The Use of Collective Dose for Optimization of a Low-Level Waste Site Closure Cover - 10158

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ABSTRACT

Low-level radioactive waste management regulations require that releases to the environment be as low as reasonably achievable. Collective dose's use in quantitative cost benefit analysis is well accepted for optimization of operational radiation safety, but seldom applied to routine environmental releases. One concern is that collective dose for large areas and long time periods may obscure the spatial and temporal distribution of risk and the magnitude of individual doses. Use of collective dose for optimization also requires that the decision maker justify subjective inputs including truncation limits for the summation of collective dose in space and time, a monetary value for collective dose, and a discount rate for future health detriment. In this study, a probabilistic collective dose model is developed and used to optimize the closure of the Area 5 Radioactive Waste Management Site (RWMS) on the Nevada Test Site. Collective dose's shortcomings are addressed by preparing a dose matrix that disaggregates the collective dose in space and time and by reporting individual doses for exposed subgroups. Important subjective inputs are assigned discrete values reflecting differing opinions, and the consequence of the differences on the final decision is described. The resulting optimization process remains subjective, but clearly identifies subjective inputs, the values selected, and their impact on the decision. For the Area 5 RWMS, the value of the collective dose is small compared to closure cover cost options over a broad range of subjective values for the spatial and temporal limits for truncation of collective dose, monetary value of collective dose, and discount rates for future dose. The collective dose matrix and individual doses indicate that the societal and individual risks are greatest for future residents within the disposal site boundary, suggesting that options deterring intrusion have the greatest potential for cost-effectiveness. The cost of various closure options far exceeds the value of the collective dose averted, indicating that there are few opportunities for cost-effective improvements when closures meet the low dose constraints in waste management regulations.

INTRODUCTION

Radioactive waste management regulations in the United States require that releases to the environment be maintained as low as reasonably achievable (ALARA) [1, 2]. Under the recommendations of the International Commission on Radiological Protection (ICRP), maintaining releases ALARA is accomplished by optimizing radiological protection [3]. Optimization of radiological protection is a subjective decision-making process that chooses the level of protection that most appropriately balances the benefits and costs of radiological operations [4]. Both qualitative and quantitative techniques are available to guide the decision maker.

Cost benefit analysis is a quantitative technique that has been widely applied in operational radiation safety [5]. Application of cost benefit analysis to environmental exposures has been much less widespread and the subject of considerable debate [6–9]. Optimization by quantitative cost benefit analysis relies on calculation of a collective effective dose (CED), which is the individual effective dose summed over the exposed population and the period of exposure. Use of CED for optimization of environmental releases has a number of problems.

The CED for exposures occurring over large populations, expansive geographic areas, and long time periods may obscure the distribution of individual doses with respect to time, space, age, gender, or living habits. The distribution of individual risk with respect to these different factors may be important to the final decision [4]. The aggregation of individual doses into the CED also hides inequities in the distribution of costs and benefits that may occur among individuals, populations, or generations [10]. Decisions based on the CED emphasize societal risks while ignoring individual risks and inequities. The ICRP's recent recommendations are to broaden the process to include constraints on individual dose and to prepare a dose matrix that disaggregates the CED with respect to space, time, and population [3, 4]. Individual elements of the dose matrix can be assigned weights based the decision maker's view of their influence on the decision.

The spatial and temporal limits for summation of individual doses are another concern when exposures occur over large areas and long time periods. Truncation of low individual doses occurring in the future or at distant locations is inappropriate according to the linear no-threshold radiation dose-effect model, which holds that any radiation exposure, no matter how small, carries some carcinogenic or hereditary risk [8]. Others have noted that including low individual doses occurring in the distant future may introduce excessive uncertainty into the decision-making process due to ignorance about the future dose and population size [7, 11].

Cost benefit analysis, which can be a quantitative decision-making tool in some applications, becomes a subjective process when applied to environmental management. The subjectivity of cost benefit analysis applied to environmental management has caused some to question its appropriateness [6]. Selection of values for the cost of health detriment and the discount rate is a subjective decision reflecting the relative weight the decision maker places on present-day and future doses. Concern over the use of subjective values has caused some to avoid the ALARA optimization process completely.

