**Management of the Area 5 Radioactive Waste Management Site using Decision-based, Probabilistic Performance Assessment Modeling**

Jhon Carilli
U. S. Department of Energy, National Nuclear Security Administration
Nevada Site Office

Bruce Crowe
Los Alamos National Laboratory

Paul Black, John Tauxe, Tom Stockton, and Kate Catlett
Neptune and Company

Vefa Yucel
Bechtel Nevada

ABSTRACT

Low-level radioactive waste from cleanup activities at the Nevada Test Site and from multiple sites across the U.S. Department of Energy (DOE) complex is disposed at two active Radioactive Waste Management Sites (RWMS) on the Nevada Test Site. These facilities, which are managed by the DOE National Nuclear Security Administration Nevada Site Office, were recently designated as one of two regional disposal centers and yearly volumes of disposed waste now exceed 50,000 m$^3$ (> 2 million ft$^3$). To safely and cost-effectively manage the disposal facilities, the Waste Management Division of Environmental Management has implemented decision-based management practices using flexible and problem-oriented probabilistic performance assessment modeling. Deterministic performance assessments and composite analyses were completed originally for the Area 5 and Area 3 RWMSs located in, respectively, Frenchman Flat and Yucca Flat on the Nevada Test Site. These documents provide the technical bases for issuance of disposal authorization statements for continuing operation of the disposal facilities. Both facilities are now in a maintenance phase that requires testing of conceptual models, reduction of uncertainty, and site monitoring all leading to eventual closure of the facilities and transition to long-term stewardship. Deterministic performance assessments have restricted utility for a maintenance program because of non-systematic conservatism and non-quantification of uncertainty; both factors limit full utilization of the disposal capability of a site. Probabilistic performance assessment models using the GoldSim simulation software are replacing the deterministic performance assessment models for the Area 5 and Area 3 RWMSs. Model conversion is following an iterative process with successive upgrading of the models guided by decision priorities and results of sensitivity and uncertainty analyses. Two important problems in this conversion are ensuring parameter distributions and model assumptions are conditioned on unbiased assessments of uncertainty and are applied consistently to the spatial and temporal scales of the modeling problem. There are multiple benefits from the use of the results of probabilistic modeling for managing the disposal facilities. First, the expected performance of a disposal site is quantified leading to more realistic waste

concentration limits and full utilization of the disposal capability of the sites. Second, iterative revisions of performance assessment models are streamlined using the GoldSim simulation software resulting in reduced program costs. New waste streams can be evaluated more efficiently and special performance assessments are not required for problematic waste streams. Third, the extent and duration of monitoring and the development of closure programs are based on risk-based, cost-benefit analysis utilizing the results of probabilistic performance assessment models. Fourth, sensitivity and uncertainty analyses are enhanced with probabilistic model results promoting fully informed decision making for efficient use of program resources. Fifth, the flexibility and efficiency of probabilistic modeling using the GoldSim simulation software allows cost-effective assessment of alternative scenarios and evaluation of model and conceptual uncertainty, important components of regulatory and stakeholder acceptance. Finally, iterative evaluation of probabilistic model results combined with cost-benefit analyses can be used to establish a defensible logic for facility closure and a transition to long-term stewardship.

INTRODUCTION

The U.S. Department of Energy (DOE), National Nuclear Security Administration Nevada Site Office (NNSA/NSO) operates and maintains two active radioactive waste management facilities on the Nevada Test Site (NTS) that dispose defense-generated low-level radioactive waste (LLW), minor volumes of mixed radioactive waste, and classified materials (Fig. 1). Disposal of LLW generated from defense activities on the NTS began in 1960 and operations were expanded in 1978 to include disposal of LLW from off-site generators across the DOE complex.

The Area 5 Radioactive Waste Management Complex (RWMS) is located in north central Frenchman Flat (Fig. 1) and is used to dispose containerized LLW from predominantly actinide-bearing waste streams (1). The majority of waste is buried in shallow trenches and pits, and large-diameter boreholes (Fig. 2). The Area 3 RWMS (Fig. 3) is located in Yucca Flat (Fig. 1) and disposes both containerized and bulk wastes in subsided surface craters created by underground testing of nuclear weapons (2).

