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RESRAD Parameter Sensitivity Analysis

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RESRAD Parameter Sensitivity Analysis

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RESRAD PARAMETER SENSITIVITY ANALYSIS

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ABSTRACT

Three methods were used to perform a sensitivity analysis of RESRAD code input parameters -- enhancement of RESRAD by the Gradient Enhanced Software System (GRESS) package, direct parameter perturbation, and graphic comparison. Evaluation of these methods indicated that (1) the enhancement of RESRAD by GRESS has limitations and should be used cautiously, (2) direct parameter perturbation is tedious to implement, and (3) the graphics capability of RESRAD 4.0 is the most direct and convenient method for performing sensitivity analyses. This report describes procedures for implementing these methods and presents a comparison of results.

1 INTRODUCTION

A sensitivity analysis of the input parameters of RESRAD, a computer code for implementing U.S. Department of Energy (DOE) guidelines for residual radioactive material (Gilbert et al. 1989), was performed. The RESRAD code establishes soil cleanup criteria on the basis of predictions of radiation doses received by an individual from radionuclides contained in the soil and transported in the environment. The RESRAD code was used to consider seven environmental transport pathways: external radiation from contaminated soil materials; internal radiation from inhalation of contaminated dust particles; internal radiation from ingestion of plant foods grown on-site and irrigated with water drawn from an on-site well or pond; internal radiation from ingestion of meat from livestock fed with fodder grown on-site and water drawn from an on-site well or pond; internal radiation from ingestion of milk from livestock fed with fodder grown on-site and water drawn from an on-site well or pond; internal radiation from ingestion of aquatic food (fish) from a nearby pond; and internal radiation from drinking water from an on-site well or pond. Figure 1 is a schematic representation of the relationships among the pathways. As with any predictive model, the accuracy of the predictions depends on the accuracy of the input parameters (see Appendixes A and B). This report presents the results of a sensitivity analysis of RESRAD input parameters. Parameters with high sensitivities will have a greater effect on the predicted results and, therefore, these parameters should be determined more accurately. Accurate sensitivity analysis results can then be used to set priorities for gathering input data.

Three methods were used to perform a sensitivity analysis of RESRAD input parameters: (1) application of the Gradient Enhanced Software System (GRESS), a sensitivity analysis package developed at Oak Ridge National Laboratory (Horwedel 1990); (2) direct perturbation; and (3) a graphics package built into RESRAD that shows parameter sensitivities while RESRAD is operational.

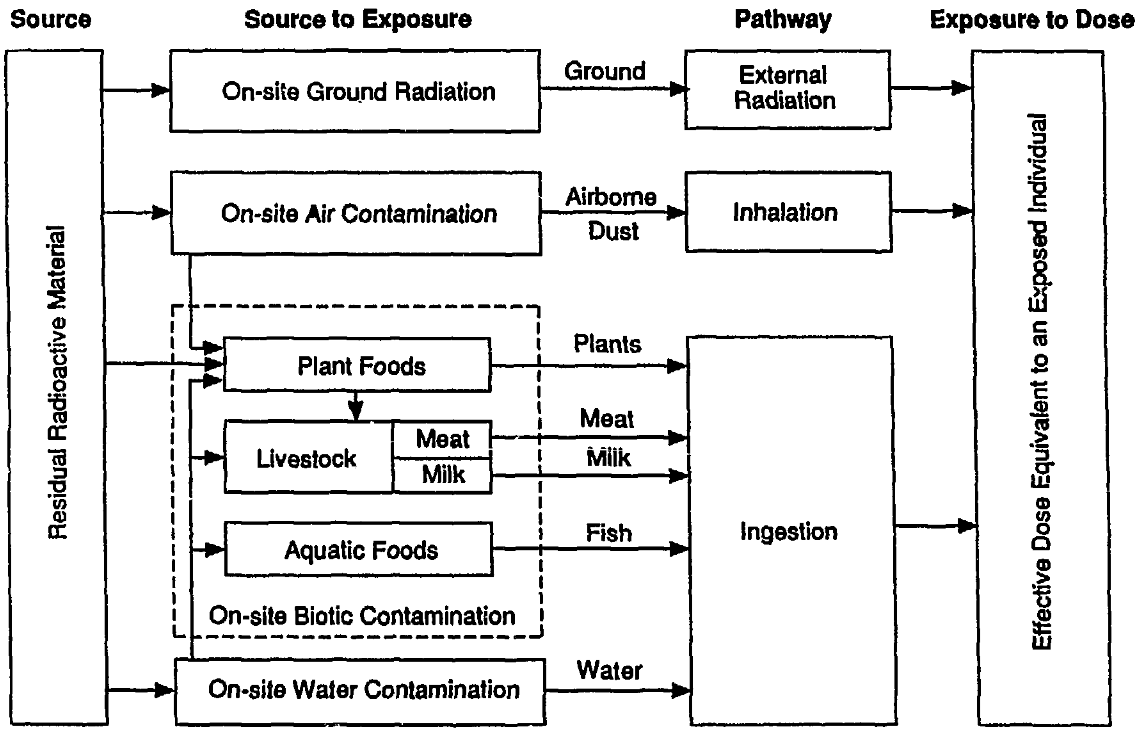


FIGURE 1 Schematic Representation of RESRAD Pathways

Section 2 of this report describes the sensitivity analysis performed via the GRESS enhancement. In Section 3, use of direct perturbation to verify the accuracy of the GRESS enhancement results is described. Section 4 describes use of the graphics package of RESRAD 4.0 for sensitivity analysis. Results and conclusions are discussed in Section 5.

2 SENSITIVITY ANALYSIS VIA THE GRESS SOFTWARE PACKAGE

In this section, the sensitivity analysis performed via the GRESS enhancement of the RESRAD code is described. Gradients and sensitivities of the calculated results (responses) with respect to specified parameters are presented.

The GRESS package is a collection of programs that allows the automatic calculation of the sensitivity of the results of a given Fortran program with respect to specified parameters, typically input parameters. The capacity of GRESS to perform a sensitivity analysis is based on the design characteristics of a computer program. Because the calculations in a computer program are sequential, that is, a variable is calculated first for its value and is then used in subsequent calculations, it is always possible to find the derivative of a variable on the left-hand side of an equation with respect to the variables on the right-hand side. With propagation of the calculations and storage of derivative information when each mathematical statement is executed, the sensitivity of the results with respect to specified parameters can finally be obtained. The procedures for using GRESS to perform a sensitivity analysis are described in detail in the GRESS manual (Horwedel 1990).

The GRESS package consists of a precompiler program (EXAP) that enhances a Fortran program; a library that contains numerous subroutines that enable the user to direct the sensitivity analysis process and that enable GRESS to perform the gradient calculations of different mathematical expressions; a program (BREDUCE) that reduces the size of the gradient matrix; and a program (BSOLVE) that inverses the gradient matrix and calculates the sensitivities. The user must first insert some "call" statements to the GRESS subroutines in his or her source program to specify the results of interest for a sensitivity analysis and to direct the analytical process. This source program is then input into the GRESS precompiler for enhancement. During the enhancement process, the precompiler reads each statement in the source code and, if necessary, replaces it with a mathematically equivalent, but GRESS-specific, statement that is usually a call statement to the GRESS library subroutines. Following the enhancement, the enhanced code is compiled, linked with the GRESS library, and then executed. After execution, the normal calculational results of the source code are generated, together with a gradient data file containing sensitivity information. The matrix component of this gradient data file can be reduced dimensionally and solved via execution of the BSOLVE program, which then triggers the sensitivity results.

The primary results from the use of GRESS are numbers that represent the gradients of calculated quantities (responses [R]) with respect to specified input quantities (parameters [P]). The gradients are dR/dP, which are perhaps more usefully specified as sensitivities; that is, (dR/R)/(dP/P), which is equivalent to d(ln R)/d(ln P). If a response R varies with a parameter P, such that $R = \text{Const} \cdot P^s$, then the sensitivity is s. A high sensitivity indicates a strong dependence on the parameter; a low sensitivity indicates a weak dependence. The primary functions of GRESS are the propagation and calculation of these gradients with as little user involvement as possible while each statement of the program is executed. The propagation of derivatives over many executed lines of code requires substantial storage capability and eventually the inversion of a large matrix. For RESRAD, the matrix size is about 58,000 × 58,000.

2.1 MODIFICATION OF RESRAD FOR GRESS PRECOMPILATION

The GRESS package was developed for implementation on a VAX computer. Consequently, the RESRAD code must be converted so that it can be run on a VAX. Fortran statements that have different expressions in a VAX computer, such as intrinsic subroutine names, must be converted so that an accurate date and time are obtained for the output. The precision specification for a real number must also be converted to avoid any compilation errors.

When the same input file, that is, SENSE.DAT, was used, the same numerical output was obtained for the VAX version of RESRAD as for the personal computer version. However, the variable values calculated during the iteration procedures by using Brent's method (Press et al. 1989) were sometimes slightly different, but within the expected error range. This slight variation is due to the difference in precision between the two computer systems.

The RESRAD code (VAX version) must be further modified to perform a sensitivity analysis. Calls to several GRESS subroutines must be inserted into RESRAD to specify the results of interest for sensitivity analysis, to direct the GRESS calculational procedure whereby derivatives of mathematical statements are obtained, and to store this information throughout the RESRAD program.

Once the statement of code is executed, GRESS calculates and stores gradients for each mathematical statement. Because of this accumulational characteristic, any trial-and-error calculational procedure may cause error in the sensitivity analysis if it is enhanced and its gradient information passed on throughout the program. Version 3.121A of RESRAD includes three calculational laps in each execution. The first lap calculates the dose/source ratio and total effective dose for each principal radionuclide at user-specified years. Lap 2 uses iterative calculations to determine the years when the minimum soil cleanup criteria for each radionuclide can be derived. Iterative calculations are also used in Lap 3 to determine the year when the maximum dose/source ratio for all radionuclides will occur. Because the iterative calculations (based on Brent's method) are actually trial-and-error procedures to find the values that best fit the data, the mathematical statements involved are purely numerical analyses without any physical basis. When RESRAD was enhanced by GRESS, only the results from Lap 1 were specified as results of interest because of the trial-and-error procedures in Laps 2 and 3; therefore, only the sensitivities of the results from Lap 1 were output and printed. The results of interest that were chosen were TDOSE(IY) -- the total dose (TDOSE [mrem/yr]) at a specified year (T[IY]) and DSR(IY,IR,I) ([mrem/yr]/[pCi/g]) -- the dose/source ratio for pathway I and radionuclide IR at a specified year (T[IY]).

The implementation of analytical differentiation in the GRESS methodology may also cause error if the sensitivity analysis involves the derivation of gradients for a discontinuous response function. In this case, the gradients are given either a zero or a wrong value. To overcome this problem, the factor that might have resulted in discontinuity in the calculation was excluded from the sensitivity analysis. Nonzero erosion rates of the cover material and the contaminated zone can cause a sudden disappearance of these two soil layers from one specified year to the next and result in an abrupt change in the gradient values. Under certain circumstances in the RESRAD model, a nonzero value for the water table drop rate will cause a sudden increase in the breakthrough time of groundwater contamination from zero to some nonzero value. Therefore, the erosion rates of the cover material and contaminated zone and the water table drop rate were assigned a value of zero. The input data file SENSE.DAT, which was used for sensitivity analysis, is provided in Appendix C.

2.2 GRESS ENHANCEMENT SENSITIVITY ANALYSIS RESULTS

The calculated sensitivities of the parameters are printed out in the program BSOLVE, which is part of GRESS. The BSOLVE routine was modified slightly so that it could sort the calculated sensitivities, if desired, and print a more detailed description of the response variables. Typical results for a specific variable, TDOSE(8), are provided in Appendix D.

