The Influence of Future Human Behaviors in Performance Assessment – 10483

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ABSTRACT

Future human exposure to materials disposed in radioactive waste repositories is potentially a low-probability / high-consequence event. Probabilistic methods are often used in performance assessments (PAs) with respect to containment of wastes and their migration in the environment, but are not commonly applied to the exposure models that describe the behavior of potentially exposed individuals and groups of people. A probabilistic framework for assessing and presenting the potential for future exposures, and associated radiation doses, is presented. The framework differentiates dose results that are conditional on exposure (consequence analysis) and dose results that account for the likelihood of exposure. Under site conditions associated with a low probability of future exposure, such as when a repository is in a remote area and/or protected by intrusion barriers, simulations of individual or population dose may show that the expected dose is essentially zero within the performance period, but with a small chance of significant doses. The implications of such conditions for measuring disposal system performance and for risk management are discussed.

INTRODUCTION

The U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC), and the U.S. Environmental Protection Agency (EPA) require the completion of performance assessments (PAs) for radioactive waste disposal facilities under their purview. The DOE PAs provide the basis for establishing with reasonable expectation that low-level radioactive waste (LLW) facilities meet the radiological performance objectives established in DOE Manual 435.1 [1]. Similarly, the NRC established performance objectives in the Code of Federal Regulations (CFR) as 10 CFR 61 [2]. Unlike the probabilistic performance objectives defined in regulations such as the EPA's 40 CFR 191 [3] governing the containment of disposed transuranic wastes, the DOE and NRC dose assessment performance objectives are defined as single values, and compliance with the objectives is commonly assessed by comparing estimated maximum hypothetical doses with these "bright line" regulatory requirements. The principle of keeping doses as low as reasonably achievable (ALARA), however, opens the door to performing decision analysis for PA modeling and decision making, and suggests a different approach to dose calculation. It does this by shifting attention from meeting a dose-based standard under a set of regulatory constraints to PA maintenance and reducing uncertainty.

Significantly more attention needs to be paid to the assumptions underlying the dose assessment to support radioactive waste management decisions. To verify uncertainty reduction requires a probabilistic assessment. To perform decision analysis under ALARA to support or optimize disposal, closure and long term management of the disposal facilities requires an evaluation of population risks in addition to, or instead of, risk to an individual.

Highly detailed (process-level) mathematical models can be useful tools in regulatory environmental decision making by capturing state-of-the-science understanding of complex real-world phenomena. In DOE and NRC PAs such complex models focus on the future release of contamination from the disposed wastes, followed by transport of contaminants in the physical environment. The process-level models used in these PAs have as their output concentrations of radionuclides in environmental media over time, or radionuclide flux across some boundary over time. Such process-level models do not extend to human radiation dose. They do not incorporate important factors that can influence human exposure, such as uncertainties related to human behaviors at an individual or population level, the practical longevity and efficiency of institutional controls, or human responses to detection of engineered barriers or warnings about site hazards. The sophistication of the fate and transport models used in many PAs stands in contrast to the relatively simplistic human exposure models.

A focus on process-level environmental fate and transport modeling in DOE PAs is largely a continuation of an underlying philosophy of "bottom-up" modeling. This approach leads to the formation of large complex models that focus on relatively well-developed areas of scientific inquiry. In a "top-down" modeling approach, the need for more refined (process-level) models is identified based on the sensitivities of a simpler system-level model that accounts for all phenomena related to the effects on the system.

Usually, only a few parameters actually drive model predictions for a given output, such as annual radiation dose. During model building, exploration of the complete model domain is necessary to ensure that those few parameters are identified. As described above, process-level environmental transport models capture only a portion of the complete model domain with respect to the output of radiation dose. Informed environmental decision making may not be enhanced by making transport models ever more complex, because those models address uncertainties in only some aspects of a chain of events that may ultimately result in human radiation doses. Instead, modeling should be driven by the decision making process. For PAs this involves establishing decision endpoints such as disposal, closure and long-term management and evaluating risk for each option. This is consistent with the National Research Council findings and recommendations in [4], which indicate the importance of performing risk assessment for evaluation of the long term effects and consequences of disposed radioactive waste. The decision options can usually be optimized by careful consideration of system-level model structures, including spatio-temporal scaling, rather than more refined process-level modeling. The "top-down" modeling approach is also consistent with the methods that form the basis of the "modeling commandments" of Morgan and Henrion [5].

A system-level model should address all factors that are important to the decision making process, including those that are important for human exposure scenarios. This paper focuses on the effect that uncertainty in future human settlement and behaviors may have on predicted radiation dose within the context of a radiological PA. The results of this analysis suggest that site-specific factors, such as probable future population density, should be accounted for if the objective of modeling is to fully support risk management decisions.