In this study, a probabilistic CED model that implements recent ICRP recommendations is developed and used to optimize the thickness of a closure cover planned for a 92-acre (ac) portion of the Area 5 Radioactive Waste Management Site (RWMS). The Area 5 RWMS is a U.S. Department of Energy (DOE) operated radioactive waste disposal site in Frenchman Flat on the Nevada Test Site (NTS). The 92-ac portion consists of 25 shallow land burial trenches containing low-level, mixed low-level, and asbestiform radioactive waste, and 10 Greater Confinement Disposal boreholes containing high specific activity and transuranic wastes. Concerns about the excessive aggregation of the CED are addressed by preparing a dose matrix and by recording the individual dose received by various groups. Important subjective decisions about the spatial and temporal limits of summation for the CED, the cost of health detriment, and the discount rate are identified and their impact on the final decision evaluated.

METHODS

The cover optimization model is developed from the existing Area 5 RWMS performance assessment (PA) model, implemented in the probabilistic GoldSim simulation platform [12–14]. The site conceptual model, based on multiple cycles of site characterization and PA, assumes that all features, events, and processes release contamination upwards to surface soils and the atmosphere. The site conceptual model is implemented in the GoldSim contaminant transport module as a series of linked one-dimensional mixing cells that estimate the time varying concentration of radionuclides in RWMS soil and air. Soil and atmospheric concentrations off the RWMS are estimated using the decayed cumulative atmospheric release, the deposition velocity, and atmospheric dispersion coefficients abstracted from the Clean Air Act Assessment Package-1988 (CAP88-PC) model [15]. Dispersion coefficients estimated for locations outside the 348-square kilometer (km^2) Frenchman Flat basin are considered very uncertain due to the complex basin and range topography.

In addition to natural release processes, settlement within the RWMS boundary, as described below, is assumed possible after the loss of institutional control. Settlement on the RWMS is assumed to follow drilling of a water well, which causes the release of contaminated cuttings to surface soil. Cuttings from one well are assumed to contaminate one residential home site.

Collective Effective Dose

The CED is the sum of individual effective doses received by all exposed persons over all time. In practice, the CED is usually calculated as the summation of the mean dose in a population times the size of the population or:

$$S = \sum_{i=1}^{m} \overline{E}_i \, N_i \qquad \text{(Eq. 1)}$$

where S is the CED, $\overline{E}_i$ is the mean total effective dose equivalent (TEDE) in population i, and N_i is the population size [3, 10, 11]. The model calculates CED using Eq. 1 for discrete populations in a single community. The CED for distributed rural populations is calculated using the population weighted mean soil and air concentrations of the region. In both cases, the CED is calculated as a rate, summed over the exposed populations, and numerically integrated as long as the exposure occurs.

Eq. 1 implies that some limit must be placed on the summation of CED in space and time. The model is spatially limited to populations within 140 km, which includes the Las Vegas metropolitan area. Individual doses beyond 140 km are not included because they are expected to be extremely small due to the distance to large population centers and extremely uncertain due to the complex terrain of the region. The CED rates are integrated to 10,000 years (y) again to limit excessive uncertainty arising from future dose rates and population sizes.

The structure of the GoldSim model makes disaggregation of the CED by location, time, and exposure scenario relatively easy. Distinct integrator elements are created to calculate and record the CED for different locations and exposure scenarios. The CED can be disaggregated by time by selecting discrete times to record CED.

Individual Dose

The PA model includes a radiological assessment model that calculates the individual TEDE to adults with average living habits as the product of an environmental media concentration and a radionuclide specific scenario dose conversion factor. Calculation of the individual TEDE is relatively simple because there is no groundwater pathway, and residents of Southern Nevada consume virtually no locally produced foods. Doses are calculated for a residential and a water well driller exposure scenario. Resident and driller exposure pathways are limited to external irradiation from soil and air, inhalation of resuspended particulates and gases, dermal sorption of HTO, and inadvertent soil ingestion. Individual doses do not include the dose from inhalation of Rn-222 and its short-lived progeny in air based on DOE guidance.

The optimization model disaggregates the exposed population into subgroups exposed to similar environmental concentrations at a common location and engaged in similar activities. These subgroups are expected to receive reasonably homogenous doses. When the group is at a single location and engaged in a single activity, the individual TEDE is calculated directly. If the group includes discrete communities at multiple locations or homesteaders dispersed over a region, a per-capita dose is calculated as the CED divided by the population size.

Location and Size of Exposed Populations

The exposed populations are divided into residents of existing communities surrounding the NTS and future residents on the NTS. Off NTS communities are assumed to be continuously present at current population levels. No persons currently reside on the NTS and permanent settlement in Frenchman Flat has not occurred in the past, making it impossible to estimate the probability of settlement from historical records. The location, timing, and size of future NTS populations are simulated stochastically using the opinions of a panel of subject matter experts (SMEs) elicited to estimate the probability of intrusion at the RWMS [16].

