APPENDIX E
DOSE MODELING PROBABILISTIC UNCERTAINTY ANALYSES

PURPOSE OF THIS APPENDIX

The purpose of this appendix is to describe probabilistic uncertainty analyses performed to evaluate the degree of conservatism in key input parameters for the conceptual models used to develop derived concentration guideline levels (DCGLs) for surface soil, subsurface soil, and streambed sediment, along with the results of these analyses.

INFORMATION IN THIS APPENDIX

This appendix provides the following information:

- Section 1 provides introductory information to help place the discussions that follow into context.
- Section 2 defines key terms used in the discussions.
- Section 3 summarizes the probabilistic analysis capabilities of the RESRAD computer code used in the analyses.
- Section 4 describes criteria used for selecting parameters for uncertainty analysis.
- Section 5 describes how parameter distributions were selected.
- Section 6 describes correlation of parameters.
- Section 7 describes the uncertainty analysis results for each of the three conceptual models, including DCGLs expressed as the peak-of-the-mean (50^{th} percentile) and 95^{th} percentile.
- Section 8 describes parameter output rank correlations.
- Section 9 provides conclusions and describes actions taken on the analysis results.
- Attachment 1 contains copies of representative probabilistic output plots.
- Attachment 2 contains the electronic files developed in performing the analyses.

RELATIONSHIP TO OTHER PLAN SECTIONS

This appendix provides supporting information for Section 5. Information provided in Section 5 and in Section 1 on the project background will help place the information in this appendix into context.

1.0 Introduction

1.1 Purpose

The probabilistic uncertainty analyses discussed in this appendix were performed to evaluate the degree of conservatism in key input parameters for the conceptual models used in developing DCGLs for surface soil, subsurface soil, and streambed sediment that are described in Section 5 of this plan. The DOE letter that forwarded Revision 0 of this plan to NRC for review (DOE 2008) noted that this matter was still under evaluation when Revision 0 was completed.

These probabilistic uncertainty analyses supplement the deterministic sensitivity analyses described in Section 5 of this plan. They compute the total uncertainty in the DCGLs resulting from the uncertainty in or the variability of the input parameters. They also help determine the relative importance of the contributions of different input parameters to the total uncertainty in the DCGLs.

These analyses thereby provide additional perspective on the relationships between conceptual model input parameters and estimated dose, along with sets of DCGLs expressed in probabilistic terms. This information supports a risk-informed approach to establishing cleanup goals for Phase 1 of the decommissioning.

1.2 Background

The DCGLs for surface soil, subsurface soil, and streambed sediment were developed using the basic RESRAD deterministic approach in which the analysis is performed by assigning each parameter a single value, as described in Section 5 of this plan. As noted in Section 5, RESRAD was selected as the mathematical model for DCGL development due to its extensive use by DOE and by NRC licensees in developing DCGLs and evaluating doses from residual radioactivity at decommissioned sites.

General NRC Guidance on Uncertainty and Sensitivity Analyses

NRC guidance on uncertainty and sensitivity analyses appears in Appendix I to NUREG-1757, Volume 2 (NRC 2006). NRC concludes that while the deterministic modeling approach has the advantage of being simple to implement and easy to communicate to a non-specialist audience, it has significant limitations:

- It does not allow consideration of the effects of unusual combinations of input parameters;
- It does not provide information on uncertainty in the results, which would be helpful to the decision-maker; and
- It often leads to overly conservative evaluations because it has to rely on the use of pessimistic estimates of each parameter of the model to ensure a bounding dose estimate, that is, results that are likely to overestimate the actual peak dose.

The first two limitations apply to the deterministic dose analysis described in Section 5, which did not include evaluation of different parameter combinations or estimates of uncertainty. And while DOE used conservative model input parameters in many cases, it is difficult to demonstrate that the results of the deterministic dose analysis are bounding.

NRC encourages the use of probabilistic techniques to evaluate and quantify the magnitude and effect of uncertainties in dose assessments, and the sensitivity of the calculated risks from individual parameter values and modeling assumptions. Probabilistic uncertainty analysis provides more information to the decision-maker than deterministic analysis, as it characterizes a range of potential doses and the likelihood that a particular dose may be exceeded. (NRC 2006)

Uncertainty analyses in the RESRAD probabilistic modules use Latin hypercube sampling[1], a modified Monte Carlo method, allowing for the generation of representative input parameter values from all segments of the input distributions. Input variables for the models are selected randomly from probability distribution functions for each parameter of interest. Parameter distribution functions may be either independent or correlated to other input variable distributions. The analysis is then performed hundreds of times to obtain a distribution of doses resulting from each set of randomly selected input parameters.

The results of a probabilistic uncertainty analysis provide a distribution of doses illustrating the effects of random combinations of input parameters. It should be recognized that some percentage of the calculated distribution of doses may exceed the regulatory limit, which is expressed as a (deterministic) single value. Compliance can be stated in terms of a metric of the distribution such as the mean falling below the limit, or only a percentage of calculated doses exceeding the limit. (NRC 2006)

NRC indicates that when using probabilistic dose modeling, the “peak-of-the-mean” dose distribution should be used for demonstrating compliance with its License Termination Rule in 10 CFR Part 20, Subpart E (NRC 2006).

Specific NRC Guidance for Phase 1 of the WVDP Decommissioning

DOE and NRC held two scoping meeting on DOE’s dose modeling plans. The NRC summary of the second meeting (NRC 2008) included the following statements:

> “NRC indicated that it might not be acceptable to use the mean or most likely value for those parameters that have the largest impact on dose in a deterministic analysis (e.g., for parameters such as K_ds that have a large parameter range and uncertainty).”
>
> “NRC warned of the potential pitfalls of performing a deterministic analysis with a sensitivity analysis in lieu of a probabilistic assessment. Depending on the combination and range of parameter values selected and models employed (e.g., mass balance versus non-dispersion model in RESRAD), key radionuclides and pathways, the results of the sensitivity analysis could be misleading and the full range of uncertainty difficult to determine. Selection of parameter values should be guided by conservative assumptions when uncertainty is large and cannot be reduced. To determine the impact of a particular parameter value on the dose results, DOE must identify key risk drivers and perform a comprehensive sensitivity analysis to ensure that its selection of parameter values in its deterministic analysis errors on the side of conservatism.”

DOE identified key risk (i.e., dose) drivers and included a comprehensive sensitivity analysis in Section 5.2.4 of Revision 1 to the plan. The analyses described in this appendix, complete DOE actions on these matters.

---

[1] The Latin hypercube method is a modified Monte Carlo method; see Section 2 below for definitions of terms such as these. NRC supported development of the probabilistic version of RESRAD for use in determining compliance with its License Termination Rule (Yu, et al. 2000). RESRAD probabilistic modeling capabilities are discussed in Section 3 below.

1.3 Analyses and Associated Electronic Files

The probabilistic dose analyses discussed herein were performed using the probabilistic modules of RESRAD Version 6.4 (LePoire, et al. 2000; Yu, et al. 2000; Yu, et al. 2001) making use of the stratified sampling of the Latin hypercube method.

For the surface soil model, three groups of results were generated for 1000 sets of input parameters, with calculated statistical parameters (minimum, maximum, mean, percentiles) output by RESRAD for each of the three input parameter datasets. For the subsurface and streambed sediment models, use of the mass balance groundwater option results in long computation times for multiple parameter input sets. Therefore, only a single set of 1000 input values for each parameter was used for the subsurface soil and sediment evaluation where simulation times were extensive.

Included in the electronic files of Attachment 1 are the RESRAD input and output files for surface soil ("RESRAD PROB SURF.zip"), subsurface soil ("RESRAD PROB SUBS.zip"), and sediment ("RESRAD PROB SED.zip"), and a Word file containing output plots of dose over time for each radionuclide in each media ("PROB Dose Plots.doc").

1.4 Products of the Probabilistic Uncertainty Analyses

The primary products of these analyses are as follows:

- Sets of peak-of-the-mean $DCGL_W$ values for surface soil, subsurface soil, and streambed sediment, that is, values that have a 50 percent probability that the specified concentration for each radionuclide would correspond to a dose of 25 mrem in the year of peak dose;
- Sets of 95th percentile $DCGL_W$ values for surface soil, subsurface soil, and streambed sediment, that is, values that have a 95 percent probability that the specified concentration for each radionuclide would correspond to a dose of 25 mrem in the year of peak dose;
- Preliminary dose estimates for the remediated Waste Management Area (WMA) 1 excavation expressed as the peak of the mean (50th percentile) and the 95th percentile; and
- Preliminary dose estimates for the remediated WMA 2 excavation expressed as the peak of the mean and the 95th percentile.

> As discussed in Section 9.2 of this appendix, the results of the probabilistic uncertainty analyses indicate that some input parameters used in the deterministic modeling to develop DCGLs may not be sufficiently conservative to ensure bounding results.

2.0 Key Terms

Because of the technical nature of the discussions in this appendix, some readers may find the following definitions to be useful. These definitions are tailored to the use of the terms in this appendix.

Behavioral parameter. Any conceptual model input parameter whose value would depend on the receptor's behavior within the scenario definition. For the same group of receptors, a behavioral parameter value could change if the scenario changed, e.g., parameters for recreational use could be different from those for residential use. (See also **metabolic parameter** and **physical parameter**.)

Correlation. A measure of the strength of the relationship between two variables (e.g., conceptual model input parameters) used to predict the value of one variable given the value of the other.

Correlation coefficient. Correlation coefficients (R values) are expressed on a scale from -1.0 to +1.0, with the strongest correlations being at both extremes and providing the best predictions. Negative values reflect inverse relationships. (See also **partial rank correlation coefficient**.)

Deterministic analysis. In a deterministic analysis, each input parameter is assumed to be an exactly known single value, as are the analysis results.

Empirical distribution. An empirical distribution is a parameter distribution well defined by available data to the extent that additional sampling would not be expected to significantly change the distribution's shape.

Latin hypercube sampling. A modified **Monte Carlo method** used to generate random samples of input parameters in the probabilistic version of RESRAD.

Lognormal distribution. In a lognormal distribution, the logarithm of the parameter has a **normal distribution**. A lognormal distribution is defined by two parameters, the logarithmic mean and its standard deviation.

Mean. The arithmetic mean as used here is the mathematical average of a set of numbers. The mean is calculated by adding a set of values and dividing the total by the number of values in the set.

Metabolic parameter. A parameter representing the metabolic characteristics of the potential receptor that is independent of scenario. (Metabolic parameters were not included in the evaluation discussed in this appendix.)

Monte Carlo method. A technique which obtains a probabilistic approximation to the solution of a problem by using statistical sampling techniques. Monte Carlo methods rely on repeated random sampling to compute their results, and are often used to simulate complex physical and mathematical systems.

Normal distribution. Probability values in a normal distribution follow a bell shaped curve centered about a mean value with the width of the "bell" described by the standard deviation. In a bounded normal distribution, upper and lower limits to the range are specified.

Overall coefficient of determination. This coefficient, denoted by R^2, provides an indication of the variability in the overall radionuclide dose accounted for by the selected input parameters. It varies between 0 and 1; the higher the value, the greater the influence. A value of 0 indicates the selected parameters do not influence the calculated dose at all.

Partial rank correlation coefficient. The partial rank correlation coefficient measures the strength of the relationship between variables after any confounding influences of other variables have been removed. (See also **rank correlation coefficient**.)

Peak of the mean. The highest dose value in a plot of the estimated mean dose over time.

Physical parameter. Any parameter whose value would not change if a different group of receptors was considered. Physical parameters are site-specific factors determined by the source, its location, and geological or physical characteristics of the site.

Probabilistic analysis. In a probabilistic analysis, statistical distributions are defined for input parameters to account for their uncertainty, and the analysis results reflect the resulting uncertainty, e.g., a distribution of values rather than a single value. Such analyses use a random sampling method to select parameter values from a distribution. Results of the calculations appear in the form of a distribution of values.

Probability density function. A graphical representation of the probability distribution of a continuously random variable illustrating the range of possible values and the relative frequency (probability) of each value within the range. Uncertainty in a conceptual model input parameter is represented by the probability density function for that parameter. Probability distribution functions provided for in RESRAD include empirical, uniform, triangular, normal, and lognormal.

Rank correlation coefficient. A correlation coefficient between two variables that is used for determining the relative importance of input parameters in influencing the resultant dose.

Regression analysis. A mathematical method of modeling the relationships among three or more variables used to predict the value of one variable given the values of the others.

Triangular distribution. In a triangular distribution of a continuous random variable, the graph of the probability density function forms a triangle, with a range defined by minimum and maximum values and a mode value which is the most frequent (probable) value.

Uniform distribution. In a uniform distribution, each value within the range has the same probability of occurrence.

3.0 The Probabilistic Version of RESRAD

The probabilistic RESRAD code is an extended and enhanced version of RESRAD. RESRAD Version 6.4, which was used for the dose analyses described in Section 5 of this plan, provides both deterministic and probabilistic analysis capabilities.

The probabilistic version of RESRAD was developed for use in site-specific dose modeling in support of NRC's License Termination Rule compliance process for decontamination and decommissioning of NRC-licensed sites. Probabilistic analysis capabilities were incorporated into RESRAD in external software modules integrated into the code. Three reports describe these probabilistic analyses capabilities and how they are applied:

- NUREG/CR-6676, *Probabilistic Dose Analysis Using Parameter Distributions Developed for RESRAD and RESRAD-BUILD Codes* (Kamboj, et al. 2000);

- NUREG/CR-6692, *Probabilistic Modules for the RESRAD and RESRAD-Build Computer Codes, User Guide* (LePoire, et al. 2000); and
- NUREG/CR-6697, *Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes* (Yu, et al. 2000).

Three basic types of input parameters are considered in probabilistic analyses: physical parameters, behavioral parameters, and metabolic parameters[2]. Certain parameters fall into more than one category, e.g., inhalation rate is both a behavioral parameter and a metabolic parameter.

The probabilistic modules in RESRAD Version 6.4 provide default values and distributions for various parameters. Default probability distributions include normal, lognormal, uniform, triangular, and empirical. These default distributions are based primarily on the quantity of relevant data available in reviewed technical literature.[3] For three parameters of interest in this plan – cover depth, precipitation rate, and well pumping rate – a default distribution type is not provided.

In a RESRAD probabilistic analysis, the results from all input samples are analyzed and presented in a statistical format in terms of the average value, standard deviation, minimum value, and maximum value. The cumulative probability distribution of the output is presented in both tabular and graphical forms.

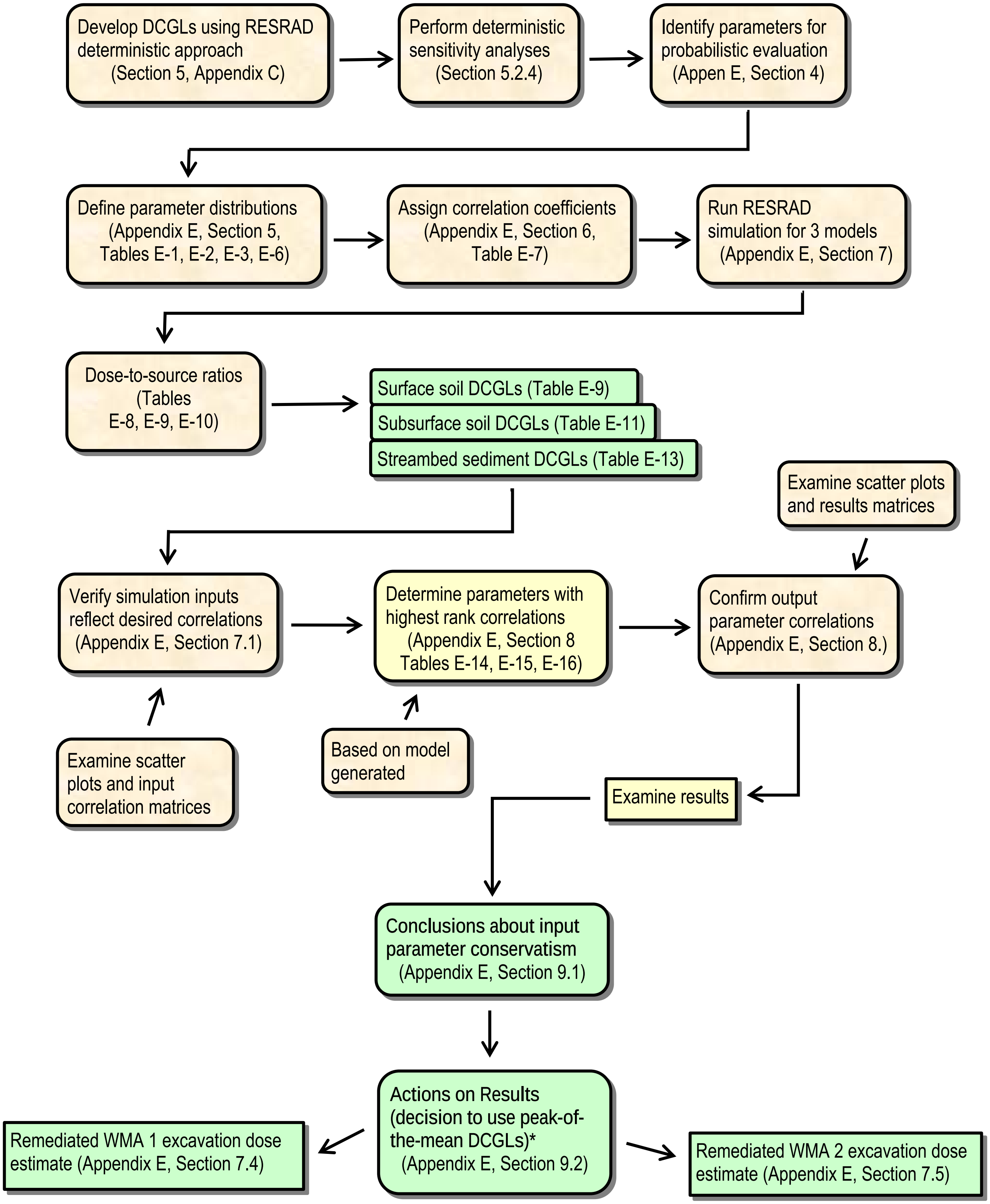
The basic process includes the following steps:

- Identifying parameters for probabilistic evaluation;
- Defining distributions of key parameters;
- Assigning correlations between input parameters, which is done to limit the occurrence of unrealistic physical conditions;
- Verifying that simulation input values reflect the desired correlations by visual inspection of scatter plots of correlated parameters;
- Determining parameters with highest rank correlation coefficients in the results, i.e., those that most influence dose; and
- Confirming output parameter correlations with scatter plots of parameter input values versus calculated dose.

Figure E-1 illustrates the process.