FRAMEWORK

The degree of uncertainty in the magnitude of future releases to the environment from a waste disposal facility has been the focus of past probabilistic PAs (e.g. Nevada Test Site [NTS] Radioactive Waste Management Sites, Yucca Mountain Project, Waste Isolation Pilot Project). Some aspects of dose assessment have been handled probabilistically, but these are generally limited to variability in contact rates such as soil or food ingestion rates, inhalation rates, etc. These PAs have been conditioned on the presence of a receptor at a location just outside of the administrative boundary of the facility throughout the modeling period. There are two reasons why this may present a distorted perspective on probable future doses: First, the likelihood that people will be residing in the vicinity of the disposal facility is ignored by assuming that it will happen, with an implied probability of one. With respect to future radiation dose, a facility located in an inhospitable environment with historically low population density is treated as equivalent to one in an area of historically high population density. Second, the administrative boundary is relevant as a constraint on the location of a receptor only if institutional control is maintained throughout the modeling period. The continued presence of institutional control suggests the monitoring of site conditions, which implies that significant releases to the environment outside the facility would be detected and potential human exposures precluded. In analyses performed for the NRC under 10 CFR 61 [2], by contrast, the primary human receptor is assumed to be exposed on the facility at a time following the institutional control period. This is a more realistic assumption for analyses supporting risk management decisions in an ALARA context.

The constraint on the location of a receptor in DOE-type PAs is the basis of differentiating member-of-public (MOP) and inadvertent human intruder (IHI) exposure scenarios [1]. The MOP scenarios apply only at locations outside the administrative boundary of the disposal facility. The IHI scenarios apply on the facility, but the IHI receptor is labeled “hypothetical”. As described in Section B.6 of DOE’s Format and Content Guide for Low-Level Waste PAs [6], “The purpose of the inadvertent intruder analysis is to provide a surrogate for the determination of LLW that is acceptable for near-surface disposal. The inadvertent intruder analysis does not have the purpose of protecting future members of the public.” In fact, IHI and MOP doses are equally hypothetical under the assumption of perpetual institutional control if monitoring is assumed to occur as part of such control.

In the framework used for this analysis, institutional control is considered as one of several factors affecting disposal facility performance, where “performance” is based on the probability and magnitude of future human radiation doses. A conceptual framework of the influences on the probability of future human doses at a closed disposal facility is shown in Figure 1. To specify the model, information on the likelihood of future settlement and development activities in the region of the disposal facility must be obtained, most likely by a structured elicitation of regional stakeholders and subject matter experts. An example of such an elicitation is that conducted for the potential for IHI into LLW disposed at the NTS [7, 8].

The continuous presence of receptors at specific locations relative to the disposal facility is not assumed in this dose assessment framework. Future exposure is treated as a combination of probability-based events rather than a condition. The primary event is the appearance of a homestead or community (see Figure 1) on or adjacent to the facility, and subsequent events may

