Decision Support System For Management Of Low-Level Radioactive Waste Disposal At The Nevada Test Site

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ABSTRACT

The long-term safety of U.S. Department of Energy (DOE) low-level radioactive disposal facilities is assessed by conducting a performance assessment -- a systematic analysis that compares estimated risks to the public and the environment with performance objectives contained in DOE Manual 435.1-1, Radioactive Waste Management Manual. Before site operations, facilities design features such as final inventory, waste form characteristics, and closure cover design may be uncertain. Site operators need a modeling tool that can be used throughout the operational life of the disposal site to guide decisions regarding the acceptance of problematic waste streams, new disposal cell design, environmental monitoring program design, and final site closure. In response to these needs the National Nuclear Security Administration Nevada Site Office (NNSA/NSO) has developed a decision support system for the Area 5 Radioactive Waste Management Site in Frenchman Flat on the Nevada Test Site. The core of the system is a probabilistic inventory and performance assessment model implemented in the GoldSim® simulation platform. The modeling platform supports multiple graphic capabilities that allow clear documentation of the model data sources, conceptual model, mathematical implementation, and results. The combined models have the capability to estimate disposal site inventory, contaminant concentrations in environmental media, and radiological doses to members of the public engaged in various activities at multiple locations. The model allows rapid assessment and documentation of the consequences of waste management decisions using the most current site characterization information, radionuclide inventory, and conceptual model. The model is routinely used to provide annual updates of site performance, evaluate the consequences of disposal of new waste streams, develop waste concentration limits, optimize the design of new disposal cells, and assess the adequacy of environmental monitoring programs.

INTRODUCTION

Low-level radioactive disposal sites operated by the U.S. Department of Energy (DOE) are required to prepare and maintain a performance assessment that provides reasonable expectation of compliance with the performance objectives contained in DOE Manual 435.1-1, Radioactive

Waste Manual [1]. Performance assessment is an iterative process where performance assessment results influence operations and operating experience feeds back into subsequent performance assessments. Before site operation, a performance assessment is prepared from preliminary site characterization data, facility designs, and estimated inventories. Performance assessment results, including uncertainty and sensitivity analyses, identify data needs that will increase confidence in performance assessment results. As site operations progress, environmental monitoring results, research and development results, and changes in facility design and inventory, feed back into each performance assessment iteration. As operations progress, uncertainty in performance assessment results should decrease as site characterization data, disposal site design, inventory, and plans closure become less uncertain. Department of Energy oversight of this process is maintained by a requirement that site operators prepare an annual report documenting waste operations and an assessment of the continuing validity of the performance assessment results.

Performance assessment is typically performed using a series of process models that simulate inventory decay, source-term release, near-field transport, far-field vadose zone transport, groundwater transport, atmospheric dispersion, and radiological assessment. The results of each preceding model feeds into the next model in the sequence. This approach has several disadvantages including:

- The iterative performance assessment process is slow and costly because of the labor intensive and error prone processes of running multiple models and passing the results between models. Consequently labor costs are high and the impacts of changes occurring during operations can only be assessed infrequently.
- The labor-intensive modeling approach makes uncertainty analysis of the total performance assessment model through Monte Carlo simulation difficult. Modelers typically vary one model parameter at a time for a limited set of model parameters to produce a set of modeling cases that bound site performance. This approach misses the potential interactions among multiple model parameters and assumes that the modeler has an intuitive understanding of which model parameters are important and how they should be varied to produce bounding results. Consequently, the uncertainty of performance assessment results is poorly known.
- Similarly, global sensitivity analysis which typically requires randomized sampling of all model input parameters is difficult to perform. Consequently, model input parameters most responsible for model output uncertainty are difficult to identify.
- The process is based on black-box models that are understandable only to subject-matter experts familiar with the program used. The labor and cost of the process is increased further because a detailed performance assessment document must be prepared to make the modeling exercise and results understandable to external reviewers.

This paper describes the implementation of a performance assessment model for the Area 5 Radioactive Waste Management Site (RWMS) at the Nevada Test Site (NTS) in the probabilistic GoldSim® modeling platform that overcomes or reduces these problems. Application of the model to common operational decisions including annual assessments, waste acceptance, waste cell design, and environmental monitoring is described.