Tables 1 through 8 give the derivatives and sensitivities of selected variables. Before the breakthrough time of the groundwater contamination (401.3 years in this case), the total dose, for which water-independent pathways are the primary contributors, decreases as time increases, as can be seen in the summary report presented in Appendix E. After the breakthrough time, the dose contributions from water-dependent pathways play a dominant role, resulting in a maximum total dose at 1406.3 years. Because of the changing dominancy in contributing pathways, parameter sensitivities to the total dose can vary from time to time. Tables 1 and 2 provide parameter sensitivities before radionuclides reach the groundwater table (401.3 years). Values obtained by the direct perturbation method are also provided for comparison with GRESS enhancement results. Parameters such as COVER0 -- thickness of cover material (0.5 m), THICK0 -- thickness of contaminated zone (1 m), DROOT -- depth of plant root (0.9 m),

TABLE 1 Sensitivity Analysis of Total Dose at 100 Years (TDOSE[6])[a]

	TDOSE(6) = 3.446×10^{-2} mrem/yr			
	Derivatives		Sensitivities	
Input Parameters	GRESS Enhancement	Direct Perturbation	GRESS Enhancement	Direct Perturbation
COVER0[b]	-8.695×10^{-2}	-8.695×10^{-2}	-1.262×10^{0}	-1.261×10^{0}
DROOT	4.776×10^{-2}	4.772×10^{-2}	1.247×10^{0}	1.246×10^{0}
DIET(1)	1.734×10^{-2}	1.734×10^{-2}	8.049×10^{-1}	8.049×10^{-1}
EVAPTR	4.277×10^{-2}	4.278×10^{-2}	7.446×10^{-1}	7.449×10^{-1}
S(39)[c]	1.763×10^{-2}	1.764×10^{-2}	5.116×10^{-1}	5.117×10^{-1}
THICK0[c]	1.711×10^{-2}	1.710×10^{-2}	4.965×10^{-1}	4.963×10^{-1}
DENSCZ[c]	1.064×10^{-2}	1.064×10^{-2}	4.941×10^{-1}	4.938×10^{-1}
S(42)[c]	1.683×10^{-2}	1.683×10^{-2}	4.884×10^{-1}	4.885×10^{-1}
PRECIP	-1.369×10^{-2}	-1.370×10^{-2}	-3.971×10^{-1}	-3.969×10^{-1}
DCACTC(39)[c]	1.735×10^{-4}	1.735×10^{-4}	2.517×10^{-1}	2.516×10^{-1}
DCACTC(42)[c]	1.670×10^{-4}	1.669×10^{-4}	2.423×10^{-1}	2.421×10^{-1}
AREA[c]	4.222×10^{-7}	4.224×10^{-7}	1.225×10^{-1}	1.226×10^{-1}
DIET(4)	5.872×10^{-5}	5.872×10^{-5}	1.073×10^{-1}	1.073×10^{-1}
LFI5	5.440×10^{-5}	5.440×10^{-5}	1.073×10^{-1}	1.073×10^{-1}

[a]Only parameters with an absolute sensitivity greater than 0.1 are listed.

[b]Parameter associated with cover material.

[c]Parameter associated with contaminated zone.

TABLE 2 Sensitivity Analysis of Total Dose at 300 Years (TDOSE[7])[a]

	TDOSE(7) = 1.390×10^{-2} mrem/yr			
	Derivatives		Sensitivities	
Input Parameters	GRESS Enhancement	Direct Perturbation	GRESS Enhancement	Direct Perturbation
EVAPTR	4.953×10^{-2}	4.958×10^{-2}	2.138×10^{0}	2.141×10^{0}
THICK0[c]	1.982×10^{-2}	1.981×10^{-2}	1.426×10^{0}	1.426×10^{0}
DENSCZ[c]	1.233×10^{-2}	1.233×10^{-2}	1.420×10^{0}	1.420×10^{0}
COVER0[b]	-3.506×10^{-2}	-3.506×10^{-2}	-1.262×10^{0}	-1.261×10^{0}
DROOT	1.926×10^{-2}	1.924×10^{-2}	1.247×10^{0}	1.246×10^{0}
PRECIP	-1.585×10^{-2}	-1.584×10^{-2}	-1.140×10^{0}	-1.140×10^{0}
DIET(1)	7.051×10^{-5}	7.051×10^{-5}	8.118×10^{-1}	8.118×10^{-1}
DCACTC(39)[c]	2.017×10^{-4}	2.016×10^{-4}	7.256×10^{-1}	7.254×10^{-1}
DCACTC(42)[c]	1.850×10^{-4}	1.850×10^{-4}	6.657×10^{-1}	6.657×10^{-1}
S(39)[c]	7.677×10^{-3}	7.678×10^{-3}	5.524×10^{-1}	5.525×10^{-1}
S(42)[c]	6.220×10^{-3}	6.221×10^{-3}	4.476×10^{-1}	4.477×10^{-1}
RI	-1.981×10^{-2}	-1.982×10^{-2}	-2.851×10^{-1}	-2.852×10^{-1}
RUNOFF	1.981×10^{-2}	1.982×10^{-2}	2.851×10^{-1}	2.852×10^{-1}
AREA[c]	1.597×10^{-7}	1.596×10^{-7}	1.149×10^{-1}	1.149×10^{-1}
DIET(4)	2.228×10^{-5}	2.228×10^{-5}	1.010×10^{-1}	1.010×10^{-1}
LFI5	2.064×10^{-5}	2.064×10^{-5}	1.010×10^{-1}	1.010×10^{-1}

[a]Only parameters with an absolute sensitivity greater than 0.1 are listed.

[b]Parameter associated with cover material.

[c]Parameter associated with contaminated zone.

DENSCZ -- density of contaminated zone (1.6 g/cm^3), and DCACTC -- distribution coefficient in contaminated zone (50 cm^3/g for uranium-234 and uranium-238) have more influence than parameters such as DWIBWT -- well intake depth below groundwater table (10 m), EPSZ -- effective porosity of saturated zone (0.2), DENSAQ -- density of saturated zone (1.6 g/cm^3), and DCACTS -- distribution coefficient in saturated zone (50 cm^3/g for uranium-234 and uranium-238), because of larger sensitivities. Parameter definitions can be found in Appendixes A and B. As expected, parameters describing the characteristics of the unsaturated and saturated zones play an important role after radionuclides break through the unsaturated zone and reach the groundwater table (saturated zone). In Table 3, the sensitivities of the parameters of the saturated zone are greater than those of the unsaturated zone before the occurrence of the maximum total dose (1406.3 years); in Table 4, the sensitivities of the parameters of the unsaturated zone greatly increase and are comparable with those of the saturated zone after the occurrence of the maximum total dose. A closer look at the magnitudes of these parameters (for both unsaturated and saturated zones in Tables 3 and 4) reveals opposite signs for the same parameters. The rise time (i.e., the time that the maximum radionuclide concentration occurs in groundwater) can be viewed as the divider between the accumulation and depletion processes of the radionuclides in the groundwater pathway. Before

TABLE 3 Sensitivity Analysis of Total Dose at 1000 Years (TDOSE[8])[a]

	TDOSE(8) = 9.650×10^{-1} mrem/yr			
	Derivatives		Sensitivities	
Input Parameters	GRESS Enhancement	Direct Perturbation	GRESS Enhancement	Direct Perturbation
DWIBWT[d]	-9.614×10^{-2}	-9.605×10^{-2}	-9.963×10^{-1}	-9.953×10^{-1}
EPSZ[d]	-4.807×10^{0}	-4.802×10^{0}	-9.963×10^{-1}	-9.953×10^{-1}
DENSAQ[d]	-5.979×10^{-1}	-5.974×10^{-1}	-9.913×10^{-1}	-9.904×10^{-1}
TPSZ[d]	2.392×10^{0}	2.391×10^{0}	9.913×10^{-1}	9.913×10^{-1}
DENSCZ[b]	5.074×10^{-1}	5.067×10^{-1}	8.413×10^{-1}	8.401×10^{-1}
THICK0[b]	8.113×10^{-1}	8.101×10^{-1}	8.407×10^{-1}	8.395×10^{-1}
FDW	7.952×10^{-1}	7.952×10^{-1}	8.240×10^{-1}	8.241×10^{-1}
DWI	1.939×10^{-3}	1.939×10^{-3}	8.240×10^{-1}	8.240×10^{-1}
FGWDW	7.872×10^{-1}	7.873×10^{-1}	8.158×10^{-1}	8.158×10^{-1}
S(39)[b]	4.961×10^{-1}	4.961×10^{-1}	5.141×10^{-1}	5.141×10^{-1}
DCACTS(39)[d]	-9.672×10^{-3}	-9.663×10^{-3}	-5.011×10^{-1}	-5.007×10^{-1}
S(42)[b]	4.689×10^{-1}	4.690×10^{-1}	4.859×10^{-1}	4.859×10^{-1}
DCACTS(42)[d]	-9.300×10^{-3}	-9.292×10^{-3}	-4.819×10^{-1}	-4.815×10^{-1}
EVAPTR	-6.801×10^{-1}	-6.845×10^{-1}	-4.229×10^{-1}	-4.256×10^{-1}
PRECIP	2.176×10^{-1}	2.165×10^{-1}	2.255×10^{-1}	2.244×10^{-1}
RI	9.815×10^{-1}	9.751×10^{-1}	2.034×10^{-1}	2.021×10^{-1}
FGWIR	1.405×10^{-1}	1.404×10^{-1}	1.456×10^{-1}	1.455×10^{-1}
H(1)[c]	-3.050×10^{-2}	-3.055×10^{-2}	-1.264×10^{-1}	-1.266×10^{-1}
EPUZ(1)[c]	-6.101×10^{-1}	-6.109×10^{-1}	-1.264×10^{-1}	-1.266×10^{-1}
TPUZ(1)[c]	3.041×10^{-1}	3.035×10^{-1}	1.261×10^{-1}	1.258×10^{-1}
DENSUZ(1)[c]	-7.603×10^{-2}	-7.611×10^{-2}	-1.261×10^{-1}	-1.262×10^{-1}

[a]Only parameters with an absolute sensitivity greater than 0.1 are listed.

[b]Parameter associated with contaminated zone.

[c]Parameter associated with unsaturated zone.

[d]Parameter associated with saturated zone.

the rise time (after the breakthrough time), the amount of radionuclides leaching through the saturated zone to a well located at the downgradient edge of the contaminated site is greater than that in water drawn from the well. Therefore, the concentration of radionuclides in the groundwater at the point of use will increase with time. After the rise time, the amount of the inflow and outflow of radionuclides reverses, causing the groundwater concentration in the well to decrease. Four parameters strongly influence the total dose regardless of whether they appear before or after the breakthrough time: EVAPTR – the evapotranspiration coefficient (0.6), PRECIP – the annual precipitation rate (1 m/yr), RI – the annual irrigation rate (0.2 m/yr), and RUNOFF – the runoff coefficient (0.2). The water infiltration rate, which is calculated on the basis of these four parameters, affects the amount of radionuclides transferred from the contaminated zone to the groundwater in the leaching process. These important parameters are also included in Tables 1 to 4.