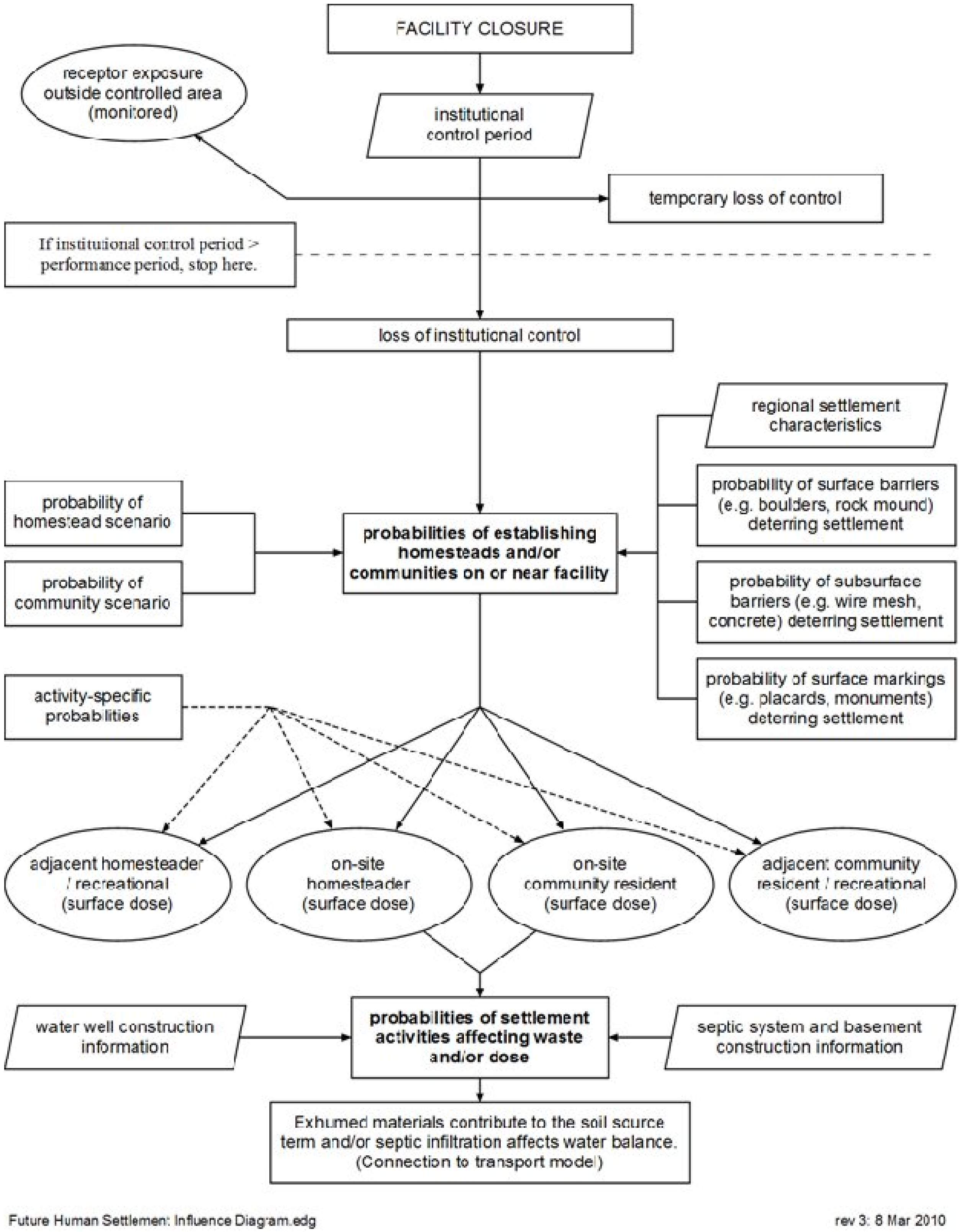

Fig. 1. Influence diagram for probability of future human settlement.

include raising produce or livestock at a homestead. Annual dose therefore follows a mixture distribution with zero dose in years when no receptors are present, and a distribution of potential individual and population doses when receptors exist. Such information on the probable annual dose through time might lead to different waste management decisions than if derived by considering only the results of a dose assessment that is conditioned on the constant presence of a receptor.

Three receptor conditions are evaluated. In the first alternative, a receptor is assumed to be present at each model year. In the second and third alternative, the receptor is present as the model dictates, depending on the probability that a successful settlement will occur. When a receptor is not present, then the dose consequences are zero. Both individual and population-based risks are considered.

Conditional Individual Maximum Annual Dose: MAX_{time}(*individual radiation dose*). This is the radiation dose traditionally compared to regulatory criteria for performance assessments. It is an estimate of the maximum annual radiation dose within the simulation time period. The maximum is used for comparison to the performance objective because, by assumption, a receptor is present at that time, and it is that receptor who receives the greatest dose and hence must be protected. For a probabilistic model that properly accounts for spatio-temporal scaling, the output of the model at each time step represents the system-level or average effect of the system, or average dose. The distribution of the maximum average dose can be obtained from this output, where maximum is expressed across time. The mean or a percentile of this distribution could be used for comparison to the performance objective.

Unconditioned Individual Annual Dose: (*individual radiation dose* × *Ind{0,1}*, where the indicator function, *Ind*, is 0 if there are no receptors present, and 1 if a receptor is present). The presence of a receptor depends on the probability of occurrence of the receptor scenario at the location and time of interest. However, the effect is that a receptor is or is not present. If a receptor is not present, then the dose is zero. If a receptor is present then the dose is the annual dose calculated by the model. The effect is that the time history of annual dose expresses zero dose at some time points and the modeled individual dose at other time steps.

Unconditioned Population Dose: SUM_{time}(*individual radiation dose* × *Ind{0,1}* × *number of individuals*). Conceptually, the population dose is calculated at each time step, and is then summed across time. The *number of individuals* is specified probabilistically. The population dose results are useful for comparing potential future doses across different prospective disposal facilities, performing ALARA assessment, and performing decision analysis for PA modeling and decision making.

ANALYSIS

An analysis of the potential influence of human activity on predicted future radiation dose was conducted in the GoldSim modeling environment. GoldSim is a dynamic simulation modeling platform that represents a system by defining mathematical relationships between variables. In this case, the system is a simplified representation of the events and factors relating to the probability that humans will live on or adjacent to a disposal facility in the future, and engage in activities that determine their potential exposure to radionuclides. The dynamic aspect of the simulation involves the sampling of probability distributions over time for different events described by the site conceptual model depicted in Figure 1. The simulation period used in this example was 1,000 years.