[2] Metabolic parameters were not included in this evaluation because the deterministic values represent means for the generic population, which would be independent of site conditions (Kamboj, et al. 2000).

[3] Parameter distributions developed for use with RESRAD and RESRAD-BUILD and their bases are described in Attachment C to NUREG/CR-6697 (Yu, et al. 2000).



*For surface soil and streambed sediment. See Section 5.2.8 for subsurface soil DCGLs.

Figure E-1. Probabilistic Uncertainty Analysis Process

4.0 Key Parameter Selection

The main criteria used for identifying key parameters to be evaluated involved the expected parameter influence on dose variability. That is, key parameters are those that have the largest effect on the dose analysis results.

Section 5.2.4 of this plan describes the results of sensitivity analyses for key input parameters for each of the three conceptual models. Tables E-1, E-2, and E-3 identify key parameters for the three conceptual models described in Section 5 of the plan, along with their assigned distributions, which are discussed in the next section.

Section 5.2.4 identifies Sr-90 and Cs-137 as likely to be the primary dose drivers for surface soil, subsurface soil and sediment exposure pathways. However, all eighteen radionuclides of interest were evaluated in the probabilistic analyses for the sake of completeness.

Other factors considered in parameter selection included the availability of site-specific information that could be used to define the distributions and NRC guidance on potentially significant parameters. Preference was also given to including parameters for which input correlations with other input variables could be defined, and where ambiguous input correlations with other input parameters was limited. Additionally, a number of parameters were used to establish a site-specific dilution factor (See Appendix C) corroborated by the detailed three dimensional flow model. These parameters were not varied with the exception of hydraulic conductivity, well pumping rate and length parallel to aquifer flow. For these parameters the probabilistic evaluation included values that would vary the dilution factor within a reasonable site-specific range.

Initial probabilistic simulations included parameters such as soil density, total porosity, and effective porosity for the contaminated, unsaturated, and saturated zones. These parameters consistently had correlation coefficients below 0.25. Because the correlation of these parameters with other more significant input parameters (i.e. hydraulic conductivity) was not clear, these parameters were dropped from subsequent analysis. Additional information regarding parameter input correlation is provided in Section 6.0.

5.0 Parameter Distribution Selection

This section first addresses the statistical distributions of model input parameters other than K_d values and then addresses K_d values.

5.1 Parameters Other Than Distribution Coefficients

Distributions selected for the input parameters are presented in Tables E-1, E-2, and E-3, and were based on applicable guidance in NUREG/CR-6676 (Kamboj, et al. 2000) and NUREG/CR-6697 (Yu, et al. 2000). Site specific parameters were generally assigned triangular distributions centered on the most likely value (e.g., source thickness, contaminated length parallel to aquifer flow).

Table E-1 identifies parameters of interest and their assigned distributions for the surface soil conceptual model that were varied during the analyses and the distribution used for each parameter, except for distribution coefficients and the plant, meat and milk biotransfer factors. The distribution coefficients for all ten elements associated with the radionuclides of interest were also varied using bounded lognormal distributions.

Table E-1. Input Parameter Distributions for Surface Soil Model (Other than K_d and Biotransfer Factor Values)[(1)(2)]

RESRAD Parameter	Parameter Description	Units	Distribution	Parameters[(3)]			
THICK0	Contaminated zone thickness	m	triangular	0.5	1	3	
LCZPAQ	Length parallel to aquifer flow	m	triangular	100	165	200	
HCSZ	Saturated zone hydraulic conductivity	m/y	triangular	630	1400	2200	
UW	Well pumping rate	m^3/y	bounded normal	5900	1270	2618	7586
RI	Irrigation rate	m/y	bounded normal	0.47	0.12	0.14	0.64
FIND	Indoor time fraction	none	triangular	0.45	0.66	0.8	
FOTD	Outdoor time fraction	none	triangular	0.1	0.25	0.45	
HCUZ(1)	Unsaturated zone hydraulic conductivity	m/y	triangular	63	140	220	
HCCZ	Contaminated zone hydraulic conductivity	m/y	triangular	63	140	220	
DROOT	Root depth	m	triangular	0.3	0.9	3	
PRECIP	Precipitation rate	m/y	bounded normal	1.03	0.13	0.86	1.36
THICK0	Contaminated zone thickness	m	triangular	0.5	1	3	
SHF1	External gamma shielding factor	none	triangular	[(4)]	[(4)]	[(4)]	

NOTES: (1) Values in RESRAD file "SUMMARY.REP".

(2) Radionuclide specific K_d values were varied (see Table E-6) and plant, meat, milk transfer factors were assigned the RESRAD default distribution.

(3) Parameters for the distributions are: TRIANGULAR - minimum, mode, maximum and BOUNDED NORMAL - mean, standard deviation, minimum, maximum.

(4) Radionuclide specific distribution. Dose drivers Cs-137 and U-232 were evaluated.

In general, site-specific physical parameters in Table E-1 were described with triangular distributions across the range of values associated with the site, including hydraulic conductivity, and indoor/outdoor time fraction, etc. Depth of roots was assigned a triangular distribution ranging from 0.3 meter (onions, lettuce) to three meters (alfalfa), centered on 0.9 m (corn).

Precipitation was based on a normal distribution described by statistical parameters (mean = 1.03 meter, standard deviation = 0.13 meter) that were calculated from meteorological data collected over the last 30 years in Buffalo, New York (http://www.weatherexplained.com/Vol-4/2001-Buffalo-New-York-BUF.html). The precipitation data was then used to assign a distribution for the irrigation rate, assuming that a total of 1.5 m/y of applied water was needed, and the well pumping rate was assigned a distribution based on the irrigation volume needed. These parameters were also correlated to ensure this relationship in the input values.

The total onsite fraction of 0.91 equates to a total of 33 days each year, or 15 hours each week, away from the site inclusive of time spent taking livestock/crops to market, assisting on neighboring farms, or other travel off-site (vacation, family occasions, religious services, etc.).

The plant-soil, meat-soil, and milk-soil bioaccumulation factors were simulated using the RESRAD default lognormal-N distributions, and were correlated (R = -0.87) with the K_d as described in Section 6.0.

Table E-2 identifies parameters of interest and their assigned distributions for the subsurface soil conceptual model, except for distribution coefficients and the plant, meat and milk biotransfer factors, that were varied during the analyses and the distribution used for each parameter. The distribution coefficients for all ten elements associated with the radionuclides of interest were also varied using bounded lognormal distributions.

Table E-2. Input Parameter Distributions for Subsurface Soil Model (Other than K_d and Biotransfer Factor Values)(1)(2)

RESRAD Parameter	Parameter Description	Units	Distribution	Parameters(3)			
UW	Well pumping rate	m^3/y	bounded normal	5900	1270	2618	7586
RI	Irrigation rate	m/y	bounded normal	0.47	0.12	0.14	0.64
FIND	Indoor time fraction	none	triangular	0.45	0.66	0.8	
FOTD	Outdoor time fraction	none	triangular	0.1	0.25	0.45	
DROOT	Root depth	m	triangular	0.3	0.9	3	
PRECIP	Precipitation rate	m/y	bounded normal	1.03	0.13	0.86	1.36
SHF1	External gamma shielding factor	none	triangular	(4)	(4)	(4)	

NOTES: (1) Values in RESRAD file "SUMMARY.REP".

(2) Radionuclide specific K_d values were varied (see Table E-6) and plant, meat, milk transfer factors were assigned the RESRAD default distribution.

(3) Parameters for the distributions are: TRIANGULAR - minimum, mode, maximum and BOUNDED NORMAL - mean, standard deviation, minimum, maximum.

(4) Radionuclide specific distribution. Dose drivers Cs-137 and U-232 were evaluated

Because the subsurface soil model is based on the well drilling scenario, only a limited amount of material is available from the excavation (approximately 30 m^3). The parameter ranges and correlation described below were selected assuming deterministic values for the contaminated zone area and depth. The sensitivity of the models to specific area and thickness combinations was evaluated in Section 5 of the body of this plan. Note that the subsurface soil evaluation is based on the mass balance groundwater model.

The plant-soil, meat-soil, and milk-soil bioaccumulation factors were simulated using the RESRAD default lognormal-N distributions, and were correlated (R = -0.87) with the K_d as described in Section 6.0.

Table E-3 identifies parameters of interest and their assigned distributions for the streambed sediment conceptual model, except for distribution coefficients and the plant and meat biotransfer factors, that were varied during the analyses and the distribution used for each parameter. The distribution coefficients for all ten elements associated with the radionuclides of interest were also varied using bounded lognormal distributions

Table E-3. Input Parameter Distributions for Streambed Sediment Model (Other than K_d and Biotransfer Factor Values)(1)(2)

RESRAD Parameter	Parameter Description	Units	Distribution	Parameters(3)			
HCCZ	Contaminated zone hydraulic conductivity	m/y	triangular	63	140	220	
PRECIP	Precipitation rate	m/y	bounded normal	1.03	0.13	0.86	1.36
FOTD	Outdoor time fraction	none	triangular	0.006	0.012	0.024	

NOTES: (1) Values in RESRAD file "SUMMARY.REP"..
(2) Radionuclide specific K_d values were varied (see Table E-6) and plant, meat, fish transfer factors were assigned the RESRAD default distribution.
(3) Parameters for the distributions are: TRIANGULAR - minimum, mode, maximum and BOUNDED NORMAL - mean, standard deviation, minimum, maximum.

Soil parameters were varied over the same ranges used for the soil models. Parameter values for the fraction of time outdoors were taken from the deterministic sensitivity analysis described in Section 5 of the plan for likely recreational exposures.

The plant-soil and meat-soil bioaccumulation factors were simulated using the RESRAD default lognormal-N distributions, and were correlated (R = -0.87) with the K_d as described previously. Fish transfer factors were also simulated using the RESRAD default lognormal-N distributions, however no correlations were included.

5.2 Distribution Coefficients

Table C-2 of this plan identifies the distribution coefficients (K_d values) used in the dose analyses described in Section 5 of the body of this plan. Section 3.7.8 and Table 3-20 of this plan provide information on measurements of the distribution coefficients in soils at the site. However, these data are not sufficient to establish a site-specific distribution of the K_d parameter for each of the 10 chemical elements represented in the 18 radionuclides of interest in dose modeling.

Sheppard and Thibault (Sheppard and Thibault 1990) and NUREG/CR-6697 (Yu, et al. 2000) recommend that the K_d parameter be described as a lognormal distribution. Table E-4 summarizes data on K_d values from two key sources compared to the values used in the dose modeling described in Section 5 of this plan. Table E-5 provides a summary of the parameters describing the lognormal distributions as given in these reports.

Consideration of the data in Table E-5 from the two sources led to the distribution parameters in Table E-6, which were used in the uncertainty analyses. The distributions were bounded based on the values presented in Table E-6 to constrain unreasonably large or small values, which is consistent with the approach suggested in NUREG-6697 (Attachment C). The values in the table were established as follows:

- When Sheppard and Thibault sand values were used for K_d in the basic RESRAD analysis, then the Sheppard and Thibault sand distribution was used in the uncertainty analysis; and
- For cases when WVDP site-specific values are available, a distribution was selected so that the distribution mean [exp(μ)] provides a closer approximation to the K_d used in the basic RESRAD analyses.

Table E-4. Summary of Data on K_d Parameter (mL/g) for the 10 Elements of Interest

Element	RESRAD Default	Geometric Mean and Range [Sheppard and Thibault 1990]				Range [EPA 1999] [EPA 2004]	Values Used in Section 5 Modeling	
		Sand	Loam	Clay	Organic		Surface Soil, Unsaturated Zone, Saturated Zone	Subsurface Soil and Sediment in Contaminated Zone
Am	20	1,900 8.2 – 300,000	9,600 400 – 48,309	8,400 25 – 400,000	112,000 6,398 – 450,000	8.2 - 2,270,000	1900 (1) (420 - 111,000)	4000 (2) (420 - 111,000)
C	0	5	20	1	7	not addressed	5 (1) (0.7 - 12)	7 (2) (0.7 - 12)
Cm	calculated	4,000 780 – 22,970	18,000 7,666 – 44,260	6,000 ND	6,000 0	93 – 51,900	calculated	calculated
Cs	460	280 0.2 – 10,000	4,600 560 – 61,287	1,900 37 – 31,500	270 0.4 – 145,000	10 – 66,700	280 (1) (48 - 4800)	480 (2) (48 - 4800)
I	calculated	1 0.04 - 81	5 0.1 - 43	1 0.2 - 29	25 1.4 - 368	0.05 – 10,200	1 (1) (0.4 - 3.4)	2 (3) (0.4 - 3.4)
Np	calculated	5 0.5-390	25 1.3-79	55 0.4-2,575	1200 857-1,900	0.36 – 50,000	2.3 (4) (0.5 - 5.2)	3 (2) (0.5 - 5.2)
Pu	2,000	550 27-36,000	1200 100-5,933	5100 316-190,000	1900 60-62,000	5 – 2,550	2600 (4) (5 - 27,900)	3000 (2) (5 - 27,900)
Sr	30	15 0.05-190	20 0.01-300	110 3.6-32,000	150 8-4800	1 -1,700	5 (5) (1 - 32)	15 (2) (1 - 32)
Tc	0	0.1 0.01-16	0.1 0.01-0.4	1 1.16-1.32	1 0.02-340	0.01 – 340	0.1 (1) (0.01 - 4.1)	4.1 (3) (1 - 10)
U	50	35 0.03-2,200	15 0.2-4,500	1600 46-395,100	410 33-7,350	0.4 – 1,000,000	35 (1) (15 - 350)	10 (3) (1 - 100)

NOTES: (1) From Sheppard and Thibault 1990, for sand.
(2) Site specific value for the unweathered Lavery till (see Section 3.7.8, Table 3-20).
(3) Site specific value for the Lavery till (see Section 3.7.8, Table 3-20).
(4) Site specific value for the sand and gravel unit (see Section 3.7.8, Table 3-20).
(5) Dames and Moore (1995a, 1995b).

Table E-5. Lognormal Distribution Parameters for K_d Values from Literature

Element	Sand Soil[1]				Clay Soil[2]				RESRAD Default[3]			
	No. of Obs.	μ[4]	σ[5]	exp(μ)[6]	No. of Obs.	μ[4]	σ[5]	exp(μ)[6]	No. of Obs.	μ[4]	σ[5]	exp(μ)[6]
Am	29	7.6	2.6	1,998	11	9.0	2.6	8,100	219	7.28	3.15	1,451
C	3	1.1	0.8	3	0[7]	0.8		2.2	NA	2.40	3.22[8]	11
Cm	2	8.4	2.4	4,447	0[7]	8.7		6,000	23	8.82	1.82	6,761
Cs	81	5.6	2.5	270	28	7.5	1.6	1,810	564	6.10	2.33	446
I	22	0.04	2.2	1.0	8	0.5	1.5	1.7	109	1.52	2.19	4.6
Np	16	1.4	1.7	4.1	4	4.0	3.8	55	77	2.84	2.25	17
Pu	39	6.3	1.7	545	18	8.5	2.1	4,920	205	6.86	1.89	953
Sr	81	2.6	1.6	13.5	24	4.7	2.0	110	539	3.45	2.12	32
Tc	19	-2.0	1.8	0.1	4	0.2	0.06	1.2	59	-0.67	3.16	0.51
U	24	3.5	3.2	33	7	7.3	2.9	1,480	60	4.84	3.13	126

NOTES: (1) From Sheppard and Thibault 1990, Table A-1.

(2) From Sheppard and Thibault 1990, Table A-3.

(3) From Yu, et al. 2000, Table 3.9-1.

(4) The mean of the underlying normal distribution after taking natural logarithm of the K_d values.

(5) The standard deviation of the underlying normal distribution after taking natural logarithm of the K_d values.

(6) Exponential of the mean value [mL/g] or the geometric mean K_d.

(7) Default values for μ and exp(μ) have been predicted using soil-to-plant concentration ratios for nuclides with 0 observations.

(8) Standard deviation for data obtained from using the RESRAD default root uptake transfer factor and the correlation between K_d and the concentration ratio for loamy soil was set to 3.22 to consider a potential wide range of distribution.

LEGEND: NA = not available

Table E-6. Lognormal Distribution Parameters Used for K_d Uncertainty Analyses

Element	Surface Soil, Unsaturated Zone Saturated Zone					Subsurface Soil and Sediment in Contaminated Zone					Bounding Range
	Source[(1)]	μ[(2)]	σ[(3)]	exp(μ)[(4)]	DP K_d	Source[(1)]	μ[(2)]	σ[(3)]	exp(μ)[(4)]	DP K_d	
Am	S&T Sand	7.6	2.6	1,900	1,900	S&T Sand	7.6	2.6	1,900	4,000	0.5 - 390
C	S&T Sand	1.1	0.8	5	5	S&T Sand	1.1	0.8	5	7	0.7 - 12
Cm	RESRAD	8.82	1.82	6,761	6760	RESRAD	8.82	1.82	6,761	6760	780 - 22970
Cs	S&T Sand	5.6	2.5	280	280	RESRAD	6.10	2.33	446	480	10 - 10000
I	S&T Sand	0.04	2.2	1.0	1	S&T Clay	0.5	1.5	1	2	0.4 - 81
Np	S&T Sand	1.4	1.7	5	2.3	S&T Sand	1.4	1.7	5	3	0.5 - 390
Pu	RESRAD	6.86	1.89	953	2,600	S&T Clay	8.5	2.1	5,100	3,000	27 - 2550
Sr	S&T Sand	2.6	1.6	15	5	D&M	2.6	1.6	15	15	1 - 190
Tc	S&T Sand	-2.0	1.8	0.1	0.1	RESRAD	-0.67	3.16	0.51	4.1	0.01 - 16
U	S&T Sand	3.5	3.2	35	35	S&T Sand	3.5	3.2	35	10	0.4 - 2200

NOTES: (1) Sources: S&T Sand is Table A-1, Sheppard and Thibault 1990; S&T Clay is Table A-3, Sheppard and Thibault 1990; D&M from Dames and Moore, 1995a, 1995b, and RESRAD is Table 3.9-1, Attachment C, NUREG/CR-6697 (Yu, et al. 2000)

(2) The mean of the underlying normal distribution after taking natural logarithm of the K_d values.

(3) The standard deviation of the underlying normal distribution after taking natural logarithm of the K_d values.

(4) Exponential of the mean value [mL/g] or the geometric mean.

6.0 Parameter Correlation

The RESRAD code allows correlation of input parameters to limit the occurrence of unrealistic physical conditions (e.g., high outdoor and also high indoor time fractions). Parameters were correlated in pairs based on the user specified rank correlation coefficient as presented in Table E-7. The basis for the correlation coefficients for each conceptual model is discussed following the table.

