MODEL EVOLUTION OF A PROBABILISTIC PERFORMANCE ASSESSMENT FOR DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE AT THE AREA 5 RADIOACTIVE WASTE MANAGEMENT SITE, NEVADA TEST SITE

B. Crowe
Apogen Technologies, Inc

P. Black, K. Catlett, T. Stockton, M. Sully, J. Tauxe
Neptune and Company

V. Yucel, G. Shott, L. Desotell
Bechtel Nevada

J. Carilli, G. Pyles
National Nuclear Security Administration Nevada Site Office

ABSTRACT

Development of a probabilistic performance assessment model is continuing for the Area 5 Radioactive Waste Management Site on the Nevada Test Site. The model simulates release, transport and radiological doses from shallow-land burial of low-level radioactive waste in unsaturated alluvial deposits. The processes that disperse waste radionuclides (predominantly upward toward the surface) include plant root uptake, burrowing by small mammals and insects, and slow upward advection/diffusion in air and water. These processes are quantified and refined through site characterization studies and numerical modeling with the results incorporated into the probabilistic model. Iterative changes during model development include creation and refinement of probabilistic density functions for model parameters, adjustments for nonlinear scaling and averaging of measurements, quantification of inventory uncertainty, and inventory updating incorporating newly disposed waste. Multiple refinements in simulation of gaseous radon diffusion have been completed and model output is now calibrated to the radon diffusion model used by the Nuclear Regulatory Commission. The evolving model changes are recorded in multiple model revisions over the last several years. Simulations using standardized inventory, disposal configurations, and modeling assumptions were run with individual model versions to assess changes in model outputs for two sensitive performance objectives: the all-pathways resident farmer scenario and the ground surface radon flux. Results show that model revisions have reduced conservatism expressed as systematic decreases in the mean dose and flux estimates. Uncertainty, defined as the 95th percentile minus the 5th percentile, has been reduced to a small component of the regulatory limits and uncertainty reduction can occur with and without changes in the mean dose and flux. The reductions in conservatism and uncertainty allow improved decision-making and increase the facility capability for accepting problematic waste streams.

INTRODUCTION

This paper describes the evolution through continuing stages of model development of a probabilistic performance assessment (PA) model for shallow-land disposal of defense-generated low-level radioactive waste (LLW) at the Nevada Test Site (NTS). The model has been developed and refined over a two-year time span with relatively modest resources. We are attempting to apply the learning experiences gained through existing PA studies (1,2) and through large-scale national and international PA studies (3-8). Program priorities and iterative sensitivity analysis are used to focus data acquisition and modeling/laboratory studies that in turn lead to incremental improvements in the PA model. The objectives in developing the probabilistic PA model include the following technical goals:

1. Reduction of conservatism in model parameters and assumptions,
2. Quantification of uncertainty in the PAs,
3. Reduction in the uncertainty of model outputs through focused characterization studies, and
4. Iterative model development using the new characterization data and insights from sensitivity analyses of model results.

Achievement of the technical goals allows evaluations of the following decision objectives:

1. Use of model results in technical assessments necessary for day-to-day decisions while managing a LLW disposal facility,
2. Evaluation of the suitability of new waste streams for disposal,
3. Assistance in facility closure and long-term stewardship, and
4. Identification of end points in model development, and active site monitoring.

Two recurring observations of decision makers using results of PA modeling studies are the lack of metrics for defining the value of modeling and the absence of clearly defined end states in model development. Modelers are often perceived as "modeling for the sake of modeling" and not necessarily to solve decision problems or to reduce uncertainty in critical components of model outputs. We have addressed these concerns through two activities. First, modeling efforts are focused on identified decision issues using programmatic priorities. Second, the results of sensitivity analysis drive data collection activities and prioritize topics for refinement in model development.

To test the validity of our approach to model development, we designed a series of Monte Carlo simulations so the output of the computer simulations could be used to assess the value of multiple stages (versions) of an evolving probabilistic PA. The metrics for assessing value in the modeling studies are reduction in conservatism measured against key regulatory performance objectives and reduction of uncertainty in model outputs. The remainder of this paper describes the PA model for a LLW disposal site and the results of the simulation exercise.

Background

The Area 5 Radioactive Waste Management Site (RWMS), located in Frenchman Flat of the Nevada Test Site (NTS), is operated by the U.S. Department of Energy (DOE), National Nuclear Security Administration Nevada Site Office (NNSA/NSO). The facility is used to dispose containerized defense-generated, LLW in shallow trenches, pits and large-diameter boreholes (Figure 1). The LLW is from cleanup activities at the NTS and from more than 25 off-site generators across the DOE complex. Greater than 90% of the volume of waste disposed at Area 5 is associated with actinide-bearing waste streams (10).

Conceptual Model

The Area 5 RWMS is sited in coalesced alluvial fans of the Frenchman Flat basin that consist of deposits of unconsolidated to weakly consolidated fragmental debris of volcanic and carbonate rocks eroded from the mountains flanking the basin. The climate is characterized by low precipitation, large diurnal temperature range, and moderate to strong winds that all maintain a high potential evaporation rate. The potential annual evaporation calculated using the Penman equation and data collected from a multi-decade record at a nearby meteorology station is 157 cm. The average annual ratio between potential evaporation and precipitation at the Area 5 RWMS is 12.4 (9,10), indicative of extremely evaporative conditions.