The inputs to a dose assessment calculation consist of radionuclide concentrations in one or more environmental media to which the receptor is exposed, such as surface soil, groundwater, and air. For this analysis, time series of radionuclide concentrations in these media were obtained from a separate publicly available GoldSim PA model: the *Generic Performance Assessment for a Shallow Radioactive Waste Disposal Facility*. Exposure concentrations for a 1,000-year modeling period were developed for forty radionuclides including tritium (H-3), Co-60, Sr-90, Tc-99, Cs-137, I-129, Np-237, Am-241, and various isotopes of radium, thorium, uranium, and plutonium. Non-zero radionuclide concentrations exist for most radionuclides and exposure media from the beginning to the end of the 1,000-year modeling period.

To highlight the potential differences that the probability of human contact with disposed radioactivity may have on dose, example calculations were conducted for two hypothetical radioactive waste disposal facilities. The “West” facility is located in a remote area of the Western United States with limited rainfall and poor agricultural prospects. The “East” facility is located near current population centers in a region with high agricultural productivity, typical of the eastern U.S. The inputs for assessing the probability of future human settlement and radiation dose are derived in part from information elicited for the Nevada Test Site [7].

Two types of human settlement are addressed: a Homestead and a Community. A Homestead is envisioned as a rural settlement whose inhabitants have a high probability of engaging in agriculture, including home gardens, orchards, and livestock. A Community is envisioned to be a development of many single family dwellings (such as a “bedroom community”), with low probability of home gardens and fruit trees and no livestock. For both the Homestead and Community, the probability of settlement on or near the disposal facility is governed by a recurrence interval for such construction within the larger region that includes the facility. If the Homestead or Community that “appears” is located on the facility, then successful settlement also depends on the effectiveness of any barriers at preventing such settlement.

The probability that a Homestead residence is located upon the facility when a Homestead appears within the larger region that includes the facility is calculated simply according to the ratio of the area of the facility to the area of the larger region. This presumes that only a single Homestead may occur on the facility at any time, and that it will not be established if a Community already exists on the Facility.

For a Community, which consists of many individual homes, there may be multiple homes sited upon the facility. The Community is “sited” within the larger region by assuming that the facility is a circular area at the center of a larger, square region. When a Community “appears”, in accordance with its recurrence interval and barrier failure rate, the coordinates of the center point of the Community are selected from uniform distributions related to size of the regional area. The distance between the center of the circular Community and the center of the circular disposal facility, X_{CF} , is given by:

$$X_{CF} = \text{abs}\left(\sqrt{(x_C - x_F)^2 + (y_C - y_F)^2} - \sqrt{A_F / \pi}\right) \quad \text{(Eq. 1)}$$

where

x_C, y_C	=	x and y coordinates of Community center (L)
x_F, y_F	=	x and y coordinates of Facility center (L)
A_F	=	area of radioactive waste disposal facility (L^2)

The condition that some portion of the Community overlaps the disposal facility is calculated based on the value of X_{CF} , and the radii of the Community and the facility. The number of houses in a Community located within the area of overlap is then calculated based on an assumed lot size. The inputs used to calculate the probability of Homestead and Community settlement for these example calculations are provided in Table I.

Once a Homestead or Community has appeared on or adjacent to the Facility at some point in time within the modeling period, radiation dose is calculated for the individual receptors. The exposure scenarios and pathways employed are summarized in Table II.

For each exposure pathway, a pathway dose conversion factor (PDCF) is calculated as a function of the exposure parameter values for that pathway and a dose conversion factor specific to the exposure route. Each PDCF has units of Sv/yr per Bq/g, or something dimensionally equivalent. For example, a PDCF for soil external radiation is calculated as

$$PDCF_{ext} = \left[\left(ET_{in} \times GSF\right) + ET_{out}\right] \times EF \times DCF_{ext} \times \rho_b \quad \text{(Eq. 2)}$$

where

ET_{in}	=	fraction of time spent indoors (dimensionless),
GSF	=	gamma shielding factor for internal exposure (unitless),
ET_{out}	=	fraction of time spent outdoors (dimensionless),
EF	=	fraction of time exposed (dimensionless),
DCF_{ext}	=	external dose conversion factor (Sv-cm^3 per yr-Bq), and
ρ_b	=	dry bulk soil density (g/cm^3).

PDCF results are then multiplied by the exposure concentration in each exposure medium (soil, groundwater, air, garden vegetables, beef, etc) to calculate individual radiation dose. Because the results of interest to this paper are driven by settlement probability, exposure parameter values have been defined as point estimates rather than stochastics. Dose conversion factors for individual radionuclides were obtained from Federal Guidance Reports 11 and 12 [9, 10]. Input parameter point estimate values and PDCF equations for other pathways are available within the GoldSim model used to conduct this analysis.