Table E-7. Input Correlations for Probabilistic Evaluation[1]

Parameter 1	Parameter 2	Correlation Coefficient	Basis	Surface Soil Model	Subsurface Model	Sediment Model
Indoor time fraction	Outdoor time fraction	-0.95	Continuity of onsite time	●	●	
Contaminated zone hydraulic conductivity	Unsaturated zone hydraulic conductivity	0.95	Homogeneity in soil column	●		
Contaminated zone hydraulic conductivity	Saturated zone hydraulic conductivity	0.95	Homogeneity in soil column	●		
Unsaturated zone hydraulic conductivity	Saturated zone hydraulic conductivity	0.95	Homogeneity in soil column	●		
Precipitation rate	Rate of irrigation	-0.95	Less irrigation when rainy	●	●	
Precipitation rate	Well pumping rate	-0.95	Less pumping for irrigation when rainy	●	●	
Rate of irrigation	Well pumping rate	0.95	Pumping volume due mainly to irrigation	●	●	
Contaminated zone K_d	Unsaturated zone K_d	0.95	Homogeneity in soil column	●		
Unsaturated zone K_d	Saturated zone K_d	0.95	Homogeneity in soil column	●		
Contaminated zone K_d	Saturated zone K_d	0.95	Homogeneity in soil column	●		
Contaminated zone K_d	Plant transfer factor	-0.87	Baes, et. al. 1984	●	●	●
Contaminated zone K_d	Meat transfer factor	-0.87	Plant correlation used for meat	●	●	●
Contaminated zone K_d	Milk transfer factor	-0.87	Plant correlation used for milk	●	●	
Unsaturated zone K_d	Plant transfer factor	-0.87	Baes, et. al. 1984	●		
Unsaturated zone K_d	Meat transfer factor	-0.87	Plant correlation used for meat	●		
Unsaturated zone K_d	Milk transfer factor	-0.87	Plant correlation used for milk	●		
Saturated zone K_d	Plant transfer factor	-0.87	Baes, et. al. 1984	●		
Saturated zone K_d	Meat transfer factor	-0.87	Plant correlation used for meat	●		
Saturated zone K_d	Milk transfer factor	-0.87	Plant correlation used for milk	●		

NOTES: (1) Presented in the RESRAD probabilistic output files “LHS.REP” for each media.

6.1 Surface Soil Model

This section discusses the parameters correlated in the surface soil model, including distribution coefficients, plant transfer factors, hydraulic conductivities, as well as irrigation, precipitation, and well pumping rates.

The strongly negative correlation (R = -0.87) of K_d with plant transfer factors is based on regression results obtained from computer simulation for a range of elements (Baes, et. al. 1984). This Oak Ridge National Laboratory investigation included all areas of the country and therefore represents average results, which are used in lieu of site-specific correlations. Similarly, the meat and milk transfer coefficients were strongly correlated with the contaminated zone K_d for the principal radionuclides. Transfer factors for principal radionuclide daughter products were not correlated. As each additional parameter requires cross correlating with transfer factors for each soil layer, reducing the number of required correlations allows for reasonable code execution times.

The rate of irrigation and the well pumping rate were strongly correlated (R = 0.95) since the majority of water pumped by the well is used for irrigation. The precipitation rate was strongly negatively correlated (R = -0.95) with the irrigation and well pumping rate, assuming less groundwater will be needed to adequately water crops during wet years.

To ensure that the soils reflect relative homogeneity, the hydraulic conductivity in the three zones (contaminated, unsaturated and saturated) were correlated (R = 0.95).

6.2 Subsurface Soil Model

The subsurface soil model is based on a cistern excavation scenario, and is therefore based on a limited volume of source material brought to the surface. The potential configurations of contaminated zone area and thickness were evaluated in the deterministic sensitivity analysis presented in Section 5. Alternate parameters were selected for probabilistic evaluation.

6.3 Streambed Sediment Model

Parameters correlated in the streambed sediment model included:

- Contaminated zone and saturated zone hydraulic conductivity (0.95), and
- Contaminated zone K_d and plant/meat transfer factors (-0.87).

To ensure that intended correlations were reflected in the RESRAD model input vectors, values were viewed graphically to verify the parameter relationships for each media and radionuclide.

7.0 RESRAD Output

7.1 Basic Approach

The results of the probabilistic evaluation are output from RESRAD in numerous summary data files and graphic displays. As suggested in NUREG/CR-6676 (Kamboj, et al. 2000), the input values generated by the specified distributions and correlations were graphically viewed to verify parameter associations. RESRAD output was tabulated and probabilistic-based DCGLs were calculated as described below.

Additionally, the tabulated output parameter correlation ranks were used to identify the parameters most significantly associated with the modeled dose, as described in subsequent sections. Plots of the modeled dose over time are included in Attachment 1 for each radionuclide and media model. DCGLs were calculated from the RESRAD DSRs in the same manner as described in Appendix C to this plan.

7.2 Surface Soil

Key results of the surface soil evaluation are presented in Table E-8. Table E-9 compares the resulting probabilistic DCGLs with the DCGLs developed using the deterministic method.

As can be seen in Table E-9, key dose drivers Cs-137, Sr-90, I-129 and U-232 had probabilistic peak-of-the-mean DCGLs below the deterministic values, as did all radionuclides except Np-237. Radionuclides were identified as key dose drivers based on preliminary characterization data in WMA1 and WMA2 (See Attachment 1, Tables Att-1 and Att-2). Cs-137, Sr-90, I-129 and U-232 are discussed below (See also Table E-14).

- The Cs-137 dose is due primarily to external exposure in the initial years of exposure. However the depth of source thickness and exposure time fractions were the probabilistic parameters that are directly related to the external pathway, and were not highly correlated with resulting dose.
- The Sr-90 dose is due primarily to plant uptake in the initial years of exposure. Plant uptake factors and depth of roots were highly correlated with the resulting dose.
- I-129 dose is primarily due to ingestion of water and milk in the initial decades of exposure. Length parallel to groundwater flow and contaminated zone thickness were the most highly correlated parameters with the resulting dose.
- U-232 dose is primarily due to external exposure during the initial years of the simulation. The gamma shielding factor, and indoor/outdoor time fractions were most highly correlated with the resulting dose.

Attachment 1 presents plots of the probabilistic (peak-of-the-mean and 95th percentile) and deterministic dose-source ratios (DSRs) for comparison, for the radionuclides listed above. Also presented are plots of deterministic results compared with the cumulative probability derived from the probabilistic modeling. For all radionuclides (with the exception of Np-237) the peak-of-the-mean DCGLs were smaller than the deterministic DCGLs.

Table E-8. Key Output Dose Statistics (DSRs) – Surface Soil Model (mrem/y per pCi/g)[(1)]

Radionuclide	Year of Peak Dose	Minimum	Maximum	Mean	95th Percentile
Am-241	2.01E+02	4.04E-02	3.49E+01	8.68E-01	1.32E+00
C-14	0.00E+00	2.12E-01	2.83E+00	1.53E+00	2.56E+00
Cm-243	0.00E+00	2.70E-01	4.69E+00	7.21E-01	1.60E+00
Cm-244	0.00E+00	4.94E-02	7.38E+00	3.85E-01	1.04E+00
Cs-137	0.0E+00	1.8E+00	2.2E+01	3.3E+00	6.3E+00
I-129	3.43E+00	3.31E-01	1.86E+03	7.68E+01	4.68E+02
Np-237	1.18E+01	9.16E-01	1.02E+03	9.59E+01	5.17E+02
Pu-238	0.00E+00	8.51E-02	8.10E+00	6.26E-01	1.78E+00

Table E-8. Key Output Dose Statistics (DSRs) – Surface Soil Model (mrem/y per pCi/g)[1]

Radionuclide	Year of Peak Dose	Minimum	Maximum	Mean	95th Percentile
Pu-239	8.84E+02	2.73E-02	1.48E+01	9.86E-01	5.83E+00
Pu-240	7.81E+02	5.28E-02	1.32E+01	9.48E-01	5.84E+00
Pu-241	5.18E+01	3.34E-03	2.47E-01	2.15E-02	6.00E-02
Sr-90	0.00E+00	2.12E-01	2.11E+02	1.22E+01	4.17E+01
Tc-99	0.00E+00	2.30E-02	1.39E+01	1.19E+00	3.64E+00
U-232	1.2E+01	1.5E+00	5.6E+02	1.7E+01	1.1E+02
U-233	1.51E+01	2.07E-02	8.61E+01	3.02E+00	2.96E+01
U-234	1.33E+01	1.41E-02	1.35E+02	2.96E+00	2.60E+01
U-235	6.63E+01	7.77E-01	2.20E+01	7.20E+00	1.60E+01
U-238	1.33E+01	3.34E-02	6.82E+01	2.54E+00	2.27E+01

NOTE: (1) From RESRAD probabilistic output file "MCSUMMARY.REP".

Table E-9. Surface Soil $DCGL_W$ Values for 25 mrem in Peak Year in pCi/g

Nuclide	Deterministic[1]	Probabilistic[2]		Percent Difference Deterministic and Peak of the Mean
		Peak-of-the-Mean	95th Percentile	
Am-241	4.31E+01	2.88E+01	1.89E+01	-33%
C-14	2.00E+01	1.63E+01	9.77E+00	-18%
Cm-243	4.06E+01	3.47E+01	1.56E+01	-15%
Cm-244	8.22E+01	6.49E+01	2.40E+01	-21%
Cs-137[3][4]	**2.43E+01**	**1.52E+01**	**7.95E+00**	-37%
I-129[4]	3.47E-01	3.26E-01	5.34E-02	-6%
Np-237	9.42E-02	2.61E-01	4.84E-02	177%
Pu-238	5.03E+01	3.99E+01	1.40E+01	-21%
Pu-239	4.53E+01	2.54E+01	4.29E+00	-44%
Pu-240	4.53E+01	2.64E+01	4.28E+00	-42%
Pu-241	1.42E+03	1.16E+03	4.17E+02	-18%
Sr-90[3][4]	**6.25E+00**	**4.10E+00**	**1.20E+00**	-34%
Tc-99	2.37E+01	2.10E+01	6.87E+00	-11%
U-232[4]	5.84E+00	1.51E+00	2.23E-01	-74%
U-233[4]	1.90E+01	8.28E+00	8.45E-01	-56%
U-234[4]	1.97E+01	8.45E+00	9.62E-01	-57%
U-235[4]	1.87E+01	3.47E+00	1.79E+00	-81%
U-238[4]	2.06E+01	9.84E+00	1.10E+00	-52%

NOTES: (1) From Table 5-8 of Section 5.
(2) From RESRAD probabilistic output file "MCSUMMARY.REP".
(3) DCGLs for these radionuclides are multiplied by a factor of two to account for decay during 30 year institutional control period.
(4) Dose driver radionuclide (see Section 5.2.4 of the plan).

7.3 Subsurface Soil

Key results of the subsurface soil evaluation are presented in Table E-10. Table E-11 compares the resulting probabilistic DCGLs with the DCGLs developed using the deterministic method. Note that the deterministic DCGLs used in this table for comparison purposes are the DCGLs from Table 5-8, which are based on the original base-case conceptual model. The DCGLs from the multi-source analysis that takes into account continuing releases from the bottom of the deep excavations are not directly comparable with the peak-of-the-mean DCGLs because the model used in development of the latter does not account for this secondary source. Table 5-11c in Section 5 of this plan compares all of the different subsurface soil DCGLs.

Note also that the DCGLs presented in Table E-11 reflect a 10 fold dilution of the source term (i.e. using 1/10th the DSRs presented in Table E-10) as described in Section 5 of the DPlan.

As can be seen in Table E-11, only Sr-90, Tc-99, and U-232 had probabilistic peak-of-the-mean DCGLs at least 10 percent below the deterministic values. These radionuclides are discussed below (See also Table E-15).

- The Sr-90 dose is due primarily to plant uptake in the initial years of exposure. Depth of roots and plant uptake factors were highly correlated with the resulting dose.
- The Tc-99 dose is due primarily to plant uptake in the initial years of exposure. Depth of roots and plant uptake factors were highly correlated with the resulting dose.
- The U-232 dose is due primarily to external exposure in the initial years of the simulation. The contaminated zone K_d and gamma shielding factors were most highly correlated with the resulting dose.

Attachment 1 presents the plots of the probabilistic (peak-of-the-mean and 95th percentile) and deterministic DSRs for comparison, for the key dose drivers Sr-90, Cs-137, and U-232. Also presented are plots of deterministic results compared with the cumulative probability derived from the probabilistic modeling. For seven other radionuclides, the peak-of-the-mean DCGLs were greater than or equal to the deterministic.

Table E-10. Key Output Dose Statistics (DSRs) – Subsurface Soil Model (mrem/y per pCi/g)[1]

Radionuclide	Year of Peak Dose	Minimum	Maximum	Mean	95th Percentile
Am-241	0.0E+00	2.4E-02	2.4E-01	3.7E-02	5.8E-02
C-14	0.0E+00	1.4E-04	1.2E-03	3.5E-04	6.9E-04
Cm-243	0.0E+00	1.6E-01	3.8E-01	2.2E-01	2.7E-01
Cm-244	0.0E+00	6.0E-03	7.3E-02	1.1E-02	2.3E-02
Cs-137	0.0E+00	1.4E+00	2.4E+00	1.7E+00	1.8E+00
I-129	1.2E+01	2.1E-03	1.7E+00	3.7E-01	9.6E-01

Table E-10. Key Output Dose Statistics (DSRs) – Subsurface Soil Model (mrem/y per pCi/g)(1)

Radionuclide	Year of Peak Dose	Minimum	Maximum	Mean	95th Percentile
Np-237	2.5E+01	6.5E-08	2.3E+01	2.7E+00	8.5E+00
Pu-238	0.0E+00	9.7E-03	1.6E-01	1.8E-02	3.7E-02
Pu-239	0.0E+00	1.1E-02	1.9E-01	2.0E-02	4.1E-02
Pu-240	0.0E+00	1.1E-02	4.7E-01	2.1E-02	3.9E-02
Pu-241	5.2E+01	2.0E-04	7.7E-03	1.0E-03	1.6E-03
Sr-90	0.0E+00	1.3E-02	5.0E+00	1.5E-01	4.8E-01
Tc-99	0.0E+00	5.5E-04	5.2E-01	1.7E-02	5.7E-02
U-232	6.4E+00	5.4E-03	5.1E+00	3.4E+00	4.6E+00
U-233	3.7E+02	2.3E-14	6.3E-01	2.5E-02	7.4E-02
U-234	3.7E+02	4.5E-07	1.3E+00	2.0E-02	6.7E-02
U-235	0.0E+00	1.5E-01	3.6E-01	2.7E-01	3.3E-01
U-238	0.0E+00	3.3E-02	1.1E-01	5.4E-02	6.6E-02

NOTE: (1) From RESRAD probabilistic output file "MCSUMMARY.REP".

Table E-11. Subsurface Soil $DCGL_W$ Values for 25 mrem in Peak Year in pCi/g

Nuclide	Deterministic(1)	Probabilistic(2)		Percent Difference Deterministic and Peak-of-the-Mean
		Peak-of-the-Mean	95th Percentile	
Am-241	7.16E+03	6.81E+03	4.30E+03	-5%
C-14	5.59E+05	7.18E+05	3.64E+05	28%
Cm-243	1.15E+03	1.12E+03	9.33E+02	-3%
Cm-244	2.37E+04	2.21E+04	1.08E+04	-7%
Cs-137(3)(4)	**4.36E+02**	**3.01E+02**	**2.72E+02**	-31%
I-129(4)	6.46E+02	6.70E+02	2.60E+02	4%
Np-237	5.77E+01	9.33E+01	2.95E+01	62%
Pu-238	1.47E+04	1.37E+04	6.83E+03	-7%
Pu-239	1.33E+04	1.23E+04	6.11E+03	-7%
Pu-240	1.33E+04	1.21E+04	6.44E+03	-9%
Pu-241	2.41E+05	2.50E+05	1.59E+05	4%
Sr-90(3)(4)	**4.36E+03**	**3.42E+03**	**1.03E+03**	-21%
Tc-99	1.59E+04	1.44E+04	4.36E+03	-10%
U-232(4)	1.06E+02	7.40E+01	5.43E+01	-30%
U-233(4)	2.72E+03	9.92E+03	3.39E+03	264%

Table E-11. Subsurface Soil $DCGL_W$ Values for 25 mrem in Peak Year in pCi/g

Nuclide	Deterministic(1)	Probabilistic(2)		Percent Difference Deterministic and Peak-of-the-Mean
		Peak-of-the-Mean	95th Percentile	
U-234(4)	2.81E+03	1.26E+04	3.75E+03	349%
U-235(4)	9.41E+02	9.33E+02	7.60E+02	-1%
U-238(4)	2.94E+03	4.60E+03	3.79E+03	57%

NOTES: (1) From Table 5-8 of Section 5. More limiting deterministic values for the resident gardener are available as an alternative comparison for some radionuclides. Refer to Section 5.2.8 for a comparison between the probabilistic DCGLs and all other sets of subsurface soil DCGLs.

(2) From RESRAD probabilistic output file “MCSUMMARY.REP” for the resident farmer with a contamination zone of 100 m^2.

(3) DCGLs for these radionuclides are multiplied by a factor of two to account for decay during 30 year institutional control period.

(4) Dose driver radionuclide (see Section 5.2.4 of the plan).

7.3 Streambed Sediment

Key results of the streambed sediment evaluation are presented in Table E-12. Table E-13 compares the resulting probabilistic DCGLs with the DCGLs developed using the deterministic method.

As can be seen in Table E-13, all radionuclides had probabilistic peak-of-the-mean DCGLs at least 10 percent below the deterministic values. Key dose drivers for sediment are Sr-90 and Cs-137. These radionuclides are discussed below (See also Table E-16).

- Sr-90 dose is due primarily to ingestion of venison in the initial years of exposure. The resulting dose is highly correlated to the contaminated zone K_d value; however, the plant and fish biotransfer factors were more closely correlated than the meat biotransfer factors.
- Cs-137 dose is primarily due to external exposure in the initial years of exposure. As expected, the outdoor time fraction was highly correlated with dose.

Attachment 1 presents the plots of the probabilistic (peak-of-the-mean and 95th percentile) and deterministic DSRs for comparison. Also presented are plots of deterministic results compared with the cumulative probability derived from the probabilistic modeling.