The hydrological properties of alluvium below the Area 5 RWMS are established from extensive site characterization studies summarized in Shott *et al.* (1) and provide the basis for development of the conceptual model for processes of fate and transport. The upper 1 to 2 m of undisturbed alluvium forms a hydrologically active region where water is exchanged between the atmosphere and soil. The direction of liquid and vapor fluxes varies temporally with changes in weather and rainfall patterns and on interacting processes of infiltration, evapotranspiration, and biotic activity. Below the dynamic zone, the high temperatures and dry evaporative surface conditions, the low water contents, the efficient transpiration of moisture by desert vegetation and the hydraulic properties of the soils result in upward flow of water from as deep as 35 m. Below the upward flow region, water-potential measurements show the existence of a static region extending between 35 to 90 m below the surface (1, 11). Here, essentially no liquid flow is occurring. Below the static region, higher water contents allow steady downward flow to the water table (236 m below the surface). The downward flux is low and the water in the lower part of the vadose zone is inferred to be old and derived from past periods of wetter climate (14). Under current conditions, there is effectively no surface recharge to the water table beneath the Area 5 RWMS (1, 11).

Figure 2 illustrates the important processes of flow and contaminant transport that operate in the upper 10 m of the unsaturated zone, including the waste zone of the pits and trenches of the Area 5 RWMS. The dominant processes that transport contaminants are plant root uptake, burrow excavation by small mammals and insects, and slow upward advection/diffusion in air and water. These processes are modeled using probabilistic simulations of the release, transport of radionuclides along multiple pathways and radiological doses to receptors.

MODEL EVOLUTION AND PARAMETERIZATION

The regulatory requirements of DOE Order 435.1, the controlling regulation for disposal facilities for defense-generated LLW, are deterministic and specify fixed-point dose limits for multiple pathways leading to radiological exposures for a hypothetical member of the public (MOP). A largely deterministic PA and Composite Analysis for the Area 5 RWMS were completed, reviewed and approved by the LLW Federal Review Group (LFRG). This review and acceptance constituted the basis for regulatory approval of the continued operation of the facility. Following approval, a decision was made to convert the deterministic PA for the Area 5 RWMS to a probabilistic model. The primary reasons for the conversion are twofold (2). First, the

Fig. 1. Color aerial photograph of the Area 5 Radioactive Waste Management Site (RWMS). Low-level and minor volumes of mixed radioactive waste are disposed in shallow trenches, pits and large diameter boreholes. Inactive waste cells are covered with an operational cover of alluvial soil. The support facilities for the RWMS are in the lower-left corner of the photograph.

conservatism assumptions and parameter values in the deterministic PA lead to underestimation of the performance capability of the disposal facility because of nonsystematic overestimation of the radiological releases and ground surface radon flux. Development of a probabilistic PA both quantifies uncertainty and allows more complete utilization of the disposal facility through estimation of *expected* radiological releases and radon flux. Second, the deterministic PA is used to establish regulatory compliance. A probabilistic PA is more useful for long-term management of the facility and for establishing and evaluating the safety basis for waste disposal (6,8).

Area 5 RWMS PA Model Version 1.0

Version 1.0 of the probabilistic PA model was developed using the GoldSim simulation programming platform (12). This probabilistic model retains the model structure, assumptions and parameter values of the deterministic PA and the model was run in deterministic mode to attempt to duplicate the results of the original approved model. The model outputs with the version 1.0 model are closely similar to the deterministic PA and differences between the two models are from underreporting of ^{210}Pb, minor typographical errors (^{242}Pu), and iterative changes in inventory estimates (^{99}Tc) that were not updated in the original deterministic PA.

