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Natural Barriers Targeted Thrust FY 2004 Projects

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PREFACE

This booklet contains project descriptions of work performed by the Department of Energy (DOE), Office of Civilian Radioactive Waste Management (OCRWM), Office of Science and Technology and International's (OST&I) Natural Barriers Targeted Thrust during Fiscal Year (FY) 2004. The Natural Barriers Targeted Thrust is part of OST&I's Science and Technology Program which supports the OCRWM mission to manage and dispose of high-level radioactive waste and spent nuclear fuel in a manner that protects health, safety, and the environment; enhances national and energy security; and merits public confidence. In general, the projects described will continue beyond FY 2004 assuming that the technical work remains relevant to the proposed Yucca Mountain Repository and sufficient funding is made available to the Science and Technology Program.

Project Title	Carbon-14 Groundwater Analyses
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	U.S. Geological Survey , Desert Research Institute
Principal Investigators	Gary Patterson, Zell Peterman, James Thomas
FY 2004 Funding	$258,000

Abstract **BACKGROUND:** The time required for groundwater to flow from beneath the proposed repository at Yucca Mountain to down gradient areas where the water may be intercepted for use is a significant factor in determining potential dose. Current estimates of groundwater travel time (i.e., residence time since recharge) at Yucca Mountain are derived from flow and transport models using Darcy's law and constrained hydrologic properties, and from radiocarbon (^{14}C) measurements on dissolved inorganic carbon (DIC) in groundwater. The basic assumption in radiocarbon dating of groundwater is that the $^{14}C/^{13}C$ ratio acquired at recharge through the soil zone changes along the flow paths only by radioactive decay of ^{14}C. Enhancements for this open-system behavior can be made by examining $^{13}C/^{12}C$ ratios in the groundwater and by making assumptions about the degree of water-rock interaction.

OBJECTIVES: The objective of this work is to provide improved estimates of the time required for groundwater to travel from the site of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, to the accessible environment.

APPROACH: An alternative to estimating travel times using flow and transport models is by carbon-14 dating of both inorganic and organic carbon dissolved in the groundwater. Radiocarbon dating of dissolved organic carbon (DOC) has the advantage of not requiring corrections based on assumed models of water-rock interaction. Like DIC, DOC is acquired from the soil zone during recharge; however, ^{14}C-bearing DOC is not likely to be present along the flow paths. Thus, radiocarbon dating of DOC will give a direct measure of the amount of time elapsed since the groundwater was recharged (Wassenaar *et al.,* 1991[1]; Wassenaar *et al.*, 1992[2]; Clark and Fritz, 1997[3]).

This study will be conducted by the U.S. Geological Survey, Yucca Mountain Project Branch, Environmental Science Team (USGS-YMPB-EST) in cooperation with the Desert Research Institute (DRI). DRI is the research division of the University and Community College System of Nevada and has the only facility in

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[1] L. Wassenaar, R. Aravena, J. Hendry, and P. Fritz, 1991. *Radiocarbon in Dissolved Organic Carbon, A Possible Groundwater Dating Method: Case Studies from Western Canada,* Water Resources Research, v. 27, no. 8, pp. 1975 to 1986

[2] L. Wassenaar, R. Aravena, and P. Fritz, 1992. *Radiocarbon Contents of Dissolved Organic and Inorganic Carbon in Shallow Groundwater Systems: Implications for Groundwater Dating, in Isotope Techniques in Water Resources Development 1991, Proceedings of an International Symposium on Isotope Techniques in Water Resources Development,* International Atomic Energy Agency, Vienna, pp. 143 to 151.

[3] I.D. Clark and P. Fritz, 1997. *Environmental Isotopes in Hydrogeology.* Boca Raton, Florida: Lewis Publishers.

the United States with the capability of extracting organic carbon from water samples to perform organic carbon isotope analyses.

The USGS-YMPB-EST will be responsible for collecting water samples and analyzing for major elements and minor elements, as well as stable (e.g., oxygen, hydrogen, sulfur) and heavy (e.g., strontium, uranium) isotopes, in accordance with this SIP. These data will be used in conjunction with existing data contained in the USGS Hydrochemical and Isotopic Database to determine flow paths.