MATERIALS AND METHODS

Performance Assessment Models

The decision support system consists of an inventory and performance assessment model implemented in GoldSim®, a modeling platform, developed specifically for performance assessment by the GoldSim® Technology Group [2]. The advantages of the selected modeling platform include:

- A fully probabilistic modeling environment developed originally for performance assessment. Native GoldSim® capabilities include Monte Carlo simulation, sensitivity analysis, simulation of discrete events, and contaminant transport pathways with built-in radioactive decay.
- GoldSim®'s hierarchal structure and graphic capabilities allow clear presentation of the conceptual model, input data and its source, mathematical model, and simulation results. The model is organized in a hierarchy of containers that each hold a module. Each container is a graphic white board that documents the module structure, assumptions, input parameters, and results. Any type of graphic image (e.g. drawings, plots, photographs etc.), note panes, and links to external electronic documents or web content can be used to document the model. A performance assessment and its results can be presented in an abbreviated form because the model itself contains much of the documentation required by reviewers.
- Integration of all models into two probabilistic models simplifies uncertainty analysis and global sensitivity analysis through the use of random sampling methods that explore the entire modeling space and include interactions among model parameters.
- GoldSim® includes a versioning feature, dependency mapping, and change note panes that create strong quality assurance documentation.

The inventory model provides probabilistic estimates of radionuclide inventories in time. Past waste disposals, extracted from waste management records, are assigned broad probability density functions to account for the large uncertainty. Waste disposals before 1993 are corrected to assign individual radionuclide activities to records which record radionuclide mixtures such as mixed fission products, depleted uranium, enriched uranium, and weapons grade plutonium. Future waste disposals are particularly difficult and uncertain. Future waste disposal is estimated as the product of a generator estimate of future waste volume and a randomly chosen past waste concentration. Past and future waste disposal rates are integrated and radioactive decay and ingrowth calculated to give stochastic realizations of site inventory over time. The outputs of the inventory model are radionuclide distributions are transferred by a cut and paste operation into the A5 RWMS performance assessment model.

The A5 RWMS performance assessment model is the result of multiple cycles of site characterization, model development and testing, and sensitivity analysis. The Area 5 RWMS is modeled as four one-dimensional (1-D) virtual disposal units corresponding to groups of actual disposal units with similar depths of burial. Virtual disposal units and their covers are divided into a series of mixing cells. The rate of change of radionuclide mass within each cell is described by a 1-D mass balance expression accounting for radioactive decay and mass transfer processes. In the graphical GoldSim® environment, these mass-balance equations are represented as a series of cells connected by links that represent each transport process. Input parameters, their probability density functions, and data sources are documented within the model. The model solves the system of equations to give the time-varying concentrations of radionuclides in air and soil in the accessible environment. An integrated radiological assessment model converts the environmental concentrations into dose received by hypothetical members of the public for four exposure scenarios.

Annual Assessments
Annual assessments are required to evaluate continuing adequacy of the performance assessment. The decision analysis tool allows calculation of performance assessment end-points on an annual basis using the best available site characterization and facility design information. The inventory model is updated on an annual basis. New waste inventory data is continuously loaded into the site data base as disposal occurs. On an annual basis, data base inventory records and waste generator volume forecasts are transferred to the inventory model and new closure inventory estimates made.

The performance assessment model is continuously updated as new data are developed. At the end of each fiscal year, the current performance assessment model is updated with the latest inventory estimate and new estimates of the performance measures are calculated. These results are reported annually to the DOE.

Waste Concentration Limits
There is a need for an administrative method for control of future waste inventory. The inventory of waste that will be disposed at the Area 5 RWMS after the time of preparation of the performance assessment is unknown and difficult to estimate. This problem is resolved by using the performance assessment model results to derive limits for future disposals. Proposed waste streams are reviewed to determine if they fall within these derived limits.

