Probabilistic Versus Deterministic Analysis for Demonstration of Compliance with the Dose Criteria in 10 CFR Part 20, Subpart E

R. (Boby) Abu-Eid
U.S. Nuclear Regulatory Commission

ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) promulgated its regulations on the "Radiological Criteria for License Termination" in 10 CFR Part 20, Subpart E. The regulations require that, for the release of sites for unrestricted use, the total effective dose equivalent (TEDE) to an average member of a critical group, resulting from residual radioactivity that is distinguishable from background radiation, does not exceed 0.25 milliSievert per year (mSv/yr), (25 millirem/yr (mrem/yr)) . Subpart E also requires that the residual radioactivity has been reduced to levels that are as low as is reasonably achievable (ALARA). In addition, Subpart E establishes the criteria for license termination with restrictions on future land use, as long as specific conditions are met. Finally, subpart E provides alternate criteria for license termination in unusual situations where the site may exceed the 0.25 mSv/yr (25 mrem/yr) limit, but would not be permitted to exceed 1.0 mSv/yr (100 mrem/yr) or 5.0 mSv/yr (500 mrem/yr), under certain conditions.

Licensees, staff, and/or stakeholders may demonstrate compliance with the dose criteria through site-specific dose impact analysis to establish derived concentration guideline levels (DCGLs). Site-specific dose impacts analysis may also be conducted to assess remedial actions or options for site release restrictions based on measured concentrations of residual radioactivity at the site.

The NRC is committed to a risk-informed performance based (RIPB) approach in regulatory decision-making and licensing activities. Staff commonly uses probabilistic analysis to assess the significance of risk and uncertainties in dose analyses. The analyst typically considers realistic bounding conditions based on probabilistic distributions of input parameters and evaluate uncertainties in the dose outputs. Licensees and stakeholders currently use two approaches for dose analysis. One approach is based on a deterministic methodology, which typically employs a highly "conservative" single value for each parameter assumed to bound variability and uncertainty in site specific conditions. The second approach is based on a probabilistic methodology which employs sensitivity and uncertainty analysis of input parameters using probabilistic distributions of sensitive parameters.

NRC staff have conducted dose analyses for decommissioning sites using both deterministic and probabilistic approaches to review and evaluate licensees' derived concentration guideline levels (DCGLs) equivalent to the dose criteria in 10 CFR Part 20, Subpart E. Review of licensee's dose analysis includes assessment of input parameters and evaluation of the dose outputs for the two approaches. Based on staff analyses, and using common codes/models acceptable by most Federal agencies, the deterministic analysis approach can produce unrealistically conservative dose values. Probabilistic dose analyses, however, generally produce more realistic dose results and help define the associated uncertainties. Detailed comparative analyses of the two approaches with an actual example is presented.

INTRODUCTION

The Nuclear Regulatory Commission (NRC) has adopted a risk-informed performance based approach in material licensing activities [1]. The Commission also endorsed staff probabilistic dose analysis approach and use of the best estimate of the dose in performing site-specific analysis for demonstration of compliance with the license termination rule in 10 CFR Part 20, Subpart E, [2]. NRC licensees, however, may choose either a

deterministic approach or a probabilistic approach in conducting site-specific dose analysis for compliance with the dose criteria in 10 CFR part 20, Subpart E [3,4]. Both approaches typically employ models and codes to simulate potential radiological releases, through dispersion and transport, from the source of residual radioactivity into the environmental media (e.g., soil, surface water, air, biosphere, subsurface media, and groundwater). The models and codes are also used to estimate exposure to radioactivity of a human receptor, represented by a member of the critical group, through direct or indirect contact with environmental media (e.g., pathways may include: direct exposure; inhalation; and direct/indirect ingestion of plant, meat, milk, aquatic food, soil; and drinking water). The models and codes used require a variety of input parameters to define the source-term and the physical conditions at the site (e.g., physical parameters), the behavior of the critical group (e.g., behavior parameters), and the metabolic characteristics of the surrounding biosphere (metabolic parameters).