TABLE 4 Sensitivity Analysis of Total Dose at 3000 Years (TDOSE[9])[a]

	TDOSE(9) = 7.425 x 10^{-2} mrem/yr			
	Derivatives		Sensitivities	
Input Parameters	GRESS Enhancement	Direct Perturbation	GRESS Enhancement	Direct Perturbation
EVAPTR	1.353 x 10^{0}	1.358 x 10^{0}	1.093 x 10^{1}	1.098 x 10^{1}
PRECIP	-4.329 x 10^{-1}	-4.341 x 10^{-1}	-5.831 x 10^{0}	-5.847 x 10^{0}
DWIBWT[d]	2.862 x 10^{-2}	2.868 x 10^{-2}	3.854 x 10^{0}	3.862 x 10^{0}
EPSZ[d]	1.431 x 10^{0}	1.434 x 10^{0}	3.854 x 10^{0}	3.862 x 10^{0}
DENSAQ[d]	1.784 x 10^{-1}	1.788 x 10^{-1}	3.844 x 10^{0}	3.852 x 10^{0}
TPSZ[d]	-7.136 x 10^{-1}	-7.114 x 10^{-1}	-3.844 x 10^{0}	-3.833 x 10^{0}
DCACTS(22)[d]	2.823 x 10^{-3}	2.828 x 10^{-3}	3.802 x 10^{0}	3.809 x 10^{0}
EPUZ(1)[c]	7.087 x 10^{-1}	7.096 x 10^{-1}	1.909 x 10^{0}	1.911 x 10^{0}
H(1)[c]	3.544 x 10^{-2}	3.548 x 10^{-2}	1.909 x 10^{0}	1.911 x 10^{0}
TPUZ(1)[c]	-3.538 x 10^{-1}	-3.530 x 10^{-1}	-1.906 x 10^{0}	-1.902 x 10^{0}
DENSUZ(1)[c]	8.844 x 10^{-2}	8.853 x 10^{-2}	1.906 x 10^{0}	1.908 x 10^{0}
DCACTU(22,1)[c]	1.399 x 10^{-3}	1.401 x 10^{-3}	1.885 x 10^{0}	1.887 x 10^{0}
THICK0[b]	1.133 x 10^{-1}	1.136 x 10^{-1}	1.526 x 10^{0}	1.530 x 10^{0}
DENSCZ[b]	7.074 x 10^{-2}	7.088 x 10^{-2}	1.524 x 10^{0}	1.527 x 10^{0}
RUNOFF	5.412 x 10^{-1}	5.313 x 10^{-1}	1.458 x 10^{0}	1.431 x 10^{0}
RI	-3.866 x 10^{-1}	-3.943 x 10^{-1}	-1.041 x 10^{0}	-1.062 x 10^{0}
S(39)[b]	7.386 x 10^{-2}	7.386 x 10^{-2}	9.947 x 10^{-1}	9.947 x 10^{-1}
DWI	9.638 x 10^{-5}	9.639 x 10^{-5}	5.322 x 10^{-1}	5.322 x 10^{-1}
FDW	3.952 x 10^{-2}	3.953 x 10^{-2}	5.322 x 10^{-1}	5.323 x 10^{-1}
FGWDW	3.912 x 10^{-2}	3.913 x 10^{-2}	5.269 x 10^{-1}	5.269 x 10^{-1}
DCACTC(22)[b]	3.168 x 10^{-4}	3.184 x 10^{-4}	4.267 x 10^{-1}	4.289 x 10^{-1}
DIET(1)	1.918 x 10^{-4}	1.918 x 10^{-4}	4.134 x 10^{-1}	4.133 x 10^{-1}
FGWIR	3.060 x 10^{-2}	3.060 x 10^{-2}	4.122 x 10^{-1}	4.121 x 10^{-1}

[a]Only parameters with an absolute sensitivity greater than 0.1 are listed.

[b]Parameter associated with contaminated zone.

[c]Parameter associated with unsaturated zone.

[d]Parameter associated with saturated zone.

Tables 5 and 6 give the dose/source ratios for uranium-234 in the water-independent plant and ground pathways, respectively. As discussed earlier, prior to the breakthrough time, parameters that are not related to the unsaturated and saturated zones have greater sensitivities because, at this time, the dominant pathways are the water-independent ones. According to the summary report in Appendix E, the water-independent plant pathway contributes the most to the total dose before 401.3 years. Evidence of this is also found in the very similar influential parameters in Tables 1 and 5. Parameters such as COVER0, DROOT, THICK0, DENSCZ, and DCACTC are still listed among the important parameters. Because Table 5 displays the

TABLE 5 Sensitivity Analysis of Dose/Source Ratio from Uranium-234 in the Water-Independent Plant Pathway at 30 Years (DSR[5,39,3])[a]

	DSR(5,39,3) = 2.167×10^{-2} (mrem/yr)/(pCi/g)			
	Derivatives		Sensitivities	
Input Parameters	GRESS Enhancement	Direct Perturbation	GRESS Enhancement	Direct Perturbation
DROOT	3.010×10^{-2}	3.007×10^{-2}	1.250×10^{0}	1.249×10^{0}
COVER0[b]	-5.418×10^{-2}	-5.418×10^{-2}	-1.250×10^{0}	-1.250×10^{0}
S(39)[c]	*2.167×10^{-2}*	*2.167×10^{-2}*	*1.000×10^{0}*	*1.000×10^{0}*
DIET(1)	1.246×10^{-4}	1.246×10^{-4}	9.195×10^{-1}	9.195×10^{-1}
EVAPTR	8.087×10^{-3}	8.087×10^{-3}	2.239×10^{-1}	2.239×10^{-1}
THICK0[c]	3.236×10^{-3}	3.232×10^{-3}	1.493×10^{-1}	1.491×10^{-1}
DENSCZ[c]	2.015×10^{-3}	2.012×10^{-3}	1.487×10^{-1}	1.485×10^{-1}
DCACTC(39)[c]	6.446×10^{-5}	6.437×10^{-5}	1.487×10^{-1}	1.485×10^{-1}
PRECIP	-2.588×10^{-3}	-2.589×10^{-3}	-1.194×10^{-1}	-1.195×10^{-1}
DIET(2)	1.246×10^{-3}	1.247×10^{-3}	8.046×10^{-2}	8.053×10^{-2}
RI	-3.235×10^{-3}	-3.241×10^{-3}	-2.985×10^{-2}	-2.991×10^{-2}
RUNOFF	3.235×10^{-3}	3.232×10^{-3}	2.985×10^{-2}	2.982×10^{-2}

[a]Only parameters with an absolute sensitivity greater than 0.01 are listed.

[b]Parameter associated with cover material.

[c]Parameter associated with contaminated zone.

dose/source ratio for uranium-234, only the distribution coefficient (DCACTC[39] -- the distribution coefficient of uranium-234 in the contaminated zone [50 cm^3/g]) for this radionuclide rather than that for both DCACTC(39) and DCACTC(42), which is the distribution coefficient of uranium-238 in the contaminated zone (50 cm^3/g), is observed. In Table 6, DENSCV -- density of cover material (1.6 g/cm^3) -- becomes important because the shielding effect of the cover material reduces the external gamma radiation from the radioactive residues. The appearance of parameter DCACTC(28), the distribution coefficient of radium-226 in the contaminated zone (70 cm^3/g), accounts for the influence of radioactive decay on the intensity of radiation in the ground pathway. Parameter DROOT does not show up because the external radiation has no relation to the depth of the plant root. As in the sensitivity analysis for total dose, no unsaturated or saturated zone parameter is observed in Table 6.

Tables 7 and 8 give the sensitivities of parameters to dose/source ratios for uranium-238 in the groundwater pathway before and after the rise time. The dominant parameters are very similar to those listed for total dose in Tables 3 and 4, which proves the importance of the contribution from the groundwater pathway for variables TDOSE(8) and TDOSE(9). The appearance of parameter DCACTS(22), the water/soil distribution coefficient of lead-210 (100 cm^3/g), in the saturated zone in Table 8 is due to decay of uranium-238 to lead-210. The sensitivities of parameters involved in the leaching process have opposite signs in Tables 7 and 8, which is also consistent with the results in Tables 3 and 4.

TABLE 6 Sensitivity Analysis of Dose/Source Ratio from Uranium-234 in the Ground Pathway at 300 Years (DSR[7,39,3])[a]

	DSR(7,39,3) = 3.652×10^{-6} (mrem/yr)/(pCi/g)			
	Derivatives		Sensitivities	
Input Parameters	GRESS Enhancement	Direct Perturbation	GRESS Enhancement	Direct Perturbation
DENSCV[b]	-1.634×10^{-5}	-1.630×10^{-5}	-7.159×10^{0}	-7.141×10^{0}
COVER0[b]	-3.859×10^{-5}	-3.849×10^{-5}	-5.284×10^{0}	-5.270×10^{0}
EVAPTR	6.827×10^{-6}	6.832×10^{-6}	1.122×10^{0}	1.123×10^{0}
FO1	6.086×10^{-6}	6.086×10^{-5}	1.000×10^{0}	1.000×10^{0}
S(39)[c]	3.652×10^{-6}	3.652×10^{-6}	1.000×10^{0}	1.000×10^{0}
FS1	3.652×10^{-6}	3.652×10^{-6}	1.000×10^{0}	1.000×10^{0}
THICK0[c]	2.733×10^{-6}	2.731×10^{-6}	7.483×10^{-1}	7.478×10^{-1}
PRECIP	-2.185×10^{-6}	-2.184×10^{-6}	-5.983×10^{-1}	-5.981×10^{-1}
DENSCZ[c]	1.274×10^{-6}	1.272×10^{-6}	5.582×10^{-1}	5.575×10^{-1}
DCACTC(39)[c]	3.081×10^{-8}	3.078×10^{-8}	4.218×10^{-1}	4.215×10^{-1}
DCACTC(28)[c]	1.686×10^{-8}	1.684×10^{-8}	3.231×10^{-1}	3.229×10^{-1}
RI	-2.731×10^{-6}	-2.733×10^{-6}	-1.496×10^{-1}	-1.497×10^{-1}
RUNOFF	2.731×10^{-6}	2.732×10^{-6}	1.496×10^{-1}	1.496×10^{-1}

[a]Only parameters with an absolute sensitivity greater than 0.1 are listed.

[b]Parameter associated with cover material.

[c]Parameter associated with contaminated zone.

TABLE 7 Sensitivity Analysis of Dose/Source Ratio from Uranium-238 in the Drinking Water Pathway at 1000 Years (DSR[8,42,6])[a]

	DSR(8,42,6) = 3.884×10^{-1} (mrem/yr)/(pCi/g)			
	Derivatives		Sensitivities	
Input Parameters	GRESS Enhancement	Direct Perturbation	GRESS Enhancement	Direct Perturbation
S(42)[b]	3.884×10^{-1}	3.884×10^{-1}	1.000×10^{0}	1.000×10^{0}
DWIBWT[d]	-3.884×10^{-2}	-3.882×10^{-2}	-1.000×10^{0}	-9.990×10^{-1}
FDW	3.884×10^{-1}	3.884×10^{-1}	1.000×10^{0}	1.000×10^{0}
EPSZ[d]	-1.942×10^{0}	-1.940×10^{0}	-1.000×10^{0}	-9.990×10^{-1}
DWI	9.474×10^{-4}	9.474×10^{-4}	1.000×10^{0}	1.000×10^{0}
DENSAQ[d]	-2.416×10^{-1}	-2.413×10^{-1}	-9.950×10^{-1}	-9.941×10^{-1}
TPSZ[d]	9.662×10^{-1}	9.661×10^{-1}	9.950×10^{-1}	9.949×10^{-1}
DCACTS(42)[d]	-7.707×10^{-3}	-7.700×10^{-3}	-9.921×10^{-1}	-9.912×10^{-1}
FGWDW	3.845×10^{-1}	3.846×10^{-1}	9.900×10^{-1}	9.901×10^{-1}
DENSCZ[b]	2.042×10^{-1}	2.042×10^{-1}	8.413×10^{-1}	8.412×10^{-1}
THICK0[b]	3.265×10^{-1}	3.265×10^{-1}	8.407×10^{-1}	8.405×10^{-1}
EVAPTR	-2.583×10^{-1}	-2.593×10^{-1}	-3.990×10^{-1}	-4.005×10^{-1}
PRECIP	8.266×10^{-2}	8.249×10^{-2}	2.128×10^{-1}	2.124×10^{-1}
DCACTC(42)[b]	-1.229×10^{-3}	-1.229×10^{-3}	-1.582×10^{-1}	-1.582×10^{-1}
EPUZ(1)[c]	-2.074×10^{-1}	-2.076×10^{-1}	-1.068×10^{-1}	-1.069×10^{-1}
H(1)[c]	-1.037×10^{-2}	-1.038×10^{-2}	-1.068×10^{-1}	-1.069×10^{-1}
TPUZ(1)[c]	1.034×10^{-1}	1.032×10^{-1}	1.065×10^{-1}	1.063×10^{-1}
DENSUZ(1)[c]	-2.584×10^{-2}	-2.587×10^{-2}	-1.065×10^{-1}	-1.066×10^{-1}
DCACTU(42,1)[c]	-8.243×10^{-4}	-8.255×10^{-4}	-1.061×10^{-1}	-1.063×10^{-1}

[a]Only parameters with an absolute sensitivity greater than 0.1 are listed.