The method is based on the assumption that there is a linear relationship between waste activity concentration and the performance measures (e.g., total effective dose equivalent [TEDE], Rn-222 flux density). Testing of model outputs confirms that this is a valid assumption. With the assumption of model linearity, a waste concentration limit (WCL) can be derived for each radionuclide that will produce a model output equal to the performance objective. A waste concentration limit is calculated as

$$WCL_{j,k} = \frac{C_{0,j}\ H_{L,k}}{\max\left(\sum_{j=1}^{n} H_{j,k}(t)\right)} \qquad \text{(Eq. 1)}$$

where

$WCL_{j,k}$ = waste concentration limit for radionuclide *j* in scenario *k*, Bq m^{-3}
$C_{0.j}$ = waste concentration of radionuclide *j* at disposal, Bq m^{-3}
$H_{L,k}$ = performance objective for scenario *k*, Sv yr^{-1}
$\sum H_{j,k}(t)$ = the mean sum of the TEDEs as a function of time for radionuclide *j* and all its progeny for scenario *k*, Sv yr^{-1}

A special model container has been developed that can be inserted into the performance assessment model used to calculate the waste concentration limit for each performance objective.

Waste Stream Evaluations

Waste generators submit approximately 100 to 150 new or revised waste streams for disposal at the NTS each year. One hundred percent of new or revised waste streams are reviewed for their potential to comply with the waste acceptance criteria and the performance objectives. The performance assessment group evaluates each new or revised waste stream for its potential to alter or invalidate the performance assessment model by answering four questions:

- Does acceptance of the waste cause a change in radionuclide inventory?
- Does acceptance of the new waste stream require a change in facility design or closure plans, or require operational constraints or conditions?
- Does acceptance of the new waste stream change the likelihood of a feature, event, or process or change a model parameter value?
- Does acceptance of the waste stream require a change in waste acceptance criteria, the performance assessment, or the disposal authorization statement?

A positive answer to any question requires a documented review. Changes in radionuclide inventory are the most common condition requiring review and screening methods are used for these changes. First, the sum of fractions is calculated for the waste stream using the limiting waste concentration limits derived above. Acceptance of the waste stream is recommended if the sum of fractions (SOFs) is less than 1.0. If the SOFs is greater than 1.0, the new waste stream inventory is inserted into the performance assessment model and evaluated with the disposed inventory. If the 95th percentile of all model outputs is less than the performance objective, the profile is recommended for approval. If the results exceed the 95th percentile, a special analysis is required. A special analysis is also required for waste streams that require changes not limited to radionuclide inventory. Common changes requiring special analysis are waste disposal cell design or disposal of nuclides not in the model. A special analysis is a more thorough and documented analysis, submitted to the NNSA/NSO for review.

Waste Disposal Cell Design and Closure Cover Optimization

A need for new waste disposal designs occasionally arises during special analyses of problematic waste streams. The performance assessment model includes two candidate waste cells, whose dimensions, cover thicknesses, and cover material properties can be modified to simulate alternative waste cell designs. Final closure cover thickness is also evaluated to support site closure planning. Performance assessment model results are used to generate disposal cell design criteria that are used in formal design. In recent years, the model has been used to design thicker covers to reduce Rn-222 emissions from large volume waste streams with elevated levels of Ra-226 and Th-230.

Performance assessments must include an analysis that demonstrates radionuclide releases to the environment are as low as reasonably achievable (ALARA). Maintaining releases ALARA means that radiation protection has been optimized considering the costs of the radiation protection and health detriment caused by radiation exposure. All release pathways for the Area 5 RWMS are upward. Therefore, cover thickness is the primary site design feature that can be varied to optimize radiation protection. The performance assessment model was used to determine the relationship between cover thickness and collective TEDE. Combined with cost estimates for construction of final closure covers of various thicknesses, the relationship between the cost differential $\Delta X/\Delta S$ where X is the radiation protection cost and S the collective dose and cover thickness can be determined. The optimum level of radiation protection occurs where $\Delta X/\Delta S = \Delta Y/\Delta S$, where $\Delta X/\Delta S$ is the health detriment cost differential.

Environmental Monitoring

Performance assessment and environmental monitoring mutually influence each other. Performance assessment results are used to assess the adequacy of the environmental monitoring program. Monitoring results are periodically reviewed for consistency with performance assessment conceptual models and results.

Current site conditions differ from the conditions assumed for performance assessment. For example, the performance assessment assumes closure with a thick cover and an inventory to be disposed in the future. Therefore, evaluation of monitoring data requires some modification of the performance assessment model to generate cases resembling current conditions. To generate the current inventory, the inventory model is simply run to the current date. The performance assessment model is modified by loading the current inventory and changing the cover thickness to match the operational covers. The results of these modified analyses are then compared with environmental monitoring results.

