0.0074		
Saturated zone total porosity	0.34 (baseline)	257	0.0074	No	0
	0.3	257	0.0074		
	0.4	256	0.0074		
	0.5	256	0.0074		
Saturated zone effective porosity	0.3 (baseline)	257	0.0074	No	0
	0.1	253	0.0074		
	0.2	255	0.0074		
	0.34	258	0.0074		
Saturated zone hydraulic conductivity (m/yr)	55,630 (baseline)	257	0.0074	Yes	39.3919
	10[c]	–[c]	–[c]		
	50[c]	–[c]	–[c]		
	100	1,000 (3,820)[d]	0 (0.1051)[d]		
	1,000	640	0.2915		
	2,000	437	0.1876		
	5,000	322	0.081		
	10,000	285	0.0409		
	30,000	262	0.0137		
	40,000	259	0.0103		
Depth of aquifer contributing to well (m)	10 (baseline)	257	0.0074	No	0.0270
	5	257	0.0074		
	20	257	0.0072		

TABLE 5 (Cont.)

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Well pumping rate (m^3/yr)	250 (baseline)	257	0.0074	No	0.0000
	500	257	0.0074		
	1,000	257	0.0074		
	5,000	257	0.0074		
	10,000	257	0.0074		
Saturated zone Kd (cm^3/g)	0.2 (baseline)	257	0.0074	No	0.0270
	0	254	0.0074		
	1	269	0.0074		
	5	333	0.0073		
	10	419	0.0072		
Unsaturated zone thickness (m)	8.4 (baseline)	257	0.0074	Yes	1.9459
	1	63.5	0.0178		
	4	138	0.0116		
	10	303	0.0065		
	15	463	0.0045		
	20	643	0.0034		
Unsaturated zone density (m)	1.76 (baseline)	257	0.0074	No	0.1216
	1.4	230	0.0082		
	1.6	245	0.0077		
	1.8	259	0.0073		
Unsaturated zone total porosity	0.45 (baseline)	257	0.0074	Yes	0.4595
	0.15	455	0.004		
	0.2	411	0.0045		
	0.3	314	0.006		
	0.4	272	0.007		
Unsaturated zone effective porosity	0.15 (base)	257	0.0074	Yes	0.6216
	0.1	212	0.0089		
	0.2	296	0.0064		
	0.3	365	0.0051		
	0.4	427	0.0043		
Unsaturated zone Kd (cm^3/g)	20 (baseline)	257	0.0074	Yes	1.8378
	0	54.5	0.021		
	5	141	0.012		
	10	187	0.0099		
Unsaturated zone hydraulic conductivity (m/yr)	0.14 (baseline)	257	0.0074	No	0
	0.7	257	0.0074		
	1.4	257	0.0074		
	5	256	0.0074		
	10	256	0.0074		
	20	256	0.0074		

TABLE 5 (Cont.)

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Unsaturated zone b parameter	11.4 (baseline)	257	0.0074	No	0
	3	257	0.0074		
	6	257	0.0074		
	9	257	0.0074		
	12	257	0.0074		
Soil-to-plant transfer factor of Tc for fruit, grain, and nonleafy vegetables	5 (baseline)	257	0.0074	No	0
	1	257	0.0074		
	10	257	0.0074		
	20	257	0.0074		
Soil-to-plant transfer factor of Tc for leafy vegetables	5 (baseline)	257	0.0074	No	0
	1	257	0.0074		
	10	257	0.0074		
	20	257	0.0074		
Soil-to-plant transfer factor of Tc for pasture, silage	5 (baseline)	257	0.0074	No	0
	1	257	0.0074		
	10	257	0.0074		
	20	257	0.0074		
Soil-to-plant transfer factor of Tc for livestock feed grain	5 (baseline)	257	0.0074	No	0
	1	257	0.0074		
	10	257	0.0074		
	20	257	0.0074		
Intake-to-animal-product transfer factor of Tc for milk	0.001 (baseline)	257	0.0074	Yes	0.8784
	0.0001	257	0.0068		
	0.01	257	0.0133		
Irrigation applied to fruit, grain, and leafy vegetable fields (m/yr)	0 (baseline)	257	0.0074	Yes	1.4324
	0.1[e]	257	0.0099		
	0.2[e]	257	0.0122		
	0.5[e]	257	0.018		
Irrigation applied to leafy vegetable fields (m/yr)	0 (baseline)	257	0.0074	Yes	0.2703
	0.1[e]	257	0.0078		
	0.2[e]	257	0.0083		
	0.5[e]	257	0.0094		
Irrigation applied to pasture and silage fields (m/yr)	0 (baseline)	257	0.0074	Yes	0.8919
	0.1[e]	257	0.0088		
	0.2[e]	257	0.01		
	0.5[e]	257	0.014		

TABLE 5 (Cont.)

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Irrigation applied to feed grain fields (m/yr)	0 (baseline)	257	0.0074	No	0.0676
	0.1[e]	257	0.0075		
	0.2[e]	257	0.0076		
	0.5[e]	257	0.0079		
Unsaturated zone longitudinal dispersivity (m)	15 (baseline)	257	0.0074	Yes	2.1216
	0	757	0.0217		
	0.1	831	0.0124		
	1	725	0.0067		
	5	425	0.006		
	10	309	0.0067		
	20	226	0.008		
Saturated zone longitudinal dispersivity (m)	15 (baseline)	257	0.0074	Yes	0.3784
	0	256	0.0071		
	1	256	0.0071		
	5	256	0.0072		
	10	257	0.0073		
	20	257	0.0075		
	40	257	0.0078		
	80	258	0.0086		
	150	260	0.0099		
Saturated zone horizontal lateral dispersivity (m)	0.03 (baseline)	257	0.0074	Yes	0.3378
	0.5	257	0.0074		
	2	257	0.0072		
	4	257	0.0067		
	6	257	0.0061		
	12	257	0.0049		
Saturated zone vertical lateral dispersivity (m)	1.5 (baseline)	257	0.0074	Yes	4.6216
	0.01	257	0.0383		
	0.1	257	0.0251		
	1	257	0.0090		
	3	257	0.0052		
	5	257	0.0041		
Distance in the direction parallel to aquifer flow from downgradient edge of contamination to well (m)	407 (baseline)	257	0.0074	Yes	1.3919
	100	254	0.0108		
	300	256	0.0082		
	500	258	0.0069		
	1,000	262	0.0005		

TABLE 5 (Cont.)

Parameter	Parameter Value	Time of Peak Total Dose (yr)	Peak Total Dose (mrem/yr)	Sensitive Parameter?	NDD[a]
Thickness of saturated zone (m)	1,000 (baseline)	257	0.0074	Yes	4.1892
	750	257	0.0074		
	500	257	0.0074		
	100	257	0.0074		
	50	257	0.0082		
	30	257	0.0128		
	10	257	0.0384		

[a] NDD is calculated by dividing the difference between the maximum and minimum peak total dose associated with an input parameter by the baseline peak total dose. It is used to gauge the influence of the studied input parameter on the dose result.

[b] Along with the change in the value of the evapotranspiration coefficient, which results in a greater water infiltration rate to soils than does the baseline case, the hydraulic conductivities of unsaturated zones 3 and 5 are also changed. They are set to the same value as the water infiltration rate to avoid the bathtub condition being formed, which is not modeled by RESRAD-OFFSITE.

[c] With the saturated hydraulic conductivity set at 10 and 50 m/yr, the groundwater flow rate calculated as the product of the hydraulic conductivity and the hydraulic gradient would be less than the recharge caused by infiltration of water from the ground surface. Because the situation would not occur in reality, dose calculations with the two input parameter values are not performed.

[d] The values in parentheses are the results obtained by extending the time period of analysis beyond 1,000 years. For the calculation of NDD, the results obtained with a time period of 1,000 years are used.

[e] Along with the change in the irrigation rate, the well pumping rate is also increased accordingly to provide enough water for irrigation.

total dose (0.0269 mrem/yr); followed by the milk ingestion pathway, contributing 27% of the total dose; and then the water ingestion pathway, contributing 25% of the total dose.

Because of the significant root uptake mechanism for Tc-99 nuclides, the irrigation rate applied to off-site agricultural areas and livestock feed areas becomes a sensitive parameter in RESRAD-OFFSITE modeling. Therefore, it is recommended that the source of irrigation water be evaluated and the irrigation rate be determined on the basis of site-specific conditions when RESRAD-OFFSITE is used for modeling Tc-99 exposures.

3.3.2 Longitudinal and Lateral Dispersivities

RESRAD-OFFSITE incorporates a three-dimensional groundwater transport model by considering the dispersion of radionuclides during transport through the unsaturated zone and groundwater aquifer. The consideration of dispersion allows for more realistic modeling of potential groundwater concentration over the RESRAD (onsite) groundwater modeling, which does not consider dispersion and would generally overestimate the peak groundwater concentrations. The dispersivity parameters employed by RESRAD-OFFSITE for the three-dimensional modeling are sensitive parameters and have significant influence on the peak total dose, as indicated by the sensitivity analysis results listed in Table 5.

Dispersivity is a measure of the heterogeneity present in soils or groundwater aquifers through which contaminants transport. It is an empirical factor that quantifies how much contaminants stray away from the mean water that carries them. Some of the contaminants will be "behind" or "ahead" of the mean water, giving rise to a longitudinal dispersivity, and some will be "to the sides of" the pure advective water, leading to a transverse (lateral) dispersivity. Dispersion in soils or groundwater aquifers is due to the fact that each water "particle," passing beyond a soil particle, must choose where to go, whether left or right or up or down, so that the water particles (and their solute) are gradually spread in all directions around the mean path. This is the "microscopic" mechanism, on the scale of soil particles. On the macroscopic scale of long distances, the flow path can have regions of larger or smaller permeability, so that some water can find a preferential path in one direction and some in a different direction, and the contamination can be spread in a completely irregular way.