Table I. Inputs for calculating the probability of Homestead and Community settlement

Parameter Name	Units	U.S. West Value	U.S. East Value	Notes
Homestead Recurrence	1/yr	Beta(0.009, 0.001) min: 0.003 max: 0.016	Beta(0.2, 0.04) min: 0.06 max: 0.5	Sampled once at the beginning of each realization.
Homestead Appearance	–	random occurrence		A timed event following a Poisson distribution with a rate equal to Homestead Recurrence
Community Recurrence	1/yr	Uniform(0.0005, 0.001)	Uniform(0.005, 0.01)	Sampled once at the beginning of each realization.
Community Appearance	–	random occurrence		A timed Event following a Poisson distribution with a rate equal to Community Recurrence
Number of Homesteads	–	Beta(5, 3) min: 0 max: 20	Beta(20, 10) min: 0 max: 50	Sampled on the event “Homestead Appearance”.
Facility Area	ha	20		The area of the disposal facility where wastes are buried.
Regional Area	ha	10,000		The regional area to which the recurrence intervals apply.
Barrier Effectiveness	–	Beta(0.8, 0.1) min: 0.001 max: 0.999		Sampled once at the beginning of each realization. This is the probability any barrier(s) prevents successful settlement.
Barrier Result	–	Binomial(batch size = 1; Probability = Barrier Effectiveness)		Sampled once at the beginning of each realization.
Homes on Facility	–	Binomial(batch size = Number of Homesteads; Probability = Facility Area / Regional Area)		Sampled on the event “Homestead Appearance”. Defines the number of hypothetical Homesteads that “appear” on the Facility.
Community Area	ha	Uniform(50, 200)		Sampled on the event “Community Appearance”.
Lot Size	ha	Triangular(0.05, 0.2, 0.8)	Triangular(0.04, 0.05, 0.2)	Sampled on the event “Community Appearance”.

Although each exposure parameter is defined deterministically, probability distributions were defined for the lifespan of a Homestead or Community, the number of occupants in a home, and the likelihood that individuals in a home engage in certain agricultural activities. These probabilities are defined in Table III.

The Community dose calculations in the model samples exist within a GoldSim construct called a “Looping” container. At each of the annual model time steps, the Looping container runs sequential dose calculations for each home sited over the Facility and stochastics within the container are resampled with each loop. Therefore, each individual house within the Community may vary with respect to the presence of a home garden and fruit trees, and the number of occupants.

Table II. Exposure scenarios and exposure pathways

Exposure Pathway	Homestead on Facility	Community on Facility	Off-Site (recreational)
Inhalation (indoor)	X	X	
Inhalation (outdoor)	X	X	X
Soil ingestion	X	X	X
Drinking Water Ingestion	X	X	
Garden Vegetable Ingestion	X	X	
Orchard Fruit Ingestion	X	X	
Beef Ingestion	X		
Chicken Ingestion	X		
Egg Ingestion	X		
External (ground)	X	X	X
External (air; immersion)	X	X	X

Table III. Probabilities affecting radiation dose at a Homestead or Community

Parameter Name	Units	West Value	East Value	Notes
Homestead Lifespan	yr	Beta(12.86, 7.89) min: 0 max: 55		Sampled on the event "Homestead Appearance".
Homestead Occupants	–	Discrete(0.1,1; 0.25,2; 0.17,3; 0.15,4; 0.13,5; 0.1,6; 0.06,7; 0.04,8)		Sampled on the event "Homestead Appearance".
Community Lifespan	yr	Cumulative(0,0; 0.1,10; 0.25,35; 0.5,50; 0.75,65; 0.95,100; 1,150)		Sampled on the event "Community Appearance".
Community Occupants	–	Discrete(0.1,1; 0.25,2; 0.17,3; 0.15,4; 0.13,5; 0.1,6; 0.06,7; 0.04,8)		Sampled on changed LoopCount for the looping Container that holds the Community dose calculations. The loop count is set equal to the number of homes sited above the Facility.
Vegetable Garden Exists (Homestead)	–	Discrete (0.25,0; 0.75,1)	Discrete (0.05,0; 0.95,1)	Sampled on the event "Homestead Appearance".
Fruit Orchard Exists (Homestead)	–	Discrete (0.5,0; 0.5,1)	Discrete (0.05,0; 0.95,1)	Sampled on the event "Homestead Appearance".
Poultry Raised (Homestead)	–	Discrete (0.8,0; 0.2,1)		Sampled on the event "Homestead Appearance".
Beef Raised (Homestead)	–	Discrete (0.9,0; 0.1,1)		Sampled on the event "Homestead Appearance".
Vegetable Garden Exists (Community)	–	Discrete (0.95,0; 0.05,1)	Discrete (0.85,0; 0.15,1)	Sampled on changed LoopCount for the looping Container that holds the Community dose calculations.
Fruit Orchard Exists (Community)	–	Discrete (0.98,0; 0.02,1)	Discrete (0.9,0; 0.1,1)	Sampled on changed LoopCount for the looping Container that holds the Community dose calculations.