The NTS LLW disposal sites were recently designated by DOE Headquarters as a regional disposal center along with the Hanford site in Washington State (*Federal Register,* February 25, 2000). This designation and the acceleration of cleanup activities across the DOE complex has led, in the last few years, to safe disposal of increased volumes of LLW on the NTS. Current forecasts of LLW for disposal at the NTS in fiscal year 2003 exceed 110,000 m$^3$ (4 million ft$^3$).

To serve the important role of a regional disposal center for LLW waste, it is imperative that the LLW facilities be managed safely, efficiently and cost-effectively. The sites are controlled under DOE Order 435.1 (3) and regulated through the Low-Level Waste Federal Review Group (LFRG).
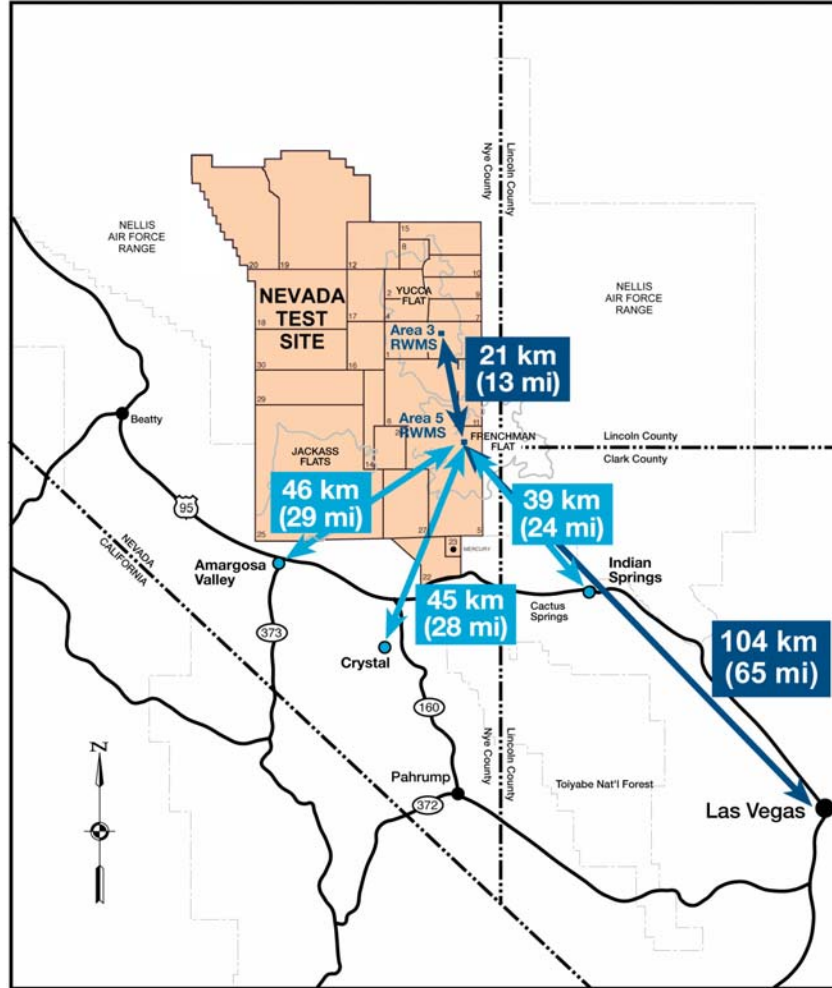
**Fig. 1. Map of southern Nevada and adjacent areas of California showing the location of the Area 3 and Area 5 Radioactive Waste Management Sites within the Nevada Site.**

There are three major steps in the lifecycle of the LLW facilities including:

1. Completion and acceptance by the LFRG of performance assessments (PA) and composite analyses (CA) for each facility leading to disposal authorization;
2. Implementation and completion of a PA maintenance program; and
3. Transition to long-term stewardship.