DRI will be responsible for analyzing the samples for isotopes of DOC (^{14}C and ^{13}C) in accordance with a separate, standalone SIP. These data, in combination with the USGS flow path data, will be used to determine travel times.

Tasks for FY 2004 and FY 2005 include:

1) Sampling and analyses of water from Nye County and Inyo County wells, and other wells of interest, including analyses of major dissolved anions and cations, trace cations, carbon isotopes (C-13 and C-14) of DIC and DOC, and stable (O, H, S) and heavy (Sr, U) isotopes.
2) Update, refine, and publish integrated hydrochemical/isotope database.
3) Calculate corrected carbon-14 groundwater ages for DIC using the USGS program NETPATH or other suitable software codes.
4) Calculate groundwater ages using carbon-13 and carbon-14 of DOC.
5) Compare corrected DIC groundwater ages with DOC calculated groundwater ages to determine a range in travel times that can be used to constrain groundwater flow and transport models.

BENEFITS TO OCRWM: This integration of conventional radiocarbon dating with the separation and dating of the dissolved organic carbon in groundwater down gradient from Yucca Mountain will yield travel times that can be used for enhanced performance assessment calculations. The conclusions and basis for the interpretations will be presented in a report that will include data used and acquired, a range in groundwater travel times for flow paths down gradient of Yucca Mountain, and a comparison of these travel times with those developed in groundwater flow and transport models.

Project Title Enhanced Retardation of Radionuclide Transport in Fractured Rock

OCRWM S&T Program Thrust Natural Barriers

Project Performers Lawrence Berkeley National Laboratory, Clemson University

Principal Investigators Hui-Hai Liu, Fred J. Molz

FY 2004 Funding $300,000

Abstract

BACKGROUND: Owing to the order-of-magnitude slower flow velocity in the matrix compared to fractures, matrix diffusion can significantly retard radionuclide transport in fractured rock. The effective matrix diffusion coefficient is an important parameter for describing matrix diffusion, and its magnitude largely determines overall radionuclide transport behavior in fractured rock. Matrix diffusion coefficient values measured from small rock samples in the laboratory have been used for modeling radionuclide transport at the Yucca Mountain site. Most recently, Liu et al.,2004[4] pointed out, for the first time, that the effective matrix diffusion coefficient for field-scale problems might be scale-dependent.

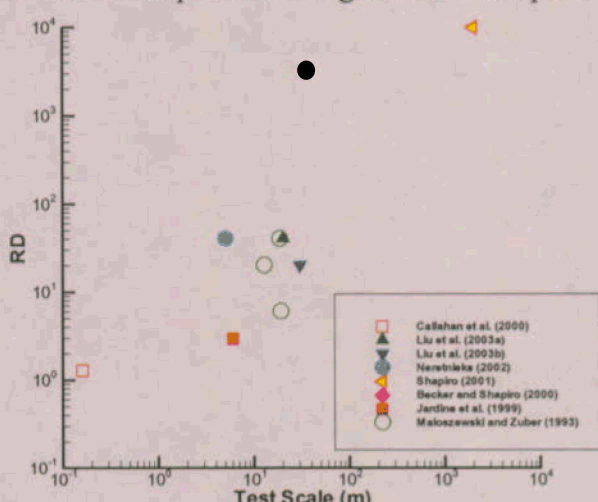

Figure 1. Effective matrix diffusion coefficient as a function of test scale (Liu et al., 2004). RD refers to the effective coefficient value (estimated from field data) divided by the corresponding local value

If the preliminary finding of Liu et al. (2004) proves to be true, the matrix-diffusion-coefficient values currently used by the Yucca Mountain Project are expected to be several orders of magnitude smaller than actual values, as suggested by Figure 1. (Note that the "test scale" for the Yucca Mountain site, or the length of a flow path from the repository to the assessable environment, is on the order of 10^3 meters.) In other words, the performance of natural systems (including both UZ and SZ) may have been significantly underestimated. Therefore, it is important that more studies are conducted to confirm this potentially important finding and to understand the physical mechanisms behind this scale-dependent behavior.