The NRC and its contractors have developed common tools, codes, and models to help staff and licensees conduct probabilistic dose analyses [5,6,7, 8, 9,]. For example, a probabilistic DandD code (version 2.1) was developed for screening analyses [5] and probabilistic RESRAD >6.0 and RESRAD-BUILD >3.0 codes were developed for generic site-specific dose analyses [6,7,8,9]. The NRC also developed technical data and information to support probabilistic analysis. For example, template distributions for most sensitive parameters were established [10,11,12]. The staff is also in the process of developing more advanced and stylized calculation approaches for complex decommissioning sites using models such as: RESRAD-OFFSITE, MEPAS, and GEN-II, and use of platform software such as FRAMES, GOLDSIM, and DIAS. This study presents approaches and methodologies used in conducting deterministic and probabilistic dose analysis using these codes and models and presents analytical results for actual decommissioning sites.

RISK-INFORMED APPROACH AND IDENTIFICATION OF SENSITIVE PARAMETERS:

Assessment of uncertainty in the dose analysis is an essential element of NRC's risk informed approach to regulatory decision-making. Therefore, identification of sensitive parameters causing large uncertainties in the dose estimates is necessary for both deterministic and probabilistic dose analysis. For the deterministic approach, sensitive parameters need to be identified to verify that they are sufficiently conservative such that the derived deterministic dose is more likely to be an overestimation rather than an underestimation. Therefore, conservative values of sensitive parameters are intended to ensure a conservative bounding analysis due to lack of information on uncertainties in the deterministic analysis.

For the probabilistic analysis, identification of sensitive parameters is essential to focus uncertainty analysis on parameters that have significant influence on the dose results. In this context, staff adopted a simple approach for initially identifying sensitive parameters. The approach is essentially based on relevancy of a parameter on the degree of influence on the peak dose calculations. A quantity called the normalized dose difference (NDD) is used as an indicator to help initial ranking and selection of sensitive parameters:

$$NDD = (D_{high} - D_{low})/D_{base} \times 100\% \quad \text{(Eq. 1)}$$

Where $(D_{high} - D_{low})$ is the range of the peak dose calculated when the parameter is set at its high and low values, and the D_{base} is the peak dose when the parameter is set at its base value. The base value uses a well studied default parameter value for a mixture of radionuclides at a concentration of 1 pCi/g, in a contaminated zone area of 2,400 m^2 and a contamination depth of 0.15 m. The radionuclide mixture includes radionuclides: Co-60, Sr-90, Cs-137, Ra-226, Th-230, U-238, Pu-239, and Am-241. The peak dose was calculated for the different parameter ranges and correlated with the base peak value. Table 1 shows examples of the most sensitive physical parameters for the RESRAD code and the degree of sensitivity using the NDD indicator for this example. Table 1 data may be used as a help tool to initiate selection of sensitive parameters for different radionuclides.

THE DETERMINISTIC DOSE ANALYSIS METHODOLOGY

The deterministic dose analysis approach relies on a single value to represent each parameter associated with the physical, behavioral, and the metabolic conditions at the site. Therefore, the dose impact results are presented by a single value of the annual peak dose occurring within the performance period (1000 yr). In other words, the deterministic analysis does not address the probability of the derived dose due to uncertainties in the physical conditions at the site, uncertainties in the scenario associated with the behavior of the critical group, or uncertainties associated with the metabolic characteristics of the surrounding biosphere.

NRC licensees frequently use a deterministic approach to demonstrate compliance with the dose criteria. Staff conduct reviews of licensee’ dose analysis to ensure that the assumptions employed and the parameters used in the dose estimates result in an overestimate, rather than an underestimate of dose. Licensees commonly use the deterministic module of the RESRAD code (Versions 5.0 and 6.0 series) to calculate the dose. In many cases RESRAD default input parameters are used in a deterministic fashion with modification of certain sensitive parameters. The common sensitive parameters frequently changed include: distribution coefficients, occupancy parameters, indoor shielding factor, plant transfer factors, hydraulic conductivity, depth of roots, and mass loading factor. In the deterministic review, staff examines justification of the input parameters considering site-specific conditions and examines the availability of characterization data supporting the selected input parameters to ensure representation of varied and uncertain conditions at the site. NRC staff also conducts bounding analysis to verify the deterministic dose results and may conduct probabilistic analysis to assess uncertainties in the dose values.