The PAs and CAs for the Area 5 and Area 3 facilities have been completed, reviewed, and conditionally accepted by the LFRG with issuance of disposal authorization statements (DAS) that provide the approval authority for continuing operation of the sites. The conditions associated with acceptance of both sites were evaluated and resolved to the satisfaction of the LFRG during calendar year 2002. The LLW disposal

**Fig. 2. Aerial photograph of the Area 5 RWMS. LLW is disposal in shallow trenches, pits, and greater confinement disposal boreholes.**



**Fig. 3. Oblique aerial view of the Area 3 RWMS. LLW is disposed in surface subsidence craters created from underground testing of nuclear weapons.**

facilities are now under a formal maintenance program managed by NNSA/NSO that requires testing of conceptual models, quantifying and attempting to reduce uncertainty, and implementing confirmatory and long-term monitoring all prior to closure of the disposal sites. Each of these tasks requires decision-making under uncertainty where the decisions require balancing the cost and time required to acquire site information to reduce uncertainty and the value of that uncertainty reduction relative to programmatic goals. To facilitate decision-making, NNSA/NSO has converted the PA models for the LLW facilities from a deterministic to a probabilistic framework using the GoldSim simulation software (4, 5). The probabilistic models coupled with decision logic are used as analytical tools to facilitate decision-making under uncertainty for optimizing management of the disposal facilities. The purpose of this paper is to describe the logic behind and the anticipated program benefits gained through application of probabilistic-based decision-making.

## DETERMINISTIC VERSUS PROBABILISTIC PERFORMANCE ASSESSMENTS

The DOE requires the completion of performance assessments and composite analyses for their LLW disposal facilities. The PAs provide the basis for establishing with reasonable expectation that disposal sites meet the radiological performance objectives established in DOE Order 435.1. The CAs provide planning documents to assess the effects of all interacting sources of radioactive materials at DOE sites and ensure doses are consistent with long-term protection of the public. The accepted PA/CA for the NTS radioactive waste management sites are based on conservative and deterministic analytical and numerical models (1, 2) that respond to the deterministic regulatory requirements of DOE Order 435.1.

The intent of a deterministic PA is to *overestimate* radiological releases from a LLW disposal site through application of presumed *conservatism.* Conservatism in a PA is based on the use of bounding parameter values in a PA model in combination with model assumptions that underestimate the containment capability of a disposal site. Such conservatism can provide an acceptable method for establishing regulatory compliance based on a concept of *reasonable expectation* as expressed in DOE Order 435.1. That is, the site is presumed to perform *better* than the conservative based estimates of releases for the multiple deterministic performance objectives of DOE Order 435.1 (atmospheric dose to the member of public, all pathway dose to the member of public, radon flux, doses to an inadvertent human intruder). All model input in a deterministic PA is in the form of fixed or single-point *conservative* values where the uncertainty of the inputs is not defined or included in analytical or numerical models.

There are multiple weaknesses of deterministic PAs when used for applications beyond assessment of regulatory compliance measured against deterministic regulations:

1. There is not an established definition of acceptable conservatism. The concept is applied non-systematically in PAs and both the developers of PAs and their regulators and stakeholders can use different perspectives in defining and applying conservatism.

2. Presumed conservatism in a deterministic PA is systematically propagated as combinations of multiple variables that are evaluated through coupled equations. An often-overlooked aspect of this propagation of conservatism is the generation of implausible results. Successive propagation of bounding parameter values through model equations leads to combinations of variables with decreasingly smaller likelihoods of occurrence. Without careful assessment of propagation effects, the modeled system behavior can yield results that are either very unlikely or cannot occur (physically implausible).

3. The hydrogeologic setting of shallowly buried LLW sites can be complex with significant variability both spatially and temporally in parameters used to model the behavior of the system. The fate and transport of contaminants in a complex setting can exhibit nonlinear behavior through the interactions of coupled processes with multiple positive and negative feedbacks. Resulting system behavior can be non-intuitive frustrating efforts to correctly formulate conservative assignments of parameter values and model assumptions.

4. Conservative deterministic models of LLW disposal sites, as noted above, underestimate the ability of a facility to isolate waste. This is the most important shortcoming of a deterministic PA model from the perspective of management of a waste disposal facility. Stated simply, the use of conservatism and the propagation of conservatism limit full utilization of the disposal capability of a site.

In contrast, a probabilistic PA uses parameter assignments that are intended to be centered at the mean or expected value of model variables, conditioned on the state of knowledge for those variables. These parameter values are input into the PA model as probability distributions that quantify parameter uncertainty. The probability distributions are propagated through model equations using Monte Carlo simulation. The output of simulation is also a probability distribution where the expected value and the uncertainty about the expected value are defined by the properties of the probability distribution. This quantification of uncertainty through application of probabilistic PA models dramatically improves the quantity and quality of information that in turn can be used for better decision-making for managing a LLW facility. The next section of the paper briefly examines the methodology that was used to establish a probabilistic PA model for the Area 5 RWMS, the first step in more efficient management of the LLW facilities on the NTS.