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[4] H.H. Liu, B.S. Bovarsson and G. Zhang, 2004. *Scale Dependency of the Effective Matrix Diffusion Coefficient*, Vadose Zone Journal, 3:312-315.

OBJECTIVES: The objectives of this study are:

1) to further evaluate the scale-dependent behavior of the effective matrix diffusion coefficient,
2) to develop a rigorous theoretical basis of the scale dependency, and
3) to quantify the conservatism in estimated natural system performance at the Yucca Mountain Site (when the scale dependency is not considered).

APPROACH: *Confirmation of the scale-dependent behavior of the effective matrix diffusion coefficient* - This task consists of three activities. First, a comprehensive survey of estimates of the effective matrix diffusion coefficient published in the literature will be conducted. The survey results, as a function of test scale, will be incorporated into Figure 1. Second, selected tracer-test results in the literature will be reanalyzed to evaluate the values for the effective diffusion coefficient reported by other researchers and to provide additional evidence for the scale dependency. Third, ^{14}C data (and the other geochemical data) have been collected from the Yucca Mountain site and used as an indicator of water travel times. Simulation results will be compared with the data set to check for the consistency between the data and potential scale-dependent behavior.

Development of a theoretical basis for the scale dependency - Two-dimensional fracture-network models (with matrix) will be used to perform numerical experiments. Previous studies have shown that both fracture roughness and fracture networks are fractals. The capabilities for computationally generating fracture networks characterized by fractal geometry will be developed as a part of this task. Detailed numerical simulations of flow and tracer transport through fracture networks (including the matrix) will be performed to generate tracer breakthrough curves as a function of test scale. Effective matrix-diffusion-coefficient values will be estimated from the simulated breakthrough curves. From these numerical experiment results, we can develop a theoretical basis for a potential relationship between the effective coefficient values and the test scale. If the explanation of Liu et al. (2004) (based on the hypothesis that solute travel paths within a fracture network are fractals) were to be rejected by the results of the numerical experiments, then alternative explanations will be explored and developed.

Demonstration of the conservatism of the natural-system performance calculated without considering the scale dependency of the effective matrix diffusion coefficient - The site-scale flow and transport models will be used for simulating radionuclide transport. Simulation results with and without considering the scale dependency of the effective matrix-diffusion coefficient will be compared for different scenarios. Special attention will be given to the scenarios used by Total System Performance Assessment (TSPA).

BENEFITS TO OCRWM: The proposed research has the potential to demonstrate that the performance of natural systems at Yucca Mountain has been significantly underestimated by the TSPA. Results from this proposed work will enhance understanding in repository performance and scientific defensibility of TSPA. The proposed research also has the potential to open up a new research area that is of interest not only for the Yucca Mountain site, but also for the other geological disposal sites (in fractured porous media) under consideration worldwide.

Project Title	Improved Characterization of Radionuclide Retardation in Volcanics and Alluvium
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	Los Alamos National Laboratory
Principal Investigators	Paul Reimus, Mei Ding
FY 2004 Funding	$200,000

Abstract: **BACKGROUND:** The current Yucca Mountain Project (YMP) approach to modeling radionuclide transport in the saturated zone (SZ) takes no credit for sorption to fracture coating minerals, and it also assumes that sorption of radionuclides to matrix material is completely reversible (described by a K_d modeling approach) and that oxidizing geochemical conditions prevail in the SZ. All of these assumptions are conservative, and significant SZ (and UZ) performance enhancements could be realized by conducting experiments designed to support realistic assumptions in a defensible manner.

OBJECTIVES: The objective of this project is to provide the data and models necessary to allow YMP to take more credit for the retardation of sorbing radionuclides in the SZ in both the volcanic rocks and the alluvium down gradient of Yucca Mountain. Because radionuclides cannot be tested in the field, this project will involve laboratory investigations of sorption and transport behavior under both static (batch) and flowing (column) conditions using waters and geologic materials obtained from the Yucca Mountain area. The experiments will be conducted to test conceptual models of reactive transport also investigate the credit that can be taken for phenomena such as the effects of mildly reducing geochemical conditions, sorption to fracture coating minerals, and the possibility of irreversible sorption or extremely slow desorption. Also, scaling of reactive transport will be addressed.