Off NTS communities are grouped in concentric bands with increasing distance from the RWMS. The groups are NTS boundary to 50 km (Amargosa Valley [population 1,521] and Indian Springs [population 1,488]), 50 to 80 km (Beatty [population 1,024] and Pahrump [population 38,882]), and 80 to 140 km (Las Vegas [population 1.9 million]) [17].

The SMEs developed multiple scenarios for settlement of individual homesteaders or small communities in Frenchman Flat. The Jackass Flats scenario, the most probable scenario according to the SMEs, assumes the appearance of homesteaders in Frenchman Flat, commuting to a small community in the adjacent valley of Jackass Flats. Although the SMEs expected a community in Frenchman Flat to be much less likely, the model includes a community settlement scenario because the larger population may generate a significant CED.

Settlement on NTS is simulated as a Poisson process using GoldSim timed event elements. Using SME opinions, the rate parameter for the Jackass Flats scenario was fit with a four parameter beta distribution with mean 0.0066 y^{-1}, standard deviation 0.0022 y^{-1}, and range from 8×10^{-4} to 0.014 y^{-1} or $B(0.0066, 0.0022^2, 8E\text{-}4, 0.014\ y^{-1})$. The mean implies a 151 y recurrence interval for a Jackass Flats community. The community settlement rate parameter is a discrete distribution with mean of 0.0001 y^{-1}.

Once settlement occurs, a GoldSim looping container randomly selects the homestead or community location, population, and lifetime. As Frenchman Flat offers no attractive resources, settlement is assumed to occur randomly within the habitable area of the basin. Once locations are selected, residences within the RWMS boundary are tallied. Homesteaders are assumed to have one well at any given time and to drill replacement wells at random intervals in time and space. Communities have four water wells and also drill replacements wells. RWMS homesteader wells always intersect waste disposal units. Community wells intersect disposal units randomly with a probability equal to the area of the community within the RWMS divided by total community area.

If the Jackass Flats community event has occurred, the population in Jackass Flats is calculated probabilistically as the community area divided by a residential lot size times the number of residents per household. Mean community size is approximately 2,000 persons. The number of homesteads in Frenchman Flat associated with the community is assumed to be distributed as $B(50, 30^2, 0, 200\ \text{residences})$. If a Frenchman Flat community has occurred, the population is calculated as is done for the Jackass Flats community. If water wells occur within the RWMS, three well drillers per well are assumed to be exposed to contaminated drill cuttings.

Settlement on the RWMS is assumed impossible a long as institutional controls remain effective. Based on the SMEs' opinions, the period of active institutional control is lognormally distributed with geometric mean of 245 y and standard deviation of 2.66 (i.e., $LN[245\ y, 2.66^2]$) . After active institutional controls, a passive institutional control period begins with a distribution of $LN(99\ y,\ 2.32^2)$. Off RWMS settlement in Frenchman Flat and Jackass Flats, is assumed to be possible immediately after closure.

Cost-Benefit Analysis

Cost-benefit analysis selects the cover option with the maximum net benefit, *B*, expressed as:

$$B = V - (P + X + Y) \qquad \text{(Eq. 2)}$$

where *V* is the gross benefit, *P* is the production costs excluding radiation protection, *X* the cost of radiation protection, and *Y* the health detriment cost. The monetary value of the health detriment, *Y*, is assumed to be the product of the CED, *S*, and *α*, a constant dollar per person-sievert (per-Sv^{-1}) conversion factor.

Optimization occurs when the maximum net benefit, *B* in Eq. 2, is achieved. If the goal is to optimize the practice with respect to the level of radiation protection, then the optimum occurs at the global maximum of Eq. 2 or where the derivative with respect to *S* equals zero.

For the case of optimizing cover thickness at the Area 5 RWMS, *V* and *P*, excluding radiation protection, appear to be independent of *S* and are assumed to have derivatives of zero. In this case, the optimum level of protection occurs where:

$$\frac{dX}{dS} + \frac{dY}{dS} = 0 \qquad \text{(Eq. 3)}$$

The expression above indicates that the optimum level of protection occurs at the minimum total closure cost, where total closure cost is the sum of the closure construction costs and health detriment cost.

Cover thicknesses evaluated in the optimization are constrained to those that meet all DOE Manual DOE M 435.1-1 performance objectives and the composite analysis 0.3 millisieverts (mSv) in a year dose constraint [2]. Discrete cover thicknesses of 2.5, 3.0, 3.5, 4.0, and 4.5 m are evaluated and meet all constraints.