THE PROBABILISTIC DOSE ANALYSIS METHODOLOGY

NRC staff commonly employs probabilistic analysis approaches to examine and review the performance of a site with regard to compliance with the dose criteria. In conducting probabilistic analysis, we follow a systematic uncertainty analyses approach using specific distributions of the significant uncertain parameters. The results of probabilistic analysis are presented either by a peak-of-the-mean dose distribution at various times along the performance time period horizon or by distribution of the peak doses with a dose value at each specific percentile.

Table I Examples of Most Sensitive Physical Parameters Using NDD[a] Indicator

Parameter	Radionuclide NDD							
	Co-60	SR-90	Cs-137	Ra-226	Th-230	U-238	Pu-239	Am-241
External γ Shielding	54	0	48	7	7	0	0	7
Cover Depth and Density of Cover Material	98	6	92	11	159	1	9	51
	250	0	85	2	0	0	0	0.1
Density of CZ	26	1.4	23	56	74	62	58	0.2
Distribution Coefficients (CZ, UZ, SZ)	0.9	3	6	0.1	51	94	95	0.1
SZ Hydraulic Conductivity and effective porosity,	0	0	0	0	0	114	117	0
	0	0	0	0	0	146	150	0
UZ Thickness	0	0	0	0	0	96	96	0
Depth of Roots	3	253	18	10	15	0	0	131
Transfer Factors for Plants, Meat, and Milk	1	89	13	42	56	0	0	480
	5	101	42	2	5	3	1	36
	3	180	55	8	10	30	0	5
Mass Loading for Inhalation	0	0	0	0	2	0	0	35

a: NDD = $(D_{high} - D_{low})/D_{base}$ x 100%
where the $(D_{high} - D_{low})$ is the range of the peak dose calculated when the parameter is set at its high and low values, and the D_{base} is the peak dose when the parameter is set at its base value. NDD "0" value is given for all values <0.1.

Figure 1 shows an overview of the generic probabilistic dose analysis methodology. NRC's approach to probabilistic dose analysis methodology, using common probabilistic codes/models, like RESRAD, includes the following aspects:

(1) Sampling of sensitive parameters from parameter distribution inputs. The sampling employs simple random sampling Monte Carlo (MC) technique based on the requested number of observations by the user or Latin Hypercube Sampling (LHS) where one sample is obtained from each non-overlapping area of equal probability;

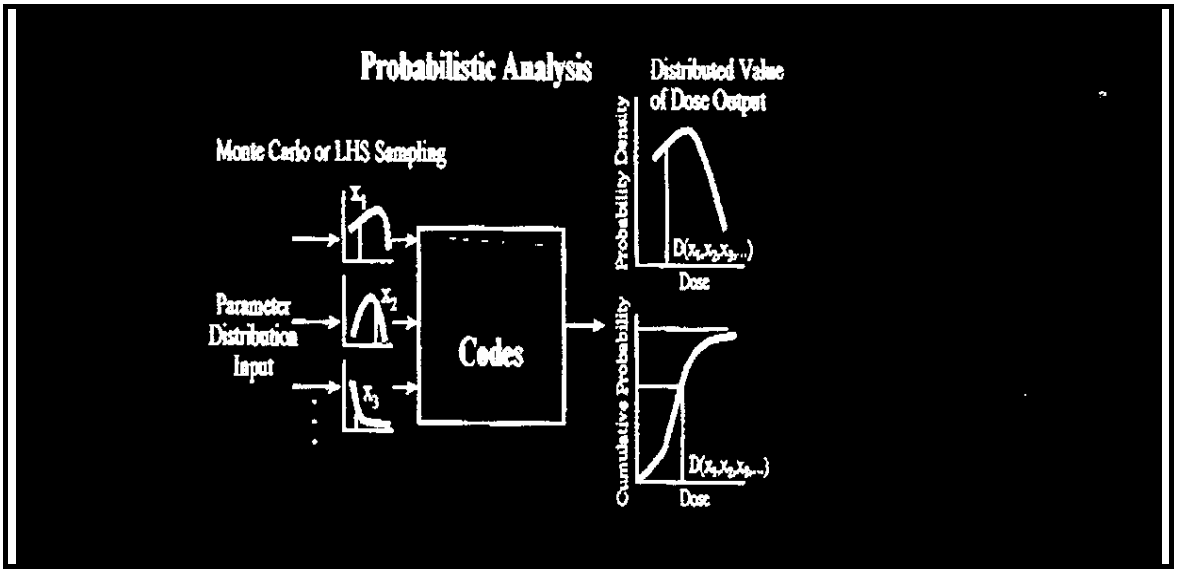
(2) Use of the parameter statistical distributions. We currently use 40 default radionuclide independent parameters' statistical distributions (e.g., the erosion rate, inhalation rate, and thickness of the unsaturated zone) and five radionulcide dependent parameters (e.g., distribution coefficients, transfer factors). For parameters that do not have default distributions, or for modifying a distribution, staff may choose from more than 30 statistical distributions (e.g., continuous: uniform, loguniform, triangular, normal).