Dispersivity is defined as the ratio between the dispersion coefficient and the pore water velocity. According to the sensitivity analysis results, the NDD value associated with the unsaturated zone longitudinal dispersivity is greater than the NDD value associated with the saturated zone longitudinal and horizontal lateral dispersivity. The NDD value associated with the unsaturated zone longitudinal dispersivity is less than that associated with the saturated zone vertical lateral dispersivity. However, the unsaturated zone longitudinal dispersivity affects not only the magnitude of the peak total dose but also the time the peak total dose would occur, while the saturated zone dispersivities affect only the magnitude of the peak total dose. Because of the influence of dispersivity on dose results, it is recommended that site-specific values be used in RESRAD-OFFSITE modeling for Tc-99 exposures. If site-specific values are not available, general rules as discussed below may be applied to obtain the parameter values.

Dispersivity is found to be dependent on the length scale of the transport; the value for transport through 100 m of a soil column/aquifer is different from that for transport through 10 m of the same material. For the longitudinal dispersivity, the value usually ranges from one-hundredth of the length to the order of the length. When measurement data are not available, EPA (2003) suggests the longitudinal dispersivity to be calculated as $0.02 + 0.022 \times L$, where L (m) is the travel length. In general, a value of one-hundredth of the length may be used for the unsaturated zone to obtain more conservative dose results (i.e., greater peak doses). A value of one-tenth of the length may be used as a median value. The horizontal lateral dispersivity is typically an order of magnitude smaller than the longitudinal dispersivity, whereas the vertical lateral dispersivity is another order of magnitude lower (Gelhar et al. 1992).

3.3.3 Distance from the Edge of Contamination to Well

RESRAD-OFFSITE models transport of radionuclides beyond the boundary of the contaminated zone in both the atmosphere and groundwater aquifer. In groundwater modeling, the transport from the edge of contamination toward an off-site well entails consideration of additional dilution for radionuclide concentration, as clean water from above the ground surface would infiltrate the unsaturated zone and discharge to the groundwater table. The longer the distance radionuclides travel to reach the off-site well, the larger the quantity of clean water that discharges to the groundwater table, resulting in greater dilution in radionuclide concentrations. Additionally, the dispersion of radionuclides would increase with increasing distance, enhancing the dilution caused by the inflow of clean water even further.

As indicated by the sensitivity analysis results listed in Table 5, the distance from the edge of contamination to the off-site well has great influence on the dose results. The peak total dose would decrease as the distance increases, while the time to the peak total dose would increase as the distance increases. The distance to the off-site well can be determined by considering the footprint of the disposal site, future land use, and any protective measures to limit access to the disposal area, for example, deed restriction and institutional control. It is the distance between the edge of the contaminated zone and the off-site well along the direction of groundwater flow. When the well is not located along the groundwater flow direction, the vertical distance off the centerline of groundwater flow needs to be specified to pinpoint the exact location. A buffer zone of at least 100 m surrounding the disposal area is generally required for Resource Conservation and Recovery Act (RCRA)-permitted low-level waste disposal in compliance with the DOE *Radioactive Waste Management Manual* (DOE 2001).

3.3.4 Thickness of Saturated Zone

The thickness of the saturated zone is used in RESRAD-OFFSITE but not in the RESRAD (onsite) code. As discussed in Section 3.1.5, when radionuclides transport from the groundwater table entry point toward downgradient locations, their vertical displacement from the groundwater table increases along the path as more and more infiltration water from the unsaturated zone discharges to the groundwater aquifer. The downward movement of radionuclides would eventually hit the bottom of the aquifer, and the movement is assumed to bounce elastically back to the aquifer. Farther down the path, a second reflection of the vertical concentration profile would occur when the upward profile hits the groundwater table. As such, the bottom of the aquifer and the water table serve alternately as a reflection mirror. In this way, the radionuclides, after entering the groundwater table, would be confined in the aquifer until they decay away or are withdrawn from the well.

A sensitivity analysis was conducted by reducing the thickness of the saturated zone from 1,000 to 10 m. When the thickness of the saturated zone was greater than 100 m, the reflection of the vertical concentration profile occurred at a distance (downgradient from the edge of the contaminated zone) greater than the distance to the off-site well. As a result, radionuclide concentrations in the well water were the same regardless of the value of the saturated zone thickness. As the thickness of the saturated zone was reduced further, the reflection occurred at a distance shorter than that to the off-site well, and the well water concentration was then boosted as a result of the reflection of the vertical concentration profile.

When RESRAD-OFFSITE is used for groundwater modeling, it is important to remember that the groundwater aquifer modeled is a confined aquifer that is bounded by impermeable bedrock at the bottom. The thickness of the saturated zone is also the upper bound of the well pump intake depth. The value of the thickness of the groundwater aquifer should be determined by reviewing site-specific data on realistic hydrogeological conditions.

4 LITERATURE DATA ON CRITICAL PARAMETERS

Dose results for Tc-99 exposure calculated with RESRAD (onsite) or RESRAD-OFFSITE are greatly influenced by some important parameters identified as sensitive through the deterministic sensitivity analyses discussed in Section 3. To obtain more precise and realistic dose results, values of the sensitive parameters need to be selected carefully to represent the site conditions within the context of the conceptual models simulated by RESRAD (onsite) and RESRAD-OFFSITE. Available site-specific values obtained from field studies or measured with soil or groundwater samples taken from the site should always be used in RESRAD (onsite) and RESRAD-OFFSITE calculations. When site-specific data are not available, literature data corresponding to similar environmental conditions may be used.

In addition to various journals and technical reports, the RESRAD project team conducted two major literature searches in the past to collect data on the influential parameters used in RESRAD (onsite) and RESRAD-OFFSITE modeling. Two reports—NUREG/CR-6697 (Yu et al. 2000) and the RESRAD-OFFSITE user's manual (Yu et al. 2007, Appendix B)—document the results of these two searches. They contain information not only on the distribution of parameter values but also on the functions and associated coefficients that best characterize the distributions.

This section supplements the NUREG/CR-6697 report and the RESRAD-OFFSITE user's manual by providing more detailed information and discussions on two critical input parameters specifically for Tc-99: Kd and the soil-to-plant transfer factor. The information on Kd is taken primarily from an EPA report (EPA 2004), while an IAEA report (IAEA 2009) is the major source for the information on the transfer factor.

4.1 SOIL-TO-WATER DISTRIBUTION COEFFICIENT (Kd)

According to the review by the EPA Office of Radiation and Indoor Air (EPA 2004), in a natural environment, the most stable valence states of Tc are +7 and +4 under oxidizing and reducing conditions, respectively. Tc(VII) in oxidizing environmental systems is highly mobile; that is, Kd ≈ 0 cm^3/g. The dominant aqueous Tc(VII) species in oxidizing waters is the oxyanion TcO_4^-, which is highly soluble and essentially nonadsorptive. However, under reducing conditions in soil and geologic systems, Tc(IV) is expected to dominate because of biotic and abiotic reactive processes, such as surface-mediated reduction of Tc(VII) by iron (Fe)(II). In the absence of aqueous complexing agents other than OH^-, Tc(IV) is considered to be essentially immobile, because it readily precipitates as sparingly soluble hydrous oxide and forms strong surface complexes with surface sites on iron and aluminum oxides and clays.

Kd measurement data reported in the literature support the above discussions. For soils with a low content of organic material under oxidizing conditions, the reported Kd values range from 0 to approximately 0.5 cm^3/g, although most values are less than 0.1 cm^3/g. Therefore, for screening calculations of off-site migration of Tc(VII), the EPA suggests that a value of 0 cm^3/g be used as a conservative minimum value for low organic soils under oxidizing conditions at pH values greater than 5 (EPA 2004). The measured Kd value increases slightly when soil pH is less than 5 and correlates positively with the organic carbon content of soils (Wildung et al. 1979, 1984). However, studies of the effect of organic material on the sorption of Tc(VII) in soils are limited. Measurable adsorption of Tc(VII) observed in experiments conducted with organic material, as well as crushed rock and Fe(II)-containing minerals, has been attributed to the reduction of Tc(VII) to Tc(IV) (EPA 2004).

Tc(VII) can be reduced to Tc(IV) by biotic and abiotic processes. Extensive studies have been conducted on the reduction of Tc(VII) to Tc(IV) by surface-mediated processes. These processes are the basis for certain remediation technologies that make use of permeable barriers composed of zero-valent iron particles (such as metallic iron or sodium-dithionite reduced soils) for immobilization of groundwater contaminants (EPA 2004). Experiments have found that reduction of Tc(VII) is more effective with mineral materials or groundwater containing Fe(II). In addition, microbial reduction of Tc(VII) has also been suggested as a potential mechanism for removal of Tc from contaminated groundwater and waste streams.

Figure 1 is a stability diagram for the dominant Tc aqueous species at 25°C based on a total concentration of 10^{-8} mol/L dissolved Tc. It may be used to determine the dominant valence state of Tc at the site under consideration and help determine an appropriate Kd value for use in RESRAD (onsite) or RESRAD-OFFSITE modeling.

For reference, Table 6 lists the statistic information developed by Thibault et al. (1990) on Kd values of Tc in different types of soil.

4.2 SOIL-TO-PLANT TRANSFER FACTOR

In comparison with other radionuclides, the transfer of Tc-99 from soil to plant through the root uptake mechanism is very effective. If vegetables or fodder are planted and grow directly above the contaminated area, and if the root systems extend to the contaminated zone where Tc-99 is present, the resulting dose from the plant ingestion–water-independent pathway could exceed that from the water-ingestion pathway, as shown by the results for the on-site variation case presented in Section 3. The soil-to-plant transfer factor is the key parameter in determining the radiation dose associated with the plant-ingestion–water-independent pathway.

Most of the literature data on the soil-to-plant transfer factor are reported on a dry weight basis; that is, they are ratios of nuclide concentration in plants based on dry weight to nuclide concentrations in soil, also based on dry weight. However, the transfer factors used in RESRAD (onsite) and RESRAD-OFFSITE are based on fresh weight for plants and dry weight for soil; therefore, the literature data need to be multiplied by the fraction of dry matter content in plants in order to be used by RESRAD (onsite) and RESRAD-OFFSITE.