APPROACH: Laboratory batch sorption and column transport experiments will be conducted using representative samples of volcanic rocks and alluvium taken from along the projected flow pathway(s) from the repository to the compliance boundary (~18 km from the proposed repository footprint). To the extent possible, water collected from wells along the flow pathway(s) will also be used in the experiments, although it is anticipated that some synthetic waters will have to be prepared based on previous geochemical analyses. Unlike previous sorption experiments, which focused primarily on determining partition coefficients (K_d values) onto bulk rocks, our experiments will be conducted using both matrix materials and fracture coating minerals, and much greater emphasis will be placed on determining the desorption behavior of the radionuclides. Multi-step and continuous desorption experiments (repeatedly introducing fresh water to test the effect on desorption) and long-duration column experiments will be conducted to determine *distributions* of desorption rate constants and to estimate fractions of irreversibly-sorbed radionuclides. Fracture transport experiments will be conducted using naturally-fractured cores obtained from drill holes near Yucca Mountain, if available, or

possibly cores obtained from the Nevada Test Site core library that has matrix and fracture mineralogy similar to Yucca Mountain tuffs.

Radionuclides emphasized in the experiments will initially be uranium (U), neptunium (Np), and technetium (Tc), as these contribute significantly to dose under some scenarios, and are not considered to be strongly sorbing. Other potentially investigated radionuclides include plutonium and cesium. Some U, Np and Tc experiments will be conducted in controlled-atmosphere gloveboxes to quantify the potential for much stronger sorption under mildly reducing conditions that have been observed in some wells near Yucca Mountain.

A number of the above experiments will be conducted with the intent of using novel post-test autoradiographic characterization methods coupled with scanning electron microscopy/transmission electron microscopy/energy dispersive spectroscopy (SEM/TEM/EDS) and/or possibly secondary-ionization mass spectrometry (SIMS) to identify specific minerals that are strong "getters" for the radionuclides. This information will be used for predictive modeling based on mineralogy data.

Additionally, flow and geochemical transients will be intentionally introduced into some experiments to determine the conditions under which such transients (or long-term changes, such as those induced by climate changes) can remobilize radionuclides. Remobilization rates under transient conditions could be more important than apparent partition coefficients and sorption/desorption rates measured under steady-state conditions.

The laboratory tests will be interpreted using an approach that accounts for *distributions* of sorption and desorption rates onto geologic materials, with an emphasis on desorption rate distributions. Some experiments will be designed to quantify these distributions and others will be designed to test them under both static and dynamic conditions. The distributions will be correlated with rock mineralogy and water chemistry to provide a mechanistic basis for understanding and predicting them. This approach is well suited to address scaling issues in reactive transport, which may be incorporated into future Yucca Mountain radionuclide models.

BENEFITS TO OCRWM: The objective of this project is to produce an enhanced reactive transport model for Yucca Mountain that accounts for distributions of desorption rates as a function of water and rock properties, as well as the effects of geochemical and hydrologic transients. The reactive transport modeling approaches used in SZ transport models and in TSPA are conservative for several radionuclides. Suggested modifications to these approaches that can be readily implemented in future process models will be recommended, with appropriate experimental data to back up the recommendations.