(3) Use of "Input Rank Correlation". We develop inputs on the relationship between two or more parameters using a correlation coefficient with a range of -1 for a strong negative correlation (e.g., porosity and bulk density) and +1 for strong positive correlation (e.g., porosity and effective porosity).

(4) Use of Output Correlation. The output correlation coefficients used to examine the sensitivity of input parameters include: (i) Partial Correlation Coefficient (PCC), which indicates how linear the correlation is; (ii) Standard Regression Coefficient (SRC) which indicates how sensitive a parameter in a linear model; (iii) Partial Rank Correlation Coefficient (PRCC), which is typically used for nonlinear models and multiple parameters; and (iv) Standard Rank Regression Coefficient (SRRC) which is used to indicate sensitivity of the parameter.

DOSE OUTPUTS:

The end point for the deterministic dose analysis is the peak dose or soil guideline derived using the peak dose. For the probabilistic analysis, the endpoint is the distribution of doses. The specific outputs in the probabilistic dose analysis include: (a) peak-of-the-mean dose and the time it occurs; (b) mean-of-the-peaks dose (i.e., the mean-of-the-peak doses from all realizations, whenever they occur); (c) The percentile dose and the CDF of the peak dose; (d) Scatter plots of the dose vs. input parameter; (e) The mean dose summed for each specific pathway. We currently use peak of the mean dose to demonstrate compliance with the dose criteria when using probabilistic dose analysis.



EXAMPLE OF DOSE ANALYSIS FOR A DECOMMISSIONING SITE

Generic Site Description The Radiological Source-Term

For this example, the main source of radiological contamination is thorium oxide sludge. Due to haphazard mixing of thorium oxide sludge into the soil the actual impacted area is not well defined and may encompass an area of 2000 - 80,000 m^2. The radionuclides of concern associated with the thorium oxide sludge include: Th-232 and its decay progenies and U-238/U-235 and their decay progenies. The main Th-232 decay series, include: Th-232, Ra-228, and Th-228. The main U-238 decay series include: U-238, U-234, Th-230, Ra-226, and Pb-210; and U-235 decay series include: U-235, Pa-231, and Ac-227. Th-232 decay chain contributes to approximately 86.5% of the initial ore activity; with the U-238 decay chain contributes to to 13%, and U-235 decay chain contributes to approximately 0.5% . The average Th-232 contamination was found to be in the range of 50 - 75 pCi/g and the range of concentration was as low as background (1 pCi/g) to a maximum level of 300 - 700 pCi/g. Radionuclide concentrations extend on the average to a depth of 5-15 cm and in certain hot spots may reach 0.5 - 3.0 m below ground surface. The geologic formation within the site area consist of inter-bedded gravel, sand, silt, and clay. There are limited agricultural activities and gardening in the neighboring areas. The area is covered by vegetation, shrubs, and trees. located in a semiarid alluvial plain environment with a mean annual precipitation of approximately 15 cm and a mean evapotranspiration of 50 cm. The depth to the uppermost aquifer varies between 100 m to 150 m.

Sensitive Parameters:

Deterministic dose analyses were conducted to evaluate the most sensitive parameters affecting dose results. The major pathways contributing to the dose were found to be the direct exposure and inhalation pathways. Therefore, sensitive parameters associated with these pathways were identified and the degree of influence for each parameter was evaluated. These parameters include: area of contamination, thickness of contamination, contaminated zone erosion rate, inhalation rate, mass loading factor for an inhalation, indoor time fraction, outdoor time fraction, external gamma shielding, and indoor dust filtration factor. Subsequently a distribution was selected for each sensitive parameter based on available site data and the degree of knowledge of the parameter. Table II presents sensitive parameters identified for the site and corresponding distributions. Table III shows some important deterministic parameters used in the dose analysis.