Detailed cost estimates, prepared for construction of a 2.5 m and 3 m closure cover, are used to develop a probabilistic model of closure costs with cover thickness as the independent variable. Costs related to cover thickness (e.g., earthwork) are assumed to scale linearly with cover thickness, while tasks specific to the closure project (e.g., fencing) are assumed constant. Model uncertainty is based on the estimator's subjective opinion.

The CED is converted to cost using, *α*, a constant dollar per CED conversion factor. The conversion factor is assumed to be constant because the constraint that all options meet the DOE M 435.1-1 performance objectives ensures that individual doses are below a level where risk aversion is expected. A subjective approach must be used to select α, because no market exists where health detriment is bought or sold [6, 18].

Morgan and Henrion [19] have suggested that parameters reflecting the decision maker's subjective views be treated as value parameters. Value parameters should not be assigned a probability density function because there is no correct value to be uncertain about. Value parameters are assigned discrete values reflecting different opinions. The model is evaluated at each value to determine if the differences impact the final decision. This approach acknowledges the subjective nature of environmental cost benefit analysis, identifies important subjective values entering the decision, and assesses their significance.

The monetary value of health detriment is commonly determined by estimating the value society places on reducing the risk of mortality. Based on reviews of multiple estimates of the value of a statistical life, regulatory agencies in the U.S. have consistently selected a monetary value of \$200,000 per-Sv^{-1} [20, 21]. Most data in these studies are based on 1990 valuations [20, 22]. A literature review found a maximum value of a statistical life of \$300 million in 1990 dollars [22–25]. Multiplying by a radiation risk coefficient of 0.05 Sv^{-1} [22], an upper limit cost of \$15 million per-Sv^{-1} is estimated. Assuming an annual inflation rate of 3.8 percent, the escalated expected and upper limit costs at site closure in 2028 are \$684,000 and \$51.3 million per-Sv^{-1}, respectively.

Costs or benefits occurring after closure in 2028 should be discounted to account for the time value of money. No consensus exists on selection of discount rates for long time periods. Therefore, the discount rate is treated as a value parameter reflecting the decision maker's relative valuation of present-day versus future costs or benefits. Reasonable values for the discount rate are zero and non-zero values in the range of 0.03 to 0.07 [26]. Any non-zero discount rate rapidly reduces the present-day value of future costs and benefits to trivial levels. For example, a discount rate of 0.03 reduces future costs by more than an order of magnitude in 100 y. Health detriment is assumed to be the only future cost or benefit. A non-zero discount rate will effectively reduce the value of future health detriment in the optimization to zero, ensuring selection of the option with the minimum present-day construction cost (i.e., the thinnest cover). Selecting a zero discount rate favors options with higher construction costs. A zero discount rate is evaluated initially. If the zero discount rate case results in unreasonable costs, explicit non-zero values can be considered.

RESULTS

An optimization model that disaggregates CED in space and time and calculates individual TEDE can be readily implemented in a PA model. The resulting model, however, can be significantly more complex. Models that require a groundwater pathway or distribution of agricultural products at a regional scale could be very complex, but were not necessary for the Area 5 RWMS.

The stochastic simulation of future settlement within NTS boundaries also adds significantly to model complexity. Using discrete event elements that trigger looping containers to simulate settlement events significantly increases model run times. The CED for rare events, such as a community in Frenchman Flat with a probability of 0.0001 y^{-1}, exhibits high variability due to the small number of events simulated in 1,000 y. The variability cannot be reduced by increasing model realizations due to the high computational cost of the integrated PA and optimization model. A more efficient approach may be simulating settlement events in a separate, simpler model that can be run with a large number of realizations, using the results to estimate the mean and standard deviation of future populations over time for regions of the model.

Individual TEDE

Individual or per-capita TEDEs are examined to confirm that the CED is not concealing unacceptably high individual doses or composed of trivial doses. The individual TEDE increases over time at all locations. The highest individual TEDEs are expected for sub-groups within the RWMS boundary. The empirical cumulative distribution function of individual dose at 1,000 y for the RWMS driller and RWMS homesteader with a 2.5 m cover indicates that there is a high probability that the individual annual TEDE is small relative to natural background (Fig. 1). Approximately 11 percent of the individual TEDEs are zero, indicating that there is an equal probability of institutional controls deterring onsite residents for 1,000 y.