Project Title	Integration of Site and Regional Flow Models
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	Los Alamos National Laboratory, U.S. Geological Survey, Sandia National Laboratories, GeoTrans Inc. (Subcontractor to Los Alamos National Laboratory)
Principal Investigators	Al A. Eddebbarh, Rick Spengler, Kenneth Rehfeldt, George Zyvoloski, Scott James, Rick Waddell, Mary Hill, Claudia Faunt, Carl Gable, Bill Arnold
FY 2004 Funding	$642,000

Abstract **BACKGROUND:** The saturated zone (SZ) at Yucca Mountain is the last barrier to radionuclide transport before the accessible environment. The SZ provides additional path length, increasing travel times, and attenuation. A regional model was developed with MODFLOW-2000 to help the understanding of flow at a regional scale and to provide global water balance information. The regional model takes advantage of the Hydrologic Unit Flow package to address the complex geology. The site-scale model uses FEHM in order to more accurately incorporate the site geology. The site-scale model contains more detail and has a higher grid resolution than the regional model, necessary for simulating radionuclide transport. The site-scale model relies on the regional model for information on the rates of water movement across the boundaries of the site-scale model. It uses the boundary fluxes, obtained from the regional model, as calibration targets. A new model will be developed to integrate the regional and the site-scale models that have been developed concurrently but were calibrated independently. In this work, the two models will be fully coupled by using a unified hydrogeologic framework model for the Yucca Mountain area. The full integration of the regional and site-scale models will provide (a) the ability to complete dual calibration of both models in a single, consistent process; (b) the potential for coupled calibration with the Nevada Test Site Environmental Restoration Underground Testing Area models being developed in the neighboring units such as Pahute Mesa and Yucca Flat; and (c) the ability to understand and quantify uncertainty in the regional model and its effects on the site-scale model.

OBJECTIVES: The objective of this work is to integrate the regional and site-scale saturated zone groundwater flow and transport model by incorporating (a) the regional-scale lateral extent, including natural boundaries and (b) site-scale detail and capability. This will enhance the understanding of the propagation of uncertainty from regional to local scales.

APPROACH: The initial phase of this study will be to assess modeling approaches and integration of regional and site databases. Plausible approaches to be examined are:

1) nest FEHM inside MODFLOW and develop the appropriate utilities to run both models simultaneously,

2) develop a single multi-grid model in MODFLOW, or

3) develop a single multi-grid model in FEHM (Figure 2 is an example of a single multi-grid model developed using FEHM.)

After a single approach is chosen and the databases have been integrated, the model implementation will be conducted. This will include alignment of numerical grids (vertical and horizontal), recharge, boundaries, time stepping, and calculation of cell or element hydraulic properties. Sensitivity and uncertainty analyses will be performed using the integrated model.

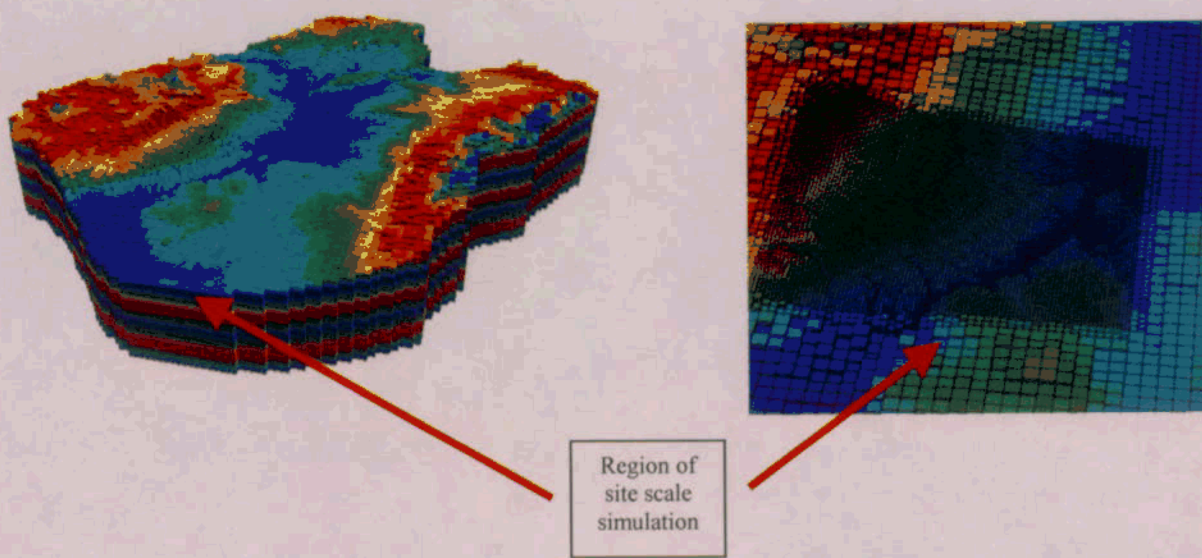

Figure 2. Basin-scale (left) and embedded local-scale (right) grids of the Espanola Basin groundwater flow and transport model where a regional and site-scale models were successfully coupled.