PA MAINTENANCE USING PROBABILISTIC MODELING

The primary goals of the NNSA/NSO PA maintenance program are to fully utilize the disposal capability of the Area 5 and Area 3 LLW facilities as a DOE-complex regional disposal center, and to provide increased confidence that the conclusions and applications of the performance assessments and composite analyses remain valid over the operational and post-closure periods of the disposal facilities (6). To accomplish these goals, the Area 5 PA and CA were converted to a fully probabilistic model using the GoldSim simulation software (3). This new modeling approach was first benchmarked against the LFRG-approved PA by retaining the conceptual model, and model assumptions, and

parameter values of the deterministic models (5). The implementation of the CA in the probabilistic model is only completed for the CA inventory; all interacting radiological sources in the facility setting have not yet been included in the revised model. After successful benchmarking, the GoldSim model was then expanded to a fully probabilistic model using the following steps:

1. Parameter values were converted systematically to probability distributions.
2. Documentation of parameter probability distributions including references to literature publications were incorporated directly into the GoldSim model both for recording and tracking parameter information and for quality assurance.
3. Model components were updated for consistency using new information from successive stages of PA and CA completions, as well as data from ongoing site monitoring.
4. Modeling assumptions were examined systematically to ensure consistency with definition of the expected behavior of a disposal site and modified where required. Much of the conservatism in model assumptions was removed from the original PA and CA models. However, all aspects of conservatism have still not been removed. For example, the current probabilistic model does not take full credit for the expected behavior of the LLW-waste setting for container degradation, waste release models and solubility limits of contaminants.
5. Model components identified as significant contributors to system variance through sensitivity analyses were upgraded with new information. This effort focused primarily on revision of conceptual models and parameter values for liquid and vapor phase components of upward advection, and the biotic transport of contaminants (plant uptake and insect burrowing). This is the first step of an iterative process of successive stages of data evaluation, changes in model parameters, and revised sensitivity and uncertainty analysis, all tied to and controlled by the decision objectives for the Area 5 RWMS.

The first iteration of a probabilistic PA GoldSim model for Area 5 was completed at the end of fiscal year 2002. The model will be tested and upgraded during fiscal year 2003 through updating disposed inventory records through fiscal year 2001, and evaluation of new waste streams under consideration for future disposal at the NTS. Significant new waste streams for these evaluations include 11(e)2 LLW waste from Fernald, thorium nitrate source materials under evaluation by Oak Ridge National Laboratory, and small volumes of sealed source waste being evaluated jointly by the Idaho National Engineering and Environmental Laboratory and the Albuquerque Site Office.

Two lessons emerge from the completion of the GoldSim model for Area 5. First, extra attention was required to ensure that parameter distributions and model assumptions are fully consistent with development of unbiased probability distributions. Incorporation of the concept of conservatism is so ingrained in PA models that a diligent effort must be made to remove bias. Second, we are still addressing the issue of spatial scaling in the assignment of parameter probability distributions. The Area 5 PA model evaluates system releases using a *virtual cell* concept. That is, radiological releases are forecast on a facility-wide basis rather than for individual trenches, pits and greater confinement

boreholes. Probability distributions for model parameters are typically evaluated from borehole data, from laboratory measurements, and from referenced data in the scientific literature. The uncertainty of these scale-specific data may not adequately represent the uncertainty of an average parameter applied to a virtual cell. This "scaling-up" of model parameters is a recognized but incompletely resolved problem in the development of flow and transport models (7) where the degree of scaling is dependent on the size of finite element or finite difference grids used in the models. This problem has not been given sufficient attention in development of performance assessment models that are scaled to the dimensions of a virtual cell (facility dimensions). This "scaling problem" also applies to temporal as well as spatial scales.

## FACILITY MANAGEMENT USING THE RESULTS OF PROBABILISTIC MODELING

What are the advantages of a probabilistic PA model for decision-making? This final section examines the most important benefits of enhanced information provided from the results of probabilistic models.