[b]Parameter associated with contaminated zone.

[c]Parameter associated with unsaturated zone.

[d]Parameter associated with saturated zone.

TABLE 8 Sensitivity Analysis of Dose/Source Ratio from Uranium-238 in the Drinking Water Pathway at 3000 Years (DSR[9,42,6])[a]

	DSR(9,42,6) = 2.666×10^{-4} (mrem/yr)/(pCi/g)			
	Derivatives		Sensitivities	
Input Parameters	GRESS Enhancement	Direct Perturbation	GRESS Enhancement	Direct Perturbation
EVAPTR	7.719×10^{-3}	7.794×10^{-3}	1.737×10^{1}	1.754×10^{1}
PRECIP	-2.470×10^{-3}	-2.458×10^{-3}	-9.266×10^{0}	-9.219×10^{0}
THICK0[b]	1.479×10^{-1}	1.483×10^{-1}	5.547×10^{0}	5.564×10^{0}
DENSCZ[b]	9.213×10^{-4}	9.242×10^{-4}	5.529×10^{0}	5.547×10^{0}
DCACTC(42)[b]	2.279×10^{-5}	2.286×10^{-5}	4.275×10^{0}	4.288×10^{0}
DWIBWT[d]	1.076×10^{-4}	1.079×10^{-4}	4.038×10^{0}	4.047×10^{0}
EPSZ[d]	5.382×10^{-3}	5.394×10^{-3}	4.038×10^{0}	4.047×10^{0}
DENSAQ[d]	6.702×10^{-4}	6.716×10^{-4}	4.022×10^{0}	4.031×10^{0}
TPSZ[d]	-2.681×10^{-3}	-2.673×10^{-3}	-4.022×10^{0}	-4.010×10^{0}
RI	-3.088×10^{-3}	-3.085×10^{-3}	-2.316×10^{0}	-2.315×10^{0}
RUNOFF	3.088×10^{-3}	3.092×10^{-3}	2.316×10^{0}	2.319×10^{0}
DCACTS(42)[d]	1.164×10^{-5}	1.166×10^{-5}	2.183×10^{0}	2.187×10^{0}
EPUZ(1)[c]	2.665×10^{-3}	2.668×10^{-3}	1.999×10^{0}	2.001×10^{0}
H(1)[c]	1.332×10^{-4}	1.334×10^{-4}	1.999×10^{0}	2.001×10^{0}
TPUZ(1)[c]	-1.329×10^{-3}	-1.326×10^{-3}	-1.994×10^{0}	-1.990×10^{0}
DENSUZ(1)[c]	3.322×10^{-4}	3.325×10^{-4}	1.994×10^{0}	1.996×10^{0}
DCACTS(22)[d]	4.806×10^{-6}	4.816×10^{-6}	1.803×10^{0}	1.806×10^{0}
DCACTU(42,1)[c]	5.768×10^{-5}	5.774×10^{-5}	1.082×10^{0}	1.083×10^{0}
FDW	2.666×10^{-4}	2.666×10^{-4}	1.000×10^{0}	1.000×10^{0}
DWI	6.502×10^{-7}	6.502×10^{-7}	1.000×10^{0}	1.000×10^{0}
S(42)[b]	2.666×10^{-4}	2.666×10^{-4}	1.000×10^{0}	1.000×10^{0}

[a]Only parameters with an absolute sensitivity greater than 1 are listed.

[b]Parameter associated with contaminated zone.

[c]Parameter associated with unsaturated zone.

[d]Parameter associated with saturated zone.

3 SENSITIVITY ANALYSIS VIA DIRECT PARAMETER PERTURBATION

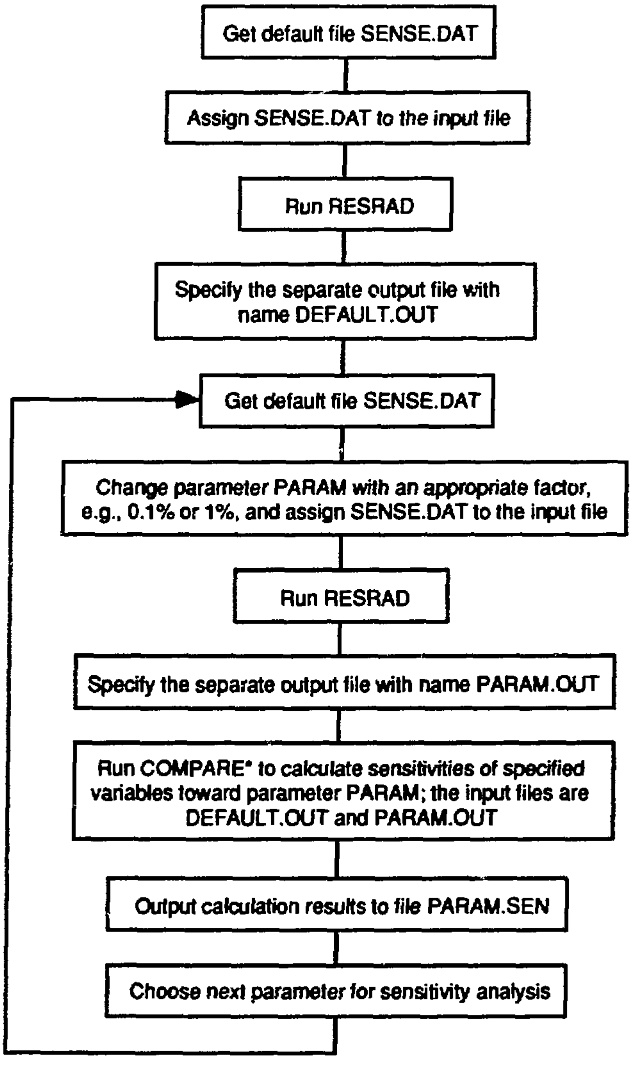
To verify the correctness of sensitivity values calculated via the GRESS enhancement of RESRAD, direct parameter perturbation analyses were also performed by varying the values of input parameters in the data file SENSE.DAT. The results obtained from this method are presented and compared with those from the application of the GRESS enhancement.

3.1 PERTURBATION OF INPUT PARAMETERS

The relationship among the resulting quantities (responses) and the input quantities (parameters) in the RESRAD model is quite complicated; it is extremely nonlinear. Consequently, the gradients and sensitivities are not constants but depend on the values of the input parameters. Finite perturbations in the input values may cause deviations in the calculated sensitivities. For parameters that are quite insensitive, a small perturbation may result in only a slight change in the response. Sometimes this slight change is beyond the resolution of the computer calculations, and either a zero sensitivity is calculated or the precision of the sensitivities is greatly reduced. On the basis of these considerations, perturbations for parameters with high or low sensitivities were set differently. A quick look at the GRESS enhancement output provided a preliminary comparison of the magnitudes of the sensitivities. To obtain observable changes in the results, a search procedure was used to find an appropriate perturbation value for each parameter. For highly sensitive parameters, a perturbation value of 0.1% was used, with an additional 0.1% in each successive step. Whenever two sequential perturbations gave almost the same sensitivity, the perturbation procedure was terminated and the final value was chosen for the sensitivity. It usually took only a few steps to reach this requirement. For parameters with low sensitivities, a perturbation value of 1% was used, with an additional 1% in each successive step; the requirement was met within a perturbation value of 5%.

3.2 CALCULATIONAL PROCEDURE

The results of the RESRAD execution were saved in two output files, SUMMARY.OUT and DETAILED.OUT, which are described in detail in the RESRAD user's manual (Gilbert et al. 1989). The data in the output files have values expressed in exponential format down to three digits after the decimal point. This is not precise enough, however, for calculating sensitivities of input parameters with only a 0.1% to 5% perturbation. Instead of using the default output files, more precise values (with more significant digits) for the variables of interest (in this case, TDOSE[IY] and DSR[IY,IR,I]) were printed by modifying the FORMAT statements in the RESRAD code. The results were saved in a separate file that was then used to calculate the sensitivities. The flow diagram in Figure 2 depicts the calculational procedure.



*COMPARE is a program written to calculate the gradients and sensitivities of input parameters.

FIGURE 2 Flow Diagram of Direct Parameter Perturbation Method

3.3 COMPARISON OF DIRECT PARAMETER PERTURBATION RESULTS WITH GRESS ENHANCEMENT RESULTS

The derivatives and sensitivities obtained by the direct parameter perturbation method are given in columns 3 and 5 of Tables 1 through 8; the results from the GRESS enhancement are given in each table for comparison. The results show good agreement. The minor differences in the calculated derivatives and sensitivities between the two methods are due to finite perturbation, which is inevitable in the direct parameter perturbation method.

4 SENSITIVITY ANALYSIS VIA RESRAD'S GRAPHICS CAPABILITY

RESRAD 4.0 can show calculational results in graphic form. Figures 3 and 4 are examples of figures produced by RESRAD 4.0. Figure 3 shows the dose/source ratio for both water-independent and water-dependent pathway subtotals of radionuclide uranium-234; Figure 4 shows the results for individual water-dependent pathways of radionuclide uranium-238. RESRAD 4.0 allows the user to select the parameters for sensitivity analysis, the results of which are then shown graphically in two-dimensional plots.

4.1 INVOKING SENSITIVITY ANALYSIS FROM THE RESRAD INPUT SCREEN

RESRAD 4.0 can also perform a sensitivity analysis while operational. For each of the data input screens, the user can select parameters for sensitivity analysis by pressing the F9 key. For example, for the contaminated zone hydrological data input screen (shown in Figure 5), sensitivity analysis for a specific parameter can be invoked by moving the cursor to that parameter and pressing the F9 key. After pressing the F9 key, a screen similar to the one in Figure 6 will appear. Pressing the F10 key when the desired perturbation factor is highlighted will invoke the sensitivity calculation during execution. The input parameters that RESRAD can analyze for sensitivity are listed in Appendix B.