BENEFITS TO OCRWM: In addition to the end product delivered in the third year, yearly progress reports outlining progress issues and scope and schedule adjustment will be submitted. A workshop will be held during the latter part of the first year to help define the options for integrating the models and the pros/cons of each option. The end product is a new calibrated model to simulate groundwater flow and radionuclide transport. The final report will provide documentation of the coupled models and conclusions of the study.

Project Title	Large-Scale (2 kilometer) Natural Gradient Tracer Test
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	U.S. Geological Survey, Los Alamos National Laboratory
Principal Investigators	Allen Shapiro, M. J. Umari , John Earle, Paul Reimus
FY 2004 Funding	$283,000

Abstract **BACKGROUND:** The performance assessment of the proposed radioactive waste repository at Yucca Mountain accounts for potential radionuclide migration in the saturated zone below and down gradient of the proposed repository site. Characterizing radionuclide migration requires the estimation of formation properties that control advective migration, dispersive spreading, and diffusive exchange between the primary and secondary porosity of the rock (matrix diffusion), as well as potential retardation and chemical reactions between the various constituents and the geologic materials. Tracer tests can be conducted under the ambient flow regime in the formation, or under forced gradient conditions. To date, tracer tests conducted at Yucca Mountain (C-Wells) have been conducted under forced-gradient conditions and at scales of tens of meters up to approximately 100 meters. Although tracer tests conducted over tens of meters have the greatest likelihood of success, tracer tests conducted over much larger distances (km scale) and under natural gradient can provide valuable information about the magnitude of various formation properties that can be used to characterize solute transport in the subsurface. For example, it is widely recognized that dispersion generally increases as a function of the distance the tracer has migrated. It has been shown that dispersion increases as a function of the travel distance in relatively homogeneous unconsolidated porous media and in fractured tuff. In addition, the magnitude of matrix diffusion has been shown in forced-gradient tests to be a function of the travel distance of a tracer plume in a heterogeneous fractured rock environment, but with mixed results. It is likely that larger estimates of dispersion and more realistic estimates of large-scale matrix diffusion will arise if controlled tracer testing, using multiple tracers with varying diffusion coefficients, is conducted under a natural gradient over larger distances. These estimates may be used in future modeling of the saturated zone transport beneath the proposed repository site at Yucca Mountain. Ultimately, increased dispersion and matrix diffusion result in a decrease or delay in dose at the compliance boundary.

APPROACH: This work involves large-scale *in-situ* natural-gradient tracer testing and developing interpretive methods that place bounds on the formation properties (dispersion/diffusion) governing solute transport, and obtaining direct estimates of solute travel times in the fractured saturated tuff at Yucca Mountain. These large-scale tracer tests will be conducted over distances of several kilometers. The Dune Wash boreholes WT2, WT1, and WT17 could be used. Tracers with varying diffusion coefficients would be released in borehole WT2 and the monitoring would be done in borehole WT1, located 2.1 km to the southeast. An alternate configuration would be to use borehole WT1 as the tracer release borehole and borehole WT17, located 1.85 km to the southeast, as the monitoring borehole. Other

borehole pairs in the fractured volcanics can be used such as WT7 and WT10 in Crater Flat where tracers would be injected in WT7 and monitored in WT10, 2.1 km down gradient. Alternately, wells WT10 and WT11 can be used by injecting tracers in WT10 and monitoring WT11, 3.3 km down gradient. Yet another alternative would be to use wells WT17 and WT12 by injecting tracers in WT17 and monitoring WT12, 2.65 km down gradient.