Expected Performance of a Disposal Site

The first and foremost benefit of a probabilistic PA model is realized from defining the expected performance of a disposal site and the uncertainty associated with that performance for the multiple performance objectives of DOE Order 435.1. By removing conservatism from a PA model, the full disposal capability of a site becomes better defined and can be applied more realistically to disposal decisions. Waste concentration limits are revised and broadened leading to less restrictive waste acceptance criteria. This provides a greater ability for the NNSA/NSO regional disposal center to serve the LLW disposal needs across the DOE complex. Additionally, by defining the uncertainty associated with expected performance, a decision maker is better informed when the combined cumulative disposed inventory and the uncertainty associated with that inventory approaches the limits of the performance objectives.

Efficiency of Iterative Revisions of Performance Assessment Models

A probabilistic model implemented through the GoldSim simulation software can be run more efficiently than traditional PA models that use multiple separate and non-coupled numerical and analytical codes. Revision of an existing probabilistic PA model using GoldSim requires only updating model parameters and model assumptions, conditioned on new information, and running revised simulations using the probabilistic model. Parameter revisions, model updates or assessment of alternative model assumptions can be run in days. In contrast most deterministic PA models are completed using non-coupled codes and revisions require sequential linking of the results of the separate codes. Completion times for revisions can extend to months. The probabilistic PA model implemented through the GoldSim simulation software reduces the time for PA revisions thus reducing program baseline costs.

More efficient iterative PA revisions also allow for faster and more efficient assessment of new waste streams including adaptation of the model to the volumes and characteristics of a waste stream under consideration for disposal. The waste concentration limits at DOE LLW disposal sites are established from PA calculations using disposed inventory and projection of that inventory to closure. These limits are generally applicable if a new waste stream has similar radionuclides and radiological activity to disposed waste streams. However, waste concentration limits are difficult to apply to unique or higher specific activity waste streams of larger volume. The GoldSim model can be easily modified to include a new waste stream in the model calculations and to iteratively revise waste concentration limits taking into account the actual characteristics of the new waste. The need for and the cost of a special PA tailored to a specific waste stream can be avoided.

Monitoring and Closure Decisions

The extent and duration of site monitoring and the development of closure programs are two major decisions problems affecting a LLW waste facility during PA maintenance. What monitoring data are needed and how long should the data be collected to establish confidence in the robustness of an existing PA model? The increased efficiency in revising the GoldSim probabilistic PA model can be used to answer this question. Monitoring data should be evaluated intermittently to assess whether the new information results in changes in model assumptions and/or distributions for model parameters. Revised data and assumptions can be entered into a probabilistic model and the PA code rerun to assess changes in the cumulative distribution functions for the performance objectives. A value of information assessment can be coupled to the probabilistic modeling results to establish the cost-benefit of uncertainty reduction from incorporation of monitoring data. A logical end to active site monitoring under a PA maintenance plan can be established by recognizing a diminished uncertainty reduction from inclusion of new monitoring data.

One of the primary costs of a site closure program is the design and construction of closure caps. The current closure plan for waste cells in both the Area 5 and Area 3 RWMSs (8) call for the addition of a vegetated, monolayer soil cover above the 2.4-meter (8 ft) thick operation cover of alluvial soil now on most inactive waste cells (1, 2). The primary benefits of the closure covers are threefold. The additional thickness of the cover serves to decrease the amount of moisture moving through the underlying waste. The greater the thickness of the closure cap, the more effectively the cap serves to recycle infiltrated water back to the atmosphere utilizing the natural high evapotranspiration potential of the arid desert setting. Second, the cover serves as a buffer to prevent or decrease penetration of plant roots and burrowing insects into the waste zone. Third, the greater the thickness of the closure cover, the greater the ability of the cover to resist modification from subsidence associated with compaction and degradation of containers and their enclosed waste matrix. The benefits of incremental increases in closure-cap thickness must be weighed against increased construction costs.

Using the increased efficiency of iterative runs of probabilistic PA models, a decision problem can be evaluated comparing the performance gains of increased cap thickness against the cost of cap construction. Enhanced sensitivity analyses conducted with the probabilistic GoldSim model for the Area 5 site show that cap thickness is a sensitive parameter up to a threshold thickness, where the parameter becomes relatively insensitive. This information indicates that increasing cap thickness beyond the threshold thickness has limited performance benefits and would not be cost effective.