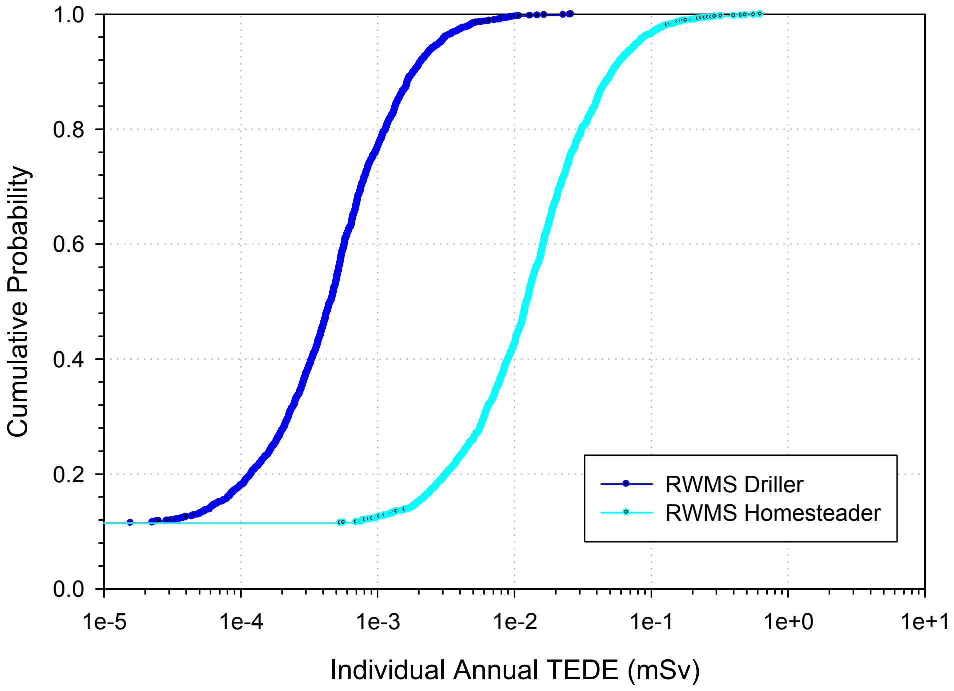

Fig. 1. Empirical cumulative distribution function of individual TEDE at 1,000 y with a 2.5 m thick closure cover for the sub-groups expected to have the highest dose.

The per-capita doses of off NTS residents are much lower. The 95th percentile per-capita annual TEDE at 1,000 y for community residents from the NTS boundary to 50 km is only 4E-9 mSv. The CED for groups beyond the NTS boundary is composed of trivial individual doses and, as per ICRP recommendations, not appropriate for use in the optimization [3].

Collective Effective Dose

The dose matrix for closure with a 2.5 m cover indicates that the CED increases significantly with each increase in time, but increases only slightly with increasing distance (Table I). Overall, the increases with time and distance are small relative to the uncertainty.

Table I. Mean CED (per-Sv) and Standard Deviation Disaggregated by Time and Location for a 2.5 m Closure Cover on the 92-ac portion of the Area 5 RWMS.

			Distance			
			< NTS Boundary	< 50 km	< 80 km	< 140 km
Time	500 y	H-3	8.6E-08	2.1E-07	1.1E-06	2.9E-05
		C-14 (gas)	6.5E-08	1.1E-07	4.0E-07	9.8E-06
		Cs-137+P	2.2E-06	2.3E-06	2.3E-06	4.0E-06
		Pb-210+P	1.8E-05	1.8E-05	1.8E-05	2.1E-05
		Rn-222+P	4.0E-04	4.0E-04	4.0E-04	4.1E-04
		Th-228+P	1.1E-06	1.1E-06	1.1E-06	1.5E-06
		Th-229+P	2.6E-06	2.6E-06	2.6E-06	3.3E-06
		U-235+P	1.2E-06	1.2E-06	1.2E-06	1.5E-06
		U-238+P	4.5E-06	4.5E-06	4.6E-06	6.5E-06
		Total	4.4E-4 ± 170E-4	4.4E-4 ± 170E-4	4.4E-4 ± 170E-4	4.8E-4 ± 170E-4
	1,000 y	H-3	8.6E-08	2.1E-07	1.1E-06	2.9E-05
		C-14 (gas)	3.0E-07	4.6E-07	1.6E-06	3.7E-05
		Pb-210+P	9.8E-05	9.8E-05	9.8E-05	1.1E-04
		Rn-222+P	2.2E-03	2.2E-03	2.2E-03	2.2E-03
		Th-228+P	4.8E-06	4.9E-06	5.0E-06	9.1E-06
		Th-229+P	1.6E-05	1.7E-05	1.7E-05	3.2E-05
		U-235+P	4.0E-06	4.1E-06	4.2E-06	8.0E-06
		U-238+P	1.9E-05	1.9E-05	2.0E-05	4.2E-05
		Total	2.3E-3 ± 89E-3	2.3E-3 ± 89E-3	2.3E-3 ± 89E-3	2.5E-3 ± 89E-3
	10,000 y	Pb-210+P	4.6E-04	4.7E-04	5.0E-04	1.6E-03
		Rn-222+P	1.6E-02	1.6E-02	1.6E-02	2.7E-02
		Th-228+P	1.9E-04	2.2E-04	2.8E-04	2.2E-03
		Th-229+P	4.5E-03	5.1E-03	6.5E-03	5.3E-02
		U-235+P	1.4E-04	1.6E-04	2.2E-04	2.0E-03
		U-238+P	8.3E-04	9.5E-04	1.3E-03	1.2E-02
		Total	2.2E-2 ± 12E-2	2.3E-2 ± 12E-2	2.6E-2 ± 12E-2	9.8E-2 ± 22E-2