RESULTS

Annual Assessments

The decision analysis tools provide an easy way to track site inventory, performance assessment results, and assess the need to revise and release a new site performance assessment. Tracking of inventory projections over several years indicates that total site volume at closure is relatively stable. Inventory forecasts are much less stable and more difficult to predict. In FY 2003, the estimated closure inventory of Tc-99 increased by approximately a factor of 20 (Fig. 1). An increase of this magnitude can significantly change performance assessment results. Predicting these increases has proven difficult. The availability or unavailability of other competing disposal sites is a major source of uncertainty. However, the modeling tools can easily evaluate the impacts of new waste streams when the generator applies for approval to ship to the disposal site. The results can then be used to determine if the waste is acceptable and whether revision of the performance assessment is required.

Changes in performance assessment results are reported annually to the DOE. Performance assessment results increased from FY 2002 to FY 2003 as a consequence of increasing Tc-99 inventory noted above (Fig. 2). In FY 2003, results from site characterization studies of insect and mammal burrowing caused a significant reduction in expected releases. The reduced releases caused the estimated TEDE to decrease from FY 2003 to FY 2004 in spite of rising inventory. The model tools allow immediate tracking of expected site performance.

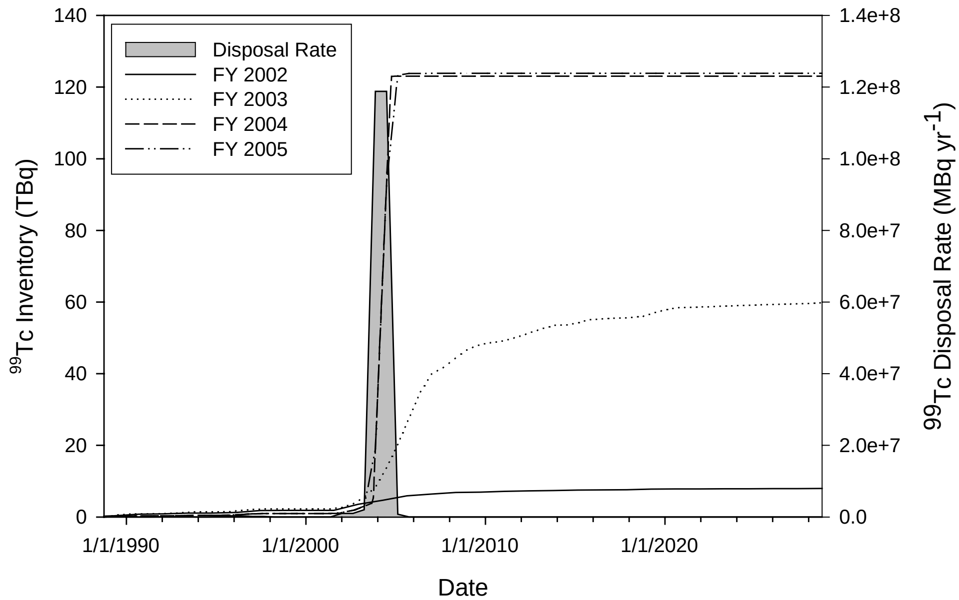

Fig. 1. Estimated Tc-99 inventory for FY 2002 through FY 2005

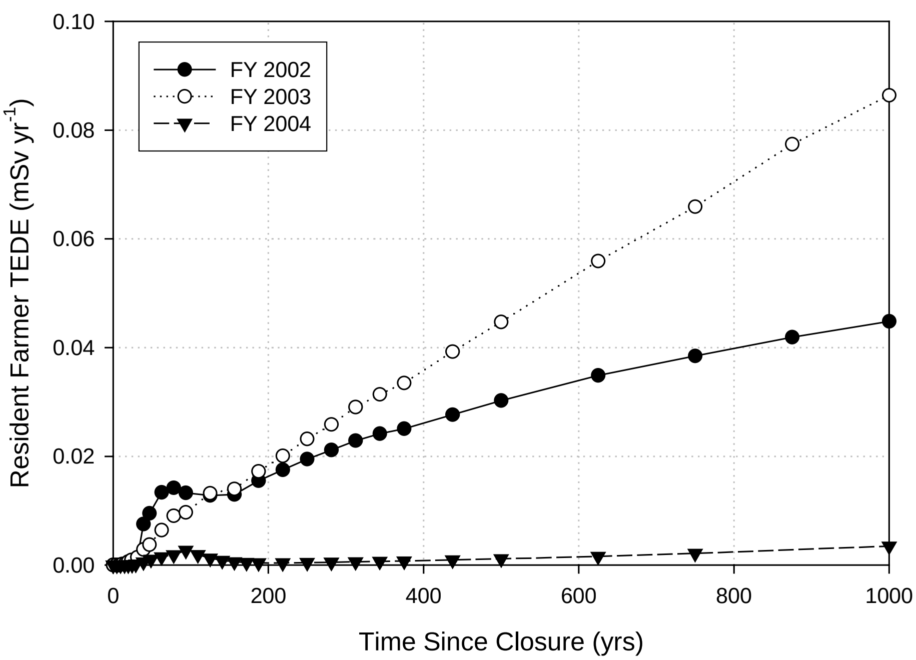

Fig. 2. Annual compliance determination for the resident farmer scenario

Waste Concentration Limits

Revised waste concentration limits have recently been developed using the performance assessment model. The limits are set in most cases by the postdrilling intruder scenario (Table I). At the planned closure cover thickness (4 m) drilling is the only intrusion method where an intruder can exhume waste. Radionuclides with high plant-soil concentration ratios and low adsorption coefficients are limited by the intruder-agriculture scenario. These radionuclides are transported into the closure cover