Table E-12. Key Output Dose Statistics (DSRs) – Streambed Sediment Model (mrem/y per pCi/g)(1)

Radionuclide	Year of Peak Dose	Minimum	Maximum	Mean	95th Percentile
Am-241	1.0E+00	9.1E-04	5.7E-02	2.5E-03	4.8E-03
C-14	0.0E+00	5.8E-03	4.5E-01	1.4E-02	3.4E-02
Cm-243	0.0E+00	3.7E-03	1.4E-02	8.2E-03	1.2E-02
Cm-244	0.0E+00	2.6E-04	2.4E-03	6.5E-04	9.9E-04
Cs-137	0.0E+00	2.3E-02	8.8E-02	4.8E-02	6.9E-02
I-129	0.0E+00	6.1E-03	6.6E-01	3.2E-02	7.2E-02

Table E-12. Key Output Dose Statistics (DSRs) – Streambed Sediment Model (mrem/y per pCi/g)(1)

Radionuclide	Year of Peak Dose	Minimum	Maximum	Mean	95th Percentile
Np-237	0.0E+00	1.0E-02	2.2E+00	7.7E-02	2.3E-01
Pu-238	1.0E+00	6.9E-04	1.4E-01	2.0E-03	3.6E-03
Pu-239	1.0E+00	8.8E-04	2.3E-02	2.1E-03	4.1E-03
Pu-240	1.0E+00	9.0E-04	1.6E-02	2.1E-03	4.2E-03
Pu-241	5.2E+01	2.8E-05	1.9E-03	7.3E-05	1.3E-04
Sr-90	0.0E+00	1.4E-03	1.5E-01	1.1E-02	3.0E-02
Tc-99	0.0E+00	3.4E-06	1.1E-03	3.8E-05	1.1E-04
U-232	7.2E+00	4.6E-02	9.3E-01	1.1E-01	1.7E-01
U-233	0.0E+00	1.1E-04	5.2E-02	1.2E-03	3.9E-03
U-234	0.0E+00	1.2E-04	2.9E-02	1.2E-03	4.2E-03
U-235	0.0E+00	4.9E-03	4.0E-02	1.1E-02	1.6E-02
U-238	0.0E+00	1.1E-03	9.0E-02	3.1E-03	5.5E-03

NOTE: (1) From RESRAD probabilistic output file "MCSUMMARY.REP".

Table E-13. Streambed Sediment DCGL$_W$ Values for 25 mrem in Peak Year in pCi/g

Nuclide	Deterministic(1)	Probabilistic(2)		Percent Difference Deterministic and Peak-of-the-Mean
		Peak-of-the-Mean	95th Percentile	
Am-241	1.55E+04	1.02E+04	5.19E+03	-34%
C-14	3.44E+03	1.84E+03	7.42E+02	-46%
Cm-243	3.59E+03	3.06E+03	2.08E+03	-15%
Cm-244	4.84E+04	3.83E+04	2.52E+04	-21%
Cs-137(3)(4)	**1.29E+03**	**1.04E+03**	**7.24E+02**	-19%
I-129	3.69E+03	7.91E+02	3.49E+02	-79%
Np-237	5.19E+02	3.25E+02	1.11E+02	-37%
Pu-238	1.99E+04	1.24E+04	7.02E+03	-38%
Pu-239	1.79E+04	1.19E+04	6.08E+03	-33%
Pu-240	1.79E+04	1.20E+04	5.98E+03	-33%
Pu-241	5.11E+05	3.44E+05	1.92E+05	-33%
Sr-90(3)(4)	**9.49E+03**	**4.72E+03**	**1.67E+03**	-50%
Tc-99	2.17E+06	6.61E+05	2.38E+05	-70%
U-232	2.61E+02	2.23E+02	1.49E+02	-15%
U-233	5.75E+04	2.16E+04	6.38E+03	-62%
U-234	6.04E+04	2.16E+04	5.94E+03	-64%

Table E-13. Streambed Sediment $DCGL_W$ Values for 25 mrem in Peak Year in pCi/g

Nuclide	Deterministic(1)	Probabilistic(2)		Percent Difference Deterministic and Peak-of-the-Mean
		Peak-of-the-Mean	95th Percentile	
U-235	2.89E+03	2.34E+03	1.58E+03	-19%
U-238	1.25E+04	8.17E+03	4.55E+03	-34%

NOTES: (1) From Table 5-8 of Section 5.
(2) From RESRAD probabilistic output file "MCSUMMARY.REP".
(3) DCGLs for these radionuclides are multiplied by a factor of two to account for decay during 30 year institutional control period.
(4) Dose driver radionuclide (see Section 5.2.4 of the plan).

7.4 Preliminary Dose Assessment for Remediated WMA 1 Excavation

As indicated in Section 5.4.4 of this plan, the preliminary dose assessment for the remediated WMA 1 excavated area estimated by using information from the multi-source deterministic analysis was a maximum of approximately 8 mrem per year. Using the probabilistic modeling results, the estimates are as follows:

- A peak-of-the-mean estimate of 1.9 mrem per year
- A 95th percentile value of 2.8 mrem per year

Table Att-1 of Attachment 1 shows the calculations of these values. The probabilistic results were not used because they were lower than the 8 mrem per year estimate produced using information from the multi-source deterministic analysis.

7.5 Preliminary Dose Assessment for Remediated WMA 2 Excavation

As indicated in Section 5.4.4 of this plan, the preliminary dose assessment for the remediated WMA 2 excavated area estimated by using information from the multi-source deterministic analysis was a maximum of approximately 0.2 mrem per year. Using the probabilistic modeling results, the estimates are as follows:

- A peak-of-the-mean estimate of 0.11 mrem per year
- A 95th percentile value of 0.13 mrem per year

Table Att-2 of Attachment 1 shows the calculations of these values. The probabilistic results were not used because they were lower than the 0.2 mrem per year estimate produced using information from the multi-source deterministic analysis.

8.0 Parameter Output Rank Correlations

The RESRAD results include several correlations of input parameters with the output modeled dose. Several correlations are available based on actual numerical calculated values and relative rankings.

Guidance for RESRAD probabilistic modeling in NUREG/CR-6676 (Kamboj, et al. 2000) indicates that correlation coefficients based on relative rankings are preferable where nonlinear relationships, widely disparate scales, or long tails are present in the input and outputs. Therefore, determinations of parameter significance presented in this section are based on the partial rank correlation coefficient (PRCC). Where strong correlations between an input parameter and the dose were indicated in the output ranking, scatter plots were inspected to confirm the conclusion.

RESRAD also calculates the overall coefficients of determination (R^2) for each model, which provides an indication of the variability in the overall radionuclide dose accounted for by the selected input parameters.

As described previously, numerous parameters were selected for probabilistic evaluation for each radionuclide. The tables presented and discussed below focus on the three highest ranked parameter correlations for all included parameters for each radionuclide in each media.

To ensure sufficient model iterations were being used to allow for convergence of the results, three sets of 1,000 iterations were selected. This was considered to be appropriate as the peak-of-the-mean doses for the three datasets were within approximately +/-10 percent. The run with the largest peak-of-the-mean dose was selected as the basis for the information in the summary tables.

8.1 Surface Soil Model

Table E-14 presents a summary of the parameters which correlate most closely with the overall dose for each radionuclide. In general, K_d, plant transfer factors, and root zone depth were most strongly correlated with dose. The plant transfer factors have the higher correlations (mostly >0.7) when compared with K_d (<0.7).

The R^2 values ranged from 0.71 (U-232) to 0.99 (I-129). Where the overall correlation is low, identification of additional probabilistic parameters for these radionuclides may better describe the variability in the model output.

Table E-14. Summary of Parameter Rankings – Surface Soil Model(1)

Nuclide	Parameter Ranking			Simulation No. (R^2)
	1	2	3	
Am-241	Plant transfer factor for Am (0.78)	Contaminated zone Thickness (0.54)	Depth of roots (-0.49)	3 (0.93)
C-14	Contaminated zone thickness (0.98)	Depth of roots (-0.79)	Plant transfer factor for C (0.08)	3 (0.96)
Cm-243	Plant transfer factor for Cm (0.86)	Contaminated zone Thickness (0.65)	Depth of roots (-0.64)	2 (0.96)
Cm-244	Plant transfer factor for Cm (0.87)	Contaminated zone Thickness (0.68)	Depth of roots (-0.67)	3 (0.96)
Cs-137	Plant transfer factor for Cs (0.71)	Depth of roots (-0.56)	Contaminated zone Thickness (0.52)	3 (0.95)
I-129	Length parallel to groundwater flow (0.64)	Contaminated zone Thickness (0.62)	Irrigation rate (0.34)	2 (0.99)
Np-237	Length parallel to groundwater flow (0.73)	Contaminated zone Thickness (0.60)	Saturated zone hydraulic conductivity (-0.45)	2 (0.99)

Table E-14. Summary of Parameter Rankings – Surface Soil Model(1)

Nuclide	Parameter Ranking 1	Parameter Ranking 2	Parameter Ranking 3	Simulation No. (R^2)
Pu-238	Plant transfer factor for Pu (0.86)	Depth of roots (-0.67)	Contaminated zone Thickness (0.66)	3 (0.96)
Pu-239	Plant transfer factor for Pu (0.72)	Depth of roots (-0.44)	Contaminated zone Thickness (0.43)	1 (0.91)
Pu-240	Plant transfer factor for Pu (0.74)	Depth of roots (-0.44)	Contaminated zone Thickness (0.43)	1 (0.91)
Pu-241	Plant transfer factor for Am (0.81)	Contaminated zone Thickness (0.39)	Depth of roots (-0.37)	1 (0.75)
Sr-90	Plant transfer factor for Sr (0.84)	Depth of roots (-0.62)	Contaminated zone thickness (0.60)	3 (0.96)
Tc-99	Contaminated zone Thickness (0.67)	Plant transfer factor for Tc (0.55)	Depth of roots (-0.33)	3 (0.92)
U-232	Gamma shileding factor (0.38)	Outdoor time fraction (0.34)	Indoor time fraction (0.21)	1 (0.67)
U-233	Contaminated zone Thickness (0.23)	Meat transfer factor for U (-0.19)	Plant transfer factor for Th (0.18)	3 (0.92)
U-234	Contaminated zone Thickness (0.32)	Meat transfer factor for U (-0.15)	Depth of roots (-0.13)	3 (0.95)
U-235	Length parallel to groundwater flow (0.78)	Contaminated zone Thickness (0.77)	Saturated zone Kd (-0.46)	3 (0.93)
U-238	Contaminated zone Thickness (0.23)	Length parallel to groundwater flow (0.16)	Depth of roots (-0.16)	1 (0.96)

NOTE: (1) From RESRAD probabilistic output file "MCSUMMARY.REP". Simulation (out of three) with largest peak-of-the-mean dose was used to determine the parameter ranking, based on the PRCCs with statistic (either R or R2) in parentheses.

8.2 Subsurface Soil Model

As shown in Table E-15, the most highly correlated parameters for the subsurface model, like with the surface soil model, are the K_d, plant transfer coefficients, and root depth. The highest correlations (-0.99) were calculated for the depth of roots; however the K_d correlations were generally lower than those for the plant transfer factors. The R^2 values ranged from 0.17 (U-233) to 1.00 (Np-237).

Table E-15. Summary of Parameter Rankings - Subsurface Soil Model(1)

Nuclide	Parameter Ranking 1	Parameter Ranking 2	Parameter Ranking 3	Simulation No. (R^2)
Am-241	Depth of roots (-0.82)	Plant transfer factor for Am (0.76)	Outdoor time fraction (0.58)	1 (0.93)
C-14	Depth of roots (-0.99)	Meat transfer factor for C (0.18)	Plant transfer factor for C (0.17)	2 (0.98)
Cm-243	Outdoor time fraction (0.91)	Indoor time fraction (0.53)	Plant transfer factor for Cm (-0.44)	1 (0.96)

Table E-15. Summary of Parameter Rankings - Subsurface Soil Model(1)

Nuclide	Parameter Ranking			Simulation No. (R^2)
	1	2	3	
Cm-244	Depth of roots (-0.93)	Plant transfer factor for Cm (0.89)	Indoor time fraction (0.40)	1 (0.97)
Cs-137	Outdoor time fraction (0.93)	Gamma shielding factor (0.92)	Indoor time fraction (0.81)	3 (0.96)
I-129	Contaminated zone K_d for I (-0.94)	Well pumping rate (-0.56)	Irrigation rate (0.27)	1 (0.99)
Np-237	Contaminated zone K_d for Np (-0.95)	Well pumping rate (-0.55)	Irrigation rate (0.29)	3 (1.00)
Pu-238	Depth of roots (-0.93)	Plant transfer factors for Pu (0.32)	Outdoor time fraction (0.32)	1 (0.97)
Pu-239	Depth of roots (-0.93)	Plant transfer factor for Pu (0.89)	Outdoor time fraction (0.29)	2 (0.97)
Pu-240	Depth of roots (-0.93)	Plant transfer factor for Pu (0.90)	Indoor time fraction (0.33)	1 (0.97)
Pu-241	Plant transfer factor for Am (0.81)	Depth of roots (-0.62)	Contaminated zone K_d for Am (0.52)	1 (0.77)
Sr-90	Depth of roots (-0.94)	Plant transfer factor for Sr (0.91)	Contaminated zone K_d for Cs (-0.10)	1 (0.98)
Tc-99	Depth of roots (-0.93)	Plant transfer factor for Tc (0.90)	Well pumping rate (-0.10)	1 (0.97)
U-232	Contaminated zone K_d for U (0.49)	Gamma shielding factor (0.48)	Outdoor time fraction (0.41)	3 (0.87)
U-233	Contaminated zone K_d for U (-0.34)	Milk transfer factor for U (-0.31)	Plant transfer factor for U (-0.29)	3 (0.17)
U-234	Contaminated zone K_d for U (-0.31)	Milk transfer factor for U (-0.24)	Meat transfer factor for U (-0.22)	3 (0.25)
U-235	Outdoor time fraction (0.71)	Indoor time fraction (0.28)	Meat transfer factor for U (-0.15)	2 (0.85)
U-238	Outdoor time fraction (0.48)	Milk transfer factor for U (-0.22)	Meat transfer factor for U (-0.21)	1 (0.62)

NOTE: (1) From RESRAD probabilistic output file "MCSUMMARY.REP". Simulation (out of three) with largest peak-of-the-mean dose was used to determine the parameter ranking, based on the Partial Rank Correlation Coefficients (PRCC) with statistic (either R or R2) in parentheses.

8.3 Streambed Sediment Model

Table E-16 shows the correlation coefficients and highest ranked sediment parameters for streambed sediment. Fourteen radionuclides have a correlation coefficient greater than or equal to 0.85 and one radionuclide has a coefficient below 0.5. The R^2 values ranged from 0.23 (U-233) to 0.99 (Cm-243). The outdoor time fraction accounted for the majority of the highest correlations.

Table E-16. Summary of Parameter Rankings – Streambed Sediment Model[1]

Nuclide	Parameter Ranking 1	Parameter Ranking 2	Parameter Ranking 3	Simulation No. (R^2)
Am-241	Outdoor time fraction (0.86)	Fish transfer factor for Am (0.43)	Meat transfer factor for Am (0.13)	1 (0.81)
C-14	Fish transfer factor for C (0.98)	Contaminated zone K_d for C (-0.43)	Meat transfer factor for C (0..07)	1 (0.97)
Cm-243	Outdoor time fraction (1.00)	Contaminated zone K_d for Cm (-0.14)	Fish transfer factor for Cm (0.11)	1 (0.99)
Cm-244	Outdoor time fraction (0.92)	Fish transfer factor for Cm (0.29)	Meat transfer factor for Cm (0.26)	1 (0.89)
Cs-137	Outdoor time fraction (0.99)	Meat transfer factor for Cs (0.33)	Plant transfer factor for Cs (0.18)	1 (0.98)
I-129	Fish transfer factor for I (0.81)	Contaminated zone K_d for I (-0.48)	Meat transfer factor for I (0.44)	1 (0.95)
Np-237	Fish transfer factor for Np (0.89)	Outdoor time fraction (0.52)	Contaminated zone K_d for Np (-0.47)	1 (0.93)
Pu-238	Outdoor time fraction (0.82)	Fish transfer factor for Pu (0.74)	Contaminated zone K_d for Pu (-0.23)	1 (0.87)
Pu-239	Outdoor time fraction (0.81)	Fish transfer factor for Pu (0.74)	Contaminated zone K_d for Pu (-0.27)	1 (0.86)
Pu-240	Outdoor time fraction (0.81)	Fish transfer factor for Pu (0.74)	Contaminated zone K_d for Pu (-0.30)	1 (0.96)
Pu-241[2]	Outdoor time fraction (0.79)	Contaminated zone K_d for Am (-0.58)	Fish transfer factor for Am (0.38)	1 (0.72)
Sr-90	Contaminated zone K_d for Sr (-0.73)	Fish transfer factor for Sr (0.59)	Plant transfer factor for Sr (0.30)	1 (0.97)
Tc-99	Fish transfer factor for Tc (0.91)	Plant transfer factor for Tc (0.17)	Meat transfer factor for Tc (0.13)	1 (0.86)
U-232	Outdoor time fraction (0.96)	Fish transfer factor for U (0.27)	Plant transfer factor for U (-0.14)	1 (0.93)
U-233	Contaminated zone K_d for Th (-0.21)	Outdoor time fraction (0.26)	Meat transfer factor for Tc (0.20)	1 (0.23)
U-234	Fish transfer factor for U (0.45)	Outdoor time fraction (0.28)	Contaminated zone K_d for U (-0.26)	3 (0.78)
U-235	Outdoor time fraction (0.94)	Fish transfer factor for U (0.35)	Meat transfer factor for U (0.20)	1 (0.90)
U-238	Outdoor time fraction (0.85)	Fish transfer factor for U (0.41)	Contaminated zone K_d for U (-0.23)	1 (0.85)

NOTES: (1) From RESRAD probabilistic output file “MCSUMMARY.REP”. Simulation (out of three) with largest peak-of-the-mean dose was used to determine the parameter ranking, based on the Partial Rank Correlation Coefficients (PRCC) with statistic (either R or R2) in parentheses.

(2) This analog was assumed give the decay of Pu-241 to Am-241.

9.0 Conclusions from the Uncertainty Analyses and Related Actions

9.1 Conclusions

The following conclusions can be drawn from the results of the probabilistic modeling described above.

Surface Soil DCGLs

Table E-9 shows that deterministic DCGLs for 17 of the 18 radionuclides of interest are not bounding because they are greater than the peak-of-the mean probabilistic DCGLs. Parameters highly correlated with the output are plant transfer factors, depth of roots, and length parallel to aquifer flow.

The length parallel to aquifer flow is a parameter selected to vary the dilution factor in groundwater.

These input parameters therefore lack sufficient conservatism insofar as the 17 radionuclides are concerned. This group of radionuclides includes three that have been identified as dose drivers: Sr-90, Cs-137, and U-235.

The lack of conservatism in these surface soil criteria can be quantified in another manner by considering the average soil concentrations at the deterministic DCGLs. If the average residual concentration of Sr-90, for example, were to be 6.25 pCi/g (the deterministic DCGL for surface soil), then the probabilistic modeling would indicate that the probability that the resulting dose would not exceed 25 mrem in the peak year would be approximately 55 percent (see Figure Att-2 in Attachment 1).