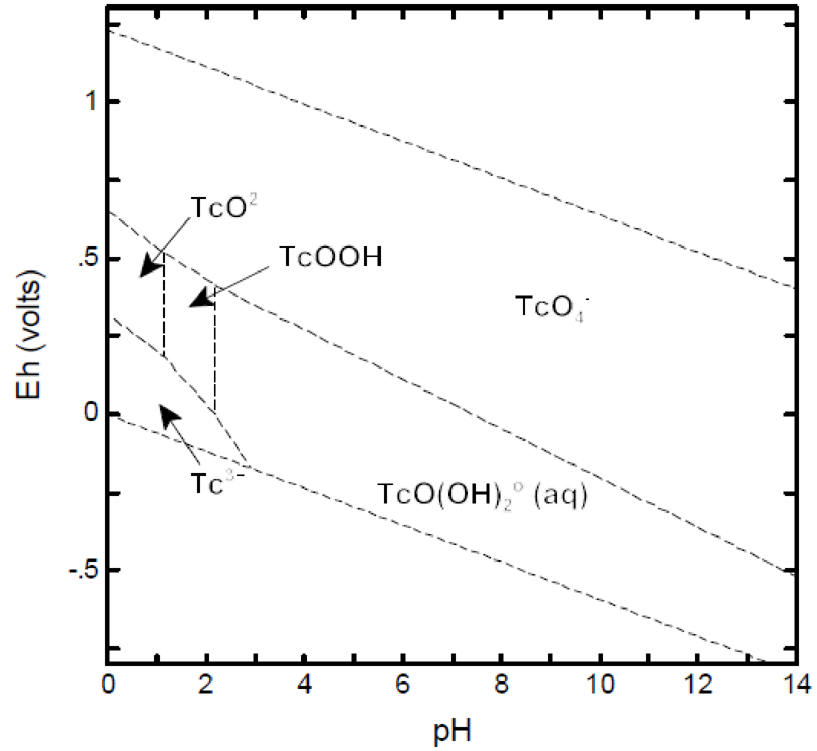

FIGURE 1 Eh-pH Stability Diagram for the Dominant Technetium Aqueous Species at 25°C (diagram based on a total concentration of 10^{-8} mol/L dissolved technetium) (Source: EPA 2004, Figure 5.9)

TABLE 6 Distribution of Kd Values (cm^3/g) for Tc in Different Types of Soil

Soil Type	Number of Observations	μ[a]	σ[b]	exp(μ)[c]	Range
Sand	19	−2	1.8	0.1	0.01 to 16
Silt	10	−2.3	1.1	0.1	0.01 to 0.4
Clay	4	0.2	0.06	1	1.16 to 1.32
Organic	24	0.4	1.8	1	0.02 to 340

[a] Mean of the logarithms of the observed values.

[b] Standard deviation of the logarithms of the observed values.

[c] Geometric mean.

Source: Thibault et al. (1990).

Table 7 lists the water content for different plant groups that, if subtracted from 1, give the fraction of dry matter content needed for the conversion.

TABLE 7 Water Contents for Different Plant Groups

Plant Group	N[a]	GM[b]	GSD[c]	Minimum	Maximum
Leafy and nonleafy vegetables	88	0.92	0.0103	0.84	0.97
Leguminous vegetables, seed	11	0.12	0.0119	0.093	0.17
Leguminous vegetables, vegetative mass	16	0.81	0.011	0.69	0.914
Root crops	39	0.87	0.0105	0.77	0.95
Tubers	10	0.75	0.0108	0.62	0.82
Fruits	102	0.85	0.0106	0.73	0.96
Grass, fodder, pasture	33	0.76	0.0107	0.67	0.9
Cereals (including rice)	22	0.12	0.0117	0.1	0.16
Maize, sweet corn	4	0.71	0.0105	0.68	0.76
Maize, feed corn	11	0.16	0.0146	0.1	0.25
Silage	13	0.66	0.0115	0.55	0.82

[a] N = number of samples.

[b] GM = geometric mean.

[c] GSD = geometric standard deviation.

Source: Davis et al. (2010).

Table 8 lists the converted soil-to-plant transfer factors that can be used readily by RESRAD (onsite) and RESRAD-OFFSITE. They were obtained by multiplying the soil-to-plant transfer factors on a dry weight basis, as reported in Table 20 of the IAEA report (2009), with the assumed dry matter contents from Davis et al. (2010). As indicated by the minimum and maximum values, the value of the soil-to-plant transfer factor can vary two orders of magnitude for the same plant group. The geometric mean and geometric standard deviation are reported when the number of samples is greater than two; otherwise, the arithmetic mean and arithmetic standard deviation are reported.

TABLE 8 Soil-to-Plant Transfer Factors for Different Plant and Soil Groups

Plant Group	Plant Compartment	Soil Group	N[a]	Fraction of Dry Matter[b]	GM[c,d]	GSD[c,e]	AM[c,f]	SD[c,g]	Minimum[c]	Maximum[c]
Cereal	Grain	All	2	0.88	NA[h]	NA	1.1E+00	1.4E+00	1.6E−01	2.1E+00
Maize	Grain	All	8	0.29	1.1E+00	2.4E+00	NA	NA	1.5E−01	1.5E+01
Leafy vegetables	Leaves	All	10	0.08	1.4E+01	1.1E+00	NA	NA	3.6E−01	2.7E+02
		Sand	4	0.08	8.8E+00	2.6E+00	NA	NA	3.6E−01	2.3E+02
		Loam	6	0.08	2.0E+01	6.6E−01	NA	NA	2.0E+00	2.7E+02
Leguminous vegetables	Seeds and pods	All	5	0.88	3.8E+00	4.6E+00	NA	NA	9.7E−01	2.6E+01
		Sand	3	0.88	1.1E+00	9.7E−01	NA	NA	9.7E−01	1.2E+00
		Loam	2	0.88	NA	NA	2.3E+01	4.1E+00	2.0E+01	2.6E+01
Root crops	Roots	All	2	0.13	NA	NA	6.0E+00	6.0E+00	1.8E+00	1.0E+01
Tubers	Tubers	All	8	0.25	5.8E−02	9.3E−01	NA	NA	3.3E−03	1.6E−01
		Sand	6	0.25	9.8E−02	4.0E−01	NA	NA	4.5E−02	1.6E−01
		Loam	2	0.25	NA	NA	2.4E−02	3.0E−02	3.3E−03	4.5E−02
Pasture	Stems and shoots	All	18	0.24	1.8E+01	7.2E−01	NA	NA	1.9E+00	1.1E+02
Maize	Stems and shoots	All	20	0.29	1.9E+00	9.6E−01	NA	NA	2.4E−01	1.1E+01

[a] N = number of samples.

[b] Data for fractions of dry matter in plants were obtained from Table 7.

[c] GM, GSD, AM, SD, minimum, and maximum were obtained by multiplying the data in Table 20 of the IAEA report (2009) with the assumed fraction of dry matter listed in this table.

[d] GM = geometric mean.

[e] GSD = geometric standard deviation.

[f] AM = arithmetic mean.

[g] SD = standard deviation.

[h] NA = data not available.

5 DEMONSTRATION OF PROBABILISTIC SENSITIVITY ANALYSES

The examination of the influence of RESRAD (onsite) or RESRAD-OFFSITE input parameters on the output dose results can be conducted with either the deterministic sensitivity analysis or probabilistic sensitivity analysis that the two computer codes are equipped to perform. The deterministic sensitivity analysis, as demonstrated in Section 3, analyzes the influence of one input parameter at a time by performing dose calculations with different values for the studied parameter while keeping the values of all other input parameters the same. The influence of the studied parameter is then analyzed by examining how the output results vary with the change in value of the studied parameter. Therefore, to study the influence of multiple input parameters, multiple deterministic sensitivity analyses have to be conducted. Furthermore, because input parameters are studied independently of each other, correlation between the parameters cannot be implemented, and this may affect the sensitivity results.

The probabilistic sensitivity analysis, on the other hand, can be employed to examine the influence of multiple input parameters at the same time. It utilizes the distribution functions specified for the input parameters to obtain multiple values for each parameter. The values of different input parameters are then combined, either randomly or in a restrictive way to achieve the specified correlation between the studied parameters, to form multiple sets of input data. Multiple calculations are performed with the input data sets generated to obtain multiple sets of output results. With multiple sets of output results available, analysis of the influence of input parameters then proceeds by fitting a linear relationship between a defined output variable with defined input variables through linear regression. The coefficients obtained for each defined input variable through linear regression are used to gauge the influence of each input parameter and rank them accordingly. More detailed information on performing a probabilistic analysis with RESRAD (onsite) and RESRAD-OFFSITE can be found in the NUREG/CR-6697 report (Yu et al. 2000) and the RESRAD-OFFSITE user's manual (Yu et al. 2007).

In this section, demonstrations of employing probabilistic analyses to evaluate the influence of multiple input parameters are provided. The input files for the base case concerning on-site exposure and off-site exposure, as described in Section 2, are used with hypothetical distribution functions assumed for the same input parameters selected for deterministic sensitivity analysis presented in Section 3. Three probabilistic analyses, each with different hypothetical distribution functions, are conducted with RESRAD (onsite) and RESRAD-OFFSITE. The dose and sensitivity results are compared with each other and with those obtained from deterministic sensitivity analyses.

5.1 PROBABILISTIC ANALYSIS WITH RESRAD (ONSITE)

5.1.1 Distribution Functions and Distribution Parameters

Because information is not available for developing distribution functions for the RESRAD (onsite) input parameters, except for the baseline values taken from the Paducah site, hypothetical distribution functions were assumed to conduct probabilistic analyses with RESRAD (onsite). Three different analyses were conducted. In the first probabilistic analysis (Analysis I), all the input parameters selected for sensitivity analysis were assigned a uniform distribution, with minimum and maximum values consistent with those used for deterministic sensitivity analyses (Section 3, Tables 3 and 4).

In the second probabilistic analysis (Analysis II), distribution functions proposed for the RESRAD (onsite) input parameters in the NUREG/CR-6697 report (Yu et al. 2000) were referenced. The uniform distribution in Analysis I was changed to a triangular distribution, if a parameter is proposed to have a normal or triangular distribution in the NUREG/CR-6697 report. The minimum and the maximum values for the selected triangular distribution were assumed to be the same as those for the initial uniform distribution; the mode of the triangular distribution was assumed to be the average of the minimum and maximum values. If a parameter is proposed to have a lognormal distribution in the NUREG/CR-6697 report, the uniform distribution assumed in Analysis I was changed to a loguniform distribution, with the same minimum and maximum values. For other types of distributions proposed in the NUREG/CR-6697 report, the uniform distribution assumed in Analysis I was maintained and used in the second analysis.