Table II Sensitive Parameters and Corresponding Distributions Selected for RESRAD 6.21 Probabilistic Runs for Surface Soil Contamination

Parameter/Unit	**Distributions**	**Minimum (Min) and Maximum (Max) Value, Mean Value, Standard Deviation & Other Selected Parameter Values**
Contaminated zone area (m^2)	Uniform	Min: 2000 Max: 9.0 E+04
Contaminated zone thickness (cm)	Uniform	Min: 5 Max: 15
Contaminated zone erosion rate (m/yr)	Continuous Logarithmic	Four Data Entries Value CDF 5E-08 0 7E-04 0.22 5E-03 0.95 0.2 1
Inhalation rate (m3/yr)	Triangular	Min: 4380 Mode: 5000 Max: 8400
Mass loading for inhalation (g/m3)	Continuous Linear	Eight Data Entries Value CDF 8.0E-06 0.0 1.8E-05 0.1365 3.0E-05 0.8119 4.0E-05 0.95 6.0E-05 0.9937 7.6E-05 0.9783 1.0E-04 1.0
Indoor time fraction	Continuous Linear	Eight Data Entries Value CDF 0 0.0 0.05 0.375 0.25 0.521 0.50 0.625 0.75 0.809 0.90 0.938 0.95 0.992 1.0 1.0
Outdoor time fraction	Uniform	Min: 0.1 Max: 0.25
External gamma shielding factor	Bounded Log-Normal	Mean: -1.3 Sigma: 0.59 Min: 0.044 Max: 0.80
Indoor dust filtration factor	Uniform	Min: 0.15 Max: 0.50

Table III RESRAD 6.21 Important Deterministic Input Parameters for Surface Soil

Parameter	Unit	Deterministic Value	Remarks
Radionuclide Concentration	pCi/g	Th-228: 5.66 Pa-231: 0.027 Th-232: 5.66 Pb-210: 0.027 Ra-228: 5.66 Ra-226: 0.027 U-238: 0.31 Ac-227: 0.027 U-234: 0.31 U-235: 0.0137	(a)The decay series ratios were based on initial concentrations in the Th-sludge and subsequent leaching of U-series based on licensee's measurement and analysis. (b) The specific concentrations represent licensee's derived DCGLs
Cover depth	m	0.0	
Density of contaminated zone (CZ)	g/cm^3	1.60	Soil type&Licensee value
Length parallel to aquifer flow	m	100	RESRAD default
CZ & unsaturated zone (UZ) hydraulic conductivity	m/yr	1.0E+01	Site
Precipitation Rate	m/yr	0.212E+0	Site
Saturated zone (SZ) hydraulic conductivity	m/yr	1.0E+02	Site
K_d for CZ, UZ, and SZ for U	g/cm^3	5.0 E+01	RESRAD Default
K_d for CZ, UZ, and SZ for Th	g/cm^3	6.0 E+04	RESRAD Default
Soil-to-plant transfer factor for U-238	-	2.5 E-03	RESRAD Default
Soil-to-plant transfer factor for Th-232	-	1.0 E-03	RESRAD Default

Outline of Site-Specific Dose Assessment Methodology

The conceptual model for the site was selected as a flat surface soil with an area of 2000 - 80,000 m^2 and a thickness reaching 15 cm. The unsaturated zone (UZ) was assumed as a 120 m thick layer. The aquifer was assumed to lie directly below the UZ. A preliminary deterministic dose analysis was conducted using RESRAD 6.21 to assess the most significant pathways and the most sensitive parameters impacting the dose results. We reviewed the licensee's deterministic dose analysis and input parameters to ensure consistency with the assumed scenario and with site-specific conditions. We found that certain parameters were not appropriate to bound variability in site-specific conditions and scenario assumptions. We conducted parameter sensitivity analysis and found that the most sensitive parameters are those associated with the source-term, the direct exposure pathway, and the inhalation pathway. The pathways and uncertainty analysis helped staff to focus on sensitive parameters (Table II). Subsequently staff conducted its own deterministic analysis using conservative parameters that bound site physical conditions and the scenario used for the unrestricted use of the site. Since the DCGLs derived using our conservative deterministic analysis were lower than those derived by the licensee, staff conducted more realistic probabilistic dose analyses using the applicable resident farmer scenario, site specific parameters, and realistic distributions of the most sensitive input parameters. In addition, staff selected the best estimate of the dose distribution, through the performance period of 1,000 years, as recommended in NUREG-1727 (NRC, 2000(b) and NUREG-1757 (NRC, 2002(b)). Finally we compared its derived DCGLs, equivalent to 0.25 mSv/yr, using probabilistic analyses with the licensee's proposed DCGLs.