Even though the main impetus of this work is conducting a natural gradient test at a large scale in the fractured volcanics, prototyping of tracers, equipment and methodology may be carried out at the Alluvial Testing Complex with a maximum interborehole distance of 50 m.

Tracer tests conducted over large distances (km scale) and under natural gradient are anticipated to indicate larger magnitudes of dispersion and enhanced estimates of matrix diffusion. Larger magnitudes of longitudinal and transverse dispersion will lead to either reduced or delayed dose at a fixed capture zone of the compliance boundary. For a pulsed radionuclide input to the saturated zone (perhaps due to wet climate events), larger longitudinal dispersion will lower the mass of tracer crossing the 18-km boundary per year, leading to a lower dose, by elongating the plume. For a constant input, longitudinal dispersion will delay the ultimate constant dose. Transverse dispersion will widen the cross-sectional area of the plume, which, if the plume width is larger than the width of the capture zone at the compliance boundary, reduces the dose.

BENEFITS TO OCRWM: Monitoring the tracer concentration over a period of years (2 to 5 years or more) and interpretation of the tracer concentration will provide bounds on estimates of formation properties and the dispersion/diffusion coefficients over large distances in the volcanic rocks at Yucca Mountain, along with providing direct measurements of solute velocities under the ambient gradient.

Project Title	Matrix/Fracture Flow in Subrepository Units
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	U.S. Geological Survey, Los Alamos National Laboratory
Principal Investigators	James Paces, Zell Peterman, David Vaniman
FY 2004 Funding	$150,000

Abstract **BACKGROUND:** The natural barrier at Yucca Mountain depends, in part, on sorption of radionuclides on unsaturated zone (UZ) flow path surfaces in rock units beneath the welded Topopah Spring Tuff (TSw). Much of the sub-repository rock mass consists of bedded tuffs exhibiting varying degrees of zeolitic alteration. The effectiveness of these zeolitized units to retard radionuclide migration is a significant factor in determining the natural barrier capability. However, zeolitization also reduces porosity in bedded tuffs so that flow through fractures, rather than matrix, may dominate percolation beneath the proposed repository.

OBJECTIVES: An enhanced understanding of the nature of flow through sub-repository units can improve assessments of the capability of the natural barrier in reducing dose to the accessible environment.

APPROACH: The current UZ flow and transport model simulates minor matrix flow through zeolitized tuffs beneath the repository and therefore takes little credit for retardation of radionuclides in the UZ. However, sub-repository zeolitized tuffs have been shown to effectively extract calcium (Ca), magnesium (Mg) and strontium (Sr) from downward percolating solutions. Other radionuclides are less effectively sorbed by the zeolitized rock; however, transport through significant amounts of the rock matrix will result in some retardation in deeper parts of the UZ. Initial chemical results indicate that zeolitized horizons have acted as barriers to transport in the past and that diversion around or rapid transport through these units is unlikely. The work will further investigate the hydrologic behavior of these units by measuring the degree of chemical and isotopic disequilibrium that may exist between samples milled from fracture surfaces and bulk-rock samples from fragment interiors.

Over millennial time scales, a hydrologic system dominated by fracture flow will develop chemical and isotopic signatures of water-rock interaction on fracture surfaces that are distinct from compositions present in the interiors of fracture-bounded blocks of rock that remained isolated from fracture flow. Uranium-series isotopes (thorium-230 (^{230}Th), uranium-234 and -238 (^{234}U and ^{238}U) have been shown to be sensitive indicators of past water-rock reactions. Other isotopic systems, such as oxygen and strontium ($^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$) as well as elemental concentrations also are likely to show the effects of water-rock interactions. Comparison of analyses from fracture-surface and bulk-rock pairs will form a statistical basis for determining whether fracture- or matrix-flow dominates in these sub-repository units.