In the third probabilistic analysis (Analysis III), the NUREG/CR-6697 report (Yu et al. 2000) was again referenced. For parameters with a proposed normal distribution in the NUREG/CR-6697 report, the triangular distribution assumed in Analysis II was changed to a normal-B distribution with the same minimum and maximum values. For parameters with a proposed lognormal distribution in the NUREG/CR-6697 report, the loguniform distribution assumed in Analysis II was changed to a lognormal-B distribution with the same minimum and maximum values. Otherwise, the distribution function assumed in Analysis II was continuously used in Analysis III.

The distribution functions assumed for Analyses I, II, and III are hypothetical. For the same input parameter, although the type of distribution assumed may be different in the three probabilistic analyses, the distributions are all bounded by the same minimum and maximum values used in the deterministic sensitivity analyses. This common basis allows meaningful comparison of the sensitivity results from the three probabilistic analyses, so that influence associated with the type of distribution can be examined. On the other hand, the minimum and maximum values are the only distribution parameters required for the selected distribution functions (a triangular distribution needs the specification of a mode value; however, it can be conveniently selected as the middle point or any value between the minimum and maximum); this provides the convenience needed when only limited information on the parameter value is available. Table 9 lists the distribution functions and distribution parameters used in the three probabilistic analyses.

A total of 6,000 sampling data were obtained for each studied input parameter in each probabilistic analysis (2,000 observations and 3 repetitions). Because there is dependency between the total porosity and effective porosity, and between total/effective porosity and density, these three parameters of the unsaturated zone and saturated zone, respectively, were assigned correlations. A correlation coefficient of 0.95 was assigned between the two porosities, and a coefficient of –0.99 was assigned between the total/effective porosity and density. The

TABLE 9 Distribution Functions and Distribution Parameters Assumed for Probabilistic Analyses with RESRAD (onsite)

	Analysis I		Analysis II		Analysis III	
Parameter	Distribution Function	Distribution Parameters	Distribution Function	Distribution Parameters	Distribution Function	Distribution Parameters
Thickness of cover (m)	Uniform[a]	0, 1.52	Uniform	0, 1.52	Uniform	0, 1.52
Depth of roots (m)	Uniform	0.9, 3.0	Uniform	0.9, 3.0	Uniform	0.9, 3.0
Contaminated zone Kd (cm^3/g)	Uniform	0, 10	Loguniform[a]	0.001, 10	Lognormal-B[a]	0.001, 10
Contaminated zone total porosity	Uniform	0.1, 0.4	Triangular[b]	0.1, 0.25, 0.4	Normal-B[a]	0.1, 0.4
Contaminated zone hydraulic conductivity (m/yr)	Uniform	10, 350	Loguniform	10, 350	Lognormal-B	10, 350
Contaminated zone b parameter	Uniform	3, 12	Loguniform	3, 12	Lognormal-B	3, 12
Length parallel to aquifer flow (m)	Uniform	100, 420	Uniform	100, 420	Uniform	100, 420
Evapotranspiration coefficient	Uniform	0.4, 0.83	Uniform	0.4, 0.83	Uniform	0.4, 0.83
Density of saturated zone (g/cm^3)	Uniform	1.4, 1.8	Triangular	1.4, 1.6, 1.8	Normal-B	1.4, 1.8
Saturated zone total porosity	Uniform	0.3, 0.5	Triangular	0.3, 0.4, 0.5	Normal-B	0.3, 0.5
Saturated zone effective porosity	Uniform	0.1, 0.34	Triangular	0.1, 0.22, 0.34	Normal-B	0.1, 0.34
Saturated zone hydraulic conductivity	Uniform	10, 55,630	Loguniform	10, 55,630	Lognormal-B	10, 55,630
Saturated zone b parameter	Uniform	3, 12	Loguniform	3, 12	Lognormal-B	3, 12
Well pump intake depth (m)	Uniform	5, 20	Triangular	5, 12.5, 20	Triangular	5, 12.5, 20
Well pumping rate (m^3/yr)	Uniform	250, 10,000	Uniform	250, 10,000	Uniform	250, 10,000
Saturated zone Kd (cm^3/g)	Uniform	0, 10	Loguniform	0.001, 10	Lognormal-B	0.001, 10
Unsaturated zone thickness (m)	Uniform	1, 20	Loguniform	1, 20	Lognormal-B	1, 20
Unsaturated zone density (g/cm^3)	Uniform	1.4, 1.8	Triangular	1.4, 1.6, 1.8	Normal-B	1.4, 1.8
Unsaturated zone total porosity	Uniform	0.15, 0.45	Triangular	0.15, 0.3, 0.45	Normal-B	0.15, 0.45
Unsaturated zone effective porosity	Uniform	0.1, 0.4	Triangular	0.1, 0.25, 0.4	Normal-B	0.1, 0.4
Unsaturated zone Kd (cm^3/g)	Uniform	0, 20	Loguniform	0.001, 20	Lognormal-B	0.001, 20
Unsaturated zone hydraulic conductivity (m/yr)	Uniform	0.33, 20	Loguniform	0.33, 20	Lognormal-B	0.33, 20
Unsaturated zone b parameter	Uniform	3, 12	Loguniform	3, 12	Lognormal-B	3, 12
Soil-to-plant transfer factor	Uniform	1, 20	Loguniform	1, 20	Lognormal-B	1, 20
Milk transfer factor	Uniform	0.0001, 0.01	Loguniform	0.0001, 0.01	Lognormal-B	0.0001, 0.01

[a] For uniform, loguniform, normal-B, and lognormal-B distributions, the distribution parameters are the minimum and the maximum values.

[b] For triangular distributions, the distribution parameters are the minimum, the mode, and the maximum values.

cover thickness was assigned a uniform distribution between 0 and 1.52 m, so that unlike the runs for the deterministic sensitivity analysis, separate probabilistic runs with and without cover materials are not necessary.

5.1.2 Probabilistic Analysis Results

Figure 2 presents the distribution of peak total doses (from all pathways) associated with the three probabilistic analyses. As shown by the distribution curves, the peak total doses calculated by Analyses II and III are greater than those calculated by Analysis I. Examination of the distribution of peak doses for individual pathways (see Table 10) shows that Analysis I produces higher peak doses for the plant ingestion–water-independent and milk ingestion–water-independent pathways than do Analysis II and Analysis III, while Analysis II and Analysis III produce higher peak doses for the water ingestion pathway than does Analysis I. This can be explained by the different distribution functions used in the three probabilistic analyses. With a uniform distribution, RESRAD (onsite) would sample input data equally within the specified range (i.e., between the minimum and the maximum values) for the studied parameter. With a loguniform or lognormal distribution, however, the sampling by RESRAD (onsite) would be tilted toward the lower end of the specified range; that is, more data would be sampled from the lower end of the distribution than from the higher end of the distribution. For example, if the minimum value is 0.01 and the maximum value is 100, then with a loguniform distribution, the amount of data sampled between 0.01 and 0.1 would be the same as that sampled between 0.1 and 1, between 1 and 10, and between 10 and 100. The specification of a loguniform or lognormal distribution to the key parameters affecting the groundwater concentration, especially the thickness of unsaturated zone and the unsaturated zone Kd, has a profound effect on the dose results. A smaller thickness would shorten the transport time required for Tc-99 nuclides to reach the groundwater table, and a lower Kd would allow more Tc-99 nuclides to dissolve in water. On the other hand, when the thickness is greater than a certain value, Tc-99 nuclides would not be able to reach the groundwater table within the analysis time frame, and with a large Kd value, the amount of Tc-99 nuclides dissolved in water would be small. Then, even if Tc-99 nuclides could reach the groundwater table within the analysis time frame, the potential contamination in groundwater would not be significant. According to the percentile values listed in Table 10, plant and milk ingestion–water-independent pathways are the dominant pathways for Analysis I, while the water ingestion pathway is the dominant pathway for Analysis II and Analysis III.

In addition to providing a statistical summary on distributions of potential radiation doses, RESRAD (onsite) and RESRAD-OFFSITE perform linear regressions to analyze the influence of input parameters on various peak dose results, including peak dose summed over all the exposure pathways and peak dose for individual pathways. Four correlation coefficients—partial correlation coefficient (PCC), standardized regression coefficient (SRC), partial rank correlation coefficient (PRCC), and standardized rank regression coefficient (SRRC)—are generated for each input parameter selected for sensitivity analysis. The PCC and SRC are calculated by performing regressions with the actual dose results and input parameter values, while the PRCC and SRRC are calculated by performing regressions with the ranks of the dose results and the input parameters, respectively. The absolute values of these four coefficients are between 0 and 1 and can be used to gauge the influence of each parameter on the various peak