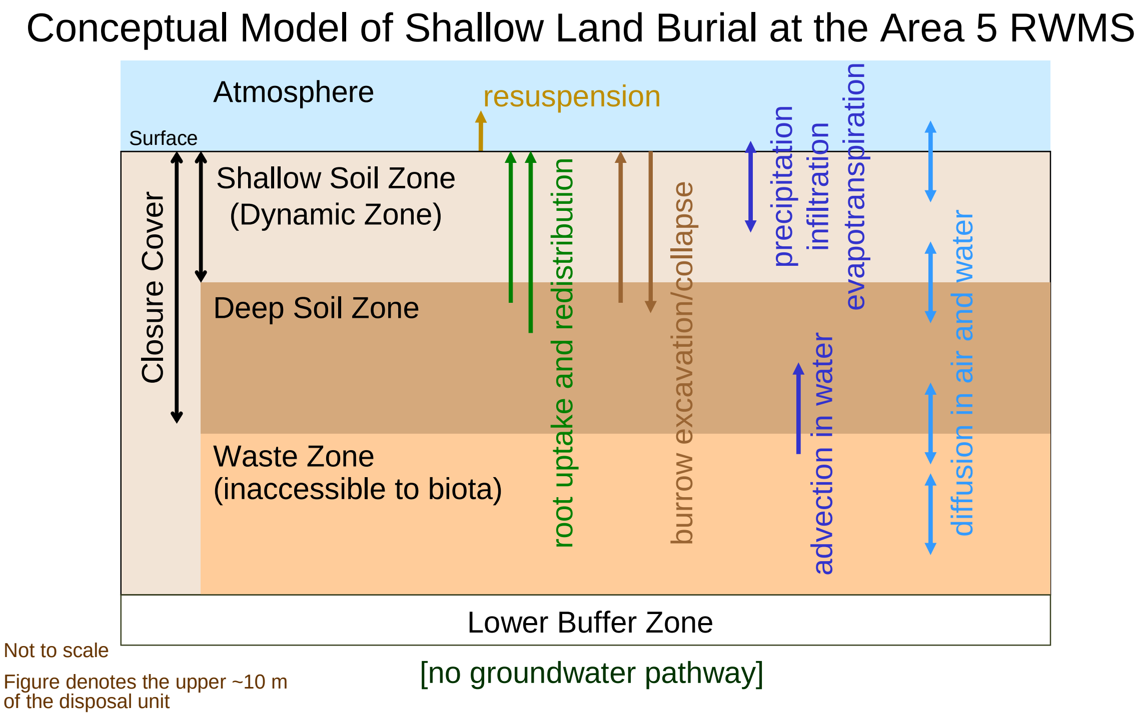


Fig. 2. Schematic diagram of the processes of fate and transport affecting shallow-land disposal of low-level radioactive waste at the Area 5 RWMS.

Version 1.0 of the Area 5 RWMS model is not included in this simulation study because it is structured for deterministic calculations and retains the conservative parameter values and assumptions of the original PA. The first step in the model evolution of the Area 5 RWMS probabilistic performance assessment was development of the Version 1.1 model.

Area 5 RWMS PA Model Version 1.1

The version 1.1 model started with the parameter values and the data justifications provided in the original Area 5 RWMS PA (1). The fixed-point parameter values of the deterministic PA were expanded to probability density functions (PDFs) where the PDFs are centered on the expected value and the distribution parameters are established from information in the original performance assessment. Documentation of the basis and supporting information for PDFs of model parameters is incorporated within the PA model, a unique feature of the GoldSim modeling platform (12). The closure cover thickness, a key parameter in the PA, is treated as a uniform distribution with minimum and maximum values as distribution parameters. Inventory for individual waste radionuclides is defined as a truncated log-normal distribution where the distribution parameters are adjusted so the 5^{th} and 95^{th} percentiles correspond to the inventory range defined in the original deterministic PA. Upward liquid advection is described as a beta distribution with a minimum value of > 0 and a maximum value of 1 mm/yr. This wide distribution is based on stable isotope data supporting higher values of upward advection (11). Gaseous diffusion of radon occurs in multiple cells that form the model structure and rates are strongly dependent on gas-phase tortuosity. Multiple models of gas-phase tortuosity are used corresponding to approaches established in the original Area 5 PA and from literature references. Institutional control is assumed to be fully operational (no inadvertent human intrusion) during the institutional control interval defined as a log-normal distribution with mean of 250 years (14). Inadvertent human intrusion is allowed to occur when the randomly sampled institutional control interval is exceeded. Retardation is implemented in the model and radionuclide releases are limited by aqueous solubility limits. Model output batches (500 realizations) are exported to text files and processed for sensitivity analysis using the **R** statistics package (15). The first screening of the output used the predicted Total Effective Dose Equivalent (TEDE) to MOP receptors using four exposure scenarios. Evaluations show that the resident farmer scenario receives the highest TEDE; sensitivity analysis was focused on this exposure scenario. A gradient boosting additive regression algorithm is used to provide estimates of sensitivity indices for the resident farmer. Results show that the version 1.1 model is sensitive to the selection among the air tortuosity models, the closure cover geometry, and the biotic uptake parameters (16).

Area 5 RWMS PA Model Version 2.0

Multiple changes were implemented in the Version 2.0 model. The biotic parameters were updated using results from field characterization studies and information from literature references. A modeling study was undertaken to estimate the modern water liquid and vapor fluxes in the shallow vadose zone (17). Fluxes were predicted from simulations of unsaturated flow and transport using the Finite Element Heat and Mass Transfer code (FEHM) and the modeling runs were optimized to match field and laboratory data using observed distributions of chloride, water potentials and stable isotopes of oxygen in shallow soil profiles from three wells near the Area 5 RWMS. On the basis of the modeling results, a maximum upper value of < 0.02 mm/yr for the probability distribution of upward liquid advection was implemented in the Version 2.0 model (16). Results from the FEHM modeling were also used to modify and simplify the implementation of air-phase tortuosity in the probabilistic PA model. Finally, simulation runs with the Version 1.1 model show recurring outlier values for radionuclide concentrations in the shallow soils. These values were traced to high radionuclide concentrations sampled from extreme tails of the log-normal distributions for inventory. The inventory distributions used in the Version 1.1 model were judged to be overly conservative and the outlier concentrations are not physically plausible. The minimum and maximum values of the distributions were adjusted to represent the 1^{st} and 99^{th} percentiles, respectively.