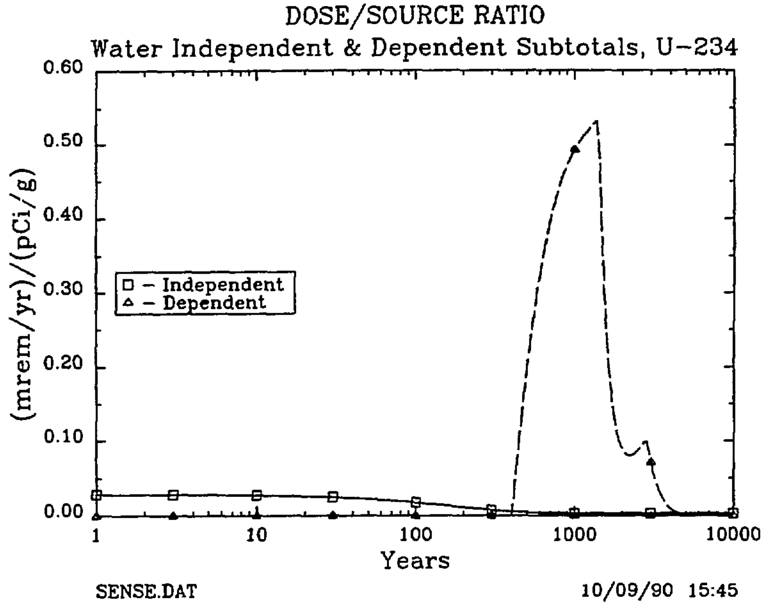


FIGURE 3 Dose/Source Ratio of Water-Independent and Water-Dependent Pathway Subtotals of Uranium-234

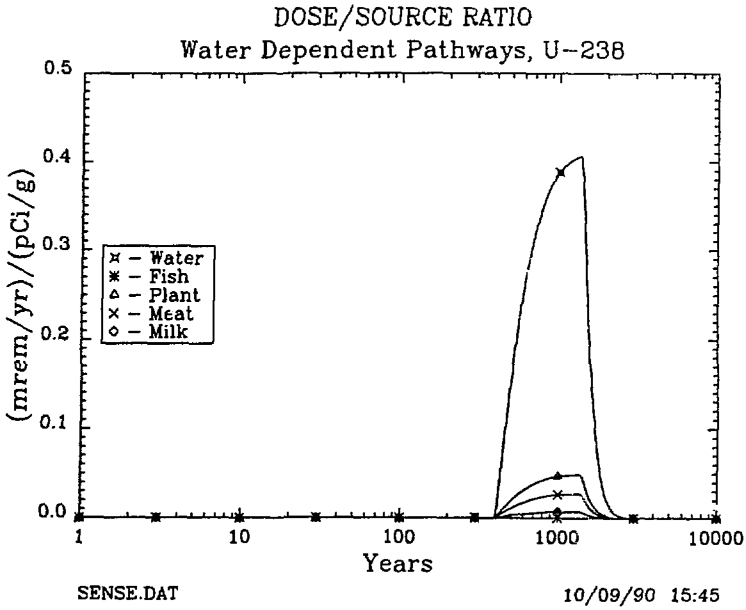


FIGURE 4 Dose/Source Ratio of Water-Dependent Pathways of Uranium-238

```
RESRAD: Residual Radioactive Material Program          Path(s): 1,2,3,4,5,6,7,8
             Cover and Contaminated Zone Hydrological Data               (R013)

                         Cover depth:          .5 meters
             Density of cover material:       1.6 grams/cubic centimeter
                   Cover erosion rate:          0 meters/year

          Density of contaminated zone:       1.6 grams/cubic centimeter
        Contaminated zone erosion rate:         0 meters/year
      Contaminated zone total porosity:        .4
  Contaminated zone effective porosity:        .2
Contaminated zone hydraulic conductivity:      10 meters/year
        Contaminated zone b parameter:        5.3

        Evapotranspiration coefficient:        .6
                        Precipitation:          1 meters/year
                           Irrigation:         .2 meters/year
                      Irrigation mode:      0 (0 for overhead; 1 for ditch)
                   Runoff coefficient:         .2
Watershed area for nearby stream or pond:  1000000 square meters

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
  Press "F9" for Sensitivity Analysis.  Press "F10" to SAVE DATA AND CONTINUE.
How deep is the cover above the site's contaminated zone?
```

FIGURE 5 Input Form R013 for Cover and Contaminated Zone Hydrological Data

```
RESRAD: Residual Radioactive Material Program        Path(s): 1,2,3,4,5,6,7,8
                    Cover and Contaminated Zone Hydrological Data        (R013)

            ╔Sensitivity Analysis╗r depth:                 .5 meters
            ║ ±   0 %  │  ±  50 %║aterial:               1.6 grams/cubic centimeter
            ║          │         ║on rate:                 0 meters/year
            ║ ± 100 %  │  ± 400 %║
            ║          │         ║ed zone:               1.6 grams/cubic centimeter
            ║ ± 900 %  │Set Factor║on rate:                0 meters/year
          Co║          │         ║orosity:                .4
       Contam║Show Range│  EXIT  ║orosity:                .2
  Contaminat╚═══════════════════╝ctivity:                10 meters/year
            Contaminated zone b parameter:               5.3

           Evapotranspiration coefficient:               .6
                            Precipitation:                1 meters/year
                               Irrigation:               .2 meters/year
                          Irrigation mode:          0 (0 for overhead; 1 for ditch)
                       Runoff coefficient:               .2
 Watershed area for nearby stream or pond:          1000000 square meters

Press "F1" or "F2" for HELP, or "Esc" to IGNORE CHANGES and return to main menu.
  Press "F9" for Sensitivity Analysis.  Press "F10" to SAVE DATA AND CONTINUE.
Remove parameter sensitivity check range (if any).
```

FIGURE 6 Input Form R013 with Sensitivity Analysis Pop-Up Menu

There is always one major calculational cycle in RESRAD. If sensitivity analysis has been requested, there are two more cycles per analysis, up to a maximum of five analyses (CYCLE1, CYCLE2, ... CYCLE9, CYCLE10). The first cycle of each pair changes the parameter being analyzed by the plus percentage set in the input screen; the second cycle decreases the parameter by the specified factor.

The factor F, which is used in the sensitivity analysis, is obtained from the screen input range R as a percent and is converted by the following formula: $F = 1 + 0.01 \times R$. Thus, a 400% range (R) converts to a factor (F) of 5. The base value of the test parameter is first multiplied by and then divided by F. Results obtained by using three parametric values are plotted in the same figure. Only the value of the parameter being tested is changed in each sensitivity cycle. A maximum of five parameters can be specified for sensitivity analysis in a single run of RESRAD.

4.2 VIEWING THE SENSITIVITY ANALYSIS RESULTS

After execution of RESRAD, the calculational results from the sensitivity analysis are not written to the output files SUMMARY.REP and DETAILED.REP as are the results from the base data. Instead, RESRAD displays the sensitivity analysis results in graphics that compare final results (such as TDOSE) calculated from the base parameters and from the perturbed parameters. This way, the user gets a clear picture of the degree of change in the results, which is usually of more concern than the values of the derivatives and sensitivities. The graphics can be output by printers or plotters. Figures 7 through 9 are examples of RESRAD sensitivity analysis graphics.

4.3 COMPARING GRAPHIC RESULTS WITH GRESS ENHANCEMENT AND DIRECT PARAMETER PERTURBATION RESULTS

The sensitivity analysis results obtained by using RESRAD 4.0 with input file SENSE.DAT are shown in Figures 7 through 9. Figure 7 shows the total dose (mrem/yr) from all isotopes summed over all pathways, along with the results of the sensitivity analysis of parameter THICK0, which was derived by multiplying the base value by a factor of 1.5 in the first cycle and by 1/1.5 in the second cycle. The total dose increases as the value of THICK0 increases and decreases as the value of THICK0 decreases. This tendency was predicted by the GRESS enhancement and direct parameter perturbation methods, as shown in Tables 1 through 4, by the positive derivatives of THICK0. In Figure 7, DWT0 -- the initial depth from the surface to the water table (5.5 m) -- was automatically adjusted by RESRAD when the value of THICK0 was changed.

The influence of the parameter PRECIP on the total dose varies from time to time because of a complex nonlinear relationship with TDOSE. Increasing the precipitation rate shifts the maximum peak to the left, as can be seen in Figure 8, and decreases the maximum dose of the peak. On the basis of the data provided in Tables 1, 2, and 4, it was predicted that increasing the precipitation rate would decrease the values of TDOSE; the contrary was predicted on the basis of the data in Table 3. Agreement with these predictions is shown in Figure 8, in which the magnitude of TDOSE at 100, 300, and 3000 years decreases as the value of PRECIP increases and vice versa. At 1000 years, however, the magnitude of TDOSE increases as the value of PRECIP increases. It is easier to interpret and understand the sensitivity analysis results in Tables 1 through 4 with the aid of figures such as Figure 8.

The influence of parameter DCACTS(42) on the total dose is shown in Figure 9. Figure 9 shows that DCACTS(42) is very sensitive to the total dose, TDOSE, in the time frame of 300 to 3000 years. The parameter DCACTS(42) is almost insensitive to TDOSE outside this range. (The three curves coincide outside the range.) This result is consistent with the results provided in Tables 1 through 4 in which only Table 3 contains a sensitivity value of -0.4815 at 1000 years. It can be seen from Figure 9 that, at 1000 years, the total dose decreases as the value of DCACTS(42) increases.

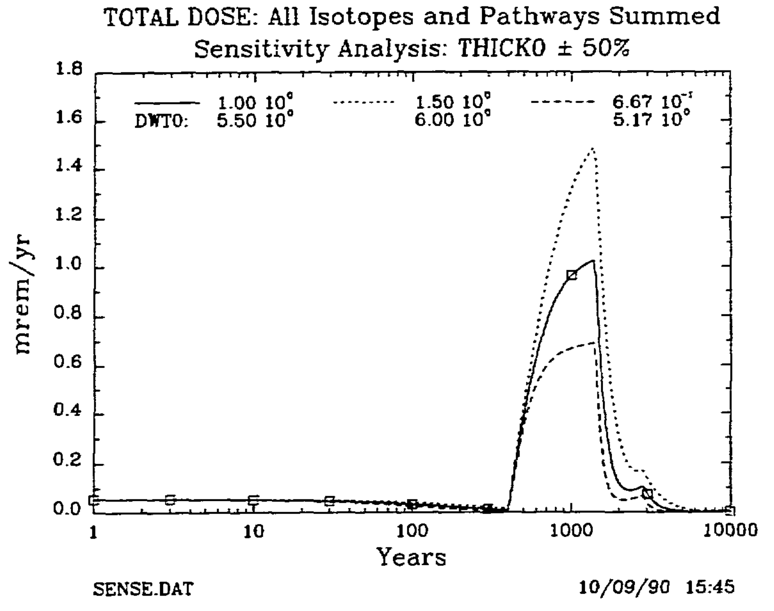


FIGURE 7 Total Dose of All Isotopes Summed over All Pathways with Sensitivity Analysis of THICK0

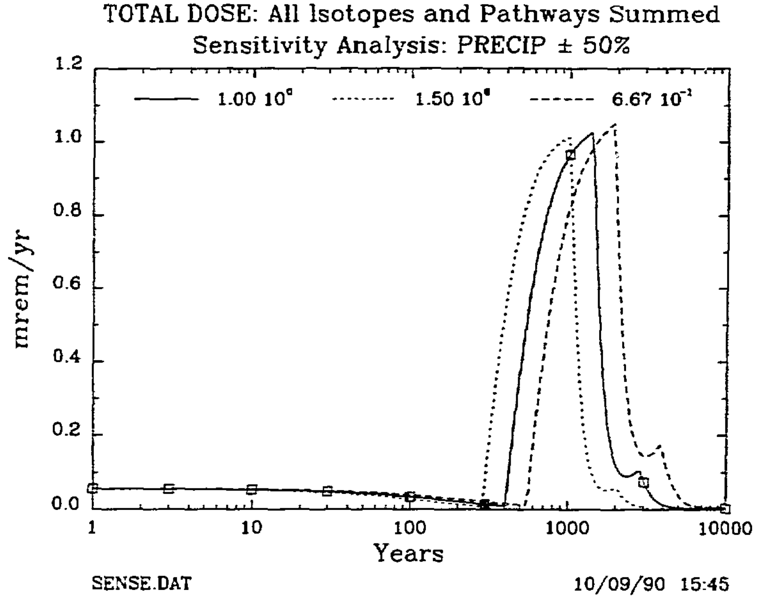


FIGURE 8 Total Dose of All Isotopes Summed over All Pathways with Sensitivity Analysis of PRECIP