+P = includes dose from short-lived progeny assumed to be in secular equilibrium

The CED increases in time due to both rising individual dose rates and exposed population sizes. Individual dose increases over time due to ingrowth of progeny of U-238, Th-232, and U-233. External irradiation from the Rn-222 progeny Pb-214 and Bi-214 is the largest source of CED at all times and locations.

The CED increases with distance as individual dose decreases and the exposed population increases. The increase with distance at 500 and 1,000 y is small because RWMS residents are the largest source of CED at these times (Fig. 2). At 10,000 y, residents from 80 to 140 km are the largest source of CED, explaining the greater increases with distance seen in Table I at 10,000 y.

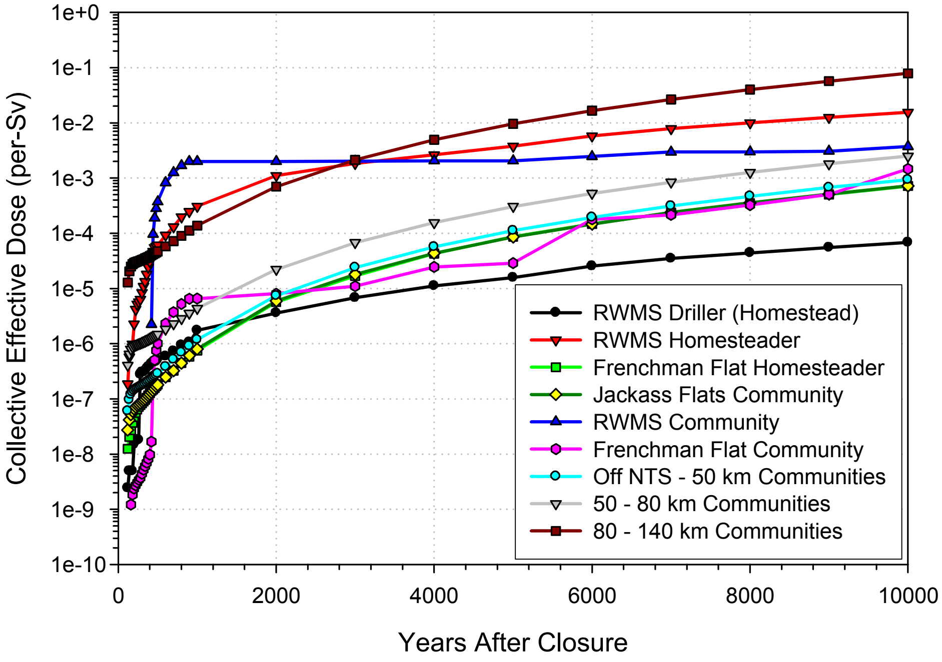

Fig. 2 Mean CED disaggregated by group over time for a 2.5 m closure cover on the 92 ac portion of the Area 5 RWMS.

The maximum individual risk is expected for RWMS residents at all times. The group with the maximum collective risk changes over time. From closure to 440 y while institutional controls are effective, communities from 80 to 140 km have the largest collective risk. Once institutional controls fail, RMWS homesteaders have the largest collective risk. By 3,000 y, communities from 80 to 140 km once again have the largest collective risk.