Results

The DCGLs were derived for the contaminated source in the surface soil (top 15 cm). The approach and methodology described above were employed in derivation of the DCGLs. The RESRAD 6.21 code was used in a deterministic as well as in a probabilistic mode. The input parameters and distributions used in these dose impact analyses are listed in Tables 2 and 3. Table 4 presents a list of the DCGLs derived for surface soil using deterministic and probabilistic runs. It should be noted that the deterministic DCGLs correspond to the annual peak dose, 0.25 mSv/yr (25 mrem/yr), during the 1000-year compliance period. However, the probabilistic DCGLs correspond to the peak-of-the-mean annual dose during the 1000-year compliance period. NUREG-1727 recommends using a more realistic probabilistic modeling approach and use of the best estimate of the dose using peak-of-the-mean dose.

All pathways were included in the exposure scenario, including the drinking water pathway. The results show that most of the dose is related to Th-232, Th-228, and Ra-228 with the main component of the dose (85- 90%) resulting from direct exposure. The plant-ingestion pathway dose corresponded to 10-15% of the total dose. Other pathways such as inhalation and ingestion of meat, milk, soil, and water corresponded to less than 5% of the total dose.

The derived DCGLs presented in Table 4 show that the probabilistic DCGLs are comparable with the licensee's proposed DCGLs. In fact, using the licensee's proposed DCGLs as input, concentration values would produce a mean probabilistic dose of 25 ± 0.16 mrem/y. Figure 2 shows the cumulative probability of the peak doses from all runs. The 50^{th} percentile of the dose is 23.8 ± 0.61 mrem/y, the 90^{th} percentile is 37.4 ± 1.39 mrem/y, and the 95^{th} percentile is 44.9 ± 2.20 mrem/y. Therefore, based on NUREG-1727 recommendations of using the mean dose for site-specific dose compliance, staff would approve the DCGLs proposed by the licensee. It should be noted that after 50-70 years the dose drops to half of its value because of the decay and erosion of Ra-228 and Th-228. The most sensitive parameters impacting the dose results were found to be the shielding and occupancy factors. These factors may change the dose results by a factor of 100% or more. The contaminated zone area was also found to be sensitive but to a lesser extent (e.g., by a factor of 10% or less).

The DCGLs derived based on RESRAD 6.21 deterministic runs (Table 4) were found to be more restrictive and approximately half of the those derived using the probabilistic analyses. These results are due to use of a single conservative value for each of the sensitive parameters listed in Table II. The main component of the deterministic dose is also due to the direct exposure pathways similar to the probabilistic dose results. Considering the lack of site-specific information, the higher dose result using conservative single-valued deterministic parameters imply that the probabilistic dose analysis using distributions of sensitive input parameters appear to be more realistic because the distributions usually bound the variability of site conditions. The dose appears to be high for the first year, decreasing after 10 years, and decreasing sharply after 100 years.

