Implementing an Alternative Modeling Strategy for Closure of the Rainier Mesa Corrective Action Unit at the Nevada National Security Site–17481

Andrew F. B. Tompson* and Kenneth R. Rehfeldt**
*Lawrence Livermore National Laboratory (tompson1@llnl.gov)
**Navarro Research and Engineering (ken.rehfeldt@nv.doe.gov)

ABSTRACT

The strategy to close the Rainier Mesa/Shoshone Mountain (RMSM) Corrective Action Unit (CAU) of the Underground Test Area (UGTA) Project at the Nevada National Security Site (NNSS) is defined under a joint agreement between the State of Nevada, the U.S. Department of Energy (DOE) and the Department of Defense (DoD). That strategy required a corrective action investigation (CAI) to define the evolution of contaminated volumes of groundwater under uncertainty as a means to define a surface-projected contaminant boundary and serve as a basis for longer term monitoring. As the initial phase of the CAI was nearing completion in 2012, concerns were raised as to whether the original Federal Facility Agreement and Consent Order (FFACO) strategy was achievable. This was evident when the complexity of the system and the additional costs required to sufficiently characterize it were judged to be out of balance with the overall perceived risks (low) associated with this particular CAU. As a result, an Alternative Modeling Strategy (AMS) and New FFACO Strategy Decision Process for UGTA RM/SM CAU were approved in November 2013. The AMS removes the requirement for developing ensembles of 3D contaminant transport simulations and replaces it with a simpler one requiring the generation of multiple 1D streamline models. These are meant to encompass a range of alternative, yet plausible release and transport scenarios as a means to bound the overall lateral extent of contaminant transport. The new Decision Process is streamlined and progresses from the revised CAI stage, to an external peer review, and then, upon favorable evaluation, directly to a closure stage. Although the project has suffered some delays from implementation of the new strategy, the new process of achieving closure is expected to save several years in time and several million dollars over the original process while still protecting human health and the environment over the 1,000-year compliance period stipulated in the FFACO.

INTRODUCTION

From 1951 to 1992, the United States government conducted 828 underground nuclear tests at the Nevada National Security Site (NNSS) [1]. About one-third of these tests occurred near or below the water table. As early as the 1970s, U.S. Department of Energy (DOE) began exploring the nature of radiologic groundwater contamination derived from underground testing activities. Today, the Underground Test Area (UGTA) activity is directed at developing an understanding of radionuclide occurrence and movement in groundwater, as derived from all underground tests conducted at the NNSS (Fig. 1). This work is proceeding through an integrated campaign of drilling and sampling, data interpretation, computer modeling, and broader monitoring activities, all of which are conducted under the auspices of a joint Federal Facility Agreement and Consent Order (FFACO) between the State of Nevada, DOE, and the Department of Defense (DoD) [2].