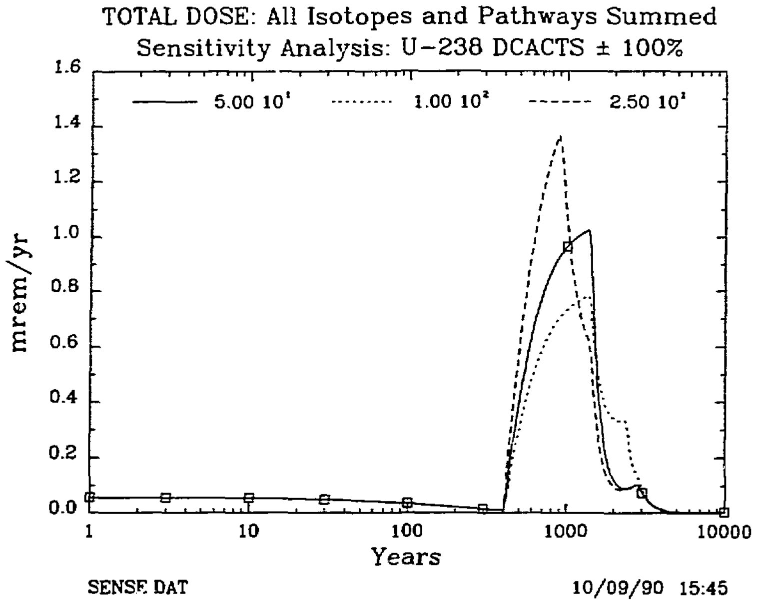


FIGURE 9 Total Dose of All Isotopes Summed over All Pathways with Sensitivity Analysis of DCACTS(42)

5 CONCLUSIONS

A sensitivity analysis of RESRAD code parameters was performed by using GRESS enhancement, direct parameter perturbation, and graphic comparison. Evaluation of these methods indicated that GRESS enhancement has limitations when the response function is discontinuous or a trial-and-error procedure is involved; that direct parameter perturbation is simple but tedious to implement; and that the graphics capability of RESRAD 4.0 is the easiest means of performing sensitivity analyses.

Good agreement in the sensitivities was found between the GRESS enhancement and direct parameter perturbation methods. The analysis showed that parameters such as COVER0, THICK0, DROOT, and DENSCZ, which are associated with the cover material or the contaminated zone, have more influence on the results than parameters of the unsaturated or saturated zone, such as DWIBWT, EPSZ, DENSAQ, and DCACTS, before the breakthrough time of the groundwater contamination. The influence of these parameters changes, however, after the breakthrough time. The parameters EVAPTR, PRECIP, RI, and RUNOFF, which are used to calculate the water infiltration rate, have considerable effect on the results regardless of whether they appear before or after the breakthrough time. The sensitivities of parameters involved in the leaching process have opposite effects on the total dose before and after the rise time as the result of an accumulation-depletion process.

The graphics produced by RESRAD 4.0 reflected the results obtained from the GRESS enhancement and direct parameter perturbation methods. In addition, they provided a direct and easy way to judge the influence of input parameters. To obtain more reliable predictions from the RESRAD code, parameters with high sensitivities should be determined more accurately whenever possible. Accurate sensitivity analysis results can then be used to establish priorities for input data collection.

REFERENCES

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Horwedel, J.E., 1990, *RSIC Peripheral Shielding Routine Collection -- GRESS 1.0 -- Gradient Enhanced Software System*, Oak Ridge National Laboratory Report PSR-31, April.

Press, W.H., et al., 1989, *Numerical Recipes -- the Art of Scientific Computing*, Cambridge University Press, Cambridge, United Kingdom, p. 283.

APPENDIX A:

INPUT PARAMETER DEFINITIONS*

FDW — Fraction of drinking water that is contaminated; that is, water that comes from the site. Default = 1.

FGWDW — Fraction of drinking water from groundwater (well). Balance is from surface water (pond). Default = 1.

FGWIR — Fraction of irrigation water from groundwater. Balance is from surface water. Default = 1; all irrigation water comes from the site.

FO1 — Occupancy and shielding factor for external gamma radiation pathways. Default = 0.6.

FS1 — Shape factor for external gamma radiation, dimensionless. Default = 1.

RUNOFF — Runoff coefficient. Default = 0.6.

S(LR) — Soil concentration (pCi/g) of principal radionuclide (LR) at initial time.

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*For definitions of the remaining parameters, see Appendix B.

APPENDIX B:

RESRAD PARAMETERS ELIGIBLE FOR SENSITIVITY ANALYSIS

The following parameters are eligible for sensitivity analysis when executing RESRAD version 3.121A:

AREA	Area of the contaminated zone (m^2)
BCZ	Soil-specific b parameter of contaminated zone
BSZ	Soil-specific b parameter of saturated zone
BUZ(i)	Soil-specific b parameter of ith unsaturated zone
COVER0	Thickness of clean cover on the contaminated zone (m)
DCACTC	K_d in contaminated zone for indicated isotope (cm^3/g)
DCACTS	K_d in saturated zone for indicated isotope (cm^3/g)
DCACTU(i)	K_d in ith unsaturated zone for indicated isotope (cm^3/g)
DENSAQ	Density of saturated zone (g/cm^3)
DENSCV	Density of cover material (g/cm^3)
DENSCZ	Density of contaminated zone material (g/cm^3)
DENSUZ(i)	Density of ith unsaturated zone (g/cm^3)
DIET(1)	Fruits, nonleafy vegetables, and grain consumption (kg/yr)
DIET(2)	Leafy vegetable consumption (kg/yr)
DIET(3)	Milk consumption (L/yr)
DIET(4)	Meat and poultry consumption (kg/yr)
DIET(5)	Fish consumption (kg/yr)
DIET(6)	Other seafood consumption (kg/yr)
DM	Depth of soil mixing area (m)
DROOT	Depth of roots (m)
DWI	Drinking water intake (L/yr)
DWIBWT	Well pump intake depth (m below water table)
EPCZ	Effective porosity of contaminated zone
EPSZ	Effective porosity of saturated zone
EPUZ(i)	Effective porosity of ith unsaturated zone
EVAPTR	Evapotranspiration coefficient
H(i)	Thickness of ith unsaturated zone (m)
HCCZ	Hydraulic conductivity of contaminated zone (m/yr)
HCSZ	Hydraulic conductivity of saturated zone (m/yr)
HCUZ(i)	Hydraulic conductivity of ith unsaturated zone (m/yr)
HGWT	Hydraulic gradient of saturated zone
INHALR	Inhalation rate (m^3/yr)
RI	Irrigation rate (m/yr)
LCZPAQ	Length of contaminated zone parallel to aquifer flow (m)
LFI5	Livestock fodder intake for meat (kg/d)
LFI6	Livestock fodder intake for milk (kg/d)
LM	Dilution length for inhalation of airborne dust (m)
LWI5	Livestock water intake for meat (L/d)
LWI6	Livestock water intake for milk (L/d)
MLFD	Mass loading for foliar deposition (g/m^3)

MLINH	Mass loading for inhalation (g/m^3)
PRECIP	Precipitation (m/yr)
RLEACH	Leach rate for indicated isotope (1/yr)
RUNOFF	Runoff coefficient
THICK0	Thickness of contaminated zone (m)
TPCZ	Total porosity of contaminated zone
TPSZ	Total porosity of saturated zone
TPUZ(i)	Total porosity of ith unsaturated zone
UW	Individual's use of groundwater (m^3/yr)
VCV	Erosion rate of cover material (m/yr)
VCZ	Erosion rate of contaminated zone (m/yr)
VWT	Water table drop rate (m/yr)
WAREA	Watershed area for nearby stream or pond (m^2)

APPENDIX C:

RESRAD SENSITIVITY INPUT DATA FILE

The RESRAD input data file SENSE.DAT, which was used for sensitivity analysis, is provided in Figure C.1.

```
'Sensitivity Analysis Default Data' /TITLE
'SENSE.DAT'                                 /SITE-SPECIFIC FILE (IN)
'SENSE.DAT'                                 /SITE-SPECIFIC FILE (OUT)
 1.000E+04 5.000E-01 1.600E+00 0.000E+00                                  /AREA,COVERO,DENSCZ,VCZ
 0.000E+00 1.000E+00 1                                                    /EMEAN,THICKO,NS
   0    1    3    10   30   100   300   1000  3000  10000                 /(T(I),I=1,10)
'Pb-210 ', 0.000E+00 0.000E+00 1.000E+02 1.000E+02                        /NUCNAM,S,RLEACH,DCACTC,DCACTS
 1.000E+02                /(DCACTU(I),I=1,NS)
'Ra-226 ', 0.000E+00 0.000E+00 7.000E+01 7.000E+01                        /NUCNAM,S,RLEACH,DCACTC,DCACTS
 7.000E+01                /(DCACTU(I),I=1,NS)
'Th-230 ', 0.000E+00 0.000E+00 6.000E+04 6.000E+04                        /NUCNAM,S,RLEACH,DCACTC,DCACTS
 6.000E+04                /(DCACTU(I),I=1,NS)
'U-234  ', 1.000E+00 0.000E+00 5.000E+01 5.000E+01                        /NUCNAM,S,RLEACH,DCACTC,DCACTS
 5.000E+01                /(DCACTU(I),I=1,NS)
'U-238  ', 1.000E+00 0.000E+00 5.000E+01 5.000E+01                        /NUCNAM,S,RLEACH,DCACTC,DCACTS
 5.000E+01                /(DCACTU(I),I=1,NS)
'LAST', 0 0 0 0                                                           /Special to mark end of nuclides
 1.600E+00 1.000E+01 2.000E-01 2.000E-01 1.500E-01                        /DENSAQ,DWIBWT,EPSZ,EPCZ,DM
 6.000E-01 1.000E+02 2.000E-02          0 5.500E+00 1.500E+02             /EVAPTR,HCSZ,HGWT,IDITCH,DWTO,UW
 1.000E+02 1.000E+00 2.000E-01 2.000E-01 1.000E+06                        /LCZPAQ,PRECIP,RI,RUNOFF,WAREA
 1.600E+00 4.000E+00 1.000E+02 2.000E-01                                  /DENSUZ,H,HCUZ,EPUZ-IS=1
 8.400E+03 2.000E-04 6.000E-01 4.500E-01                                  /INHALR,MLINH,FO1,FO3
 1.600E+02 1.400E+01 9.200E+01 6.300E+01 5.400E+00 9.000E-01 4.100E+02    /(DIET(I),I=1,6),DWI
 5.000E-01 6.800E+01 5.500E+01 5.000E+01 1.600E+02 1.000E-04         0    /FR9,LFI5,LFI6,LWI5,LWI6,MLFD,MODEL%
 1.000E+00 3.000E+00                                                      /FS1,LM
 1.000E+00 1.000E+00 1.000E+00 1.000E+00                                  /FDW,FGWDW,FGWLW,FGWIR
 4.000E-01 4.000E-01 1.000E+01 5.300E+00                                  /TPCZ,TPSZ,HCCZ,BCZ
 4.000E-01 5.300E+00                                                      /TPUZ,BUZ-IS=1
 1.000E+02                                                                /BRDL
 1.600E+00 0.000E+00 0.000E+00                                            /DENSCV,VCV,VWT
 5.300E+00 9.000E-01                                                      /BSZ,DROOT
```

FIGURE C.1 SENSE.DAT Data File

APPENDIX D:

TYPICAL RESULTS OF GRESS SENSITIVITY ANALYSIS

Figure D.1 shows typical sensitivity analysis results obtained by using GRESS. The response function used is the total dose at the eighth year. The parameter sensitivities have been sorted.