by upward liquid advection and plant uptake. An intruder constructing a residence at the site then excavates the contaminated cover soil. Three radionuclides Ra-226, Th-230, and U-234 are limited by radon flux density. The waste concentration limits can be used to calculate the inventory sum of fractions. At the end of FY 2004, the sum of fractions was 0.44, indicating that the site is at 44 percent of capacity. Tritium and Tc-99 are the largest contributors to the sum of fractions.

Table I. Waste Concentration Limits for Wastes Disposed Below a 4 M Closure Cover at the Area 5 Radioactive Waste Management Site

Nuclide	Limiting WCL (Bq m^{-3})	FY 2004 Sum of Fractions	Limiting Scenario/Limiting Performance Objective
H-3	6.2E+11	1.9E-01	Resident Farmer/All Pathways
C-14	5.4E+15	7.7E-11	Open Rangeland-NTS Boundary/All Pathways
Al-26	9.7E+07	1.6E-09	Intruder Agriculture/Intruder
Cl-36	1.9E+08	4.9E-06	Intruder Agriculture/Intruder
Ar-39	9.9E+20	4.2E-18	Transient Occupancy/Air Pathway
K-40	9.4E+10	2.5E-07	Postdrilling/Intruder
Ca-41	2.8E+12	2.3E-09	Postdrilling/Intruder
Ni-59	1.7E+14	7.5E-12	Postdrilling/Intruder
Ni-63	3.2E+14	7.9E-10	Postdrilling/Intruder
Co-60	1.6E+12	2.6E-07	Postdrilling/Intruder
Kr-85	2.0E+20	2.2E-17	Transient Occupancy/Air Pathways
Sr-90	4.3E+11	2.5E-04	Postdrilling/Intruder
Zr-93	1.1E+14	2.1E-13	Postdrilling/Intruder
Nb-93m	4.6E+15	8.6E-13	Postdrilling/Intruder
Nb-94	1.2E+10	4.4E-07	Postdrilling/Intruder
Tc-99	3.2E+09	1.8E-01	Intruder Agriculture/Intruder
Pd-107	2.9E+14	3.4E-15	Postdrilling/Intruder
Cd-113m	6.2E+12	6.1E-10	Postdrilling/Intruder
Sn-121m	2.1E+14	2.8E-10	Postdrilling/Intruder
Sn-126	1.1E+10	1.0E-09	Postdrilling/Intruder
I-129	3.4E+09	1.6E-06	Intruder Agriculture/Intruder
Ba-133	5.4E+12	8.2E-10	Postdrilling/Intruder
Cs-135	2.8E+12	6.5E-12	Postdrilling/Intruder
Cs-137	2.5E+11	1.0E-02	Postdrilling/Intruder
Eu-150	9.4E+10	8.9E-08	Postdrilling/Intruder
Eu-152	4.7E+11	9.0E-08	Postdrilling/Intruder
Eu-154	1.7E+12	6.8E-09	Postdrilling/Intruder
Sm-151	2.4E+15	9.7E-12	Postdrilling/Intruder
Ho-166m	1.2E+10	1.7E-08	Postdrilling/Intruder
Bi-207	1.1E+11	1.3E-12	Postdrilling/Intruder
Pb-210	3.5E+11	5.0E-07	Postdrilling/Intruder
Ra-226	2.1E+07	1.0E-02	Radon Flux Density
Ra-228	1.7E+12	1.2E-06	Postdrilling/Intruder
Ac-227	1.7E+11	7.3E-08	Postdrilling/Intruder