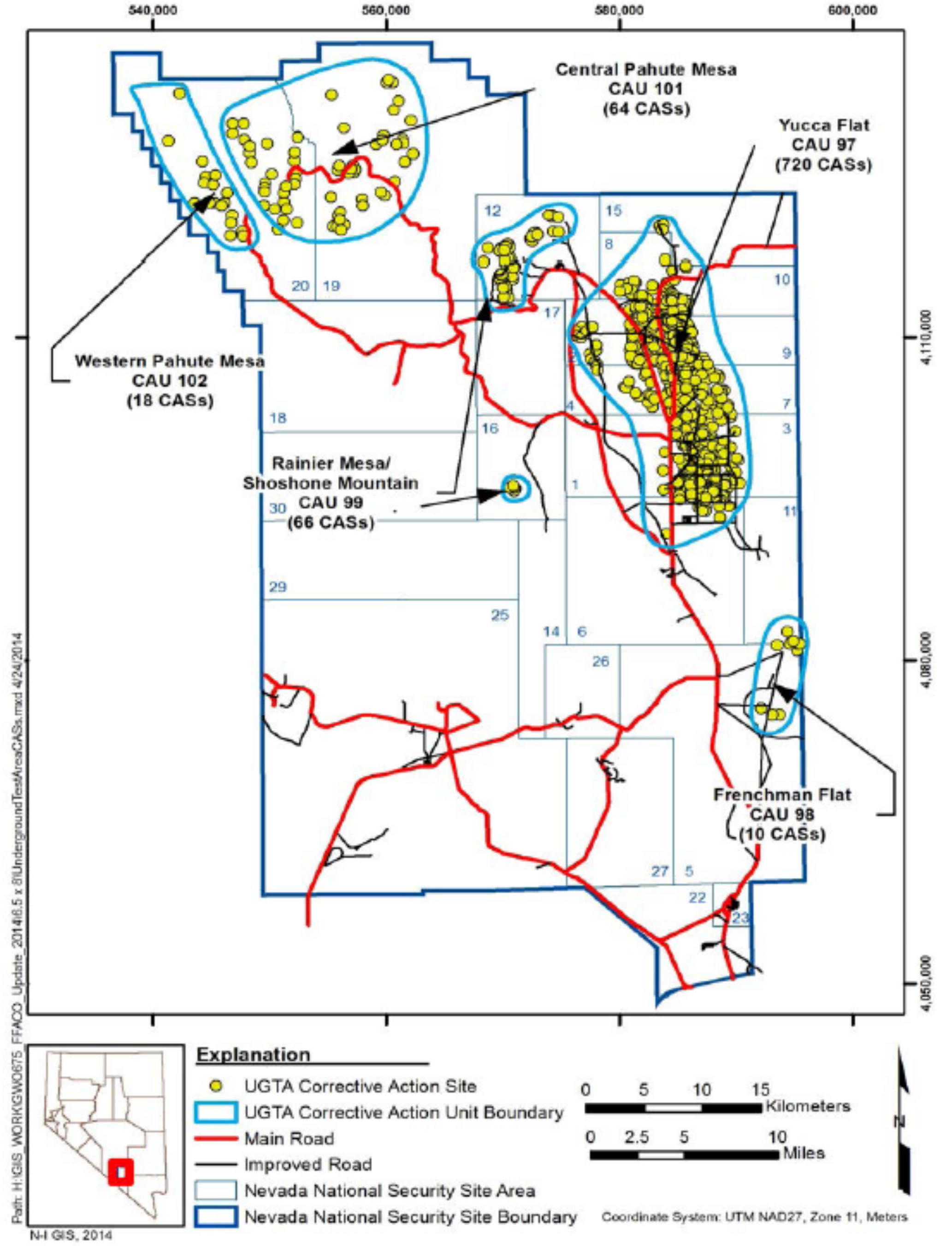

Fig. 1: Map of the Nevada National Security Site, showing the Corrective Action Sites associated with underground tests conducted in 5 Corrective Action Units, as defined in the FFACO [2].

The FFACO Process

Under the FFACO, the underground tests are classified into a series of individual Corrective Action Sites that are organized geographically into a series of five Corrective Action Units (CAUs), which are illustrated in Fig. 1. The primary strategy of the FFACO involves a series of stages and activities conducted within each CAU that include (1, 2) Corrective Action Investigation Planning (CAIP) and formal Investigation (CAI), (3) development of a Corrective Action Decision (CADD) and Closure Plan (CAP), and (4) completion of a Closure Report (CR) that defines that nature of closure and long term monitoring requirements. Each stage is accompanied by regulatory decision points, in some cases, peer review, and restart options as a means to assure sufficiency of available data, adequacy of analyses, or achievability of the overall analytical approach and strategy.

The Corrective Active Investigation

The Corrective Active Investigation (2) itself is conducted to gather data sufficient to characterize the nature, extent, and rate of radionuclide migration or potential rate of radionuclide migration from releases or discharges from the underground tests (Corrective Action Sites) in each CAU. This process includes a modeling component designed to evaluate the volume(s) of groundwater that may become contaminated with radionuclides above drinking water standards over the next 1,000 years. The modeling approach is expected to be probabilistic in the sense that ties in data and the underlying conceptualization will be translated into confidence intervals for the simulation results. The desired outcome of the CAI process is to identify contaminant boundaries for the CAU, defined as one or more closed perimeter(s) on the ground surface that encircle – at a 95% confidence interval – the vertically projected volume(s) of all potentially contaminated groundwater (derived from the underground tests within that CAU) over the next 1,000 years. These results feed into later stages (3, 4) that involve identification of use restriction boundaries and longer term monitoring activities.

THE RAINIER MESA/SHOSHONE MOUNTAIN CORRECTIVE ACTION UNIT

The Rainier Mesa/Shoshone Mountain (RMSM) CAU is an amalgam of two isolated testing areas in Area 12 (Rainier Mesa) and Area 16 (Shoshone Mountain) in the remote northern and central part of the NNSS (Fig. 1). Rainier Mesa itself is topographically elevated, receives the highest levels of precipitation across the NNSS, and is situated on a regional groundwater high. The RMSM CAU is surrounded by the Central and Northern Pahute Mesa CAUs to its west, by the Yucca Flat CAU to its east, and by the Nevada Test and Training Range (NTTR), operated by the U.S. Air Force (USAF), across the NNSS boundary to its north.

The Tunnel Systems

Underground nuclear testing occurred at Rainier Mesa and Shoshone Mountain between 1957 and 1992 [1]. A total of 67 underground tests were conducted here, 61 at Rainier Mesa proper and 6 at Shoshone Mountain [1]. These represent a small fraction of the 828 underground tests conducted throughout all of the NNSS during its period of testing between 1951 and 1992 [1]. All but two of the tests at RMSM were conducted within tunnel systems mined into the faces of Rainier Mesa or Shoshone Mountain, with the remaining two being conducted in vertical shafts constructed at the top of Rainier Mesa (Fig. 2). The residual long-lived radiologic inventory associated with these 67 tests represents a small fraction (approximately 0.72% by Curies) of the inventory associated with all underground nuclear tests at the NNSS [3].