Area 5 RWMS PA Model Version 2.1

The Version 2.1 model implemented a major change in the variance of PDFs defined in the probabilistic PA model. The PA model is a 1-dimensional representation of processes of fate and transport in an approximately 9.2 km^2 waste zone beneath a 4-m thick closure cover of vegetated alluvial soil. The model outputs represent radiological doses measured to a MOP located outside the boundaries of the facility (surface radon flux is modeled at the surface of the disposal cell). The parameters used in the performance assessment model are conceptualized values integrated across the disposal facility (virtual cell concept). Most performance assessment studies represent the variance of these parameters as the maximum observed range of point-source parameter measurements and measurements of processes of flow and transport. Avoiding bias in assigning probability distributions requires averaging of measurements and compensating for scaling nonlinearities (18). We systematically re-evaluated all probability distributions for model parameters to ensure they represent the variance of average properties across the virtual cell. This approach generally resulted in a reduction in the variance of the PDFs used in the probabilistic PA model. The disposal inventory included in the Area 5 PA model was updated to account for waste streams disposed after completion of the original Area 5 PA (post-1994 inventory). This inventory has slightly higher average specific activity and significantly higher specific activities for individual waste radionuclides. Finally, we continue to struggle with implementation of gaseous diffusion of ^{222}Rn due primarily to limitations in the number of diffusion cells used in the model (essentially a coarse 1-D finite difference matrix). Large numbers of diffusion cells increase execution time for the simulations and limit the practicality of running large numbers of simulations needed for output convergence. Smaller numbers of diffusion cells allow faster run times but give higher than expected surface radon flux because of artificially rapid "spreading" (numerical dispersion) of gaseous radon. After experimenting with optimizing the number of diffusion cells and run times, we chose to calibrate the model estimates of the surface radon flux to the results obtained using an established radon diffusion model developed by the Nuclear Regulatory Commission (NRC) for analysis of cover thickness for uranium mill tailings sites (19, 20).

Area 5 RWMS PA Model Version 3.0

The procedures for calibration of radon flux in the Area 5 PA model to the NRC model were incorporated into the Version 3.0 revision. The capability for assigning waste-specific radon emanation factors to individual disposal configurations (disposal pits and trenches) was added to the model, and the model implementation of gas-phase tortuosity was changed to the NRC model (20) for increased consistency with the calibration procedures. A major update in the PDFs and distribution parameters used in the biotic model was added in the Version 3.0 model reflecting an additional phase of in situ field data for plants, ants, termites and small mammals. These revisions led to decreases in the maximum depth of penetration of plants and animals and the new data coupled with a 4-m cover thickness places most biotic activity above the waste zone. Additionally, the plant model was simplified using insights gained through sensitivity analysis of model outputs. The dimensions of the facility disposal units were reworked in the model to improve the consistency of area and volume numbers in the virtual cell averaging. Finally, a separate GoldSim model was developed for updating disposal inventory, and this model integrates with the probabilistic PA model to allow frequent updates of disposal inventory.

Simulation Comparisons

A series of standardized simulations were run with versions 1.1, 2.0, 2.1 and 3.0 of the probabilistic Area 5 RWMS PA model. All simulations used GoldSim version 8.02, service pack 1 except for the Version 1.1 model that required GoldSim Version 7.40.2 to execute properly. Latin hypercube sampling with 1000 realizations was used in all the simulations, a sufficient number of realizations to provide acceptable convergence of model outputs. The duration of all simulations was 10,000 years, a sufficiently long interval to evaluate contrasting model behavior.

The waste inventory was updated to include post-September 1988 waste (date of implementation of DOE Order 435.1) disposed through the end of September 2003. Forecast inventory through facility closure was not included in the simulations to remove a poorly constrained component of uncertainty and to focus the assessments on waste in the ground. Similar disposal configurations were used in all simulations since the intent of the exercise is to evaluate output changes from differences in the model versions.