Th-228	4.3E+13	5.6E-08	Postdrilling/Intruder
Th-229	2.8E+10	1.0E-07	Postdrilling/Intruder
Th-230	6.0E+07	1.7E-02	Radon Flux Density
Th-232	8.1E+09	2.5E-04	Postdrilling/Intruder
Pa-231	1.0E+10	1.7E-06	Postdrilling/Intruder
U-232	4.3E+10	7.0E-06	Postdrilling/Intruder
U-233	8.2E+10	1.4E-05	Intruder Agriculture/Intruder
U-234	1.3E+10	2.4E-02	Radon Flux Density
U-235	1.1E+11	1.2E-04	Postdrilling/Intruder
U-236	2.8E+11	3.7E-05	Intruder Agriculture/Intruder
U-238	3.5E+11	1.5E-03	Postdrilling/Intruder
Np-237	3.4E+10	6.2E-06	Postdrilling/Intruder
Pu-238	1.8E+12	5.9E-06	Postdrilling/Intruder
Pu-239	5.1E+11	3.2E-05	Postdrilling/Intruder
Pu-240	5.2E+11	7.3E-06	Postdrilling/Intruder
Pu-241	5.8E+12	1.4E-06	Postdrilling/Intruder
Pu-242	3.7E+11	4.8E-06	Postdrilling/Intruder
Pu-244	4.8E+10	3.8E-14	Postdrilling/Intruder
Am-241	1.7E+11	2.2E-05	Postdrilling/Intruder
Am-243	5.8E+10	2.4E-08	Postdrilling/Intruder
Cm-243	8.3E+11	1.2E-10	Postdrilling/Intruder
Cm-244	3.4E+12	2.4E-07	Postdrilling/Intruder
Cm-245	4.6E+10	2.4E-08	Postdrilling/Intruder
Cm-246	9.2E+10	1.9E-09	Postdrilling/Intruder
Cm-248	2.9E+10	2.4E-13	Postdrilling/Intruder

Waste Stream Evaluations

In FY 2005, 136 new or revised waste streams were evaluated for compliance with the performance objectives in DOE M 435.1-1. Eighty six percent involved only inventory changes and were found acceptable based on a sum of fractions calculation. Five waste streams required inventory screening. Sum of fractions and inventory screening evaluations can be performed within a few minutes. Five waste streams required special analyses that require a few weeks to complete. The modeling tools allow direct calculation of the effect of proposed waste stream acceptance on site performance, providing a clear justification for acceptance or rejection.

Waste Disposal Cell Design and Closure Cover Optimization

The primary means available to control releases to the environment from the Area 5 RWMS is to increase or decrease the thickness of the closure cover. The performance assessment evaluates a 4 m closure cover and concludes that all performance objectives can be met.

The modeling tools have been used to design cover thicknesses required to reduce Rn-222 emissions from large volume thorium waste streams. These wastes include small amounts of Th-230 that will produce Ra-226 over time. Disposal covers designed to attenuate radon flux usually include an impermeable layer of clay to retard radon releases. The extremely arid conditions and xeric vegetation at the Area 5 RWMS are expected over time to cause clay to dry and crack, requiring that a thick cover be installed. The dry conditions of the cover material also contribute to a high degree of permeability. The model has been used to determine the cover thickness required to reduce the Rn-222 flux density from a large volume high-purity thorium nitrate waste stream to 0.74 Bq m^{-2} s^{-1}. High-purity thorium waste streams typically require covers greater than 7 m thick to reduce radon emission.