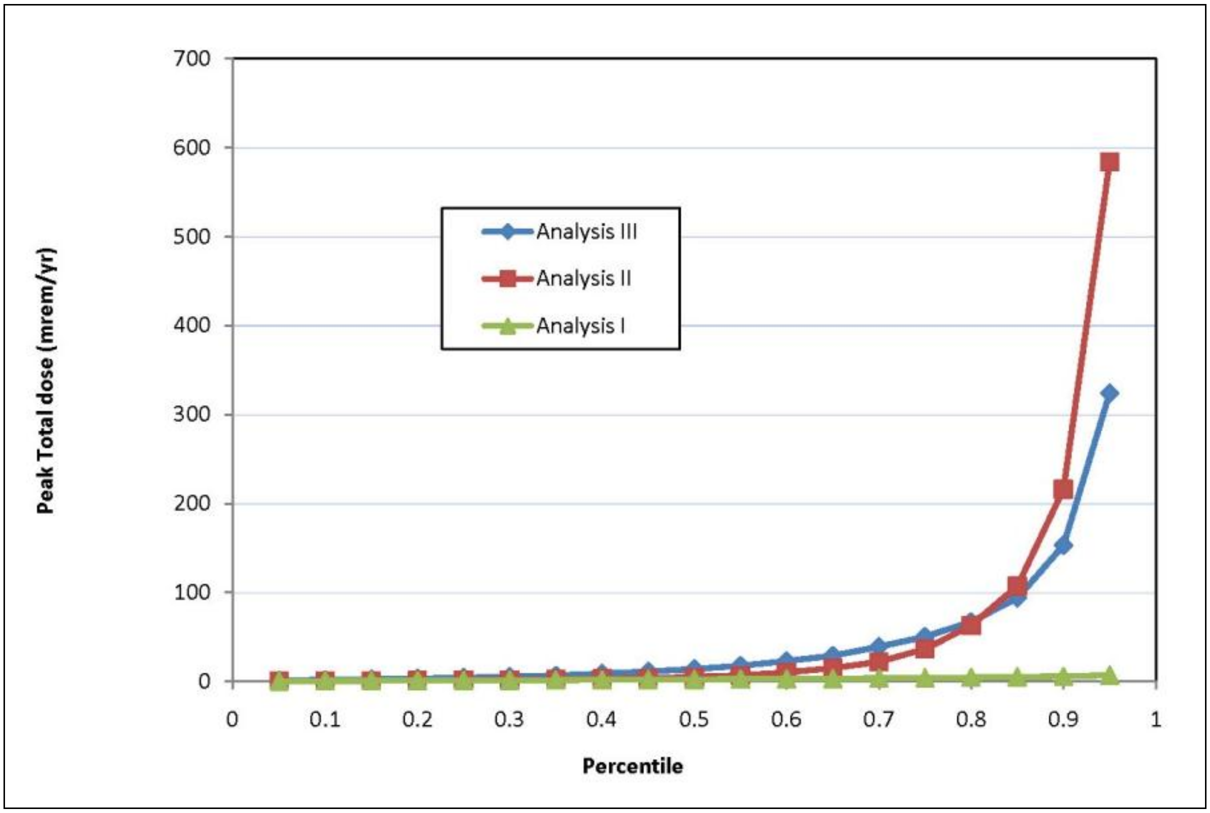

FIGURE 2 Comparison of the Distributions of Peak Total Doses Associated with the Three Probabilistic Analyses with RESRAD (onsite)

dose results. In addition to the four correlation coefficients, RESRAD (onsite) and RESRAD-OFFSITE quantify how well the variation in the peak dose can be explained by the regression on the input parameters with the calculation of a variable called R-SQUARE. The value of R-SQUARE also ranges from 0 to 1; the closer the value is to 1, the better the variation in the peak dose is explained by the variation in the input parameters selected for the analysis. For the three probabilistic analyses, the influence of the input parameters on the dose results was analyzed by examining the values of PRCC and SRRC, because the associated R-SQUAREs are closer to 1 than are the values of R-SQUAREs associated with PCC and SRC. More details on the definitions and use of the four correlation coefficients are provided in the NUREG/CR-6697 report (Yu et al. 2000).

Table 11 compares sensitive parameters for the peak total doses identified through probabilistic analyses with those identified through deterministic analyses. The sensitive parameters identified through probabilistic analyses are selected to be those that have either all three PRCC or all three SRRC values equal to or greater than 0.1 as calculated by the correlation regression analyses (three correlation regressions were performed by RESRAD (onsite) for each probabilistic analysis, corresponding to the sampling specifications of 2,000 observations and 3 repetitions). The three repetitions of each probabilistic analysis identified the same set of most critical input parameters whose correlation coefficients are obviously greater than those of the

TABLE 10 Comparison of the Distributions of Peak Doses from Different Exposure Pathways Associated with Analyses I, II, and III with RESRAD (onsite)

	Analysis I			Analysis II			Analysis III		
Percentile	Plant Ingestion Water-Independent	Milk Ingestion Water-Independent	Water Ingestion	Plant Ingestion Water-Independent	Milk Ingestion Water-Independent	Water Ingestion	Plant Ingestion Water-Independent	Milk Ingestion Water-Independent	Water Ingestion
5%	1.39E-01	2.36E-02	0.00E+00	1.16E-02	4.51E-04	1.88E-02	7.14E-04	5.01E-05	4.31E-01
10%	2.79E-01	5.47E-02	0.00E+00	1.20E-01	3.70E-03	5.59E-02	1.51E-01	8.29E-03	8.92E-01
15%	4.07E-01	9.24E-02	9.74E-03	1.90E-01	6.34E-03	1.21E-01	2.70E-01	1.48E-02	1.41E+00
20%	5.47E-01	1.34E-01	1.99E-02	2.46E-01	9.43E-03	2.11E-01	3.45E-01	2.05E-02	2.13E+00
25%	7.05E-01	1.79E-01	2.72E-02	2.90E-01	1.36E-02	3.24E-01	4.16E-01	2.58E-02	3.13E+00
30%	8.49E-01	2.27E-01	3.45E-02	3.42E-01	1.83E-02	5.09E-01	4.77E-01	3.13E-02	4.23E+00
35%	1.02E+00	2.87E-01	4.29E-02	4.02E-01	2.40E-02	7.97E-01	5.40E-01	3.70E-02	5.59E+00
40%	1.19E+00	3.49E-01	5.15E-02	4.72E-01	3.15E-02	1.31E+00	5.98E-01	4.36E-02	7.34E+00
45%	1.38E+00	4.18E-01	6.11E-02	5.54E-01	4.09E-02	2.07E+00	6.66E-01	5.03E-02	9.55E+00
50%	1.57E+00	5.05E-01	7.35E-02	6.47E-01	5.21E-02	3.24E+00	7.28E-01	5.74E-02	1.22E+01
55%	1.76E+00	5.93E-01	8.90E-02	7.71E-01	6.68E-02	5.09E+00	7.91E-01	6.55E-02	1.54E+01
60%	1.98E+00	7.02E-01	1.07E-01	9.03E-01	8.40E-02	8.05E+00	8.65E-01	7.52E-02	2.01E+01
65%	2.21E+00	8.31E-01	1.32E-01	1.06E+00	1.10E-01	1.25E+01	9.46E-01	8.72E-02	2.55E+01
70%	2.46E+00	9.74E-01	1.62E-01	1.25E+00	1.48E-01	1.86E+01	1.03E+00	1.01E-01	3.35E+01
75%	2.69E+00	1.15E+00	1.92E-01	1.49E+00	1.93E-01	2.99E+01	1.12E+00	1.18E-01	4.40E+01
80%	2.99E+00	1.35E+00	2.35E-01	1.80E+00	2.55E-01	5.02E+01	1.24E+00	1.39E-01	5.85E+01
85%	3.36E+00	1.59E+00	3.14E-01	2.20E+00	3.59E-01	9.08E+01	1.41E+00	1.69E-01	8.19E+01
90%	3.83E+00	1.93E+00	4.35E-01	2.69E+00	5.23E-01	1.84E+02	1.63E+00	2.11E-01	1.41E+02
95%	4.43E+00	2.45E+00	8.85E-01	3.49E+00	9.38E-01	4.93E+02	2.05E+00	3.02E-01	2.82E+02

TABLE 11 Comparison of Sensitive Parameters[a] Identified through Probabilistic Analyses with Those Identified through Deterministic Analyses with RESRAD (onsite) for the Peak Total Dose

	Probabilistic Analysis				
Parameter	I	II	III	Deterministic Analysis[b]	NDD[c]
Cover depth	√	√			
Depth of roots	√			√	3.4524
Contaminated zone Kd of Tc-99	√	√	√	√	46.48
Contaminated zone total porosity		√	√		0.0702
Contaminated zone hydraulic conductivity					0.0184
Contaminated zone b parameter					0.0318
Length parallel to aquifer flow			√	√	0.7978
Evapotranspiration coefficient		√	√	√	3.8613
Saturated zone density					0.0033
Saturated zone total porosity					0.0033
Saturated zone effective porosity					0.0078
Saturated zone hydraulic conductivity		√	√	√	8.9827
Saturated zone b parameter					0.0022
Well pump intake depth				√	1.4999
Well pumping rate		√	√		0
Saturated zone Kd of Tc-99		√	√	√	0.2139
Unsaturated zone thickness				√	1.0022
Unsaturated zone density					0.0017
Unsaturated zone total porosity				√	1
Unsaturated zone effective porosity				√	1
Unsaturated zone hydraulic conductivity					0.0039
Unsaturated zone b parameter					0
Unsaturated zone Kd of Tc-99				√	0.0022[d]
Soil-to-plant transfer factor for Tc	√	√		√	3.798
Milk transfer factor for Tc	√			√	0.7733
R-SQUARE[e]	0.81-0.83	0.72-0.73	0.84	Not applicable	

[a] Significant parameters are those that have either all three PRCC or all three SRRC values ≥0.10 as calculated by the correlation regression analyses. For each probabilistic analysis, the correlation regression analysis was repeated three times, each time with 2,000 sets of calculation results.

[b] Sensitive parameters listed under the deterministic analysis were identified by considering their influence on the peak total dose over all exposure pathways or on the occurrence time of the peak total dose.

[c] NDD was calculated with the deterministic sensitivity analysis results.

[d] Although the NDD for the “unsaturated zone Kd of Tc-99” parameter is small, it has great influence on the occurrence time of the peak total dose; therefore, it is designated as a sensitive parameter.

[e] R-SQUARE varies between 0 and 1 and is called the coefficient of determination; it provides a measure of the variation in the dependent variable (dose) explained by regression on the independent parameters. The listed value is the range of the three repetitions associated with each probabilistic analysis.

other input parameters. The correlation coefficients for less influential parameters may vary among the three repetitions. The use of 0.1 as the cut-off value for selecting sensitive input parameters was determined after comparing the coefficient values calculated for all the studied input parameters. Different cut-off values may be selected for different probabilistic analyses.