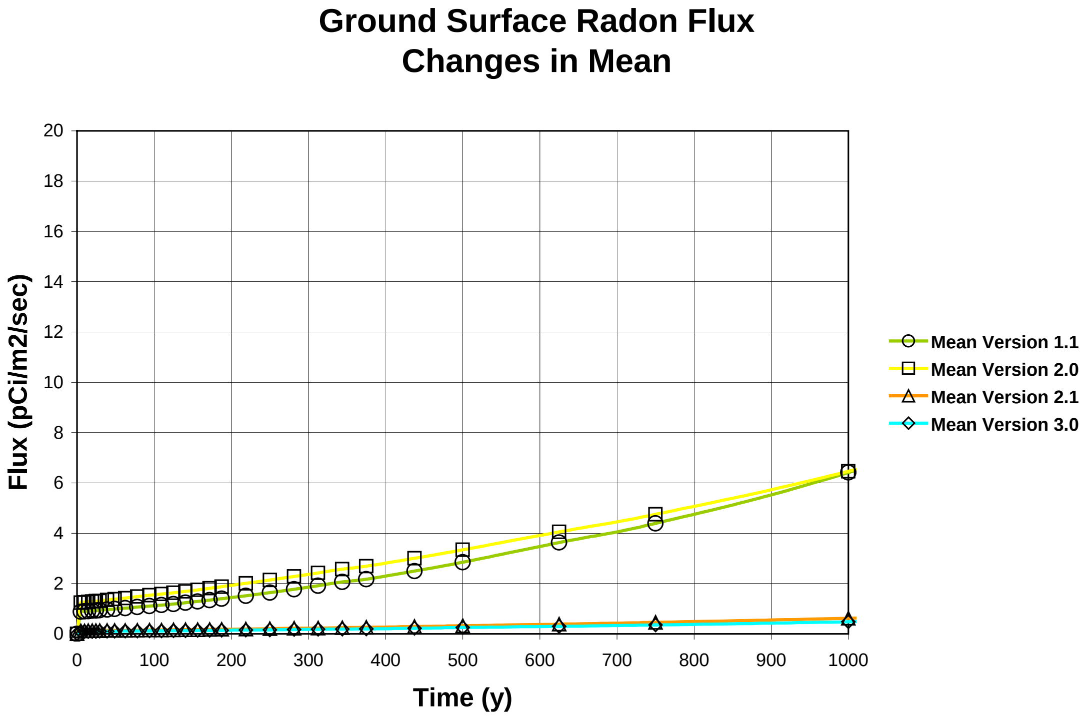
Model Output Comparisons

The model comparisons use two required performance objectives from DOE Order 435.1 shown through uncertainty analysis to be the most important performance objectives for the Area 5 PA (16). These are the resident farmer all-pathways TEDE and the ground surface ^{222}Rn flux. Evaluations of model outputs for these two objectives allow assessment of the reduction in model conservatism and uncertainty in the output results for the sensitive performance objectives. A reduction in conservatism in model results is inferred from a reduction in the mean estimates for the two objectives. A reduction in uncertainty is defined as a decrease in a representative percentile range in the model output. For this study, we used the 95th and the 5th percentiles and defined model output uncertainty (U) as the 95th percentile minus the 5th percentile.

Figure 3a is a plot of the mean dose estimates in mrem in a year (1 mrem = 0.01 mSv) for the resident farmer all pathways TEDE. The x-axis, time, on the plot is shown for 1000 years, the compliance period for disposal of LLW. The y-axis is scaled to the regulated performance objective, 25 mrem in a year. Individual curves are fitted to the simulation time steps for respectively, the 1.1, 2.0, 2.1 and 3.0 model versions. The early peak in dose (~ 30-50 years) during the period of institutional control when no receptors are present is associated with the release of gaseous tritium. The doses decrease with time due to the short half-life of tritium (12.3 years). The plot shows consistent decreases in mean estimates of the resident farmer TEDE with the successive model versions. The largest reduction in doses (decreased conservatism) is associated with changes between the 1.1 and 2.0 and the 2.1 and 3.0 model versions. The estimated dose at 1,000 years for the version 1.1 model is slightly less than 50% of the performance objective. The 1,000-yr doses for the version 2.0 and 2.1 models are about 20% of the performance objective and the same doses for the version 3.0 model are < 5% of the regulatory limit (Note: these doses cannot be used for assessment of compliance because the inventory does not include disposal forecasts to facility closure).

Figure 3b is a plot of the uncertainty (U) in model output for the all-pathways resident farmer TEDE. The uncertainty in the TEDE remained largely unchanged through the model version 2.1 but decreased significantly with the changes in the biotic uptake models implemented in the model version 3.0. While the mean doses are relatively small, the uncertainty in the doses over the compliance interval are a relatively large component of the performance objective for model Versions 1.1, 2.0, 2.1; uncertainty was substantially reduced in the version 3.0 model. The lower doses associated with the tritium peak for the 1.1 model version is probably from instability in the upper percentile tails of the output distribution from the diversity of models used for gas-phase tortuosity.

Figure 4a is the mean estimates of the surface radon flux in picocuries per square meter per second ($pCi/m^2 \cdot s$) for the 1000-yr simulations with the curve fits and plotting symbols the same as Figure 3a. Figure 4a shows a moderate reduction in surface radon flux with the Version 2.0