RESPONSE 22 TDOSE(8) = 9.650144D-01
Total Dose Year: 8

NAME	DERIVATIVE	SENSITIVITY
DWIBWT	-9.61422E-02	-9.96277E-01
EPSZ	-4.80711E+00	-9.96277E-01
DENSAQ	-5.97910E-01	-9.91339E-01
TPSZ	2.39164E+00	9.91339E-01
DENSCZ	5.07441E-01	8.41341E-01
THICKO	8.11325E-01	8.40739E-01
FDW	7.95160E-01	8.23988E-01
DWI	1.93942E-03	8.23988E-01
FGWDW	7.87209E-01	8.15748E-01
S(39)	4.96128E-01	5.14115E-01
DCACTS(39)	-9.67174E-03	-5.01119E-01
S(42)	4.68886E-01	4.85885E-01
DCACTS(42)	-9.29975E-03	-4.81845E-01
EVAPTR	-6.80095E-01	-4.22851E-01
PRECIP	2.17631E-01	2.25521E-01
RI	9.81492E-01	2.03415E-01
FGWIR	1.40472E-01	1.45565E-01
N(IS)	-3.05030E-02	-1.26435E-01
EPUZ(IS)	-6.10059E-01	-1.26435E-01
TPUZ(IS)	3.04099E-01	1.26049E-01
DENSUZ(IS)	-7.60247E-02	-1.26049E-01
DIET(1)	4.85380E-04	8.04763E-02
DCACTC(39)	-1.46561E-03	-7.59371E-02
DCACTC(42)	-1.46383E-03	-7.58452E-02
AREA	6.81759E-06	7.06475E-02
RUNOFF	-2.72038E-01	-5.63801E-02
DIET(4)	8.50407E-04	5.55180E-02
DCACTU(39,1)	-1.03446E-03	-5.35981E-02
DCACTU(42,1)	-9.94672E-04	-5.15366E-02
LFI5	5.64437E-04	3.97732E-02
DIET(2)	1.71484E-03	2.48781E-02
FGWLW	2.34728E-02	2.43238E-02
DCACTU(22,1)	-1.91525E-04	-1.98469E-02
LWI5	3.03878E-04	1.57448E-02
DIET(3)	1.51514E-04	1.44447E-02

FIGURE D.1 GRESS Sensitivity Analysis Results for TDOSE(8)

APPENDIX E:

RESRAD/VAX VERSION SUMMARY REPORT

The following pages show the RESRAD/VAX Version summary report obtained when the SENSE.DAT input file is used. The table of contents for the summary report is provided below.

Residual Radioactivity Program, Version 3.121A VAX 9-OCT-90 14:54 Page 1
Summary : Sensitivity Analysis Default Data File: SENSE.DAT

Table of Contents

Part I: Mixture Sums and Single Radionuclide Guidelines

Site-Specific Parameter Summary

Menu	Parameter	Used	Default
R011	Area of contaminated zone (m**2)	1.000E+04	1.000E+04
R011	Thickness of contaminated zone (m)	1.000E+00	1.000E+00
R011	Length parallel to aquifer flow (m)	1.000E+02	1.000E+02
R011	Basic radiation dose limit (mrem/yr)	1.000E+02	1.000E+02
R011	Times for calculations (yr)	1.000E+00	1.000E+00
R011	Times for calculations (yr)	3.000E+00	3.000E+00
R011	Times for calculations (yr)	1.000E+01	1.000E+01
R011	Times for calculations (yr)	3.000E+01	3.000E+01
R011	Times for calculations (yr)	1.000E+02	1.000E+02
R011	Times for calculations (yr)	3.000E+02	3.000E+02
R011	Times for calculations (yr)	1.000E+03	1.000E+03
R011	Times for calculations (yr)	3.000E+03	3.000E+03
R011	Times for calculations (yr)	1.000E+04	1.000E+04
R012	Initial principal radionuclide (pCi/g): U-234	1.000E+00	0.000E+00
R012	Initial principal radionuclide (pCi/g): U-238	1.000E+00	0.000E+00
R013	Cover depth (m)	5.000E-01	5.000E-01
R013	Density of cover material (g/cm**3)	1.600E+00	1.600E+00
R013	Cover depth erosion rate (m/yr)	0.000E+00	0.000E+00
R013	Density of contaminated zone (g/cm**3)	1.600E+00	1.600E+00
R013	Contaminated zone erosion rate (m/yr)	0.000E+00	0.000E+00
R013	Contaminated zone total porosity	4.000E-01	4.000E-01
R013	Contaminated zone effective porosity	2.000E-01	2.000E-01
R013	Contaminated zone hydraulic conductivity (m/yr)	1.000E+01	1.000E+01
R013	Contaminated zone b parameter	5.300E+00	5.300E+00
R013	Evapotranspiration coefficient	6.000E-01	6.000E-01
R013	Precipitation (m/yr)	1.000E+00	1.000E+00
R013	Irrigation (m/yr)	2.000E-01	2.000E-01
R013	Irrigation mode	overhead	overhead
R013	Runoff coefficient	2.000E-01	2.000E-01
R013	Watershed area for nearby stream or pond (m**2)	1.000E+06	1.000E+06
R014	Density of saturated zone (g/cm**3)	1.600E+00	1.600E+00
R014	Saturated zone total porosity	4.000E-01	4.000E-01
R014	Saturated zone effective porosity	2.000E-01	2.000E-01
R014	Saturated zone hydraulic conductivity (m/yr)	1.000E+02	1.000E+02
R014	Saturated zone hydraulic gradient	2.000E-02	2.000E-02
R014	Distance from surface to water table (m)	5.500E+00	5.500E+00
R014	Water table drop rate (m/yr)	0.000E+00	0.000E+00
R014	Well pump intake depth (m below water table)	1.000E+01	1.000E+01
R014	Model: Nondispersion (ND) or Mass-Balance (MB)	ND	ND
R015	Number of unsaturated zone strata	1	1
R015	Unsat. zone 1, thickness (m)	4.000E+00	4.000E+00
R015	Unsat. zone 1, soil density (g/cm**3)	1.600E+00	1.600E+00
R015	Unsat. zone 1, total porosity	4.000E-01	4.000E-01
R015	Unsat. zone 1, effective porosity	2.000E-01	2.000E-01
R015	Unsat. zone 1, soil-specific b parameter	5.300E+00	5.300E+00
R015	Unsat. zone 1, hydraulic conductivity (m/yr)	1.000E+02	1.000E+02

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Summary : Sensitivity Analysis Default Data File: SENSE.DAT

Site-Specific Parameter Summary (continued)

Menu	Parameter	Used	Default
R016	Distribution coefficients for U-234		
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01
R016	Unsaturated zone 1 (cm**3/g)	5.000E+01	5.000E+01
R016	Saturated zone (cm**3/g)	5.000E+01	5.000E+01
R016	Leach rate (/yr)	0.000E+00	0.000E+00
R016	Distribution coefficients for U-238		
R016	Contaminated zone (cm**3/g)	5.000E+01	5.000E+01
R016	Unsaturated zone 1 (cm**3/g)	5.000E+01	5.000E+01
R016	Saturated zone (cm**3/g)	5.000E+01	5.000E+01
R016	Leach rate (/yr)	0.000E+00	0.000E+00
R016	Distribution coefficients for daughter Pb-210		
R016	Contaminated zone (cm**3/g)	1.000E+02	1.000E+02
R016	Unsaturated zone 1 (cm**3/g)	1.000E+02	1.000E+02
R016	Saturated zone (cm**3/g)	1.000E+02	1.000E+02
R016	Leach rate (/yr)	0.000E+00	0.000E+00
R016	Distribution coefficients for daughter Ra-226		
R016	Contaminated zone (cm**3/g)	7.000E+01	7.000E+01
R016	Unsaturated zone 1 (cm**3/g)	7.000E+01	7.000E+01
R016	Saturated zone (cm**3/g)	7.000E+01	7.000E+01
R016	Leach rate (/yr)	0.000E+00	0.000E+00
R016	Distribution coefficients for daughter Th-230		
R016	Contaminated zone (cm**3/g)	6.000E+04	6.000E+04
R016	Unsaturated zone 1 (cm**3/g)	6.000E+04	6.000E+04
R016	Saturated zone (cm**3/g)	6.000E+04	6.000E+04
R016	Leach rate (/yr)	0.000E+00	0.000E+00
R017	Inhalation rate (m**3/yr)	8.400E+03	8.400E+03
R017	Mass loading for inhalation (g/m**3)	2.000E-04	2.000E-04
R017	Occupancy and shielding factor, external gamma	6.000E-01	6.000E-01
R017	Occupancy factor, inhalation	4.500E-01	4.500E-01
R017	Shape factor, external gamma	1.000E+00	1.000E+00
R017	Mixing height for airborne dust, inhalation (m)	3.000E+00	3.000E+00
R018	Fruits, vegetables and grain consumption (kg/yr)	1.600E+02	1.600E+02
R018	Leafy vegetable consumption (kg/yr)	1.400E+01	1.400E+01
R018	Milk consumption (L/yr)	9.200E+01	9.200E+01
R018	Meat and poultry consumption (kg/yr)	6.300E+01	6.300E+01
R018	Fish consumption (kg/yr)	5.400E+00	5.400E+00
R018	Other seafood consumption (kg/yr)	9.000E-01	9.000E-01
R018	Drinking water intake (L/yr)	4.100E+02	4.100E+02
R018	Fraction of drinking water from site	1.000E+00	1.000E+00
R018	Fraction of aquatic food from site	5.000E-01	5.000E-01
R019	Livestock fodder intake for meat (kg/day)	6.800E+01	6.800E+01
R019	Livestock fodder intake for milk (kg/day)	5.500E+01	5.500E+01
R019	Livestock water intake for meat (L/day)	5.000E+01	5.000E+01
R019	Livestock water intake for milk (L/day)	1.600E+02	1.600E+02
R019	Mass loading for foliar deposition (g/m**3)	1.000E-04	1.000E-04

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Summary : Sensitivity Analysis Default Data   File: SENSE.DAT

Site-Specific Parameter Summary (continued)

Menu	Parameter	Used	Default
R019	Depth of soil mixing layer (m)	1.500E-01	1.500E-01
R019	Depth of roots (m)	9.000E-01	9.000E-01
R019	Drinking water fraction from ground water	1.000E+00	1.000E+00
R019	Livestock water fraction from ground water	1.000E+00	1.000E+00
R019	Irrigation fraction from ground water	1.000E+00	1.000E+00

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Summary : Sensitivity Analysis Default Data   File: SENSE.DAT

Contaminated Zone Dimensions		Initial Soil Concentrations, pCi/g	
Area:	10000.00 square meters	U-234	1.000E+00
Thickness:	1.00 meters	U-238	1.000E+00
Cover Depth:	0.50 meters		

Total Dose TDOSE(t), mrem/yr
Basic Radiation Dose Limit = 100 mrem/yr
Total Mixture Sum M(t) = Fraction of Basic Dose Limit Received at Time (t)

t (years):	0	1	3	10	30	100	300	1000	3000	10000
TDOSE(t):	5.635E-02	5.607E-02	5.552E-02	5.362E-02	4.856E-02	3.446E-02	1.390E-02	9.650E-01	7.425E-02	3.062E-03
M(t):	5.635E-04	5.607E-04	5.552E-04	5.362E-04	4.856E-04	3.446E-04	1.390E-04	9.650E-03	7.425E-04	3.062E-05