The modeling tools have also been used to investigate required closure cover thickness. A differential cost-benefit analysis was performed to determine the closure cover thickness that optimizes radiation protection. Cover options considered range from the thinnest cover that the A5 RWMS GoldSim® model can evaluate, 2.5 m to 4.5 m. Before an ALARA determination can be made, it must be confirmed that all the radiation protection options comply with the performance objectives. To make this determination, the relationship between the performance measures (e.g., mean member of public TEDE, mean probability weighted intruder TEDE, mean Rn-222 flux density), cover thickness, and time was determined from the A5 RWMS GoldSim® model. The means were determined from 5,000 model realizations. Among member of public exposure scenarios, the resident farmer scenario was found to produce the highest mean TEDE at all times and for all cover thicknesses. The mean all pathways resident farmer TEDE complies with the all pathways performance objective, 0.25 mSv in a year, for cover thicknesses ranging from 2.5 to 4.5 m.

The optimum level of radiation protection occurs when the radiation protection cost differential, dX/dS is equal to the health detriment cost differential dY/dS. The radiation protection cost differential was derived from model output and cover construction cost estimates. The health detriment cost differential was assumed to be a constant $200,000/person-Sv [4]. Comparison of the cost differentials for all performance assessment scenarios indicates that increasing cover thickness beyond 2.5 m (8.2 ft) is not cost effective and is not required to maintain releases ALARA (Fig. 3). Other concerns, such as erosion control or revegetation, may require consideration of thicker covers. Closure of the Area 5 RWMS with a cover at least 2.5 m thick will maintain releases to the environment ALARA. Integration of all performance assessment models with a single model facilitates this type of complex study requiring multiple model runs.

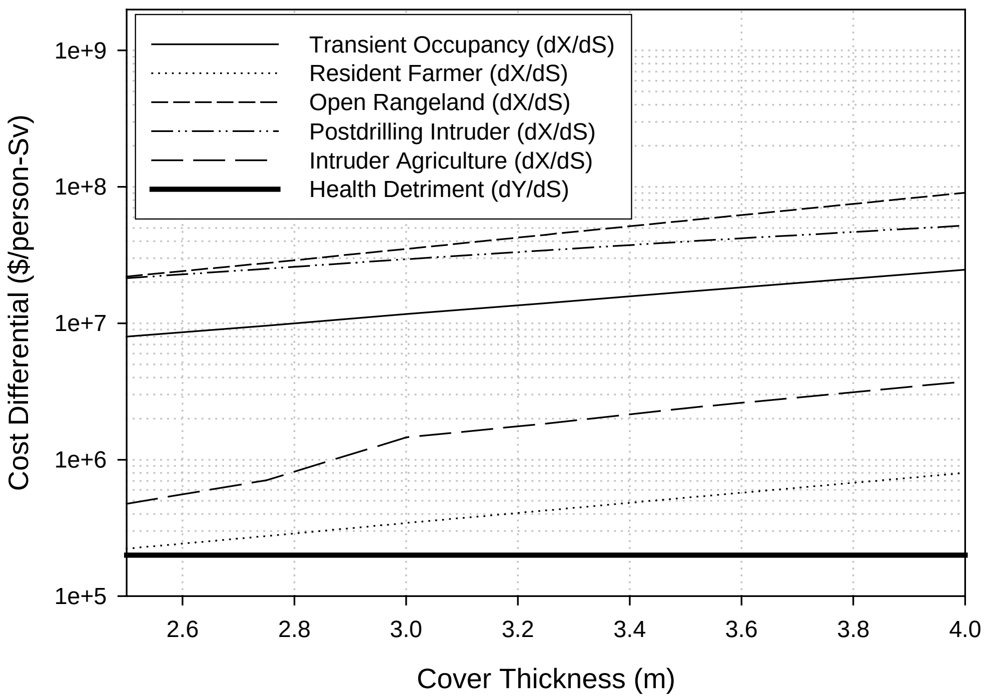

Fig. 3. Comparison of radiation protection and health detriment cost differentials as a function of cover thickness for a cover constructed with an Area 5 borrow source

Environmental Monitoring

The performance assessment model indicates that volatile radionuclides (i.e., H-3, Rn-222) and radionuclides with volatile precursors (i.e., Pb-210) should be preferentially released from the site. In the near term, tritium is expected to have the highest airborne concentration at the site. The model projects a peak airborne H-3 concentration for the last year with available data, FY 2004 (Fig. 4). Significant releases of Rn-222 and Pb-210 are not expected for several thousand years when Ra-226 has been produced by the decay of it long-lived parents. Groundwater contamination is not expected under current climatic conditions.