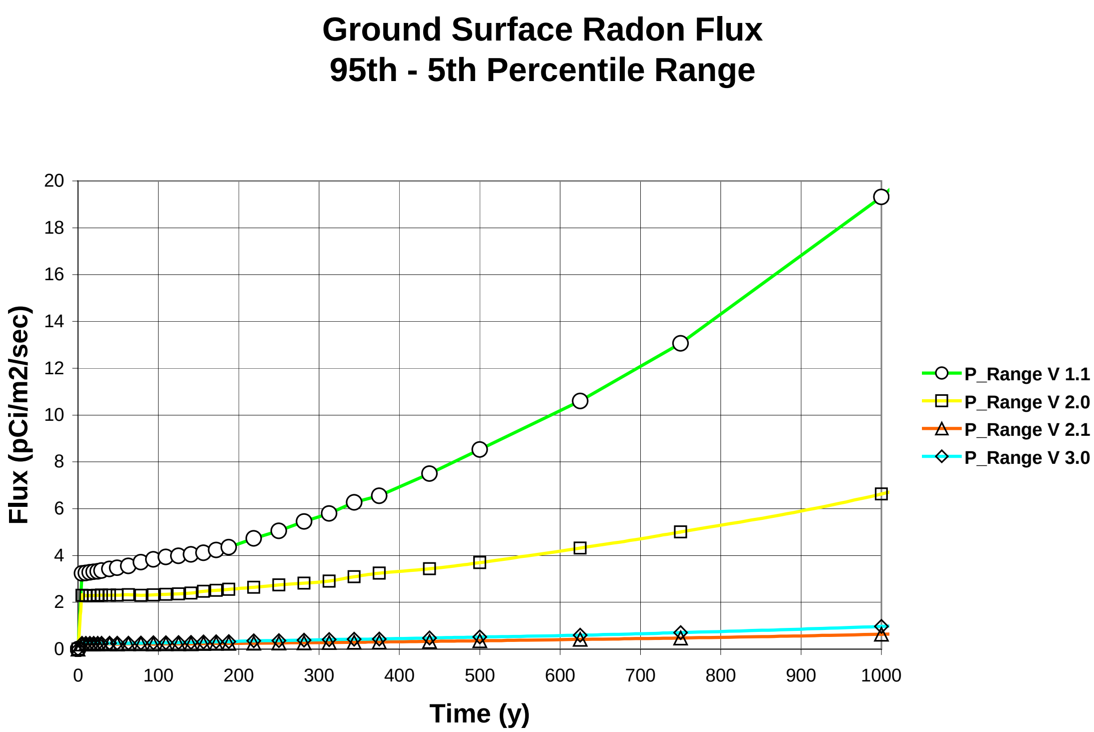


Fig. 4a (top). Mean ground surface radon flux versus time. Note the significant reduction in the mean radon flux with calibration to the NRC radon diffusion model (incorporated in model version 2.1).

Fig. 4b (bottom). Model output uncertainty for the ground surface radon flux versus time. Note the significant decrease in uncertainty with model version 2.0 despite minor change in the mean.

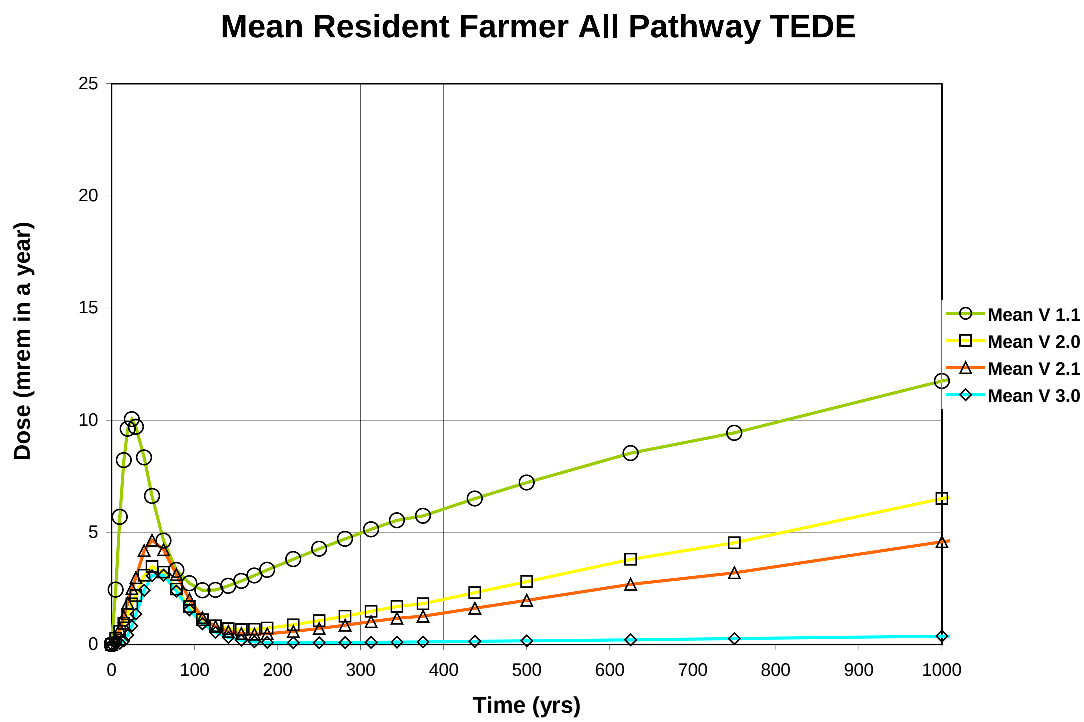
adjustments in the gas-phase tortuosity and a significant reduction in ground surface radon flux with calibration to the NRC radon release model.

Figure 4b illustrates uncertainty reduction (U) for the ground surface radon flux with two major steps in uncertainty reduction. The first occurred with the Version 2.0 model that implemented a modified approach to gas-phase tortuosity using the modeling results from the upward advection study (17). The second occurred with the Version 2.1 model when surface radon flux was calibrated to estimates using the NRC radon diffusion model. While the mean radon flux is relatively low for all models (Figure 4a), the uncertainty range in the version 1.1 model was nearly equal to the 20 pCi/m^2·s regulatory limit. This range decreased to about 30% of the performance objective for the Version 2.0 model and is about 5% of the performance objective for both the 2.1 and 3.0 model versions.