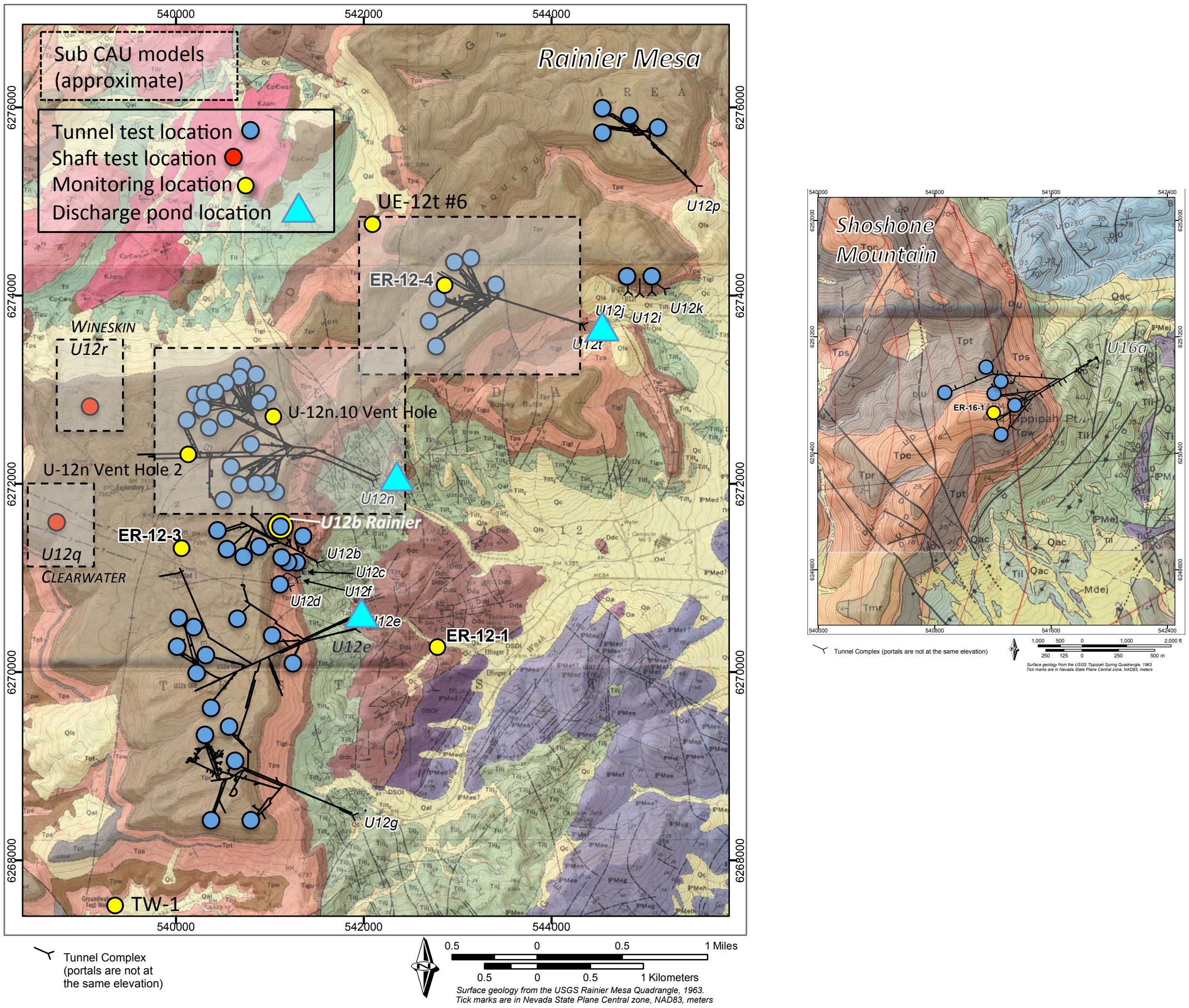

Fig. 2: Maps of the Rainier Mesa (L) and Shoshone Mountain (R) areas at the NNSS, showing the tunnel networks (lines), tunnel and shaft test locations (large circles), nearby monitoring wells (small circles), and the E-, N-, and T-tunnel discharge ponds (lower, mid, and upper triangles at left, respectively). Localized modeling domains used for the N and T –Tunnel complexes and the CLEARWATER and WINESKIN (shaft) tests are shown (see next section).

The tunnel systems offered a unique environment for conducting nuclear tests. Although all tests were situated well above the regional water table, many of the Rainier Mesa tests were placed in or close to zones of perched groundwater that existed within the mesa. In general, the tunnel networks were constructed incrementally to support the evolving sequence of tests. During their periods of construction or expansion, perched groundwater was frequently or continuously intercepted, and was channeled in drains towards the tunnel portals if the flows were persistent and significant. Specifically, in the E-, N-, and T-Tunnel systems where such flows occurred, these discharges became increasingly contaminated with radioactivity from the recurring tests conducted inside. This prompted the construction of three separate pond systems to capture and contain what became continuous radiologic discharges from the E-, N-, and T-Tunnel systems. The water entering the pond systems eventually evaporated or infiltrated into the subsurface. In 1993, the N-, and T-Tunnel portals were plugged, effectively ending all of their surface water discharges and inducing the retention of all subsequent contaminated drainage within the tunnel drifts behind the plugs. The contaminated N- and T-Tunnel complexes are now, effectively, completely flooded “reservoirs” extending back to all testing locations. A similar attempt to plug the E-Tunnel portal at that time was unsuccessful, so the E-Tunnel system continues to drain today.