Environmental monitoring results are generally consistent with expectations based on performance assessment model results. To date, no groundwater contamination has been detected. Tritium is the only radionuclide routinely detected in air at the site. A comparison of the modeled air concentration of tritium with the measured concentrations is shown in Fig 4. Model results appear conservative relative to measured values. The model is expected to over estimate H-3 releases because it does not account for the effects of waste containers and waste forms. In recent years, measured H-3 in air has been decreasing at the site, a result not expected from the performance assessment model. Differences between the model and measurements has stimulated a review of the model and monitoring methods and identified potential biases in monitoring results over time.

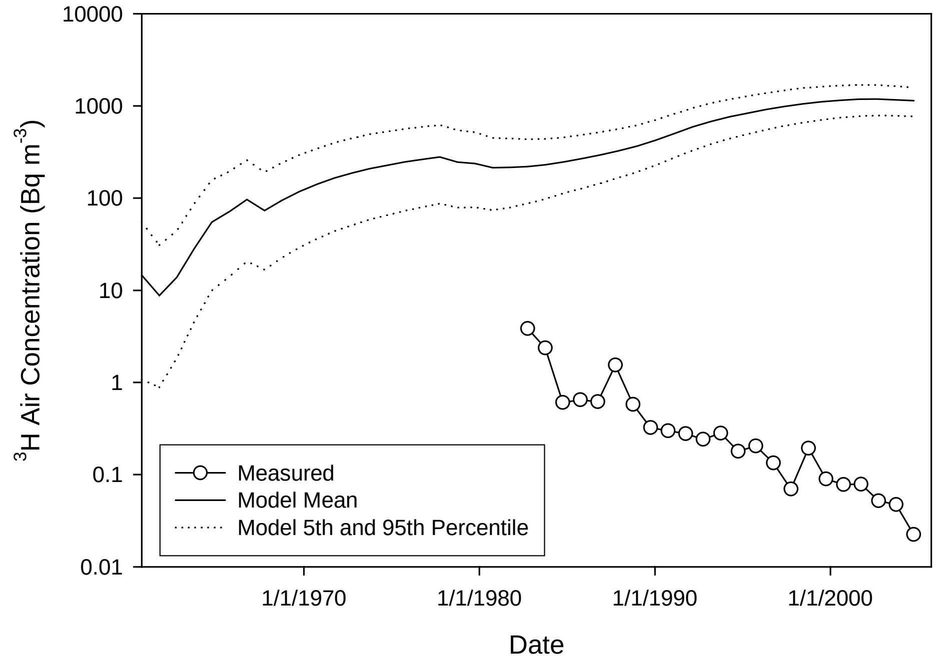

Fig. 4. Measured and simulated Tritium concentrations in air

SUMMARY

Low-level radioactive disposal sites operated by the DOE are required to prepare and maintain a performance assessment that provides reasonable assurance of compliance with the performance objectives contained in DOE M 435.1-1. The decision support system consisting of an inventory and performance assessment model implemented in GoldSim® is indispensable to the maintenance of the PAs at the disposal facilities at the NTS. The NNSA/NSO performs annual reviews by evaluating operational factors and research results that impact the continuing validity of the results of the PAs. Operational factors, such as the waste form and containers, facility design, waste receipts, closure plans, as well as monitoring results and research and development activities, are reviewed for the determination of the adequacy of the PAs.

The modeling system allows rapid assessment of the consequences of waste management decisions using the most current site characterization information, radionuclide inventory, and conceptual model. The model is routinely used to provide annual updates of site performance, evaluate the consequences of disposal of new waste streams, optimize the design of new disposal cells, and assess the adequacy of environmental monitoring programs.

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