The primary conclusion for the surface soil model is that some input parameters used in the deterministic modeling are not sufficiently conservative and, consequently, the deterministic DCGLs for 17 radionuclides are not bounding.

Subsurface Soil DCGLs

Table E-11 shows that 10 of the deterministic DCGLs are not bounding because they exceed the peak-of-the mean probabilistic DCGLs, however only three radionuclides were below the deterministic DCGL by more than 10 percent. The comparisons above are based on the deterministic values for the resident farmer scenario, however more limiting values are available for the resident gardener scenario for comparison. The most limiting of all deterministic and probabilistic scenarios will be used to establish the cleanup levels (See Section 5). Parameters highly correlated with the output are depth of roots, contaminated zone K_d, and outdoor time fraction. The outdoor time fraction is based on assumptions of anticipated activity and may be refined with additional site-specific considerations. Refer to Section 5.2.8 for comparisons between the probabilistic DCGLs and other sets of subsurface soil DCGLs.

Streambed Sediment DCGLs

Table E-13 indicates that none of the deterministic DCGLs are bounding because they all exceed the peak-of-the-means DCGLs. For the key sediment dose drivers Sr-90 and Cs-137, the probabilistic values less than the deterministic by 50 percent and 19 percent respectively. The outdoor time fraction is most highly correlated with the dose for Cs-137, and Sr-90 was most highly correlated with the contaminated zone K_d. The outdoor time fraction is based on assumptions of anticipated activity and may be refined with additional site-specific considerations.

Preliminary Dose Assessments

The probabilistic dose estimates for the WMA 1 excavation area show that doses are likely to be less than 1.9 mrem/y, due primarily to Sr-90. The probabilistic dose estimates for the WMA 2 excavation area show that the doses are likely to be less than 0.11 mrem/y, due primarily to Cs-137.

Based on these results, it is anticipated that a small number of radionuclides will account for the majority of the dose.

Input Parameters and Dose Variability

The determination of which input parameters account for the majority of variability in the output was accomplished by inspection of the output correlation coefficients, which indicated the following:

- For surface soil, output dose results were well described by the input parameters, as only two radionuclides (Pu-241 and U-232) had coefficients of determination <+/-0.9. The highest parameter correlations (>+/-0.7) were for plant transfer factors and contaminated zone thickness.
- For subsurface soil, the variability in the calculated dose was moderately well described by the input parameters (six radionuclides with R^2 <+/-0.9). The highest correlations for individual parameters (>+/-0.9) were the depth of roots, contaminated zone K_d, and outdoor time fraction
- Sediment dose variability was well described by the input parameters (nine radionuclides with R^2 <+/-0.9), with the highest correlations (>+/-0.9) observed for the outdoor time fraction and fish transfer factor.

The probabilistic evaluation has identified parameters that are well correlated with the calculated dose. Based on these results, the input parameters that account for the majority of variability in the output are plant transfer factors, contaminated zone thickness, depth of roots, contaminated zone K_d , outdoor time fraction, and fish transfer factors.

9.2 Actions

The conclusions on the probabilistic uncertainty analysis results just described led to the decision to make use of the probabilistic peak-of-the-mean DCGLs in place of the deterministic DCGLs provided in Revision 0 to this plan for surface soil and streambed sediment. The probabilistic peak-of-the-mean DCGLs were used for subsurface soil for three radionuclides as discussed in Section 5.2.8. Changes in Section 5 made as part of Revision 2, including changes to the cleanup goals, reflect these decisions.

10.0 References

Baes. et.al. 1984, *A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture*, ORNL-5786. Base, C.F. III, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September, 1984.

DOE 2008, DOE letter from Cynthia Anderson (Deputy Chief Operations Officer) to Keith McConnell of NRC (Deputy Director, Decommissioning and Uranium Recovery Licensing Directorate) dated December 3, 2008.

EPA 1999, *UNDERSTANDING VARIATION IN PARTITION COEFFICIENT, K_d, VALUES, Volume II: Review of Geochemistry and Available K_d Values for Cadmium, Cesium, Chromium, Lead, Plutonium, Radon, Strontium, Thorium, Tritium (^3H), and Uranium*, Report EPA 402-R-99-004B. US Environmental Protection Agency, Washington, D.C., August 1999.

EPA 2004, *UNDERSTANDING VARIATION IN PARTITION COEFFICIENT,K_d, VALUES, Volume III: Review of Geochemistry and Available K_d Values for Americium, Arsenic, Curium, Iodine, Neptunium, Radium, and Technetium,* Report EPA 402-R-99-004C. US Environmental Protection Agency, Washington, D.C., July 2004.

Kamboj, et al. 2000, *Probabilistic Dose Analysis Using Parameter Distributions Developed for RESRAD and RESRAD-BUILD Codes*, NUREG/CR-6676, ANL/EAD/TM-89. Kamboj, S. et al. Environmental Assessment Division, Argonne National Laboratory, Chicago, Illinois, May 2000.

LePoire, et al. 2000, *Probabilistic Modules for the RESRAD and RESRAD-Build Computer Codes, User Guide*, NUREG-CR-6692, ANL/EAD/TM-91. LePoire, D., et al. Environmental Assessment Division, Argonne National Laboratory, Chicago, Illinois, November 2000.

NRC 2006, *Consolidated NMSS Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria, Final Report,* NUREG 1757 Volume 2, Revision 1. NRC, Office of Nuclear Material Safety and Safeguards, Washington, DC, September, 2006.

NRC 2008, *Report of October 21, 2008 Meeting With U.S. Department of Energy on Dose Modeling Approach for Phase 1 Decommissioning Plan*. Forwarded by letter from NRC (Rebecca Tadesse, Chief, Materials Decommissioning Branch, Decommissioning and Uranium Recovery Licensing Directorate) to DOE (Bruce Bower, WVDP) dated November 18, 2008.

Sheppard and Thibault 1990, "Default Soil Solid/Liquid Partition Coefficients, Kds, for Four Major Soil Types: A Compendium," Sheppard, M.I., and D.H. Thibault, *Health Physics*, 59:471-482, 1990.

Yu, et al. 2000, *Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes*, NUREG/CR-6697, ANL/EAD/TM-98. Yu, C., et al., Environmental Assessment Division, Argonne National Laboratory, Argonne, Illinois, November 2000.

Yu, et al. 2001, *User's Manual for RESRAD Version 6*, ANL/EAD-4. Yu, C., et al., Environmental Assessment Division, Argonne National Laboratory, Argonne, Illinois, July 2001.

11.0 ATTACHMENTS

(1) Plots of Probabilistic and Deterministic Results

(2) Electronic Files Described in Section 1.3 (provided separately)

ATTACHMENT 1

Plots of Probabilistic and Deterministic Results

Note that the deterministic results used in this attachment are the deterministic results based on the original base-case conceptual model. The multi-source analysis results were not used because they are not directly comparable with the probabilistic results.

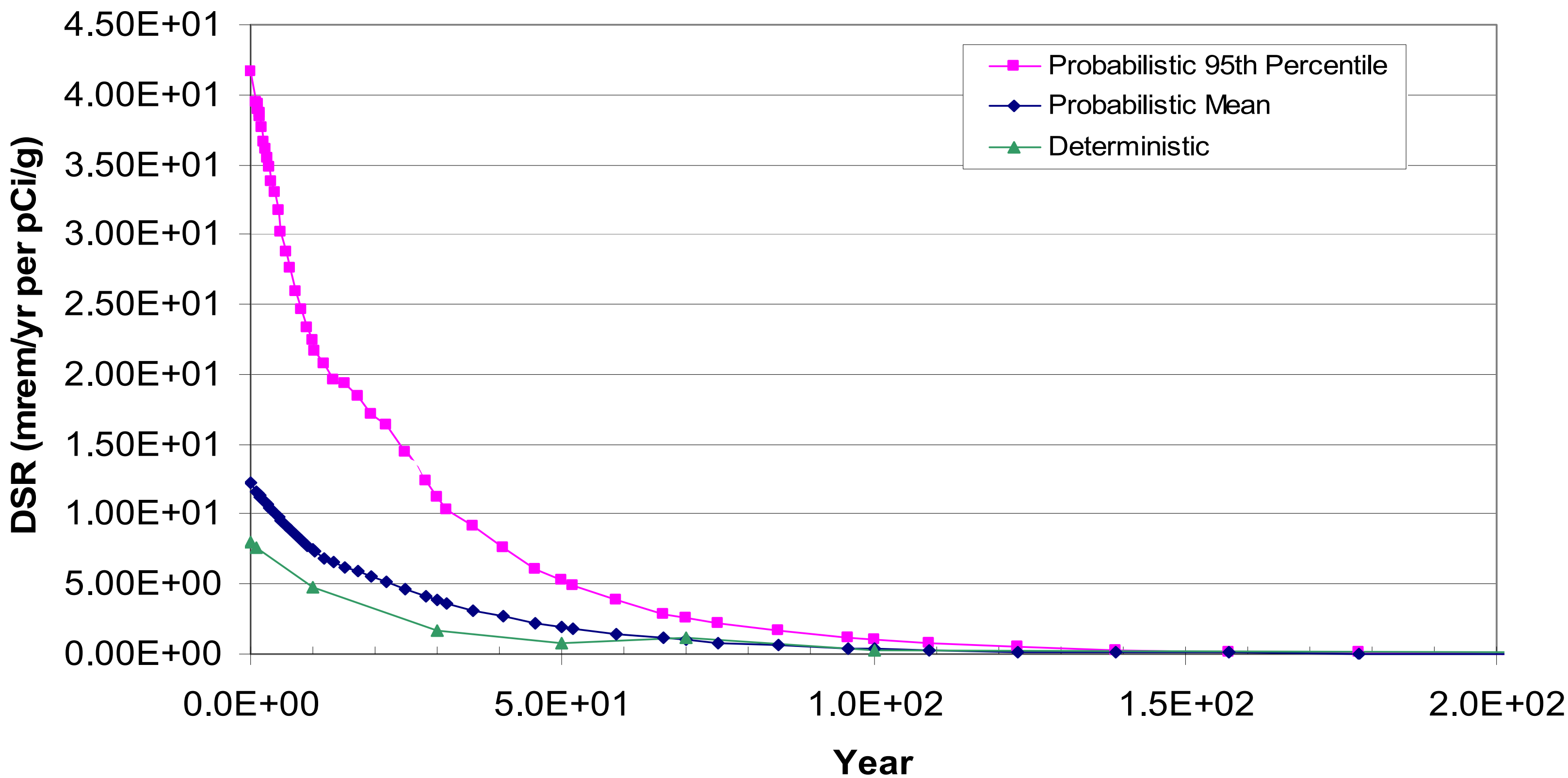


Figure Att-1. Probabilistic and Deterministic Dose-Source Ratio vs. Time, Sr-90 – Surface Soil

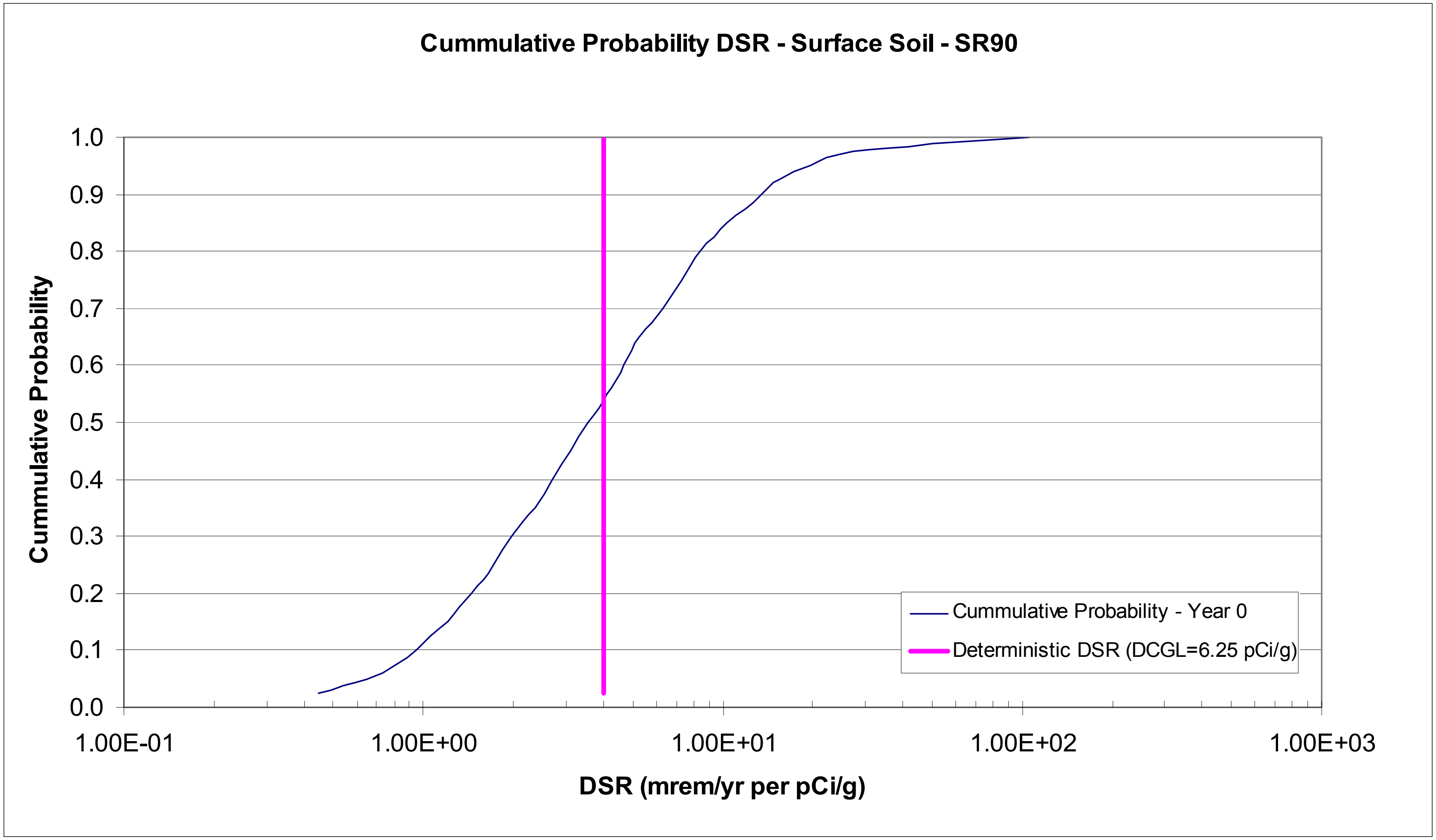


Figure Att-2. Cumulative Probability Dose-Source Ratio, Sr-90 – Surface Soil

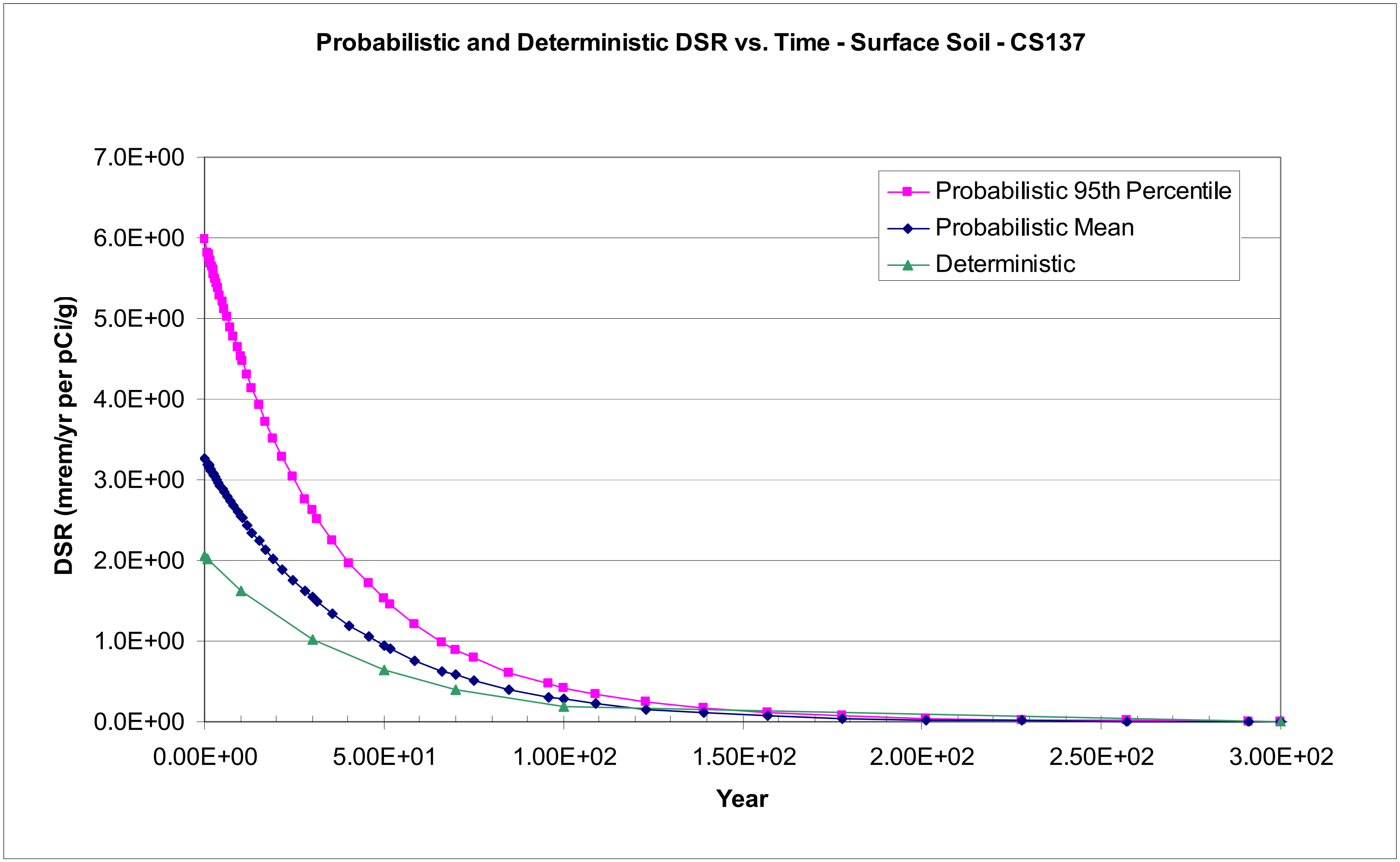


Figure Att-3. Probabilistic and Deterministic Dose-Source Ratio, Cs-137 – Surface Soil