Contamination Source Zones

Within the Rainier Mesa/Shoshone Mountain CAU, there are (now) three types of contaminant (radionuclide) source zones: (1) The test cavity and exchange volumes, which include a roughly spherical zone of damaged and altered rock surrounding each test detonation (work) point [4, 5]; (2) the three tunnel pond systems that served as disposal sites for contaminated tunnel drainage emanating from the E-, N-, and T-Tunnel complexes at Rainier Mesa during and after the periods of testing; and (3) the flooded N- and T-tunnel complexes that evolved after their plugging in 1993.

The test cavity and exchange volumes associated with each test contain the majority of the post-testing contaminant inventory at Rainier Mesa and Shoshone Mountain. This residual inventory may generally be found dissolved in solid melt glass debris concentrated below the work point or distributed as aqueous, soluble, or gaseous species across the broader cavity exchange zones [5]. Residual contamination may be transported out of these environments by groundwater movements through them (as dissolved aqueous species or colloidal forms), or, in some cases, via diffusion (as uncondensed gases) into accessible zones of unsaturated rock.

The pond and flooded tunnel systems receive contamination in the form of dissolved or colloidal radionuclides that are leached out of test cavity and exchange volumes by perched groundwater draining into the tunnels. In the case of the ponds, contamination entered (or continues to enter, in the case of E-Tunnel) as dissolved aqueous or colloidal species in the tunnel discharges and left (or leaves) by direct evaporation (for more volatile species) or infiltration into the subsurface below the ponds. Chemical retention (adsorption) of the contaminants onto pond sediments or subsurface rock may also occur. In the case of the flooded N- and T-tunnel complexes, leached contamination (that was discharged to ponds prior to 1993) is now incorporated in the impounded volume of water behind the plugs. In this sense, the impounded water can act as a more distributed source or reservoir of contamination eligible for movement in groundwater connected to the entire length of the tunnel networks.

It is worth noting that the only known measurements of radionuclides in groundwater attributable to the tests in Rainier Mesa and Shoshone Mountain are associated with analyses of water samples extracted from tunnel discharges, tunnel water impoundments, and pond water at Rainier Mesa. Measurements to date in all nearby wells (with a one-time possible exception in well ER-12-1, in Fig. 2) have shown no radionuclide contamination.

Implementation of the CAI Process at RMSM

The initial CAI within the Rainier Mesa/Shoshone Mountain CAU was based upon the conceptualization that groundwater flow (and initial radionuclide transport pathways) near the testing areas primarily followed vertical, downward trajectories through variably saturated volcanic rocks toward the saturated lower carbonate aquifer (LCA; Fig. 3). The LCA is viewed as the principal geologic unit in this area through which consequential radionuclide transport away from Rainier Mesa and Shoshone Mountain and toward potential down-gradient receptors would occur. The vertical flow scenario is consistent with other prevailing transport concepts [6,7] and represented the shortest transport distance from the testing areas to the LCA.

The CAI process began development of localized and detailed numerical models to examine details of vertical flow and radionuclide transport (Part 1) below the N- and T-Tunnel complexes, (Part 2) away from the CLEARWATER and WINESKIN (shaft) tests, and (Part 3) beneath the tunnel ponds (Fig. 2), all of which were connected to (Part 4) a larger scale saturated zone flow and transport model underlying much of Areas 12 and 17 at the NNSS (Fig. 1). The larger scale model includes the LCA aquifers but excludes the shallower volcanic rocks and tunnel horizons where perched water exists. These models all involved the application of fairly sophisticated 3D numerical models of variably saturated fluid flow and species transport in multi-continuum, fractured porous media systems [9, 10, 11]. Simpler analyses (Part 5) of radionuclide transport away from Rainier Mesa tunnels other than N and T are made via analogy as opposed to additional detailed numerical models. A separate model (Part 6) of vertical flow and radionuclide transport was developed at Shoshone Mountain but was not connected to any other large-scale model. In addition, supplemental (or updated) models of (Part 7) groundwater recharge, (Part 8) the underlying hydrogeologic framework, (Part 9) the hydrogeologic conceptualization, and (Part 10) radiologic releases from individual RMSM source zones into hydrologic systems were also undertaken and developed to support these efforts.