The base case CED used in the optimization is truncated at 1,000 y and the NTS boundary. The 1,000 y limit is based on the 1,000 y compliance period required by DOE M 435.1-1. The 1,000 y compliance period is interpreted as a policy to weigh present-day and future dose equally during this period. Collective doses beyond 1,000 y are considered highly uncertain. The spatial limit at the NTS boundary is selected based on the opinion that doses calculated using atmospheric dispersion coefficients over complex terrain are too uncertain beyond the NTS boundary. In addition, the CED beyond the NTS boundary is composed of thousands of trivial individual doses, and the ICRP has recommended that the use of such CEDs should be avoided [3].

The base case value of the CED for future populations on the NTS over 1,000 y is low with a maximum of $1,600 for a 2.5 m cover (Table II). The mean value of the CED decreases with increasing cover thickness, but the decreases are small relative to the standard deviation. At 1,000 y, RWMS homesteaders are the predominant source of CED. Contaminated drill cuttings are an important source of dose for RWMS homesteaders. The activity of radionuclides released by drilling is independent of cover thickness. The importance of RWMS homesteaders to the CED suggests that institutional controls deterring intrusion may be effective at reducing future dose. However, the low value of the CED indicates that controls would have to be relatively inexpensive to be cost-effective.

Table II. Value of the Base Case CED as a Function of Cover Thickness for the 92 ac portion of the Area 5 RWMS.

Cover Thickness(m)	Mean CED ($ thousands [k])	CED Standard Deviation ($)
2.5	1.6 k	61 k
3.0	1.1 k	41 k
3.5	0.7 k	28 k
4.0	0.5 k	19 k
4.5	0.4 k	13 k

Cover Optimization

The optimum closure cover is the cover with the minimum total closure cost, which is the sum of the health detriment and cover construction cost. A total of 2,000 realizations of total closure cost as a function of cover thickness were generated using the CED truncated at 1,000 y and the NTS boundary. In every case the total closure cost was found to be a monotonic increasing function of cover thickness. The minimum total closure cost corresponded with the minimum cover thickness, 2.5 m (Fig. 3).

Table I indicates that the maximum CED occurs with temporal and spatial limits of 10,000 y and 140 km, respectively. The consequence of increasing the spatial and temporal limits is evaluated by repeating the optimization with the CED limits extended to 10,000 y and 140 km. A total of 2,000 realizations of total closure cost as a function of cover thickness are generated. For all but two realizations, the total cost is an increasing function of cover thickness (Fig. 4). The optimum cover thickness is 2.5 m for the extended spatial and temporal limits. The spatial and temporal limits for summation of CED, over the ranges evaluated, have no impact on the result of the optimization.

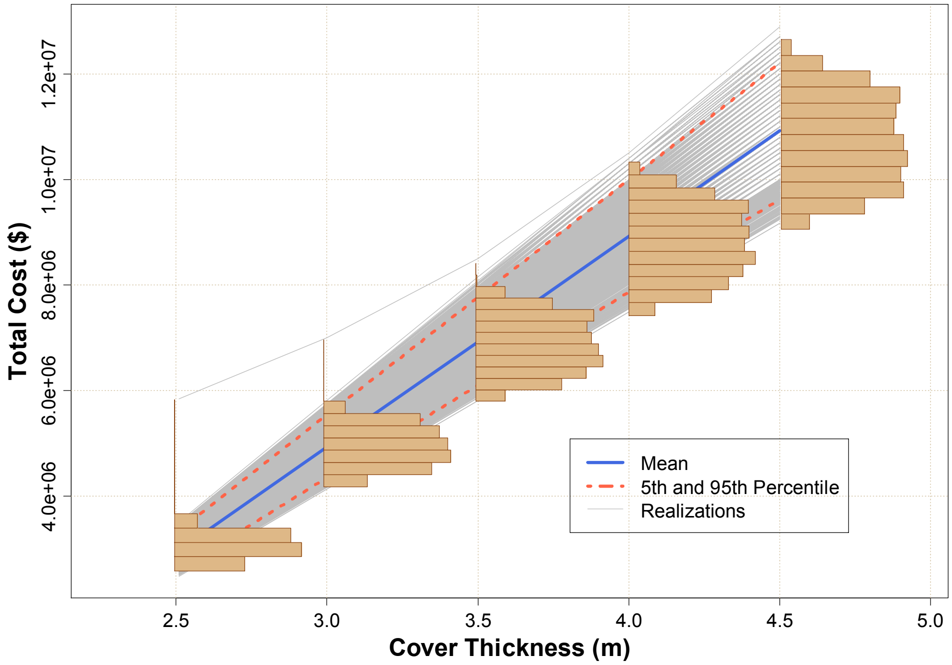

Fig. 3 Total closure cost assuming the base case CED versus cover thickness for closure of the 92-ac portion of the Area 5 RWMS.