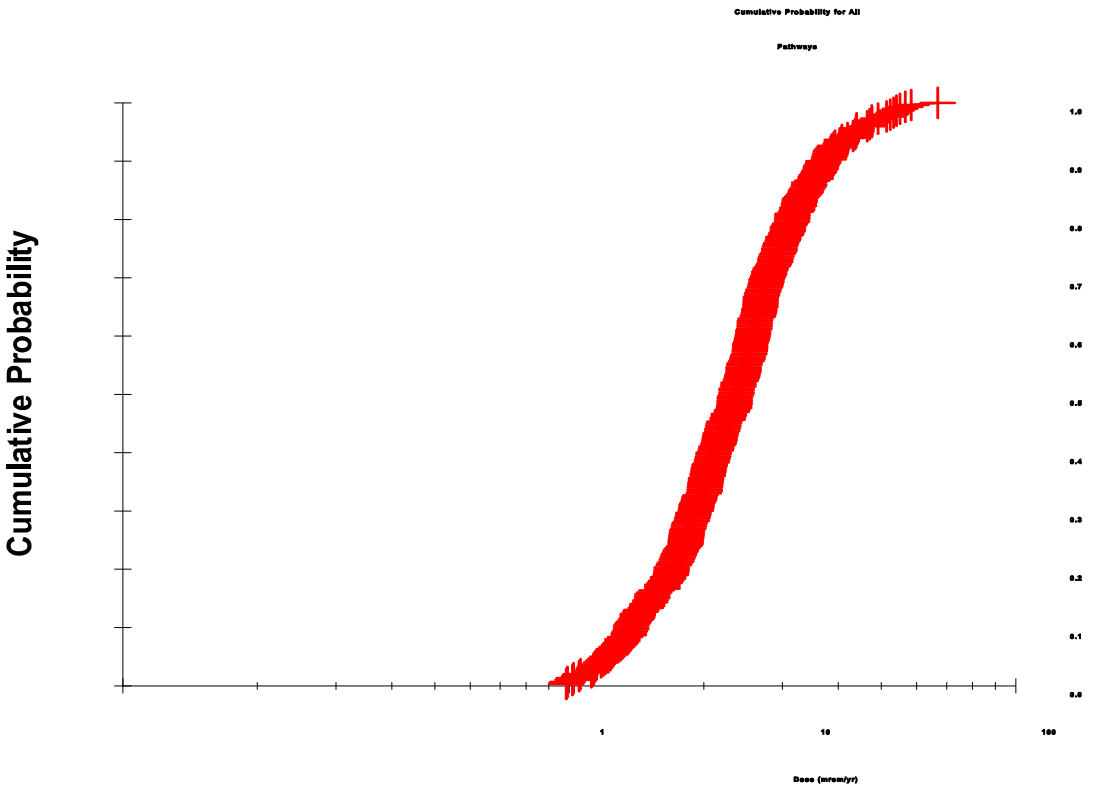
Staff conducted dose analysis for other sites and found that deterministic analysis result in more restrictive dose results for all cases. In general, the derived DCGLs using deterministic runs were higher than those of probabilistic runs by approximately a factor of two.

SUMMARY AND CONCLUSION

Sensitive parameters may impact the dose results by a factor that may reach one to two orders of magnitude or more. Therefore, it is recommended to assess sensitive parameters based on site specific conditions and examine the causes of their impacts on the dominant pathway doses and the overall output dose value. Parameter uncertainties could be reduced significantly through establishing interrelationships between the influential factors, or parameters, and through assessment of the ranges between the probabilistic variables that have the most influence on each other and the dose. Our comparative analysis and evaluation show that the probabilistic analysis is an appropriate, and more realistic, approach for the risk-informed performance-based decision-making. However; deterministic analysis, when properly performed to bound uncertain conditions and variable parameters, was found to produce unnecessary restrictive dose results. For the cases studied, the deterministic dose results were found to be, on the average, higher by a factor of approximately two than the probabilistic results. For site-specific dose analysis, NRC staff recommend use of a probabilistic analysis approach (NUREG-1727, NUREG-1757) and use of the best estimate of the dose (e.g., peak-of-the-mean of the annual dose) for compliance with the dose criteria. Therefore, staff would approve the higher probabilistically derived DCGLs for the example case.

Table IV DCGLS Derived for Surface Soil Using Probabilistic and Deterministic RESRAD 6.21 Code

Radionuclide	Radionuclide DCGLs Calculated by Staff Equivalent to TEDE of 0.25 mSv/yr (25 mrem/y) **Using Probabilistic Analysis**	Radionuclide DCGLs Calculated by Staff Equivalent to TEDE of 0.25 mSv/yr (25 mrem/y) **Using Deterministic Analysis**
Th-232 Decay Series		
Th-232	5.661	2.424
Ra-228	5.661	2.424
Th-228	5.661	2.424
U-238 Decay Series		
U-238	0.3113	0.133
U-234	0.3113	0.133
Th-230	0.6198	0.265
Ra-226	0.2785	0.1192
Pb-210	0.2785	0.1192
U-235 Decay Series		
U-235	0.0137	0.0059
Pa-231	0.02712	0.0116
Ac-227	0.02712	0.0116



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