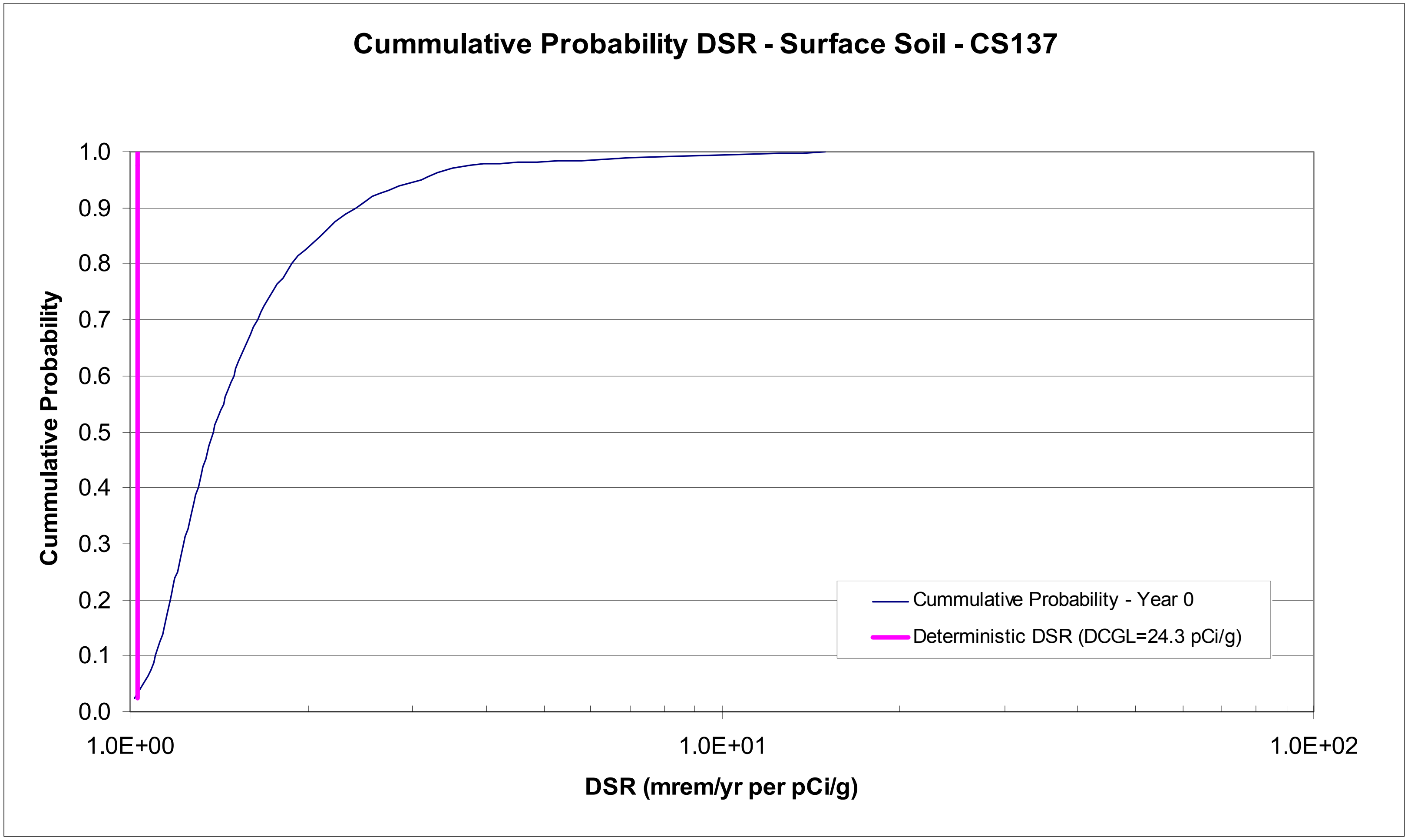


Figure Att-4. Cumulative Probability Dose-Source Ratio, Cs-137 – Surface Soil

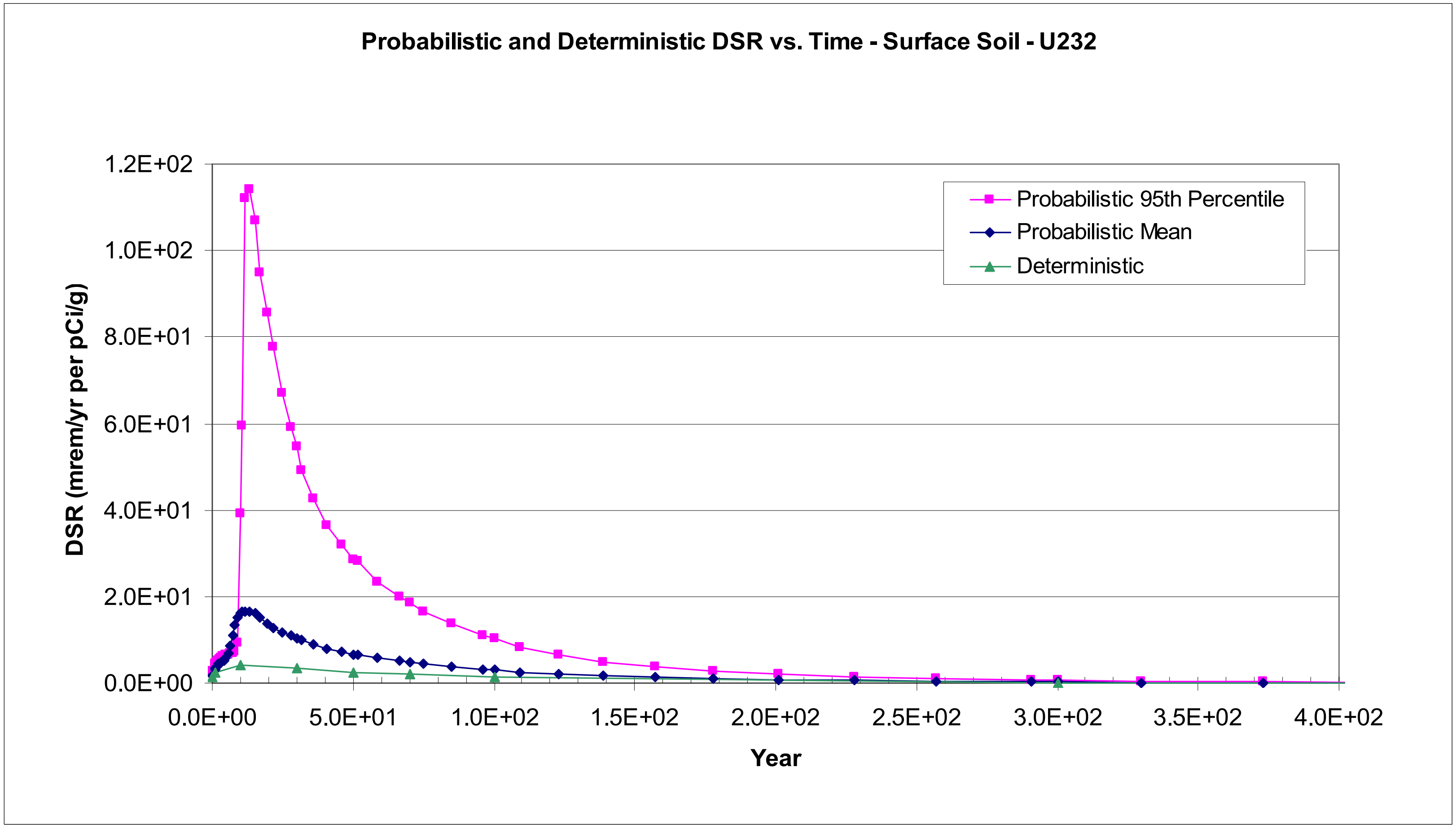


Figure Att-5. Probabilistic and Deterministic Dose-Source Ratio vs. Time, U-232 – Surface Soil

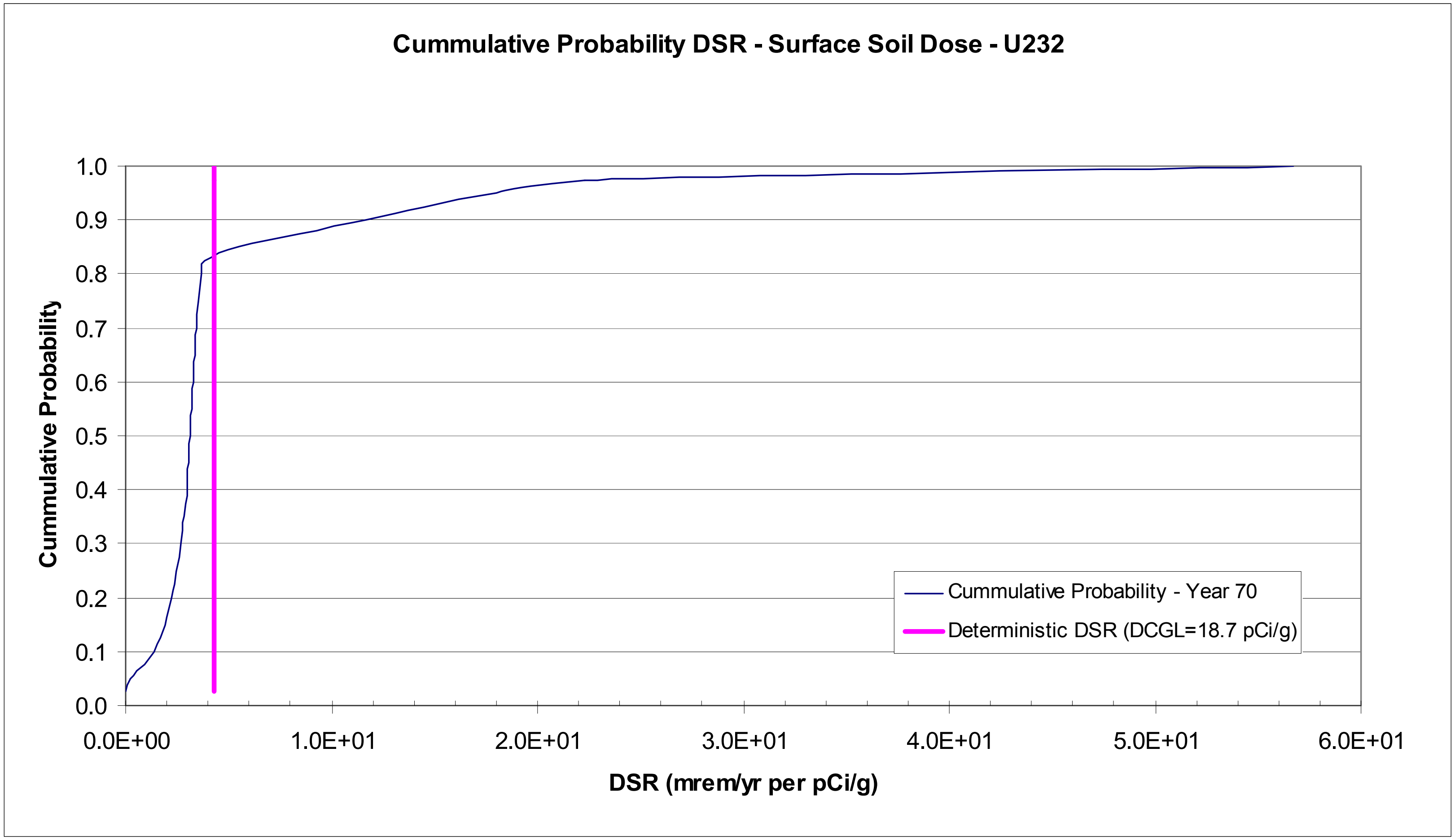


Figure Att-6. Cumulative Probability Dose-Source Ratio, U-232 – Surface Soil

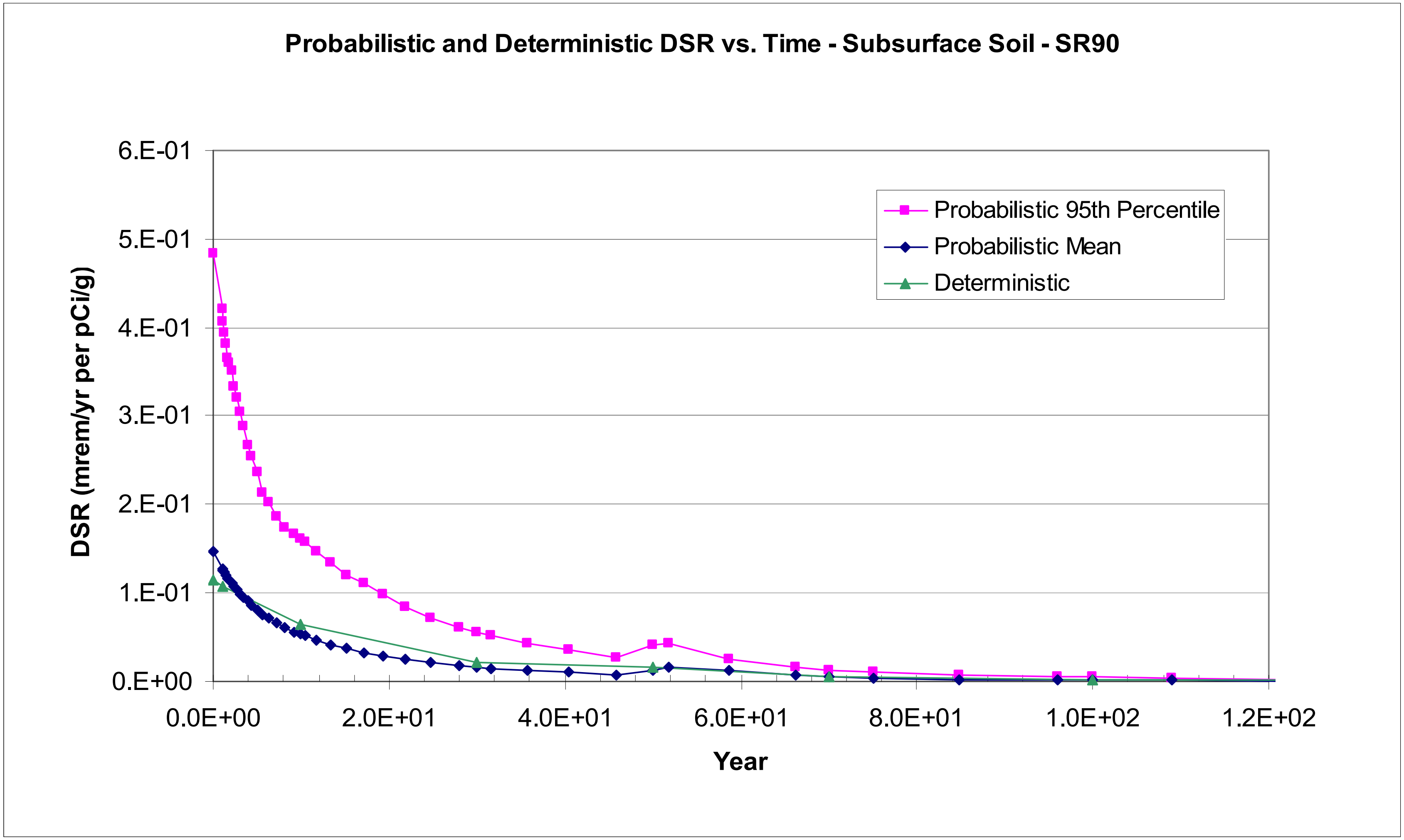


Figure Att-7. Probabilistic and Deterministic Dose-Source Ratio vs. Time, Sr-90 – Subsurface Soil