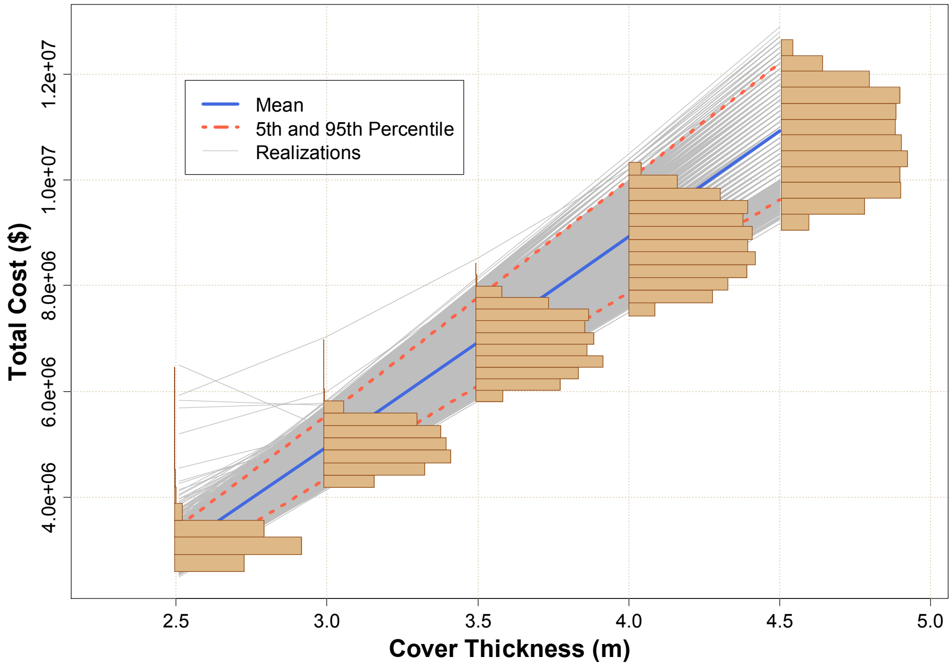

Fig 4. Total closure cost versus cover thickness for closure of the 92-ac portion of the Area 5 RWMS extending the temporal and spatial limits of the CED to 10,000 y and 140 km, respectively.

The significance of the selected cost of the health detriment was evaluated by repeating the optimization, assuming an upper limit cost of \$51.3 million per-Sv^{-1}. A total of 2,000 realizations were generated using the CED with temporal and spatial limits of 10,000 y and 140 km. This bounding case produces minima at cover thicknesses ranging from 2.5 to 4.5 m. The minimum of the mean cost occurs at 3 m, while the minimum of the median is unchanged at 2.5 m. Although the combined upper limits for time, distance, and the cost of health detriment generate realizations with optimum covers greater than 2.5 m, the majority of realizations indicate that the optimum cover thickness is still the minimum thickness, 2.5 m.

The consequence of a non-zero discount rate need not be evaluated because the optimum cover thickness in every case was the minimum cover thickness. A non-zero discount rate will reduce the value of the CED and favor selection of thinner covers. Since the thinnest cover is selected in every case, the result of the optimization is insensitive to the discount rate over the range of values considered. The optimum cover thickness is found to be insensitive to all of the value parameters considered in the analysis, including the spatial and temporal truncation limits of the CED, the cost of health detriment, and the discount rate.

Conclusions

A PA model can be readily modified to calculate the total CED, the spatial and temporal distribution of CED, and individual doses. Calculation and evaluation of individual or per-capita doses is useful for confirming that unacceptably high individual doses are not masked by the CED and for identifying groups with large numbers of trivial doses that should not be included in the CED. Spatial and temporal disaggregation of the CED is useful for identifying the groups with the highest CED and suggesting the most effective radiological controls.

The value of the CED for 1,000 y for future populations within the NTS boundary is small compared to the cost of constructing a thicker closure cover for the 92-ac portion of the Area 5 RWMS. The thinnest closure cover considered, 2.5 m, meets all DOE M 435.1-1 performance objectives and is the most cost-effective option. The results of the optimization are insensitive to the spatial and temporal limits of the CED, the monetary value of health detriment, and the discount rate. The low monetary value of the CED suggests that there are few cost-effective options for lowering doses from this isolated waste disposal site.

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