To summarize, simulation comparisons using similar model setups, waste configurations and waste inventories show clear reductions in model conservatism (mean estimates of the sensitive performance objectives) and model uncertainty. The reductions in the mean estimates are mostly systematic whereas uncertainty reduction is more variable and occurs both with and without reduction in the mean estimates. The overall reductions in conservatism and uncertainty demonstrate measurable benefits from continuing development of the probabilistic PA model for the Area 5 RWMS.

COMMENTS

Evaluating the results of performance assessment models requires examination of multiple components of model outputs. This study emphasizes the importance of assessing both the mean estimates of regulated performance objectives and the uncertainty associated with those estimates. Reductions in model uncertainty are most significant when uncertainty represents a significant component of an overall performance objective. These studies show that the mean estimates of the resident farmer all pathway TEDE and the ground surface radon flux can be relatively small percentages of the performance objectives while the uncertainty in those estimates can be a large percentage of the performance objective. Prudent decision making in the management and operation of disposal facilities should be based on examination of both components of modeling results. Probabilistic performance assessment studies can facilitate decision making and also lead to a logical and measurable basis for completing model development studies. The simulation modeling for this study shows that continued model development of the Area 5 RWMS PA model has decreased both conservatism and uncertainty in the performance assessment model. The probabilistic model outputs allow quantification of the decision uncertainty in meeting performance objectives. The reductions in conservatism and uncertainty increase the potential for acceptance of problematic waste streams, an important facility capability for responding to accelerated clean-up across the DOE complex.



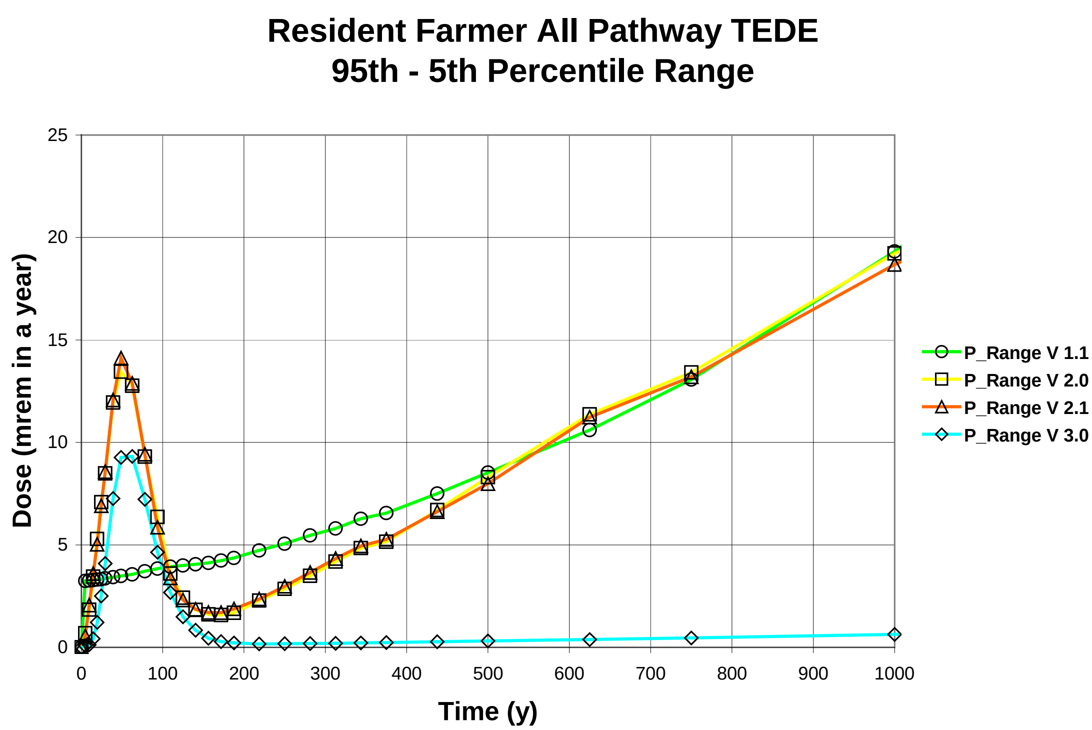


Fig. 3a (top). Mean dose for the resident farmer all pathways TEDE versus time for the model simulations. The plotted points are individual time steps and the curves are from simulations using different versions of the PA model. Note the progressive decrease in estimated mean dose with successive model versions.

Fig. 3b (bottom). Diagram of the estimated model output uncertainty ($U_{95th} – U_{5th}$) for the resident farmer all pathways TEDE versus time. Curves and the plotting symbols are the same as Figure 3a. Note the significant uncertainty reduction with the revised biotic model incorporated in the version 3.0 model.