RESULTS AND DISCUSSION

Both the East and West versions of the model were run with 10,000 realizations in order to attempt to capture the upper percentiles of dose related to rare events. For the sake of brevity, recreational scenario results (see Figure 1) for receptors who reside beyond the facility boundaries have not been shown here. The results of the example calculations for the Homestead and Community settlements are organized according to

1. conditional maximum individual annual radiation dose (Table IV),
2. unconditioned individual annual radiation dose (Tables V and VI), and
3. unconditioned population annual radiation dose (Tables VII and VIII).

The results for conditional maximum individual annual radiation dose are shown in Table IV. The dose percentiles are evaluated for the 10,000 maximum annual doses obtained from the simulated model. As expected, the calculations show that the conditional maximum annual doses are equal for the West and East example sites, and are not affected by the nature of expected settlement events. The results in Table IV were identical when the simulation was conducted assuming no engineered barriers, because the assumed probability that the barriers will be ineffective at presenting settlement and exposure is sufficiently high (about 20%) that maximum annual dose within 1,000 years is unaffected when a receptor is assumed to attempt settlement every year. Because these Homestead and Community results are identical, it is evident that the additional agricultural exposure pathways included for the Homestead scenario (see Table II) did not affect the maximum annual dose in these example calculations. The results in Table IV are representative of a dose assessment for a traditional PA, which is conditioned on the presence of a receptor at all times during the simulation period.

Table IV. Summary of conditional maximum individual annual radiation dose

On-Site Homestead Settlement				On-Site Community Settlement			
Eastern site		Western site		Eastern site		Western site	
percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)
0.1	8.9	0.1	8.9	0.1	8.9	0.1	8.9
0.25	8.9	0.25	8.9	0.25	8.9	0.25	8.9
0.5	16	0.5	16	0.5	16	0.5	16
0.75	55	0.75	55	0.75	55	0.75	55
0.9	82	0.9	82	0.9	82	0.9	82
0.95	85	0.95	85	0.95	85	0.95	85
0.99	85	0.99	85	0.99	85	0.99	85

The unconditioned individual annual radiation dose is also evaluated for the maximum annual value within the simulation period, and also for all values within the simulation period. A summary of these results is provided in Table V for the case when engineered barriers are present. Unlike the analogous results that are conditioned on the presence of a receptor, the unconditioned maximum individual average doses are very different for the West and East example sites, making it an informative discriminator between these disposal sites. The most striking difference between the conditional and unconditioned maximum doses is that, for the majority of realizations, the annual dose in the example calculations is zero when accounting for the probability that a receptor is present to receive radiation dose. The difference is related to the higher probability of an individual residing on the facility at the East example site at a time following closure. There is also a difference between the Homestead and Community results. This difference reflects a higher probability that an individual home will be located on the facility in the Community scenario than in the Homestead scenario.

Table V. Summary of unconditioned individual annual radiation dose (barriers present)

On-Site Homestead Settlement				On-Site Community Settlement			
Eastern site		Western site		Eastern site		Western site	
percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)
maximum annual value within the simulation period							
0.1	0	0.1	0	0.1	0	0.1	0
0.25	0	0.25	0	0.25	0	0.25	0
0.5	0	0.5	0	0.5	0	0.5	0
0.75	0	0.75	0	0.75	0	0.75	0
0.9	7.1	0.9	0	0.9	0	0.9	0
0.95	8.5	0.95	0	0.95	0.058	0.95	0
0.99	35	0.99	1.5	0.99	8.8	0.99	6.1
all annual values within the simulation period							
0.1	0	0.1	0	0.1	0	0.1	0
0.25	0	0.25	0	0.25	0	0.25	0
0.5	0	0.5	0	0.5	0	0.5	0
0.75	0	0.75	0	0.75	0	0.75	0
0.9	0	0.9	0	0.9	0	0.9	0
0.95	0	0.95	0	0.95	0.010	0.95	0
0.99	0	0.99	0	0.99	8.3	0.99	0.69

Summary results in Table V are also provided for all annual doses predicted by the model. For the Homestead settlement scenario, more than 99% of the time no receptors are expected to be present. Hence, the 99th percentile of the expected annual dose is 0 mSv/yr for Homestead settlements. For the East Community scenario, which has a recurrence rate tenfold higher than the West example site and denser housing (see Table I), the 95th percentile unconditioned dose (0.01 mSv/yr) is far below the conditional dose (85 mSv/yr) shown in Table IV.