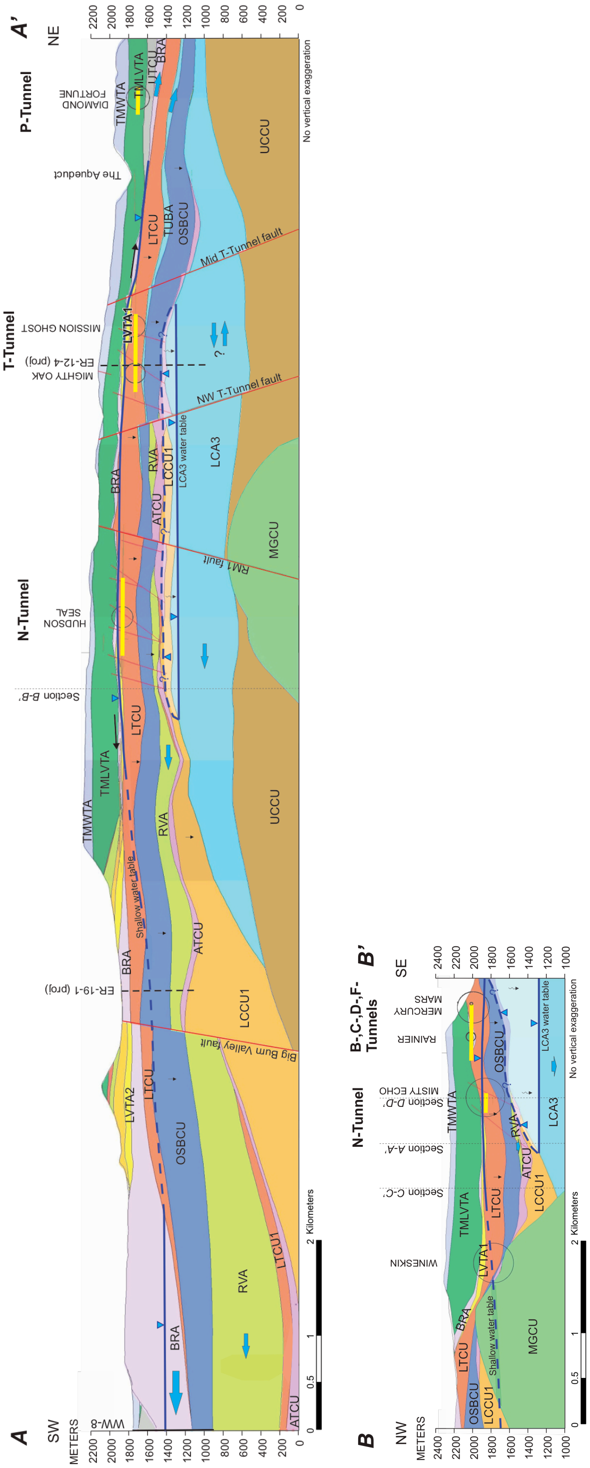

Fig. 3: Perpendicular geologic cross sections through Rainier Mesa showing principal hydrogeologic flow units, faults, perched and deeper lower carbonate aquifer (LCA3) water levels, intersections with various tunnel networks (yellow bars) and nearby tests (named), where portions of three cavity radii (3Rc) spherical exchange volumes are shown as circles where they intersect the section (test cavity radii are calculated using the maximum announced yield in [1] and equation 1 of [8]).

Initial CAI Results and Reviews

The application and integration of these models proved to be a significant and technically challenging task. Prior to embarking on a campaign to develop additional ensembles of contaminant transport simulations (as required by the modeling strategy), the initial results of the CAI analyses were documented in an interim draft Flow and Transport (F&T) modeling report and a series of supporting technical documents, all of which currently remain unreleased. Local internal reviews of this work, accumulated as it was conducted and of the draft reports completed later, revealed a number of important concerns with (or limitations of) the modeling approach, its completeness, and the defensibility of its results.

First, the mapped geology of Rainier Mesa and Shoshone Mountain in the vicinity of the testing areas – as shown in the hydrogeologic framework model in Fig. 3 – is extremely complex. This model was developed from numerous data accrued from wells and boreholes, tunnel maps, surface observations, and other interpretive activities, yet it can still be uncertain in a number of respects. The continuity and spatial connectedness of many of the more permeable geologic units are debatable in several areas, and this reflects on the importance of this model as an aid in identifying potential transport pathways away from the testing areas. Physical parameters describing flow processes in these units are also variable and uncertain, and were not well constrained when used in the model exercises.

Second, the mapped transitions of the perched groundwater in the center of the mesa to the regional groundwater table at the horizontal extremities of the mesa sections shown in Fig. 3 are not well understood or substantiated. The relative proclivities of the perched water to flow, either laterally over underlying confining units, vertically through the confining units, or both, were not fully considered. Shallow lateral transport scenarios in the perched system could not even be investigated because the full lateral extent of the shallower volcanic rocks and tunnel horizons where the perched water exists was not (yet) included in any model.

It has also been difficult to attribute (or replicate in models) the causes of short- and long-term water level transients, observed in monitoring wells at differing depths, to specific or unifying causes, such as fluctuating precipitation and recharge, lingering impacts of testing, tunnel drainage and recovery, or other local or regional effect. As such, their potential impacts on radionuclide transport, especially in the shallow perched zones, could not be investigated in any model either.

REVISION OF THE FFACO PROCESS

As the initial phase of the CAI process was nearing completion in 2012, a series of meetings between DOE and the State of Nevada (via NDEP) raised doubts as to whether the primary FFACO modeling strategy was achievable – that is, whether a technically defensible contaminant boundary could be identified in a timely and economical fashion when balanced against the overall perceived risks at RMSM.