REFERENCES

1. SHOTT, G.J., L.E. BARKER, S.E. RAWLINSON, M.J. SULLY, AND B.A. MOORE, "Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada," DOE/NV/11718-176 UC-721 Nevada Operations Office, Las Vegas, (1998).
2. CROWE, B. V. YUCEL, S. RAWLINSON, P. BLACK, J. CARILLI AND F. DISANZA, "Application of Probabilistic Performance Assessment Modeling for Optimization of Maintenance Studies for Low-Level Radioactive Waste Disposal Sites at the Nevada Test Site," in *Proceedings Waste Management '02 Tucson, Arizona, paper 364, 13 p.* (2002)
3. CRANWELL, R.M., J.E. CAMPBELL, J.C. HELTON, R.I. IMAN, D.E. LONGSINE, N.R. ORTIZ, G.E. RUNKLE, AND M.J. SHORTENCARIER, "Risk Methodology for Geologic Disposal of Radioactive Waste: Final Report," Sandia National Laboratories Reportt. SAND81-2573, NUREG/CR-2452 (1987).
4. CRWMS M&O, "*Total System Performance Assessment—Viability Assessment,*" (TSPA-VA) analyses technical basis document. Las Vegas, Nevada, CRWMS M&O ACC:11981008.0001 to .0011 (1998).
5. NUCLEAR ENERGY AGENCY (NEA), "The Probabilistic System Assessment Group—History and Achievements 1985 – 1994," NEA/OECD Publication 72 p., Paris, France (1997).
6. NEA, "Lessons Learnt from Ten Performance Assessment Studies," NEA/OECD Publication, 132 p., Paris, France (1997).
7. NEA AND INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), "An International Peer Review of the Yucca Mountain Project Total System Performance Assessment for the Site Recommendation," NEA/OECD/IAEA Publication, 96 p., Paris, France (2002).
8. LINKOV, I., AND BURMISTROV, D., "Model Uncertainty and Choices Made by Modelers: Lessons Learned from the International Atomic Energy Agency Model Intercomparisons," *Risk Analysis,* volume 23, No. 6, p. 1294-1308 (2003).
9. LEVITT, D. G., C. F. LOHRSTORFER, M. J. SULLY, AND J. M. GINANNI, "An Arid Zone Lysimeter Facility for Performance Assessment and Closure Investigations at the Nevada Test Site." *Proceedings of the Waste Management '96 Conference, Tucson, Arizona* (1996).
10. LEVITT, D. G., M. J. SULLY, AND C. F. LOHRSTORFER, "Modeling Evapotranspiration from Arid Environments." Literature Review and Preliminary Modeling Results. Bechtel Nevada report to U.S. Department of Energy, Nevada Operations Office, Las Vegas, Nevada (1996).
11. TYLER, S. W., J. B. CHAPMAN, S. H. CONRAD, D. P. HAMMERMEISTER, D. O. BLOUT, J. J. MILLER, M. J. SULLY, AND J. M. GINANNI, "Soil-Water Flux in the Southern Great Basin, United States: Temporal and Spatial Variations over the Last 120,000 Years." *Water Resources Research* 32(6):1481-1499 (1996).

12. GOLDSIM TECHNOLOGY GROUP, *GoldSim Software®*, GoldSim Technology Group, Redmond, WA (2004). www.goldsim.com

13. SHOTT, G.J., V. YUCEL, M.J. SULLY, L.E. BARKER, S.E. RAWLINSON, AND B.A. MOORE, "Performance Assessment/Composite Analysis for the Area 3 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada," DOE/NV-491 Nevada Operations Office, Las Vegas (2000).

14. BLACK, P., K. BLACK, L. STAHL, M. HOOTEN, T. STOCKTON AND D. NEPTUNE, "Assessing the Probability of Inadvertent Human Intrusion at the Nevada Test Site Radioactive Waste Management Sites," DOE/NV—593. Report to U.S. Department of Energy, Nevada Operations Office (March 2001).

15. R DEVELOPMENT CORE TEAM "R: A language and environment for statistical computing. R Foundation for Statistical Computing," Vienna, Austria. ISBN 3-900051-00-3, URL http://www.R-project.org. (2004).

16. NEPTUNE AND COMPANY, "A Radiological Performance Assessment Model of the Area 5 Radioactive Waste Management Site, Nevada Test Site using the GoldSim Modeling Framework," Milestone Report for the National Nuclear Security Administration Nevada Site Office September 30 (2002).

17. WOLFSBERG, A., AND P. STAUFFER, "*Vadose-zone Fluid and Solute Flux: Advection and Diffusion at the Area 5 Radioactive Waste Management Site,*" Los Alamos National Laboratory Report LA-UR-03-4819. 94 pp. (2003).

18. ZHAND, X., N.A DRAKE AND J. WAINRIGHT, "*Scaling Issues in Environmental Modeling,*" in J. Wainwright and M. Mulligna, editors, "*Environmental Modelling Finding Simplicity in Complexity*, John Wiley & Sons, Ltd, Chichester, England (2004).

19. NUCLEAR REGULATORY COMMISSION, "Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers," Washington, DC, U. S. Nuclear Regulatory Commission Regulatory Guide 3.64 (1989).

20. ROGERS, V.C., AND K. K. NIELSON, "Correlations for Predicting Air Permeabilities and Rn222 Diffusion Coefficients of Soils," Health Physics 61, v. 2, p. 225-230 (1991).