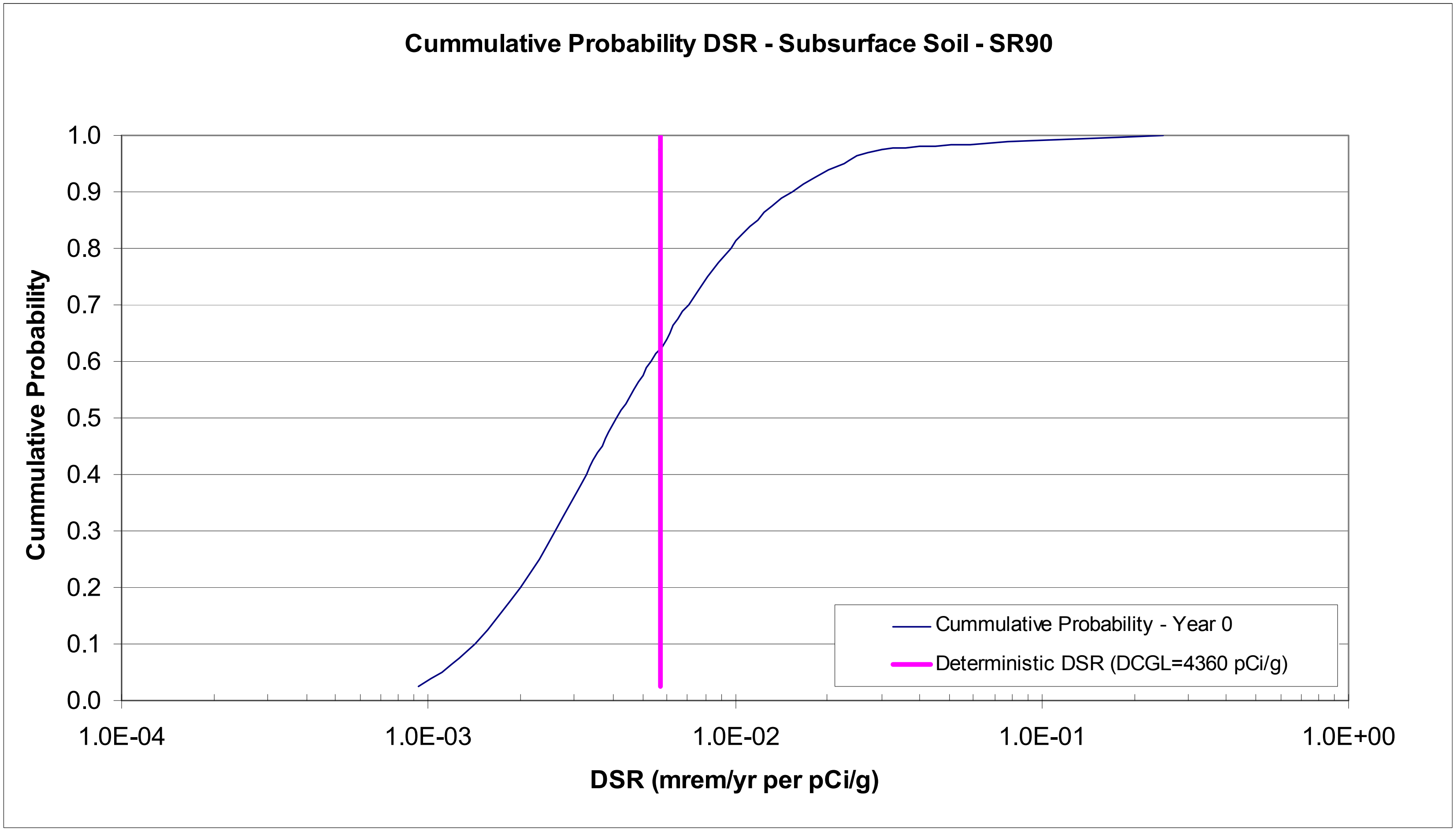


Figure Att-8. Cumulative Probability Dose-Source Ratio, Sr-90 – Subsurface Soil

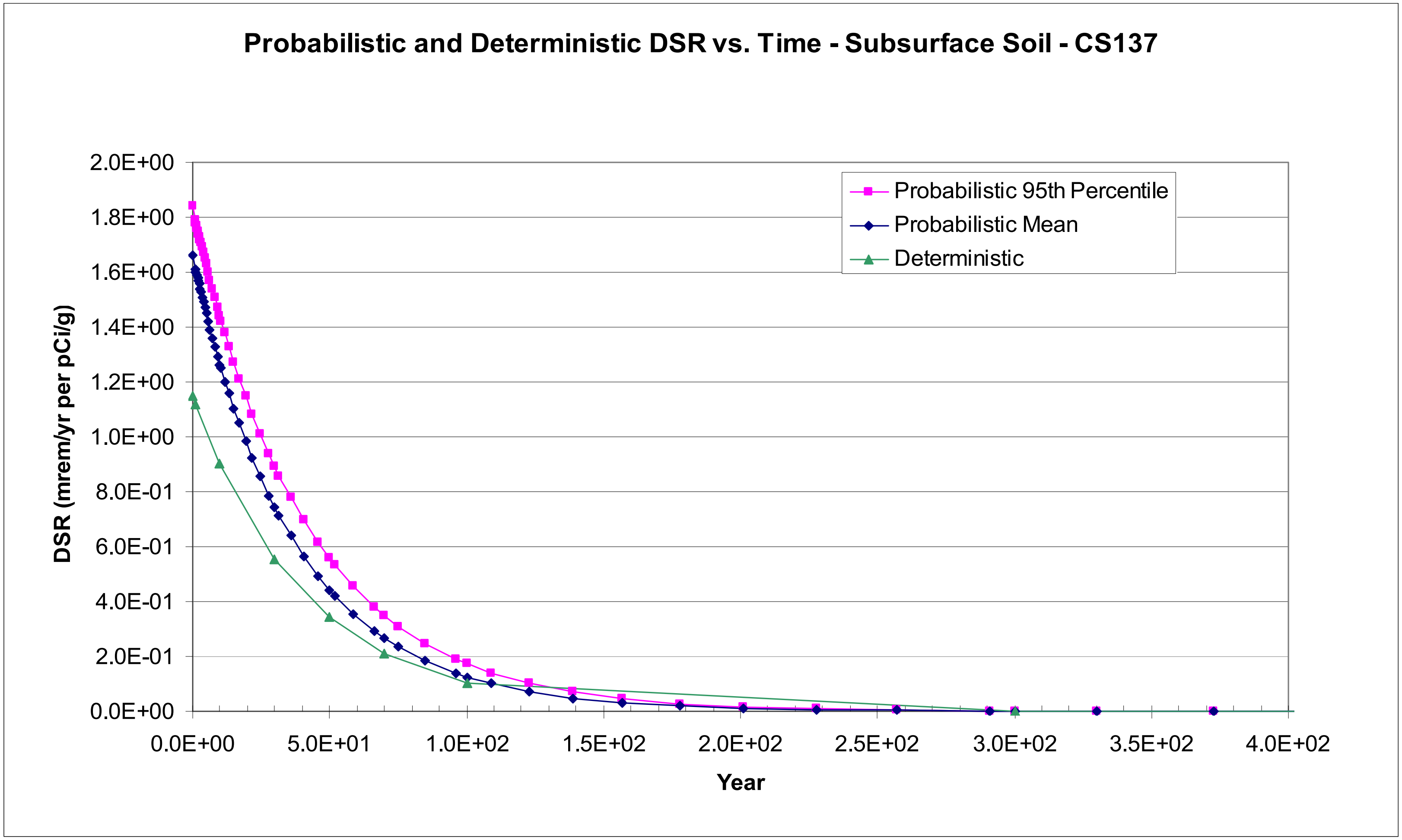


Figure Att-9. Probabilistic and Deterministic Dose-Source Ratio vs. Time, Cs-137 – Subsurface Soil

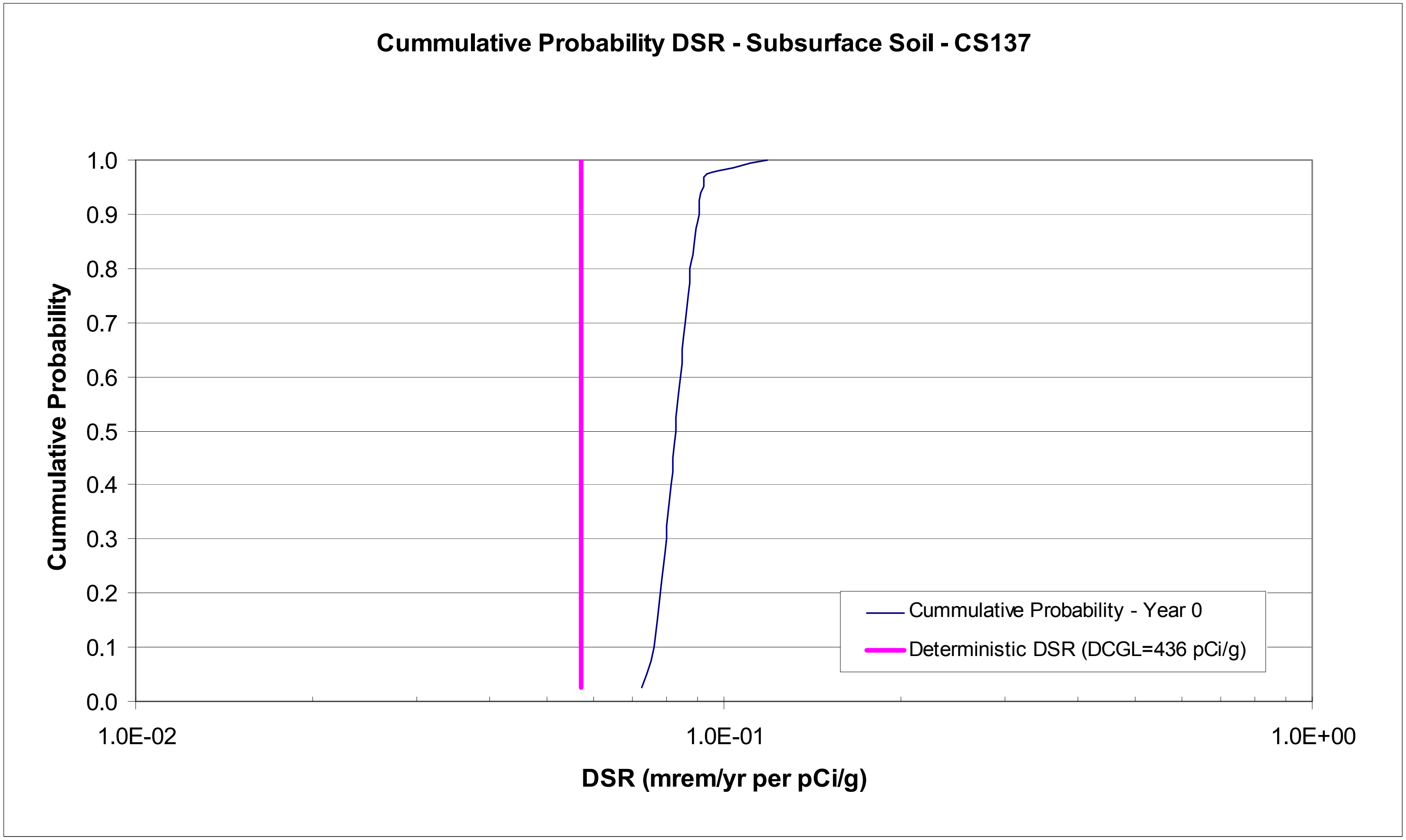


Figure Att-10. Cumulative Probability Dose-Source Ratio, Cs-137 – Subsurface Soil

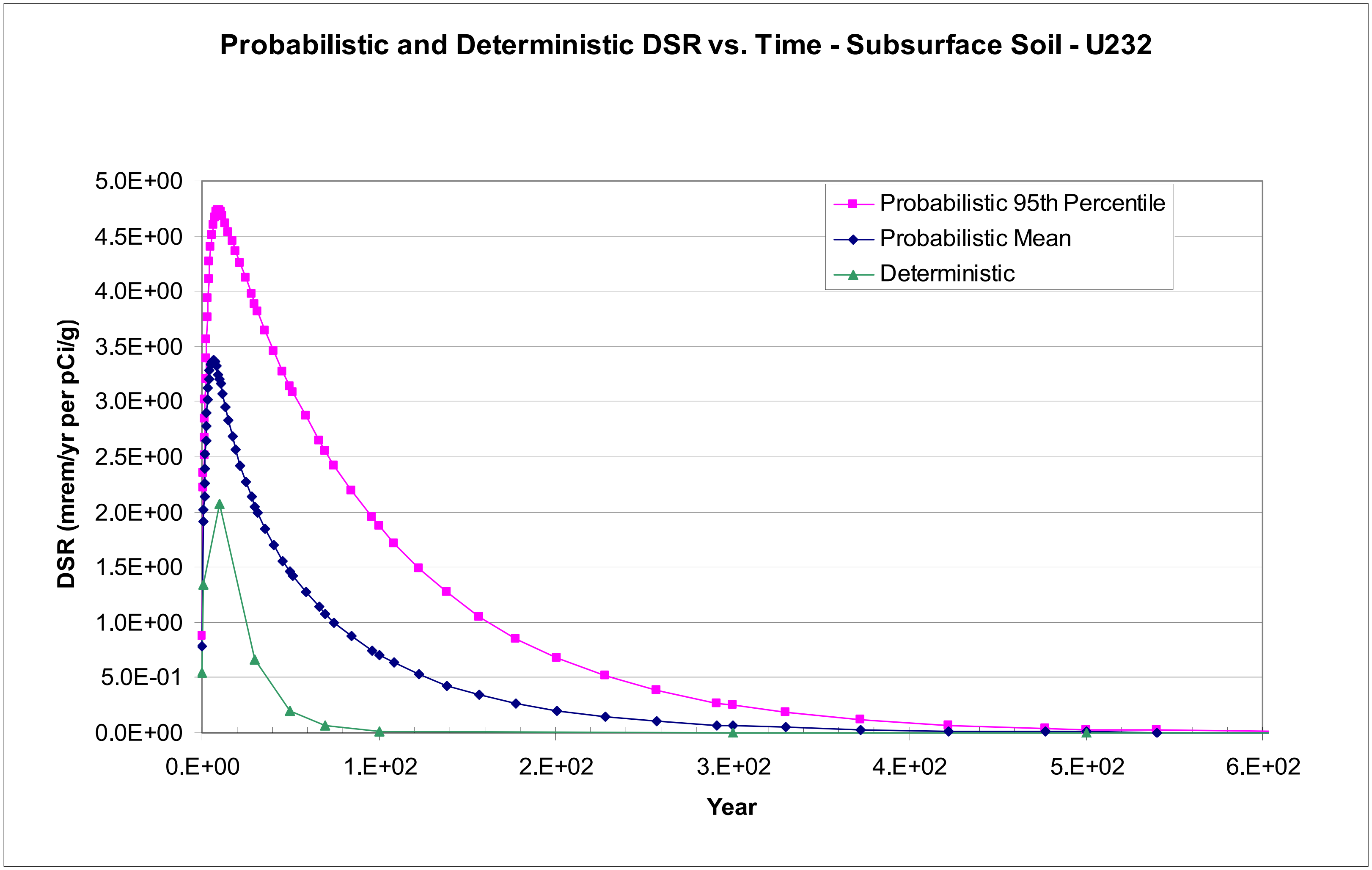


Figure Att-11. Probabilistic and Deterministic Dose-Source Ratio vs. Time, U-232 – Subsurface Soil

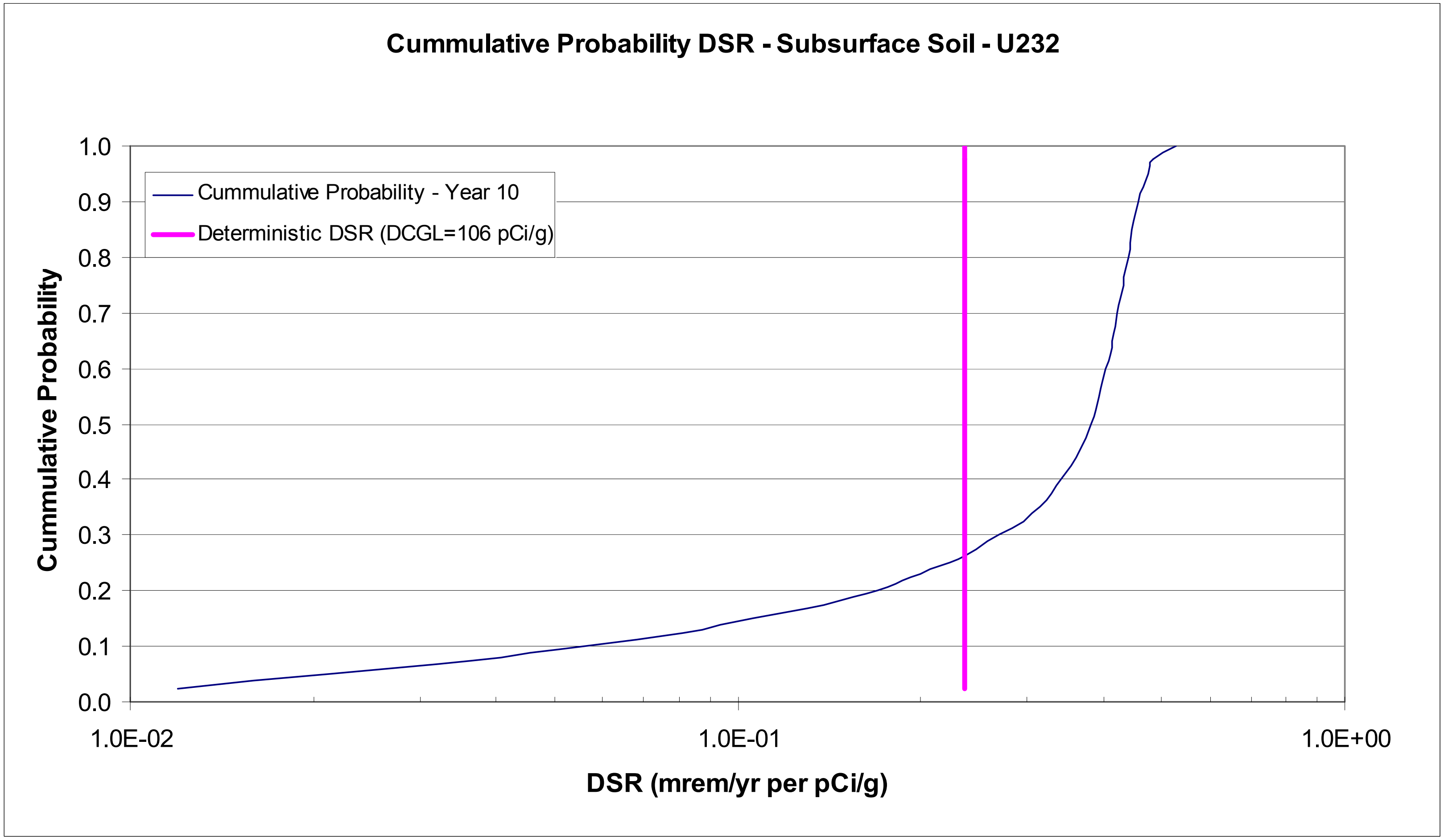


Figure Att-12. Cumulative Probability Dose-Source Ratio, U-232, Subsurface Soil

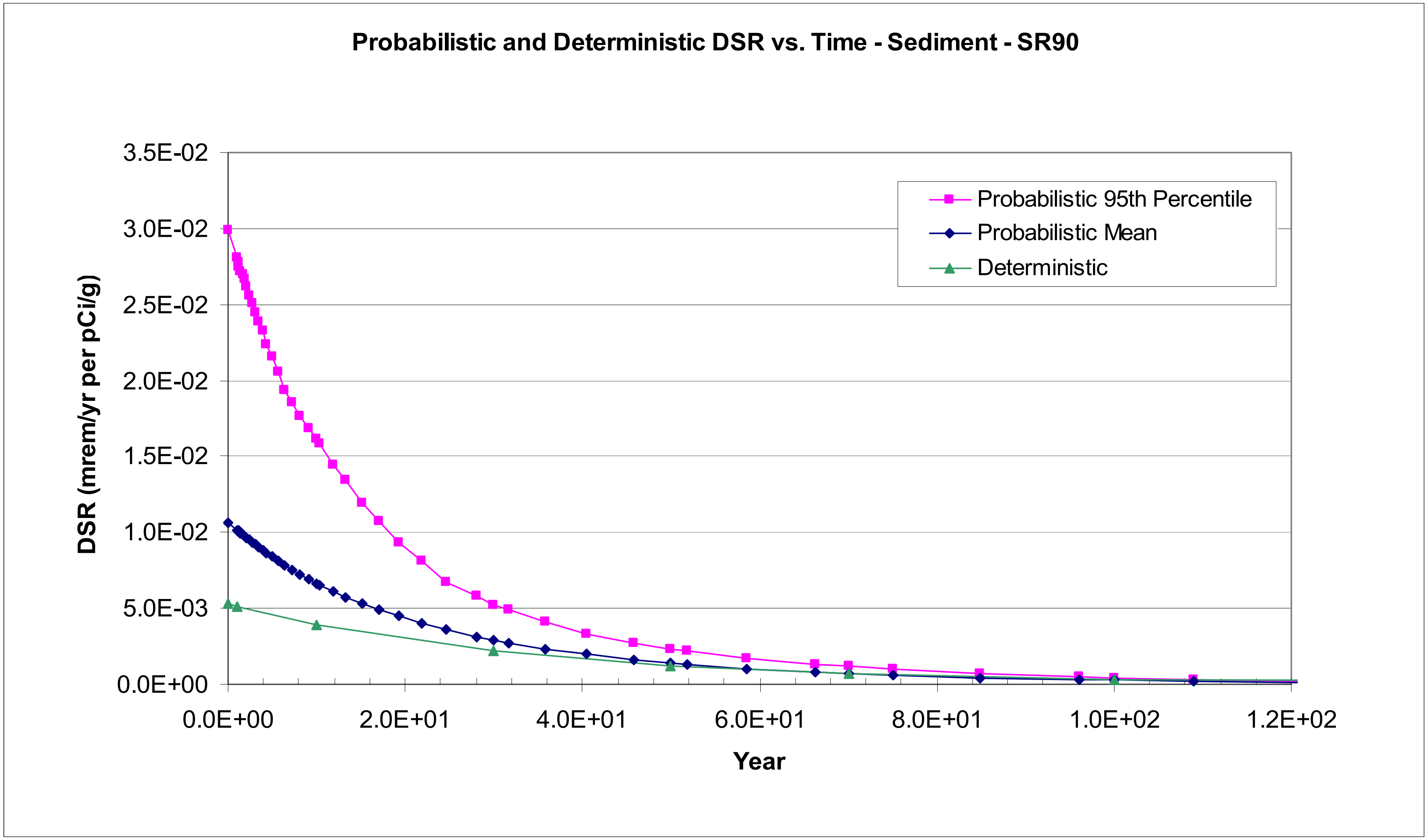


Figure Att-13. Probabilistic and Deterministic Dose-Source Ratio vs. Time, Sr-90 – Streambed Sediment