Many of these concerns grew out of the ongoing reviews of the CAI work discussed above. Those doubts were articulated in a formal TBAD drafted by DOE and later accepted by NDEP in mid-2013. The TBAD made a case for changing the existing FFACO strategy – essentially, executing a restart option – to develop and adopt an alternative and simpler modeling strategy for the RMSM CAU.

Specifically, it was argued that meaningful sets of model runs needed to evaluate a contaminant boundary under the existing FFACO strategy would be extremely expensive to complete and defend because of the significant geologic complexity and parametric uncertainty that, in light of mounting reviews and assessments, would need to be further addressed and quantified. When balanced against the facts that:

- The RMSM radionuclide inventory is comparatively low and separated above the regional water table at all source locations;

- The RMSM CAU is geographically isolated within the NNSS and furthest removed of all CAUs from potential down-gradient receptors; and

- Initial CAI simulations, although incomplete, strongly suggest radionuclide transport would not challenge NNSS boundaries in the next 1,000 years,

the overall perceived risks at this CAU were judged to be out of balance (low) with the anticipated expense and effort of completing the primary FFACO strategy and that an AMS is required for the RMSM CAU.

Elements of the Alternative Modeling Strategy for the RMSM CAU

An AMS and modified FFACO decision process for the RMSM CAU were developed by DOE and accepted by NDEP in November 2013. The AMS replaces the requirement for the development of a contaminant boundary (based upon ensembles of contaminant transport simulations) in the CAI stage with a set of simpler modeling requirements. The AMS also streamlines the FFACO decision process to progress from the (revised) CAI stage directly to a CR stage following a successful peer review of the CAI accomplishments. An intermediate model evaluation (CADD) stage is only pursued if there are significant concerns with the peer review, as directed by the Nevada regulators.

As written, the simpler modeling requirements in the AMS call for a defensible range of potential transport scenarios (or pathway alternatives) to be identified for the RMSM CAU sources, which are supported by (or not inconsistent with) available data. These scenarios shall be investigated using simpler particle tracking (or similar) techniques to assess potential radionuclide transport distances in the identified pathway scenarios under sensible choices of transport processes (e.g., decay, sorption, matrix diffusion), driving forces (e.g., flow velocities) and ranges of pertinent parameters. Formally gridded, three-dimensional, variably saturated flow and transport models are not an absolute requirement of this approach. Rather, it seeks to identify reasonable transport pathways and bounded sets of transport results for these scenarios that can be used to aid in the evaluation of potential exposure pathways, support future monitoring strategies, and provide information pertinent for identifying future use restriction boundaries.

Revised Modeling Approach

The revised modeling approach is ongoing. It is based upon the use of a one-dimensional species transport model to examine the fate of radionuclides as they migrate along streamlines chosen to emanate from the various radiologic source zones in the RMSM CAU to down-gradient locations. The actual pathways have been identified from a heuristic (non model-based) approach that anticipates travel pathways in the most permeable (fracture flow) units and in lateral directions that are compatible with locally measured potentiometric surfaces or confining unit topographies and simple water balance estimates based upon local precipitation and recharge inputs.

Pathways consistent with multiple alternative transport scenarios have been identified, as called for in the AMS. Mass transport along these streamlines has been analyzed with the GoldSim model [12]. In this method, each streamline is divided into a series of connected and saturated “pipe” segments along which specific fluid (Darcy) fluxes are evaluated from estimates of fracture permeability and the local hydraulic gradient in each segment. For simplicity, the gradients are estimated from the potentiometric surface at each location (which is effectively equivalent to an assumption of hydrostatic conditions throughout the system). Mass transport along the entire streamline is simulated through aggregating analytic solutions of the advection dispersion equation obtained within each streamline pipe segment. An initial (source) concentration held fixed at the up-gradient end of the first streamline segment is used to calculate a time series of concentration at its down-gradient end as a function of Darcy flux, specified porosity, dispersion, matrix diffusion, retardation (sorption), and radioactive decay parameters in that segment. Initial (source) concentrations can be established using measurements (as in the tunnels) or from radiologic source term evaluations. The resultant time series of concentration from the first pipe segment is then used as an up-gradient condition in the second pipe segment to evaluate concentration histories at its down-gradient end. This process is repeated across all streamline segments to identify the point (or distance) along the streamline where the concentration falls below a prescribed limit (usually a Safe Drinking Water Act action limit [13]) at a prescribed time (1,000 years). For the entire streamline, an ensemble of such solutions may be obtained from different choices of (uncertain) parameters (such as porosity and permeability), providing, in the end, a distributional sense of the travel distances along that streamline (Fig. 4), a result that is regarded as compatible with the requirements of the AMS.

In keeping with the desire for a more simplified approach, many aspects of this approach are, understandably, approximate and broad. These include the ways in which the streamline pathways are chosen, the ways in which fluid fluxes are specified and calculated along these streamlines, the manner in which mass transport along these streamlines is conceptualized, and the choices available for determining initial concentrations. Because of the way in which fluid fluxes are calculated along each streamline segment, fluid mass is not necessarily conserved along the entire streamline pathway. Similarly, since concentration histories are preserved from the end of one streamline segment to the beginning of the next, the solute mass is not necessarily conserved across the junction (unless the fluid fluxes match). Holding up-gradient streamline concentrations at fixed levels is also inconsistent with preserving radionuclide mass. These are seen as being acceptable approximations in that they are consistent with the AMS desire to examine transport distances at nominal concentration levels as opposed to evaluating the volumetric fate of a fixed, three-dimensional body of distributed radionuclide mass in the RMSM system.