Maximum TDOSE(t): 1.029E+00 mrem/yr   at t = 1406.32 : 0.07 years

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t =1406.32 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	9.228E-06	0.000E+00	3.290E-03	9.754E-05	1.376E-06	4.366E-01	4.545E-04	6.118E-02	2.864E-02	7.424E-03	5.377E-01
U-238	1.182E-07	0.000E+00	2.384E-05	2.766E-06	3.851E-07	4.069E-01	3.217E-04	4.914E-02	2.748E-02	7.170E-03	4.911E-01
Total	9.347E-06	0.000E+00	3.314E-03	1.003E-04	1.761E-06	8.435E-01	7.762E-04	1.103E-01	5.612E-02	1.459E-02	1.029E+00

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t =1406.32 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	8.971E-04	0.000E+00	3.198E-01	9.482E-03	1.338E-04	4.244E+01	4.418E-02	5.947E+00	2.784E+00	7.217E-01	5.226E+01
U-238	1.149E-05	0.000E+00	2.318E-03	2.689E-04	3.744E-05	3.956E+01	3.127E-02	4.777E+00	2.671E+00	6.970E-01	4.774E+01
Total	9.086E-04	0.000E+00	3.222E-01	9.750E-03	1.712E-04	8.199E+01	7.545E-02	1.072E+01	5.455E+00	1.419E+00	1.000E+02

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Summary : Sensitivity Analysis Default Data   File: SENSE.DAT

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 0 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	3.751E-09	0.000E+00	2.513E-02	3.094E-03	4.385E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.867E-02
U-238	1.245E-04	0.000E+00	2.417E-02	2.975E-03	4.217E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.769E-02
Total	1.245E-04	0.000E+00	4.930E-02	6.069E-03	8.602E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.635E-02

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 0 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	6.656E-06	0.000E+00	4.460E+01	5.490E+00	7.782E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.087E+01
U-238	2.209E-01	0.000E+00	4.288E+01	5.279E+00	7.483E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.913E+01
Total	2.210E-01	0.000E+00	8.748E+01	1.077E+01	1.526E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+02

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Summary : Sensitivity Analysis Default Data   File: SENSE.DAT

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 1 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	3.827E-09	0.000E+00	2.501E-02	3.079E-03	4.364E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.852E-02
U-238	1.239E-04	0.000E+00	2.405E-02	2.960E-03	4.196E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.755E-02
Total	1.239E-04	0.000E+00	4.906E-02	6.039E-03	8.559E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.607E-02

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 1 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	6.824E-06	0.000E+00	4.460E+01	5.490E+00	7.782E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.087E+01
U-238	2.209E-01	0.000E+00	4.288E+01	5.279E+00	7.482E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.913E+01
Total	2.209E-01	0.000E+00	8.748E+01	1.077E+01	1.526E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+02

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Summary : Sensitivity Analysis Default Data File: SENSE.DAT

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 3 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	4.538E-09	0.000E+00	2.476E-02	3.048E-03	4.320E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.824E-02
U-238	1.227E-04	0.000E+00	2.381E-02	2.931E-03	4.154E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.728E-02
Total	1.227E-04	0.000E+00	4.857E-02	5.979E-03	8.474E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.552E-02

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 3 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	8.173E-06	0.000E+00	4.460E+01	5.491E+00	7.781E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.087E+01
U-238	2.209E-01	0.000E+00	4.288E+01	5.279E+00	7.482E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.913E+01
Total	2.209E-01	0.000E+00	8.748E+01	1.077E+01	1.526E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+02

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Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 10 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	1.273E-08	0.000E+00	2.392E-02	2.945E-03	4.172E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.728E-02
U-238	1.185E-04	0.000E+00	2.299E-02	2.831E-03	4.012E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.634E-02
Total	1.185E-04	0.000E+00	4.691E-02	5.775E-03	8.184E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.362E-02

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 10 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	2.374E-05	0.000E+00	4.461E+01	5.491E+00	7.780E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.087E+01
U-238	2.209E-01	0.000E+00	4.288E+01	5.278E+00	7.481E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.913E+01
Total	2.209E-01	0.000E+00	8.748E+01	1.077E+01	1.526E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+02

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Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 30 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	8.094E-08	0.000E+00	2.167E-02	2.667E-03	3.776E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.472E-02
U-238	1.072E-04	0.000E+00	2.081E-02	2.562E-03	3.632E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.385E-02
Total	1.073E-04	0.000E+00	4.249E-02	5.230E-03	7.408E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.856E-02

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 30 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	1.667E-04	0.000E+00	4.463E+01	5.492E+00	7.776E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.090E+01
U-238	2.208E-01	0.000E+00	4.286E+01	5.276E+00	7.478E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.910E+01
Total	2.210E-01	0.000E+00	8.749E+01	1.077E+01	1.525E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+02

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Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 100 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	7.061E-07	0.000E+00	1.547E-02	1.891E-03	2.665E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.763E-02
U-238	7.567E-05	0.000E+00	1.469E-02	1.809E-03	2.563E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.683E-02
Total	7.637E-05	0.000E+00	3.017E-02	3.699E-03	5.228E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.446E-02

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 100 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	2.049E-03	0.000E+00	4.490E+01	5.486E+00	7.732E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.116E+01
U-238	2.196E-01	0.000E+00	4.263E+01	5.248E+00	7.438E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.884E+01
Total	2.216E-01	0.000E+00	8.753E+01	1.073E+01	1.517E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+02

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Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 300 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	3.652E-06	0.000E+00	6.840E-03	7.351E-04	9.869E-05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.677E-03
U-238	2.795E-05	0.000E+00	5.429E-03	6.683E-04	9.473E-05	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	6.220E-03
Total	3.160E-05	0.000E+00	1.227E-02	1.403E-03	1.934E-04	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.390E-02

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 300 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	2.628E-02	0.000E+00	4.922E+01	5.289E+00	7.102E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.524E+01
U-238	2.011E-01	0.000E+00	3.907E+01	4.809E+00	6.816E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	4.476E+01
Total	2.274E-01	0.000E+00	8.828E+01	1.010E+01	1.392E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.000E+02

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Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 1000 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	8.798E-06	0.000E+00	3.275E-03	1.119E-04	3.934E-06	4.067E-01	3.539E-04	5.133E-02	2.721E-02	7.088E-03	4.961E-01
U-238	8.601E-07	0.000E+00	1.681E-04	2.055E-05	2.907E-06	3.884E-01	3.070E-04	4.690E-02	2.623E-02	6.844E-03	4.689E-01
Total	9.658E-06	0.000E+00	3.443E-03	1.325E-04	6.840E-06	7.952E-01	6.609E-04	9.823E-02	5.344E-02	1.393E-02	9.650E-01

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 1000 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	9.117E-04	0.000E+00	3.394E-01	1.160E-02	4.076E-04	4.215E+01	3.667E-02	5.319E+00	2.820E+00	7.345E-01	5.141E+01
U-238	8.913E-05	0.000E+00	1.742E-02	2.129E-03	3.012E-04	4.025E+01	3.181E-02	4.860E+00	2.718E+00	7.092E-01	4.859E+01
Total	1.001E-03	0.000E+00	3.568E-01	1.373E-02	7.088E-04	8.240E+01	6.848E-02	1.018E+01	5.538E+00	1.444E+00	1.000E+02

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Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 3000 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	9.173E-06	0.000E+00	3.252E-03	9.405E-05	9.754E-07	3.925E-02	2.999E-04	3.021E-02	7.237E-04	1.849E-05	7.386E-02
U-238	5.265E-09	0.000E+00	1.860E-06	5.454E-08	6.934E-10	2.666E-04	1.040E-06	1.107E-04	1.206E-05	2.622E-06	3.949E-04
Total	9.178E-06	0.000E+00	3.254E-03	9.411E-05	9.761E-07	3.952E-02	3.009E-04	3.032E-02	7.358E-04	2.111E-05	7.425E-02

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 3000 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	1.235E-02	0.000E+00	4.379E+00	1.267E-01	1.314E-03	5.286E+01	4.039E-01	4.069E+01	9.747E-01	2.490E-02	9.947E+01
U-238	7.090E-06	0.000E+00	2.505E-03	7.345E-05	9.339E-07	3.590E-01	1.400E-03	1.491E-01	1.625E-02	3.532E-03	5.319E-01
Total	1.236E-02	0.000E+00	4.382E+00	1.267E-01	1.315E-03	5.322E+01	4.053E-01	4.084E+01	9.909E-01	2.843E-02	1.000E+02

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Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), mrem/yr

At t = 10000 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	8.366E-06	0.000E+00	2.965E-03	8.577E-05	8.894E-07	5.752E-09	4.419E-11	4.479E-09	1.053E-10	2.028E-12	3.060E-03
U-238	4.765E-09	0.000E+00	1.689E-06	4.885E-08	5.066E-10	6.860E-11	5.271E-13	5.342E-11	1.256E-12	2.418E-14	1.743E-06
Total	8.370E-06	0.000E+00	2.967E-03	8.582E-05	8.899E-07	5.821E-09	4.472E-11	4.532E-09	1.065E-10	2.052E-12	3.062E-03

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p), percent

At t = 10000 years

Radio-	Water Independent Pathways					Water Dependent Pathways					
Nuclide	Ground	Dust	Plant	Meat	Milk	Water	Fish	Plant	Meat	Milk	Total
U-234	2.732E-01	0.000E+00	9.684E+01	2.801E+00	2.904E-02	1.879E-04	1.443E-06	1.463E-04	3.438E-06	6.622E-08	9.994E+01
U-238	1.556E-04	0.000E+00	5.516E-02	1.595E-03	1.654E-05	2.240E-06	1.721E-08	1.744E-06	4.100E-08	7.898E-10	5.693E-02
Total	2.733E-01	0.000E+00	9.689E+01	2.803E+00	2.906E-02	1.901E-04	1.460E-06	1.480E-04	3.479E-06	6.701E-08	1.000E+02

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Dose/Source Ratios Summed Over All Pathways, (mrem/yr)/(pCi/g)

Nuclide (i)	t= 0	1	3	10	30	100	300	1000	3000	10000
U-234	2.867E-02	2.852E-02	2.824E-02	2.728E-02	2.472E-02	1.763E-02	7.677E-03	4.961E-01	7.386E-02	3.060E-03
U-238	2.769E-02	2.755E-02	2.728E-02	2.634E-02	2.385E-02	1.683E-02	6.220E-03	4.689E-01	3.949E-04	1.743E-06

Single Radionuclide Soil Guidelines G(i,t) in pCi/g
Basic Radiation Dose Limit = 100 mrem/yr

Nuclide (i)	t= 0	1	3	10	30	100	300	1000	3000	10000
U-234	3.488E+03	3.506E+03	3.541E+03	3.666E+03	4.046E+03	5.671E+03	1.303E+04	2.016E+02	1.354E+03	3.268E+04
U-238	3.612E+03	3.630E+03	3.666E+03	3.796E+03	4.193E+03	5.941E+03	1.608E+04	2.133E+02	2.532E+05	*3.360E+05

*At specific activity limit

Summed Dose/Source Ratios DSR(i,t) in (mrem/yr)/(pCi/g)
and Single Radionuclide Soil Guidelines G(i,t) in pCi/g
at tmin = time of minimum single radionuclide soil guideline
and at tmax = time of maximum total dose = 1406.32 : 0.07 years

Nuclide (i)	Initial pCi/g	tmin (years)	DSR(i,tmin)	G(i,tmin) (pCi/g)	DSR(i,tmax)	G(i,tmax) (pCi/g)
U-234	1.000E+00	1406.28 : 0.07	5.377E-01	1.860E+02	5.377E-01	1.860E+02
U-238	1.000E+00	1406.33 : 0.07	4.911E-01	2.036E+02	4.911E-01	2.036E+02

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