According to Table 11, none of the probabilistic analyses identified as many sensitive parameters as the deterministic analyses. Analysis I identifies only five sensitive parameters related to the plant and milk ingestion–water-independent pathways, except for the contamination zone Kd parameter, which is also related to the drinking water pathway. Analysis II and Analysis III identify sensitive parameters mostly related to the drinking water pathway but miss those associated with the unsaturated zone. In addition to sensitive parameters associated with the drinking water pathway, Analysis II also identifies two sensitive parameters related to the plant ingestion–water-independent pathway. In general, the sensitivity results align with the dose distribution results, with input parameters associated with the dominant exposure pathways being identified as sensitive.

To avoid missing sensitive parameters, the regression results concerning the peak dose of individual pathways (plant ingestion–water-independent, milk ingestion–water-independent, and water ingestion) were examined. The same cutoff value of 0.1 for PRCC and SRRC was used to identify sensitive parameters, which are listed in Table 12 for each individual pathway. Table 13 presents the combined list of sensitive parameters over the three exposure pathways. The sensitive parameters, along with NDDs, identified through the deterministic analyses are also listed for comparison.

According to Table 13, the combined list of sensitive parameters associated with Analysis I is almost the same as that associated with the deterministic analyses, except for unsaturated zone total porosity and unsaturated zone effective porosity, which were not identified by Analysis I as sensitive parameters. This may be related to the correlation between these two porosities as implemented in the probabilistic analyses. Other than the unsaturated zone sensitive parameters and one or two sensitive but less critical parameters, Analyses II and III identify the same parameters as being most critical as those identified by the deterministic analyses. The influence of the unsaturated zone parameters is primarily on the occurrence time of the peak total dose, as shown by the results listed in Table 3, which would not be picked up by the correlation regression analyses performed for only the peak doses.

Because the distribution functions selected for input parameters affect the identification of sensitive parameters, multiple tiers of sensitivity analyses should be conducted if a realistic, site-specific dose assessment is desired. At the earlier stage when site-specific data on the distribution of a parameter value are limited, a wider range encompassing possible values of that parameter, along with a uniform distribution, can be used for a probabilistic sensitivity analysis. To avoid bias, the correlation regression results on the peak dose for all exposure pathways as well as for each important exposure pathway should be examined. The parameters excluded as sensitive from this probabilistic analysis can then be assigned a value on the basis of professional judgment and knowledge about the site and excluded from the next probabilistic analysis. Those parameters identified as sensitive would require data collection efforts to check the type of distribution and narrow the range of distribution. The refined distribution function and

TABLE 12 Comparison of Sensitive Parameters[a] Identified through Probabilistic Analyses with RESRAD (onsite) for the Peak Doses of Individual Pathways

	Plant Ingestion Pathway[b]			Milk Ingestion Pathway[b]			Water Ingestion Pathway		
Parameter	Analysis I	Analysis II	Analysis III	Analysis I	Analysis II	Analysis III	Analysis I	Analysis II	Analysis III
Cover depth	√	√	√	√	√	√			
Depth of roots	√	√	√	√	√	√			
Contaminated zone Kd of Tc-99							√	√	√
Contaminated zone total porosity								√	√
Contaminated zone hydraulic conductivity									
Contaminated zone b parameter									
Length parallel to aquifer flow							√		√
Evapotranspiration coefficient							√	√	√
Saturated zone density									
Saturated zone total porosity									
Saturated zone effective porosity									
Saturated zone hydraulic conductivity							√	√	√
Saturated zone b parameter									
Well pump intake depth							√		
Well pumping rate								√	√
Saturated zone Kd of Tc-99								√	√
Unsaturated zone thickness							√		
Unsaturated zone density									
Unsaturated zone total porosity									
Unsaturated zone effective porosity									
Unsaturated zone hydraulic conductivity									
Unsaturated zone b Parameter									
Unsaturated zone Kd of Tc-99							√		
Soil-to-plant transfer factor for Tc	√	√	√	√	√	√			
Milk transfer factor for Tc				√	√	√			
R-SQUARE[c]	0.86−0.88	0.84−0.87	0.86−0.88	0.83−0.85	0.87	0.85	0.67− 0.69	0.78− 0.79	0.84− 0.85

[a] Significant parameters are those that have either all three PRCC or all three SRRC values ≥0.1 as calculated by the correlation regression analyses. For each probabilistic analysis, the correlation regression analysis was repeated three times, each time with 2,000 sets of calculation results.

[b] Plant ingestion and milk ingestion pathways refer to the water-independent components.

[c] R -SQUARE varies between 0 and 1 and is called the coefficient of determination; it provides a measure of the variation in the dependent variable (dose) explained by regression on the independent parameters. The listed value is the range of the three repetitions associated with each probabilistic analysis.

TABLE 13 Combined List of Sensitive Parameters[a] Identified through Probabilistic Analyses with RESRAD (onsite) for Peak Doses of Individual Pathways

	Probabilistic Analysis				
Parameter	I	II	III	Deterministic Analysis[b]	NDD[c]
Cover depth	√	√	√	√	7.0167
Depth of roots	√	√	√	√	3.4524
Contaminated zone Kd of Tc-99	√	√	√	√	46.48
Contaminated zone total porosity		√	√		0.0702
Contaminated zone hydraulic conductivity					0.0184
Contaminated zone b parameter					0.0318
Length parallel to aquifer flow	√		√	√	0.7978
Evapotranspiration coefficient	√	√	√	√	3.8613
Saturated zone density					0.0033
Saturated zone total porosity					0.0033
Saturated zone effective porosity					0.0078
Saturated zone hydraulic conductivity	√	√	√	√	8.9827
Saturated zone b parameter					0.0022
Well pump intake depth	√			√	1.4999
Well pumping rate		√	√		0
Saturated zone Kd of Tc-99		√	√	√	0.2139
Unsaturated zone thickness	√			√	1.0022
Unsaturated zone density					0.0017
Unsaturated zone total porosity				√	1
Unsaturated zone effective porosity				√	1
Unsaturated zone hydraulic conductivity					0.0039
Unsaturated zone b Parameter					0
Unsaturated zone Kd of Tc-99	√			√	0.0022[d]
Soil-to-plant transfer factor for Tc	√	√	√	√	3.798
Milk transfer factor for Tc	√	√	√	√	0.7733

[a] Significant parameters are those that have all three PRCC or all three SRRC values ≥0.1 as calculated by correlation regression analyses. For each probabilistic analysis, the correlation regression analysis was repeated three times, each time with 2,000 sets of calculation results.

[b] Sensitive parameters listed under the deterministic analysis were identified by considering their influence on the peak total dose over all exposure pathways or on the occurrence time of the peak total dose.

[c] NDD was calculated with the deterministic sensitivity analysis results.

[d] Although the NDD for the “unsaturated zone Kd of Tc-99” parameter is small, it has great influence on the occurrence time of the peak total dose; therefore, it is designated as a sensitive parameter.

coefficients then can be used in the next probabilistic analysis. With the use of more representative distribution data, attention can be focused on examining the regression results for the peak total dose only.

5.2 PROBABILISTIC ANALYSIS WITH RESRAD-OFFSITE

5.2.1 Distribution Functions and Distribution Parameters

Three probabilistic analyses were also conducted with RESRAD-OFFSITE. To differentiate them from the probabilistic analyses conducted with RESRAD (onsite), they are designated as Analysis IV, Analysis V, and Analysis VI. The distribution functions and distribution parameters used for Analysis I were continuously used in Analysis IV; those used for Analyses II and III were continuously used in Analyses V and VI, respectively. A total of 6,000 values were sampled for each input parameter with the distribution information (2,000 observations and 3 repetitions).

Table 14 lists the additional distribution functions and distribution parameters assumed for the input parameters used only by RESRAD-OFFSITE. For the probabilistic analyses, the correlation between the effective and total porosity in the unsaturated and saturated zones, respectively, was specified with a correlation coefficient of 0.95. The two porosities were then correlated, respectively, with the bulk density with a correlation coefficient of –0.99. Because dispersion generally increases with travel distance, the dispersivity of the unsaturated zone was correlated with its thickness, and so were the dispersivities of the saturated zone with the distance to the downgradient off-site well. Because of the dependency of each dispersivity parameter of the saturated zone on the distance to the off-site well, correlations among the three dispersivities—longitudinal, horizontal lateral, and vertical lateral—were also specified, all with a coefficient value of 0.99. Irrigation was assumed for the off-site agricultural fields as well as for the off-site fodder and silage fields with groundwater drawn from an off-site well. The irrigation then formed several secondary contamination sources when Tc-99 nuclidescontaminated the groundwater.

Uniform distributions were assumed for the irrigation rate, distance to the off-site well, thickness of groundwater aquifer, and dispersivity parameters in Analysis IV. They then were changed to triangular distributions in Analysis V. The mode of distance to the off-site well was assumed to be 300 m. The mode of the triangular distribution for the dispersivity parameter was set to 10% of the travel distance in the longitudinal direction, 1% of the travel distance in the horizontal lateral direction, and 0.1% of the travel distance in the vertical lateral direction. The distributions of the dispersivity parameters were assumed to be “bounded normal” in Analysis VI. The mean of the normal distribution was kept the same as the mode of the triangular distribution. The standard deviation was assumed to equal the mean value. Although the same range of distribution as that used in Analysis IV and Analysis V was attempted for the same input parameter in Analysis VI, the maximum value of 20 m for the unsaturated zone longitudinal dispersivity and the maximum value of 5 m for the saturated zone vertical lateral dispersivity were not accepted by RESRAD-OFFSITE. Therefore, the allowed maximum values

TABLE 14 Additional Distribution Functions Assumed for Probabilistic Analysis with RESRAD-OFFSITE

	Analysis IV		Analysis V		Analysis VI	
Parameter	Distribution Function	Distribution Parameters	Distribution Function	Distribution Parameters	Distribution Function	Distribution Parameters
Irrigation (from groundwater) applied per year (m/yr)	Uniform[a]	0, 0.5	Triangular[b]	0, 0.2, 0.5	Triangular	0, 0.2, 0.5
Unsaturated zone longitudinal dispersivity (m)	Uniform	0, 20	Triangular	0, 0.84, 20	Bounded normal[c]	0.84, 0.84, 0, 4.83
Saturated zone longitudinal dispersivity (m)	Uniform	0, 150	Triangular	0, 30, 150	Bounded normal	30, 30, 0, 150
Saturated zone horizontal lateral dispersivity (m)	Uniform	0.03, 12	Triangular	0.03, 3, 12	Bounded normal	3, 3, 0.03, 12
Saturated zone vertical lateral dispersivity (m)	Uniform	0.01, 5	Triangular	0.01, 0.3, 5	Bounded normal	0.3, 0.3, 0.01, 1.72
Distance from the edge of contamination to well (m)	Uniform	100, 1,000	Triangular	100, 300, 1,000	Triangular	100, 300, 1,000
Thickness of saturated zone (m)	Uniform	0, 1,000	Triangular	0, 100, 1000	Triangular	0, 100, 1,000

[a] For uniform distribution, the distribution parameters are the minimum and the maximum values.