The probability that barriers are effective averages close to 80%, in which case it is reasonable that at least 80% of the simulations generate a zero dose. Further zeros are obtained when receptors are not present, which occurs more often for the Western site.

The difference between the maximum results in Tables IV and V show the effect of taking credit for the site-specific settlement probabilities. Since 10,000 realizations were run in these simulations, the maximum annual dose results reflect percentiles of 10,000 values, while the latter reflect percentiles of 1×10^7 values (10,000 realizations × 1,000 model years). This distinction is important to understand from both a risk perspective and an ALARA perspective. From a risk perspective, the results demonstrate how rarely a receptor may be exposed under the assumptions of the model. If decision analysis in the context of ALARA is used to optimize disposal, closure and long term management decisions, then the basis will be dose to all exposed receptors. It makes a huge difference for ALARA analysis if the conditional maximum dose is used, the unconditioned maximum dose is used, or, more appropriately, if all the annual doses are used.

The simulations shown in Table V were also conducted assuming no engineered barriers were present. These results are shown in Table VI. The differences in the results are relatively minor when looking at the percentiles based on all annual values. As expected, the unconditioned doses are higher in the absence of engineered barriers. Without barriers, receptors are absent only based on the probability of Homestead of Community settlement in the vicinity of the disposal facility, and not also on the presence of an effective engineered barrier.

Table VI. Summary of unconditioned individual annual radiation dose (no barriers)

On-Site Homestead Settlement				On-Site Community Settlement			
Eastern site		Western site		Eastern site		Western site	
percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)
maximum annual value within the simulation period							
0.1	2.5	0.1	0	0.1	0	0.1	0
0.25	5.1	0.25	0	0.25	0	0.25	0
0.5	7.2	0.5	0	0.5	0	0.5	0
0.75	8.5	0.75	0	0.75	0.066	0.75	0
0.9	16	0.9	0	0.9	6.5	0.9	0
0.95	40	0.95	1.6	0.95	8.8	0.95	6.7
0.99	81	0.99	8.9	0.99	54	0.99	47
all annual values within the simulation period							
0.1	0	0.1	0	0.1	0	0.1	0
0.25	0	0.25	0	0.25	0	0.25	0
0.5	0	0.5	0	0.5	0	0.5	0
0.75	0	0.75	0	0.75	0.014	0.75	0
0.9	0	0.9	0	0.9	4.8	0.9	0
0.95	0	0.95	0	0.95	8.7	0.95	0.94
0.99	8.9	0.99	0	0.99	8.9	0.99	8.9

The results in Tables IV through VI are all potentially applicable for comparison to the annual dose metrics in DOE Manual 435.1 [1] and 10 CFR 61 [2]. Although the individual annual doses might form the basis for an ALARA analysis, such an analysis should be based on a population-based assessment, in which each individual annual dose is multiplied by the number of receptors present at the time. Tables VII and VIII show percentiles of the population dose integrated over the 1,000-year modeling period for conditions with, and without, engineered barriers. The values in Table VII and VIII are expressed as time-averaged doses, calculated by dividing the cumulative population dose (Sv) by the length of the simulation period (1000 yr). The large difference between the Community results in Tables VII and VIII, compared to the Homestead results, reflects the much larger number of potentially exposed individuals in the Community scenario.

Table VII. Summary of unconditioned population annual radiation dose (barriers present)

On-Site Homestead Settlement				On-Site Community Settlement			
Eastern site		Western site		Eastern site		Western site	
percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)
0.1	0	0.1	0	0.1	0	0.1	0
0.25	0	0.25	0	0.25	0	0.25	0
0.5	0	0.5	0	0.5	0	0.5	0
0.75	0	0.75	0	0.75	0	0.75	0
0.9	3.3	0.9	0	0.9	0	0.9	0
0.95	6.3	0.95	0	0.95	0.048	0.95	0
0.99	17	0.99	1.7	0.99	150	0.99	25

Table VIII. Summary of unconditioned population annual radiation dose (no barriers)

On-Site Homestead Settlement				On-Site Community Settlement			
Eastern site		Western site		Eastern site		Western site	
percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)	percentile	dose (mSv/yr)
0.1	0.56	0.1	0	0.1	0	0.1	0
0.25	1.5	0.25	0	0.25	0	0.25	0
0.5	3.5	0.5	0	0.5	0	0.5	0
0.75	7.0	0.75	0	0.75	0.14	0.75	0
0.9	12	0.9	0	0.9	59	0.9	0
0.95	18	0.95	1.5	0.95	165	0.95	33
0.99	38	0.99	34	0.99	470	0.99	540

With the type of results presented in Tables VII or VIII a decision analysis could be performed, in the context of ALARA, to evaluate and optimize disposal, closure and long term management options. Cost information would be needed, and the cost of implementation of an option would be evaluated against the residual dose, which must also be translated into monetary terms as per DOE and NRC guidance [11, 12]. There are large consequences for such a quantified ALARA assessment depending on which approach is used to measure dose, and this would have a substantial effect on the choice of disposal, closure or long term management options.