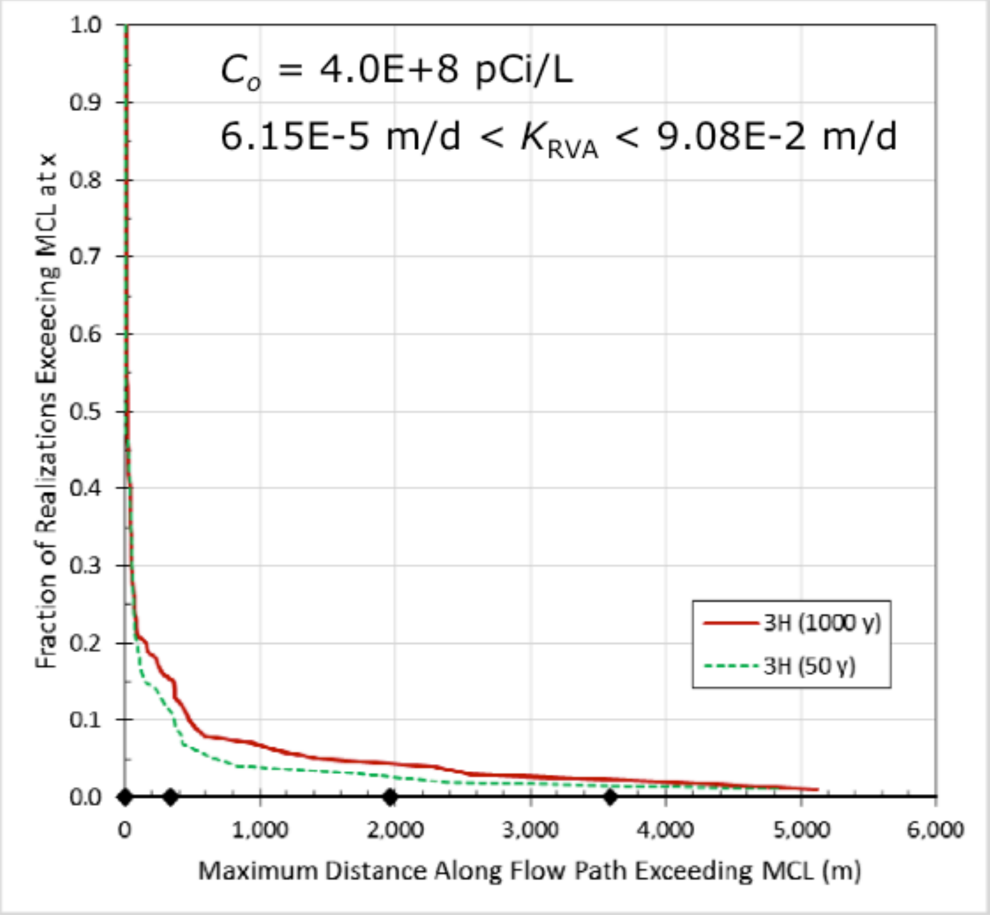

Fig. 4: Distribution of maximum (travel) distances along a hypothetical streamline passing through the Redrock Valley Aquifer (RVA) where action limits (MCLs) for tritium ($t_{1/2}$ = 12.3 years) are exceeded over 50- and 1,000-year periods, as based upon a high initial concentration C_0 ~ 4E+08 pCi/L. Black dots indicate locations of streamline segments used in GoldSim model (see text). Results correspond to 100 ensemble simulations that sampled hydraulic conductivities in the indicated range.

CONCLUSIONS

The shift in modeling strategy for addressing radionuclide transport in groundwater underlying the Rainier Mesa and Shoshone Mountain areas of the NNSS can be thought of as moving from a more complex “bottoms up” approach to a simpler “top down” approach:

- The former modeling strategy is based upon a paradigm of conducting multiple, large, complex numerical model simulations as a means to describe groundwater flow and the evolution of radionuclide movements throughout the entire contaminated RMSM system. These models are designed to address intricate, layered and faulted geology in the RMSM testing areas under a spectrum of uncertainty characterized by unclear, multi-connected zones of saturated and unsaturated rock, transient effects from natural and manmade impacts, and poorly parameterized multi-continuum flow and transport processes. They are also designed to evaluate the fate of a known inventory of contaminant mass in terms of potentially contaminated volumes of water. Such models and modeling strategies have been employed successfully in other areas of the NNSS [14, 15] and will be followed in other areas of the NNSS where the potential risks justify the use of this more detailed approach.