Enhanced Sensitivity Analysis

A major advantage of a probabilistic PA model is the ability to conduct enhanced sensitivity and uncertainty analysis. Deterministic PA models are restricted to assessments of changes in model output with changes in a subset of parameter inputs. These assessments correspond to a limited sensitivity analysis where the changes in parameter subsets are correlated with changes in model output. With probabilistic PA models, sensitivity analysis can simultaneously incorporate changes in all model inputs and the uncertainty in those changes. This enhanced capability allows the decision-maker to identify more precisely those system elements that control facility performance. Additional studies or site resources can be focused on the most significant problems from a performance perspective. Enhanced sensitivity analysis can be particularly useful in optimizing a monitoring program. The focus of monitoring programs during the period of confirmatory monitoring in PA maintenance can be guided by the results of sensitivity analysis where acquisition of monitoring data are increased for parameters that are identified as the most significant in sensitivity analysis. This analysis must be coupled with a corresponding value of information analysis that includes the cost of data collection to promote fully informed decision making for management of a LLW facility.

Enhanced "What-if" Analyses

An important component of the PA maintenance program is the requirement to evaluate alternative conceptual models of the disposal site and assess alternative scenarios of future events and processes that affect a site. Acquisition of additional site characterization data and evaluations of the results of monitoring data after completion of the compliance phase of an RWMS are used to test conceptual models and increase confidence in the results of PA models. The primary basis for testing models and increasing confidence is through iterative reruns of PA model results to test for output changes in performance objectives. Both are enhanced by the increased efficiency of rerunning the probabilistic PA model using the GoldSim simulation software.

The raising of new and often unexpected questions outside the scope of a completed PA is an almost inevitable result of continuing regulatory and stakeholder review of PA results. Traditionally, these questions are difficult to answer without rerunning PA models, and are answered typically with subjective statements that modeling results are not expected to change. The efficiency of probabilistic modeling using the GoldSim software can again be utilized to cost-effectively rerun PA models where the reruns can be structured to address directly the new review questions.

Long-Term Stewardship

The final goal of all LLW disposal facilities across the DOE complex is to close the sites and return the land to the public domain or to the custody of long-term landowners (DOE, Federal, State or local governments). A largely unresolved question is how to establish the basis for the decision maker to make a transition to long-term stewardship? Answers to this question are variable and suggested solutions in some cases are to extend active monitoring at a LLW site for up to 100 years after closure. The use of results from probabilistic PA modeling provides a logical approach to this problem. Successive iterations of probabilistic PA models can be run using incremental results from continuing site characterization and site monitoring. The initial results of modeling runs should show changes, most commonly reduction in uncertainty, in probability distributions for performance objectives. With continuing assessment of results, there should be a reduction in the changes to the probability distributions. Cost-benefit analysis using output from probabilistic modeling can be used to establish a point of diminished uncertainty reduction that can be identified as a logical point for transition to long-term stewardship.

## ACKNOWLEDGMENTS

## REFERENCES

1. G.J. SHOTT, 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. G.J. SHOTT, 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).
3. U.S. DEPARTMENT OF ENERGY, *Radioactive Waste Management, DOE* Order 435.1 (July, 1999).
4. GOLDER ASSOCIATES, INC, *GoldSim Software*, GoldSim Consulting Group, Golder Associates., Redmond, WA (2001).
5. 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, (2002) Paper 364 13 p.*
6. U.S. DEPARTMENT OF ENERGY, "Maintenance Plan for the Performance Assessments and Composite Analyses for the Area 3 and Area 5 Radioactive Waste

Management Sites at the Nevada Test Site," National Nuclear Security Administration, Nevada Operations Office, Bechtel Nevada, DOE/NV/11718-49 (2000).

7. ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT/NUCLEAR ENERGY AGENCY, "Modeling the Effects of Spatial Variability on Radionuclide Migration," in *Proceedings of a Workshop, Paris, France, June 9-11,* Paris, France, (1997).

8. BECHTEL NEVADA, "Integrated Closure and Monitoring Plan for the Area 3 and Area 5 Radioactive Waste Management Sites at the Nevada Test Site, DOE/NV/11718—449-Rev 1. Bechtel Nevada, Las Vegas, Nevada (2001).