DISCUSSION AND CONCLUSIONS

The results shown in Tables IV though VIII address several factors related to the probability and magnitude of post-closure future human radiation doses at a radioactive waste disposal facility. The most obvious conclusion of this analysis is that considering the probability that future human behaviors will cause receptors to reside in the vicinity of the disposal facility can have a profound influence on the outcome of a dose assessment. The 90^{th} percentile conditional maximum individual annual dose of approximately 80 mrem in Table IV may be compared to the unconditioned 90^{th} percentile maximum annual dose results in Tables V and VI to confirm this. For the Western U.S. example site, where settlement probability was lowest, these 90^{th} percentile values for either Homestead of Community settlements were zero.

Tables V and VI show percentiles for both the unconditioned maximum individual annual dose within the 1,000-year simulation period, and for the percentiles of results across all model years. Which percentiles are most appropriate for comparisons to dose-based performance metrics is an open question, although the choice of model output may significantly influence the conclusions drawn from the results of a dose assessment. The public protection requirements of 10 CFR 61 [2] states that there should be "reasonable assurance" that doses are below performance objectives. The individual protection requirements of 40 CFR 191 [3] and DOE Order 435.1 [13] both substitute the phrase "reasonable expectation" in place of "reasonable assurance".

The type of expected future settlement pattern (individual homesteads vs communities) in the area of the disposal facility might also influence the outcome of a PA that utilizes a methodology that accounts for the probability that receptors will be present over time. This is most evident in the results of the population dose assessment in Tables VII and VIII. Population dose integrates individual doses over the simulation period, and is higher in the Community settlement scenario than in the Homestead scenario because of the much greater number of people who may potentially reside on the facility. The methodology developed here can be used to perform quantitative cost-benefit analysis for investing in engineered barriers to prevent future doses, and more generally to optimize disposal, closure and long term management decisions. The example shown confirms that the benefits of engineered barriers are likely to be higher for disposal facilities in areas where entire communities of individuals, rather than individual homesteads, might be affected. Population-level dose assessment results would also be useful for comparing the relative performance of different proposed disposal facilities, or of different proposed disposal systems at the same facility.

REFERENCES

1. *Radioactive Waste Management Manual*, DOE M 435.1-1, U.S. Department of Energy (1999).
2. 10 CFR 61, *Licensing Requirements for Land Disposal of Radioactive Waste*, Code of Federal Regulations, as amended
3. 40 CFR 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, Code of Federal Regulations, as amended
4. National Research Council, *Risk and Decisions About Disposition of Transuranic and High-Level Radioactive Waste*, 2005.
5. Morgan and Henrion, *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge: Cambridge University Press (1990).
6. *Format and Content Guide for U.S. Department of Energy Low-Level Waste Disposal Facility Performance Assessments and Composite Analyses*, U.S. Department of Energy (1999).
7. Black, P.K., K.J. Black, M.M. Hooten, L.P. Mathai, T.S. Stockton, and M.D. Neptune. *Assessing the Probability of Inadvertent Human Intrusion at the Nevada Test Site Radioactive Waste Management Sites –Volumes I and II*, Prepared for the U.S. DOE Nevada Operations Office under Argonne National Laboratory Contract Number W-31-109-Eng-38 (2001).

8. Black, P.K., Moore, B., Crowe, B., Black, K.J., Hooten, M.M., Barker, L.E., and Rawlinson, S.E., *A Common Sense Approach to Assessing the Probability of Inadvertent Human Intrusion at Nevada Test Site Radioactive Waste Management Sites*, Proceedings of the Waste Management Conference, Tucson, AZ, (Best Paper Award), March 1997.
9. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion factors for Inhalation, Submersion, and Ingestion, Federal Guidance Report No. 11*, Oak Ridge National Laboratory, prepared for the Office of Radiation Programs, U.S. Environmental Protection Agency, DE89-011065, 1988.
10. *External Exposure to Radionuclides in Air, Water, and Soil, Federal Guidance Report No. 12*, Oak Ridge National Laboratory, prepared for the Office of Radiation and Indoor Air, U.S. Environmental Protection Agency, EPA-402-R-93-081, September 1993.
11. *Applying the ALARA Process for Radiation Protection of the Public and Environmental Compliance with 10 CFR Part 834 and DOE 5400.5 ALARA Program Requirements*, U.S. Department of Energy (1997).
12. *Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission, Revision 4*, NUREG/BR-0058, Division of Systems Analysis and Regulatory Effectiveness, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission (2004).
13. *Radioactive Waste Management Order*, DOE O 435.1, U.S. Department of Energy (1999).