- The latter (alternative) strategy is based on developing a simpler means to calculate radionuclide movements (or travel distances) along transport pathway options identified from defensible conceptual model arguments and water balance calculations. Here the emphasis is more on the evaluation of potential travel distances and directions that contaminant mass may follow. This approach was eventually adopted and supported by an argument of lower overall technical risk at Rainier Mesa and Shoshone Mountain in comparison with other areas at the NNSS.

Following the transition between modeling strategies at Rainier Mesa and Shoshone Mountain, project participants entrenched in the original process had some difficulty adjusting to the new approach. This is believed to be a result of concerns about their investments in the work being abandoned, passed over, or lost. On the contrary, the original work will be completed, slightly amended, and released as important technical case studies, outside of the regulatory thread associated with RMSM. Important lessons learned in the process will be folded into the newer work as it progresses.

Although the project has suffered some delays from implementation of the new strategy, the new process of achieving closure is expected to save several years time and several million dollars over the original process while still protecting human health and the environment over the 1,000-year compliance period stipulated in the FFACO.

REFERENCES

1. *United States Nuclear Tests, July 1945 through September 1992*, U.S. Department of Energy, National Nuclear Security Administration, Nevada Field Office, Las Vegas, Nevada, DOE/NV--209-REV 16 (2015).
2. *Federal Facility Agreement and Consent Order,* Agreed to by the State of Nevada; U.S. Department of Energy, Environmental Management; U.S. Department of Defense; and U.S. Department of Energy, Legacy Management (1996, as amended).
3. D. L. FINNEGAN, M. SCOTT, J. L. THOMPSON, C. M. MILLER, P. L. BACA, L. F. OLIVAS, C. G. GEOFFRION, D. K. SMITH, W. GOISHI, B. K. ESSER, J. W. MEADOWS, N. NAMBOODIRI, and J.F. WILD, *Nevada Test Site Radionuclide Inventory, 1951–1992: Accounting for Radionuclide Decay through September 30, 2012,* LA-UR-16-21749, Los Alamos National Laboratory, Los Alamos, NM (2016).
4. *The Containment of Underground Nuclear Explosions,* U.S. Congress, Office of Technology Assessment, OTA-ISC-414, U.S. Government Printing Office, Washington, D.C. (1989).
5. A. F. B. TOMPSON, C. J. BRUTON, G. A. PAWLOSKI, D. K. SMITH, W. L. BOURCIER, D. E. SHUMAKER, A. B. KERSTING, S. F. CARLE, and R. M. MAXWELL, "On the Evaluation of Groundwater Contamination from Underground Nuclear Tests," *Environmental Geology*, 42, 235-247 (2002).
6. W. THORDARSON, *Perched ground water in zeolitized-bedded tuff, Rainier Mesa and vicinity, Nevada Test Site, Nevada,* U. S. Geological Survey Open-File Report 66-130 (1965).
7. B. A. EBEL and J. R. NIMMO, *Estimation of unsaturated zone travel times for Rainier Mesa and Shoshone Mountain, Nevada Test Site, Nevada, using a source-responsive preferential- flow model*: U. S. Geological Survey Open-File Report 2009–1175 (2009).
8. G. A. PAWLOSKI, *Development of Phenomenological Models of Underground Nuclear Tests on Pahute Mesa, Nevada Test Site—BENHAM and TYBO*, UCRL-ID-136003, Lawrence Livermore National Laboratory, Livermore, CA (1999).
9. G. A. ZYVOLOSKI, B. A. ROBINSON, Z. V. DASH, and L. L. TREASE, *Models and Methods Summary for the FEHM Application*, FEHM MMS SC-194, Los Alamos National Laboratory, Los Alamos, NM (1999).
10. J. J. NITAO, *Reference Manual for the NUFT Flow and Transport Code, Version 3.0,* UCRL-MA-130651-REV-1, Lawrence Livermore National Laboratory, Livermore, CA (2000).
11. Y. HAO, Y. SUN, and J. J. NITAO, "Overview of NUFT: A Versatile Numerical Model for Simulating Flow and Reactive Transport in Porous Media," in *Groundwater Reactive Transport Models*, F. ZHANG, G.-T. YEH, and J. C. PARKER eds., Bentham Science Publishers, Oak Park, IL (2012).
12. *User's Guide, GoldSim, Probabilistic Simulation Environment*, GoldSim Technology Group, Issaquah, Washington 98027 (2014).
13. *Radionuclides Rule: A Quick Reference Guide,* EPA 816-F-01-003 June 2001 United States Environmental Protection Agency, Office of Water (4606), Washington, D.C. (2001).

14. *Phase II Transport Model of Corrective Action Unit 98: Frenchman Flat, Nevada Test Site, Nye County, Nevada, Rev. 1,* N-I/28091--004, S-N/99205--122, Navarro Nevada Environmental Services, LLC, Las Vegas, NV (2010).
15. *Phase I Flow and Transport Model Document for Corrective Action Unit 97: Yucca Flat/Climax Mine, Nevada National Security Site, Nye County, Nevada, Rev. 1,* N-I/28091-080, Navarro-Intera, LLC, Las Vegas, NV. (2013).

ACKNOWLEDGEMENTS

LLNL-CONF-709519. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Approved for public release under Log No. 2017-006.