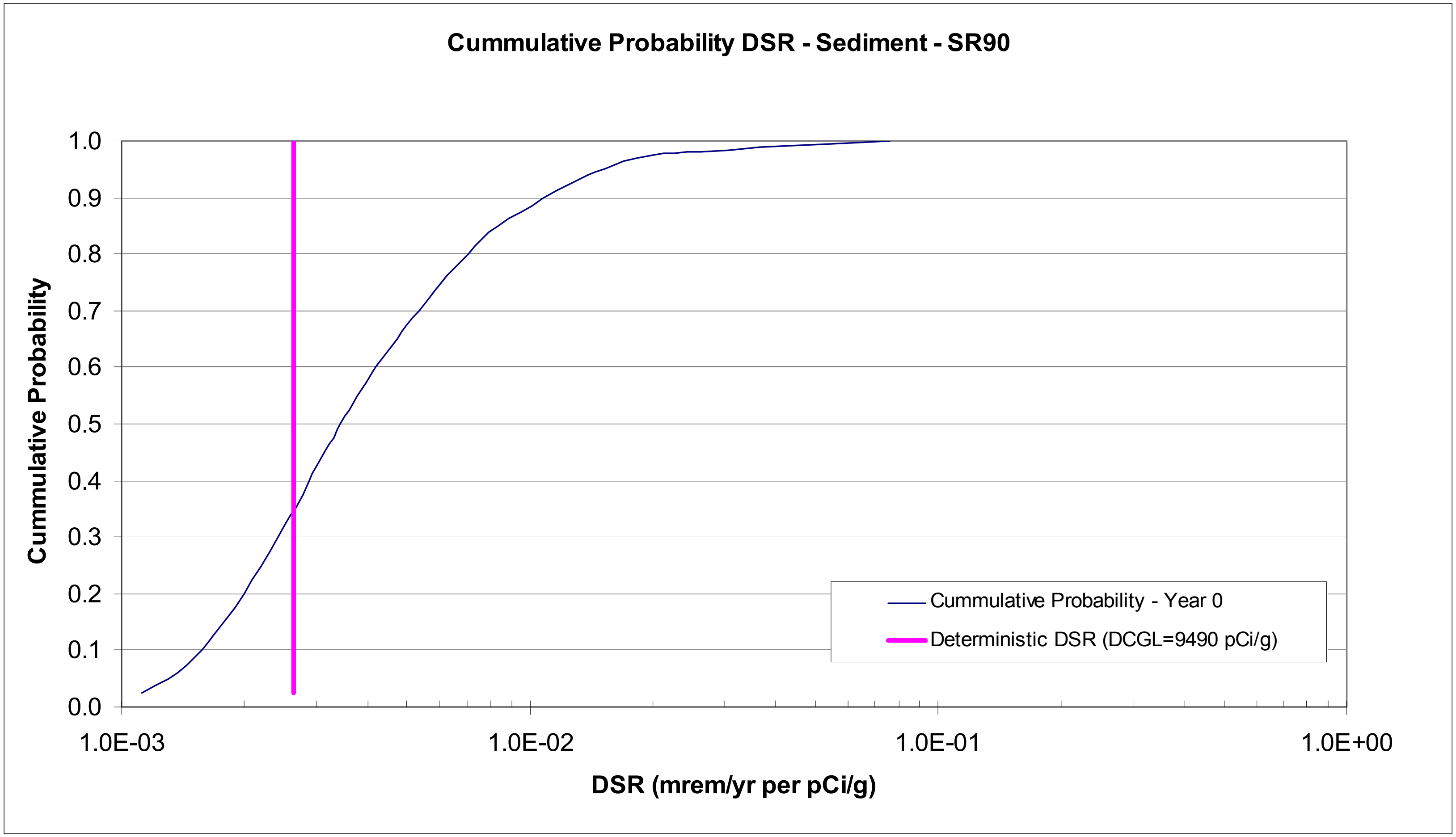


Figure Att-14. Cumulative Probability Dose-Source Ratio, Sr-90 – Streambed Sediment

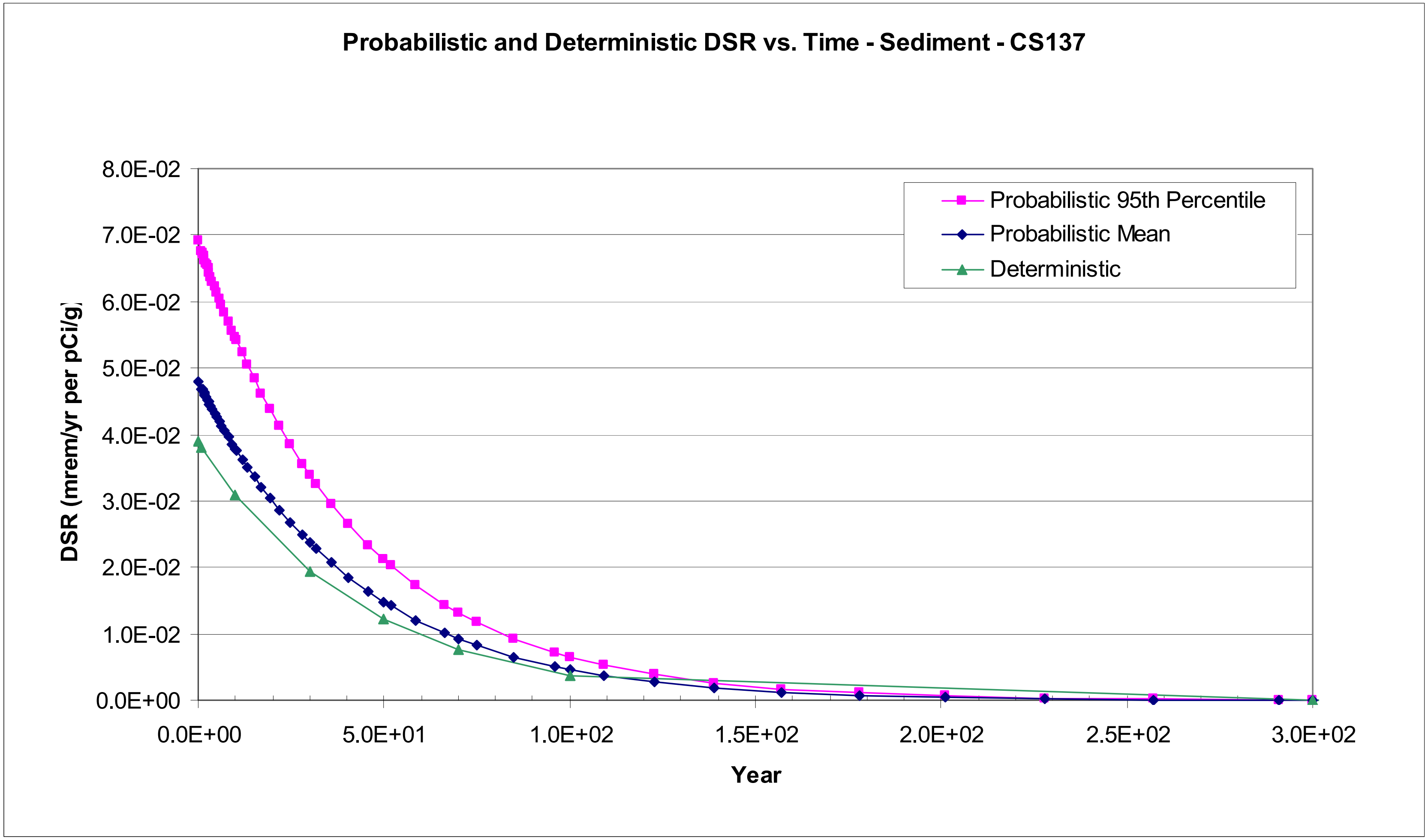


Figure Att-15. Probabilistic and Deterministic Dose-Source Ratio vs. Time, Cs-137 – Streambed Sediment

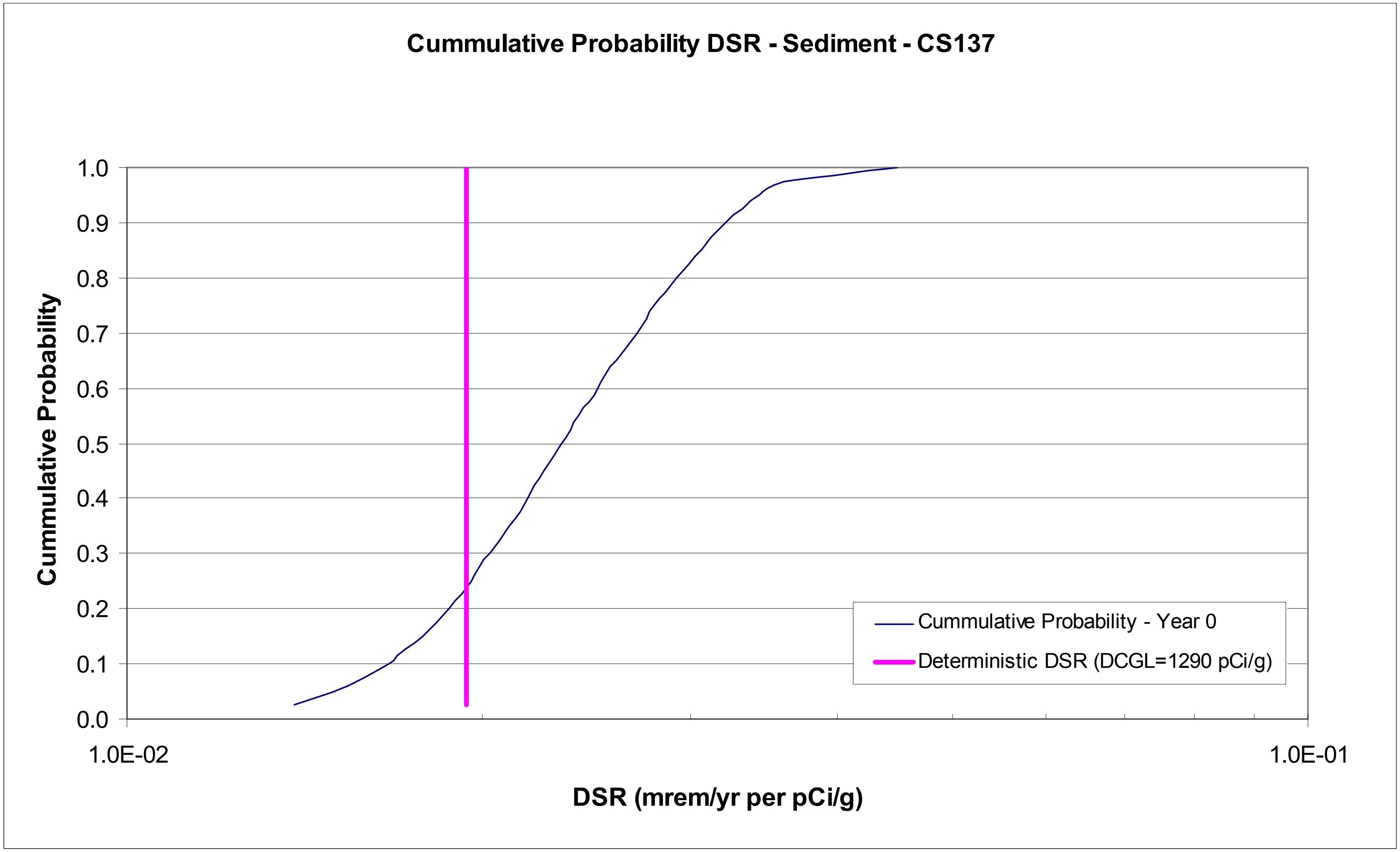


Figure Att-16. Cumulative Probability Dose-Source Ratio, Cs-137 – Streambed Sediment

Table Att-1. Estimated WMA 1 Doses from Observed Maximum Radionuclide Concentrations in the Lavery Till

Radionuclide	Maximum Detection (pCi/g)(1)	Depth (ft)	Peak-of-the-Mean Subsurface Soil $DCGL_w$ (pCi/g)(2)	95th Percentile Subsurface Soil $DCGL_w$ (pCi/g)	Peak-of-the-Mean Estimated Dose (mrem/y)(3)	95th Percentile Estimated Dose (mrem/y)(3)
Am-241	1.3E-01	38-40	6.8E+03	4.3E+03	4.8E-04	7.6E-04
C-14	1.1E-01	38-40	3.7E+05	3.6E+05	7.3E-06	7.5E-06
Cs-137	3.9E+00	38-40	3.0E+02	2.7E+02	3.6E-01	3.6E-01
Cm-243	2.3E-02	38-40	1.1E+03	9.3E+02	6.2E-04	6.2E-04
Cm-244	2.3E-02	38-40	2.2E+04	1.1E+04	5.3E-05	5.3E-05
I-129	2.9E-01	38-40	5.2E+01	5.2E+01	1.4E-01	1.4E-01
Np-237	2.1E-02	37-39	4.3E+00	4.3E+00	1.2E-01	1.2E-01
Pu-238	2.3E-02	38-40	1.4E+04	6.8E+03	4.2E-05	8.4E-05
Pu-239	6.4E-02	38-40	1.2E+04	6.1E+03	1.3E-04	2.6E-04
Pu-240	6.4E-02	38-40	1.2E+04	6.4E+03	1.3E-04	2.5E-04
Pu-241	5.7E-01	38-40	2.4E+05	1.6E+05	5.9E-05	8.9E-05
Sr-90	5.9E+01	38.5-39	3.2E+03	1.0E+03	4.6E-01	1.4E+00
Tc-99	5.5E-01	37-39	1.1E+04	4.4E+03	1.2E-03	3.2E-03
U-232	4.1E-02	24-26	7.4E+01	5.4E+01	1.4E-02	1.9E-02
U-233	2.3E+00	38-40	1.9E+02	1.9E+02	3.0E-01	3.0E-01
U-234	2.3E+00	38-40	2.0E+02	2.0E+02	2.9E-01	2.9E-01
U-235	1.4E-01	24-26	2.1E+02	2.1E+02	1.7E-02	1.7E-02
U-238	1.4E+00	41-43	2.1E+02	2.1E+02	1.7E-01	1.7E-01
				Total Estimated Dose	1.9E+00	2.8E+00

NOTES: (1) Maximum detections from Table 5-1. Radionuclides with maximum detections below the detection limit were evaluated at the detection limit.

(2) Subsurface DCGLs are presented in Appendix E and account for 10 to 1 dilution of contaminated till with clean overlying soil during excavation. Subsurface DCGL are the lower of the deterministic values for the resident gardener and farmer or the probabilistic value for the farmer.

(3) Estimated dose (mrem/y) = 25 (mrem/y) x (maximum detection / $DCGL_W$)

Table Att-2. Estimated WMA 2 Doses from Observed Maximum Radionuclide Concentrations in the Lavery Till

Radionuclide	Maximum Detection (pCi/g)(1)	Depth (ft)	Peak-of-the-Mean Subsurface Soil $DCGL_w$ (pCi/g)(2)	95th Percentile Subsurface Soil $DCGL_w$ (pCi/g)	Peak-of-the-Mean Estimated Dose (mrem/y)(3)	95th Percentile Estimated Dose (mrem/y)(3)
Am-241	3.0E-02	12-14	6.8E+03	4.3E+03	1.1E-04	1.7E-04
C-14	None	None	3.7E+05	3.6E+05	NA	NA
Cm-243	None	None	1.1E+03	9.3E+02	NA	NA
Cm-244	None	None	2.2E+04	1.1E+04	NA	NA
Cs-137	4.5E-01	12-14	3.0E+02	2.7E+02	4.1E-02	4.1E-02
Np-237	None	None	4.3E+00	4.3E+00	NA	NA
I-129	None	None	5.2E+01	5.2E+01	NA	NA
Pu-238	1.0E-02	12-14	1.4E+04	6.8E+03	1.8E-05	3.7E-05
Pu-239	5.9E-03	12-14	1.2E+04	6.1E+03	1.2E-05	2.4E-05
PU-240	5.9E-03	12-14	1.2E+04	6.4E+03	1.2E-05	2.3E-05
Pu-241	1.3E+00	12-14	2.4E+05	1.6E+05	1.4E-04	2.0E-04
Sr-90	8.5E-01	12-14	3.2E+03	1.0E+03	6.7E-03	2.1E-02
Tc-99	None	None	1.1E+04	4.4E+03	NA	NA
U-232	1.2E-02	12-14	7.4E+01	5.4E+01	4.1E-03	5.5E-03
U-233	1.8E-01	12-14	1.9E+02	1.9E+02	2.3E-02	2.3E-02
U-234	1.8E-01	12-14	2.0E+02	2.0E+02	2.3E-02	2.3E-02
U-235	5.9E-03	12-14	2.1E+02	2.1E+02	7.1E-04	7.1E-04
U-238	1.1E-01	12-14	2.1E+02	2.1E+02	1.3E-02	1.3E-02
				Total Estimated Dose	**1.1E-01**	**1.3E-01**

NOTES: (1) Maximum detections from Table 5.1. Radionuclides with maximum detections below the detection limit were evaluated at the detection limit.

(2) Subsurface DCGLs are presented in Appendix E and account for 10 to 1 dilution of contaminated till with clean overlying soil during excavation. Subsurface DCGL are the lower of the deterministic values for the resident gardener and farmer or the probabilistic value for the farmer.

(3) Estimated dose (mrem/y) = 25 (mrem/y) x (maximum detection / $DCGL_W$)

LEGEND: NA = not available