[b] For triangular distribution, the distribution parameters are the minimum, mode, and maximum values.

[c] For bounded normal distribution, the distribution parameters are the mean, standard deviation, minimum, and maximum values.

of 4.83 m and 1.72 m were used for these two parameters, respectively. The smaller range of distribution may affect the sensitivity results of these two parameters.

5.2.2 Probabilistic Analysis Results

Because radiation exposures are assumed to occur at off-site locations, they are mostly related to groundwater contamination because groundwater is used for drinking by humans and livestock and for irrigation. As a result, the primary exposure pathways are the plant ingestion–water-dependent pathway, milk ingestion–water-dependent pathway, and water ingestion pathway. Figure 3 presents the distributions of peak total doses over all the exposure pathways obtained in Analyses IV, V, and VI, respectively. Table 15 lists the percentile values for the peak dose of the individual pathway obtained in Analyses IV, V, and VI.

Unlike Analyses I, II, and III, which have one or two prominent exposure pathways dominating the peak total dose, Analyses IV, V, and VI show that the contributions to the peak total dose from the plant ingestion–water-dependent, milk ingestion–water-dependent, and water ingestion pathways are comparable. Therefore, sensitive parameters identified through regression analyses for the peak total dose would include input parameters associated with each of these

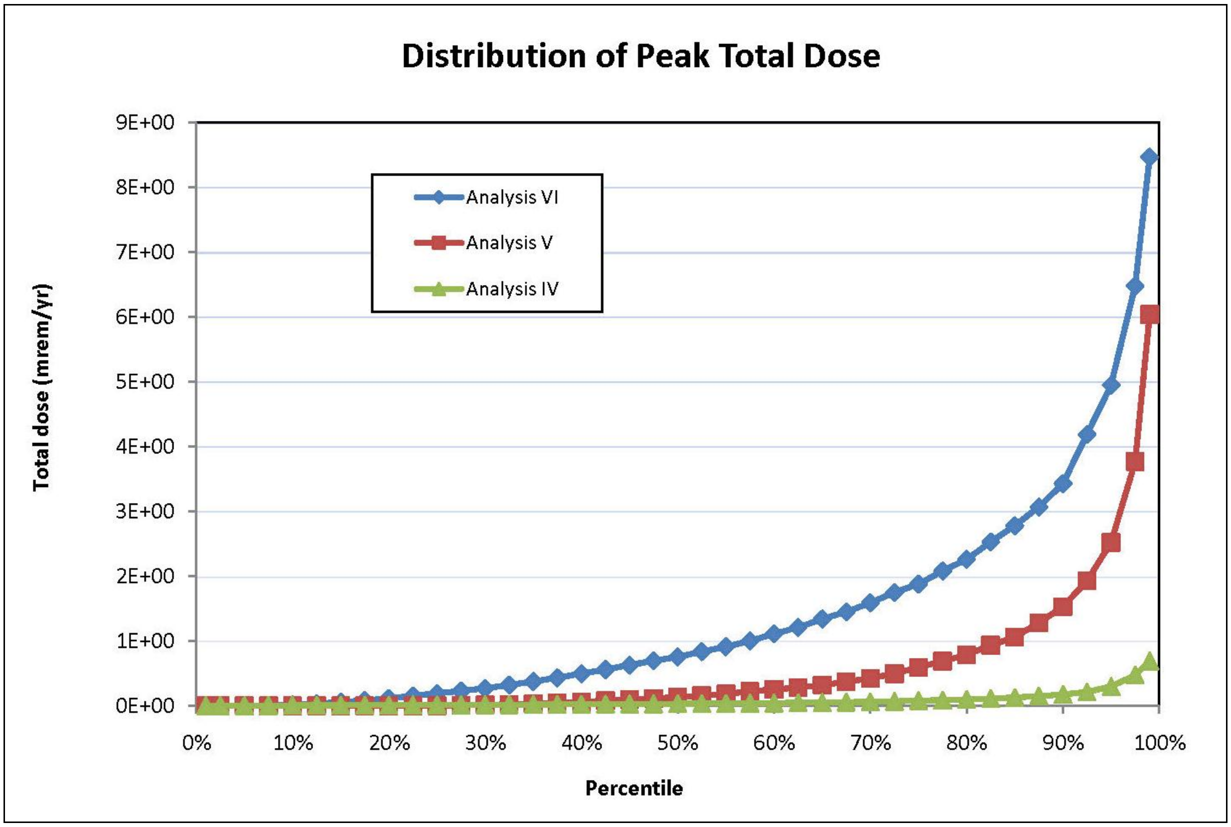

FIGURE 3 Comparison of the Distributions of the Peak Total Doses Associated with the Three Probabilistic Analyses with RESRAD-OFFSITE

TABLE 15 Comparison of the Distributions of Peak Doses from Different Exposure Pathways Associated with Analyses IV, V, and VI with RESRAD-OFFSITE

	Analysis IV			Analysis V			Analysis VI		
Percentile	Plant Ingestion Water-Dependent	Milk Ingestion Water-Dependent	Water Ingestion	Plant Ingestion Water-Dependent	Milk Ingestion Water-Dependent	Water Ingestion	Plant Ingestion Water-Dependent	Milk Ingestion Water-Dependent	Water Ingestion
5%	7.53E-04	8.90E-04	9.50E-04	0.00E+00	0.00E+00	0.00E+00	1.26E-04	7.39E-05	1.56E-04
10%	1.26E-03	1.72E-03	1.53E-03	0.00E+00	0.00E+00	0.00E+00	5.14E-03	2.76E-03	6.29E-03
15%	1.89E-03	2.67E-03	1.92E-03	3.69E-08	1.08E-08	2.95E-08	1.94E-02	9.21E-03	2.23E-02
20%	2.43E-03	3.76E-03	2.29E-03	2.26E-05	8.21E-06	1.94E-05	3.68E-02	1.94E-02	4.46E-02
25%	3.15E-03	5.15E-03	2.71E-03	5.62E-04	2.67E-04	5.54E-04	6.05E-02	3.33E-02	7.47E-02
30%	3.88E-03	6.48E-03	3.25E-03	4.37E-03	1.70E-03	4.41E-03	8.71E-02	4.78E-02	1.05E-01
35%	4.65E-03	7.94E-03	3.86E-03	9.50E-03	3.74E-03	1.12E-02	1.18E-01	6.38E-02	1.46E-01
40%	5.50E-03	1.03E-02	4.52E-03	1.73E-02	6.84E-03	2.08E-02	1.66E-01	8.16E-02	1.93E-01
45%	6.50E-03	1.27E-02	5.12E-03	2.88E-02	1.15E-02	3.14E-02	2.05E-01	1.12E-01	2.43E-01
50%	7.61E-03	1.53E-02	5.89E-03	4.15E-02	1.88E-02	4.67E-02	2.53E-01	1.42E-01	2.97E-01
55%	9.05E-03	1.80E-02	6.83E-03	5.56E-02	2.87E-02	6.46E-02	3.05E-01	1.74E-01	3.53E-01
60%	1.10E-02	2.21E-02	7.95E-03	7.67E-02	4.16E-02	8.30E-02	3.68E-01	2.13E-01	4.27E-01
65%	1.30E-02	2.68E-02	9.25E-03	9.90E-02	5.73E-02	1.08E-01	4.46E-01	2.59E-01	5.16E-01
70%	1.59E-02	3.20E-02	1.11E-02	1.35E-01	8.29E-02	1.45E-01	5.28E-01	3.31E-01	6.14E-01
75%	1.95E-02	4.07E-02	1.37E-02	1.78E-01	1.20E-01	1.93E-01	6.39E-01	3.99E-01	7.08E-01
80%	2.45E-02	5.24E-02	1.70E-02	2.31E-01	1.86E-01	2.48E-01	7.83E-01	5.08E-01	8.39E-01
85%	3.21E-02	7.02E-02	2.20E-02	3.38E-01	2.86E-01	3.24E-01	9.58E-01	7.00E-01	1.03E+00
90%	4.82E-02	9.55E-02	3.14E-02	5.34E-01	4.93E-01	4.73E-01	1.26E+00	1.00E+00	1.30E+00
95%	8.54E-02	1.68E-01	4.93E-02	8.45E-01	9.39E-01	8.03E-01	1.76E+00	1.56E+00	1.75E+00

three exposure pathways. As such, identification of additional sensitive parameters by examination of the regression coefficients associated with the peak doses of individual pathways was not attempted. Sensitive parameters were selected to be those that had all three PRCC or all three SRRC values equal to or greater than 0.1 as calculated by the regression analyses for the peak total dose over all exposure pathways.

Table 16 compares the sensitive parameters identified through Analyses IV, V, and VI with those identified through deterministic sensitivity analyses. The R-SQUARE associated with PRCCs and SRRCs with Analysis V ranges from 0.59 to 0.61, indicating that the attempt to fit the relationship between the peak total dose and the studied input parameters with the correlation coefficients was not very satisfactory. Therefore, gauging the influence of input parameters with the PRCCs and SRRCs may not be adequate. In comparison with the R-SQUARE value for Analysis V, the R-SQUARE values for Analyses IV and VI are relatively higher, ranging from 0.74 to 0.76 for Analysis IV and from 0.75 to 0.76 for Analysis VI, indicating the fit for the relationship between the peak total dose and the studied input parameters for Analyses IV and VI is better than the fit for Analysis V. This is evidenced by the comparison presented in Table 16. The sensitive parameters identified by Analyses IV and VI match those identified by the deterministic sensitivity analyses better than do those identified by Analysis V.

Although probabilistic analysis is a convenient technique for studying the influence of multiple input parameters on the dose result simultaneously, it is important to understand its limitation when the regression analysis results are used. The relationship between the peak dose and the input parameters modeled by RESRAD-OFFSITE is far from linear for the groundwater-related pathways. Therefore, in some cases, fitting the dependency of output results on the input parameters with linear regressions would not be successful, even when the regressions are performed by utilizing the ranks rather than the actual values of the input and output data. Consequently, identifying sensitive parameters with the correlation coefficients obtained from ill-fitting relationships between the input and output data could lead to falsely identifying some input parameters and leaving out the truly influencing parameters.

Like the sensitivity results obtained by Analysis I, the sensitive parameters identified by Analysis IV match those identified by the deterministic sensitivity analyses fairly well. The only sensitive parameters missed by Analysis IV are the effective and total porosities of the unsaturated zone, the unsaturated zone longitudinal dispersivities, the saturated zone longitudinal and horizontal lateral dispersivities, and the thickness of the saturated zone. The correlations assigned between the input parameters for the probabilistic analyses may affect the sensitivity results of those parameters. On the other hand, the effect on the peak total dose with changes in the longitudinal dispersivity is not monotonic; that is, the peak total dose would decrease and then increase with increasing dispersivity values (see the deterministic sensitivity results listed in Table 5). This opposite effect may result in smaller PRCCs and SRRCs being calculated by the regression analysis, so the longitudinal dispersivity is not identified as a sensitive parameter. Analyses V and VI missed the sensitive unsaturated zone parameters identified by the deterministic analyses. Because these unsaturated zone parameters would influence the magnitude of the peak total dose as well as the occurrence time of the peak total dose, should the regression analysis concerning the occurrence time of the peak total dose be performed, these unsaturated zone parameters may be identified as sensitive by Analyses V and VI.

TABLE 16 Comparison of Sensitive Parameters[a] Identified through Probabilistic Analyses with Those Identified through Deterministic Analyses with RESRAD-OFFSITE for the Peak Total Dose

Parameter	Probabilistic Analysis IV	Probabilistic Analysis V	Probabilistic Analysis VI	Deterministic Analysis[b]	NDD[c]
Thickness of cover					0
Root depth of fruit, grain and nonleafy vegetables (m)					0
Root depth of leafy vegetables (m)					0
Root depth of pasture and silage (m)					0
Root depth of feed grain (m)					0
Contaminated zone Kd of Tc-99 (cm^3/g)	√	√	√	√	1.6892
Contaminated zone total porosity					0.027
Contaminated zone hydraulic conductivity (m/yr)					0.0135
Contaminated zone b parameter					0.0135
Length of contamination parallel to aquifer flow (m)	√		√	√	0.7432
Evapotranspiration coefficient in area of primary contamination	√		√	√	2.5
Saturated zone dry bulk density (g/cm^3)					0
Saturated zone total porosity		√			0
Saturated zone effective porosity					0
Saturated zone hydraulic conductivity (m/yr)	√	√	√	√	38
Depth of aquifer contributing to well (m)					0.027
Well pumping rate (m^3/yr)			√		0
Saturated zone Kd of Tc-99 (cm^3/g)	√	√	√	√	0.027[d]
Unsaturated zone thickness (m)	√			√	1.95
Unsaturated zone dry bulk density (g/cm^3)					0.1216
Unsaturated zone total porosity				√	0.4595
Unsaturated zone effective porosity				√	0.6216
Unsaturated zone Kd of Tc-99 (cm^3/g)	√			√	1.8378
Unsaturated zone hydraulic conductivity (m/yr)					0
Unsaturated zone b parameter					0
Soil to plant transfer factor of Tc for Fruit, grain, nonleafy vegetables	√				0
Intake to animal product transfer factor of Tc for milk	√	√	√	√	0.8784
Soil to plant transfer factor of Tc for leafy vegetables					0
Soil to plant transfer factor of Tc for pasture, silage					0
Soil to plant transfer factor of Tc for livestock feed grain					0
Irrigation applied per year to fruit, grain and nonleafy vegetables fields (m/yr)	√		√	√	1.4324

TABLE 16 (Cont.)

Parameter	Probabilistic Analysis IV	Probabilistic Analysis V	Probabilistic Analysis VI	Deterministic Analysis[b]	NDD[c]
Irrigation applied per year to leafy vegetables fields (m/yr)				√	0.2703
Irrigation applied per year to pasture and silage fields (m/yr)	√			√	0.8919
Irrigation applied per year to feed grain fields (m/yr)					0.0676
Unsaturated zone longitudinal dispersivity (m)				√	2.1216
Saturated zone to well longitudinal dispersivity (m)				√	0.3784
Saturated zone to well horizontal lateral dispersivity (m)				√	0.3378
Saturated zone vertical lateral dispersivity (m)	√			√	4.6216
Distance in the direction parallel to aquifer flow from downgradient edge of contamination to well (m)	√	√	√	√	1.3919
Thickness of saturated zone (m)				√	4.1892
R-SQUARE[e]	0.71−0.74	0.59−0.61	0.75−0.76	Not applicable	

[a] Significant parameters are those that have either all three PRCC or all three SRRC values ≥0.1 as calculated by the correlation regression analyses. For each probabilistic analysis, the correlation regression analysis was repeated three times, each time with 2,000 sets of calculation results.

[b] Sensitive parameters listed under the deterministic analysis were identified by considering their influence on the peak total dose over all exposure pathways or on the occurrence time of the peak total dose.

[c] NDD was calculated with the deterministic sensitivity analysis results.

[d] Although NDD for the "saturated zone Kd of Tc-99" parameter is small, it has great influence on the occurrence time of the peak total dose; therefore, it is designated as a sensitive parameter.

[e] R-SQUARE varies between 0 and 1 and is called the coefficient of determination; it provides a measure of the variation in the dependent variable (dose) explained by regression on the independent parameters. The listed value is the range of the three repetitions associated with each probabilistic analysis.

As stated for probabilistic analyses with RESRAD (onsite), multiple tiers of sensitivity analysis are recommended when probabilistic analyses are conducted with RESRAD-OFFSITE. When limited information is available for an input parameter, it is suggested that a uniform distribution with a range wide enough to cover all possible values be used. The distribution can then be modified as more information is collected, if the parameter turns out to be sensitive as indicated by the preliminary probabilistic analysis. Otherwise, an appropriate value can be assigned to the parameter, and the parameter can be excluded from study in the next round of probabilistic analysis.

6 REFERENCES

Cheng, J.-J., 2010a, "Revised RESRAD Input Values," personal communication from Cheng (Argonne National Laboratory, Argonne, Ill.) to J. Volpe (Performance Results Corporation), Sept. 30.

Cheng, J.-J., 2010b, "Findings on RESRAD-OFFSITE Input Values," personal communication from Cheng (Argonne National Laboratory, Argonne, Ill.) to J. Volpe (Performance Results Corporation), Oct. 21.

Davis, P.A., et al., 2010, "Specific Activity Models and Parameter Values for Tritium, ^{14}C, and ^{36}Cl," in *Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments*, IAEA-TECDOC-1616, International Atomic Energy Agency, Vienna, Austria, May.

DOE (U.S. Department of Energy), 2001, *Radioactive Waste Management Manual,* DOE M 435.1-1, approved July 9, 1999, Change 1, June 16, 2001, Office of Environmental Management, Washington, D.C., June.

EPA (U.S. Environmental Protection Agency), 2003, *EPA's Composite Model for Leachate Migration with Transformation Products (EPOA ACMTP), Parameters/Data Background Document,* EPA530-R-03-003, Office of Solid Waste, Washington, D.C., April.

EPA, 2004, *Understanding Variation in Partition Coefficient, Kd, Values, Volume III: Review of Geochemistry and Available Kd Values for Americium, Arsenic, Curium, Iodine, Neptunium, Radium, and Technetium*, EPA402-R-04-002C, Office of Air and Radiation, Office of Radiation and Indoor Air, Washington, D.C., July.

Gelhar, L.W., et al., 1992, "A Critical Review of Data on Field-Scale Dispersion in Aquifers," *Water Resources Research* 28(7):1955–1974.

IAEA (International Atomic Energy Agency), 2009, *Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments,* IAEA-TECDOC-1616, Vienna, Austria, May.

Thibault, D.H., et al., 1990, *A Critical Compilation and Review of Default Soil Solid/Liquid Partition Coefficients,* K_d*, for Use in Environmental Assessments*, AECL-10125, Whiteshell Nuclear Research Establishment, Atomic Energy of Canada Limited, Pinawa, Canada.

Volpe, J., 2010a, "RESRAD Input Files," personal communication from Volpe (Performance Results Corporation) to J.-J Cheng and C. Yu (Argonne National Laboratory, Argonne, Ill.), Sept. 15.

Volpe, J., 2010b, "RESRAD-OFFSITE," personal communication from Volpe (Performance Results Corporation) to J.-J. Cheng (Argonne National Laboratory, Argonne, Ill.), Oct. 15.

Wildung, R.E., et al., 1979, “Technetium Sources and Behavior in the Environment,” *Journal of Environmental Quality* 8:156–161.

Wildung, R.E., et al., 1984, “Technetium Sorption in Surface Soils,” pp. 115–129 in *Technetium in the Environment*, G. Desmet and C. Myttenaere (editors), Elsevier Applied Science Publishers, London, England.

Yu, C., et al., 2000, *Development of Probabilistic RESRAD 6.0 and RESRAD BUILD 3.0 Computer Codes,* NUREG/CR-6697, ANL/EAD/TM-98, prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Division of Risk Analysis and Applications, Office of Nuclear Regulatory Research, Washington, D.C., Nov.

Yu, C., et al., 2001, *User’s Manual for RESRAD Version 6,* ANL/EAD-4, Argonne National Laboratory, Argonne, Ill., July.

Yu, C., et al., 2007, *User’s Manual for RESRAD-OFFSITE Version 2*, ANL/EVS/TM/07-1, DOE/HS-0005, NUREG/CR-6937, prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Department of Energy and U.S. Nuclear Regulatory Commission, June.

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