Samples of bedded tuffs within the UZ but below the proposed repository will be collected from existing surface-based boreholes. Appropriate materials will be identified at the Sample Management Facility and shipped to Denver for analysis. Targets for analytical work will be based on mineralogical data published by Los Alamos National Laboratory. Subsamples will be paired to include both material milled from natural fracture surfaces and chipped from the interiors of intact core fragments. Additional quantitative mineralogy data will be used to characterize differences between fracture surfaces and core interiors. Subsamples will be analyzed for U-series disequilibrium (^{230}Th-^{234}U-^{238}U) as well as O and Sr isotopes and trace elements by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS). U-series isotopes have an advantage of supplying information relevant to a Pleistocene temporal framework. If the isotopic and chemical differences were established during Miocene zeolitization and little affected since, both $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ will have returned to secular equilibrium. This outcome is unlikely given the widespread observation of disequilibrium in TSw rocks.

Data from subsample pairs will be collected from multiple depths in several boreholes distributed in the north and south of the site. Mineralogical, chemical, and isotopic data will be compiled and submitted to Thermal Desorption Mass Spectrometry. In addition, an interpretive report will document findings.

BENEFITS TO OCRWM: Several outcomes of this study offer benefits to repository performance. If data indicate that flow is dominantly through fracture networks, results of this study if incorporated, could enhance the current UZ flow and transport model. If rock interiors and fracture surfaces have similar compositions, greater proportions of matrix flow are likely indicated. This result would support the likelihood of greater retardation of radionuclides than currently credited for natural barriers.

Project Title	Natural Analogue Studies of the Drift Shadow Effect
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	Lawrence Berkeley National Laboratory , U.S. Geological Survey
Principal Investigators	Timothy J. Kneafsey, Patrick Dobson, Jim Houseworth, Eric Sonnenthal, Zell Peterman
FY 2004 Funding	$470,000

Abstract **BACKGROUND:** The drift shadow model (Figure 3) is based on the concept that under low infiltration rates, flow diversion will occur around underground openings (such as an emplacement drift, tunnel, lava tube, cave, or lithophysal cavity) in the unsaturated zone (UZ). In the absence of significant water seepage into the opening, this process would result in a reduced water flux immediately below the opening, resulting in molecular diffusion being the primary mechanism of solute transport in this zone. The drift shadow will significantly reduce the mobility of radionuclides, since they require water for transport. Natural analogues will offer the opportunity to demonstrate the existence of the drift shadow and to provide corroborating information that may be used by future process models.

OBJECTIVES: The primary objectives of this study are to:

1) identify natural analogue sites that would demonstrate the existence of a drift shadow zone, and
2) perform field studies at a selected site to confirm the presence or absence of such a feature.

APPROACH: Drift shadow in analogues will be evaluated using the following steps:

Evaluation of natural analogue sites for drift shadow field study - Using numerical modeling and flow physics, identify key characteristics that a drift shadow natural analogue site should possess. These characteristics should include:

1) location within the UZ having sufficient offset from the water table,
2) absence of surface flow,
3) minimal amount of seepage into opening (as evidenced by speleothem deposits and/or dripping or standing water),
4) presence of sufficient overburden to help dampen large infiltration events that might lead to seepage, and
5) similar climate to Yucca Mountain.

Other aspects that need to be considered include:

1) similarity of fracture-matrix network to Yucca Mountain system,
2) possible impact of ventilation on area surrounding underground opening,

3) flow diversion properties (capillary suction) of rock, and

4) site access, security, environmental and cultural concerns. Information on a number of promising locations will be gathered. Several deep lava tubes in central Oregon are currently under consideration as possible candidates for this study.

Numerical modeling to screen natural analogue candidates for drift shadow studies and evaluate field verification methods - The methodology developed by Houseworth et al.[5] to evaluate specific natural analogue field candidates for drift shadow studies and the sensitivity of different methods that could be used to detect the presence of a drift shadow will be utilized. The objectives of the modeling study would be to screen potential field sites to help determine which one would be most likely to have developed a drift shadow, and to determine what methods would be most effective to verify the presence of a drift shadow. Possible methods include:

1) absence of anthropogenically induced tracers in the UZ, such as bomb-pulse tritium and chlorine-36 (^{36}Cl), and lead from burning of fossil fuels,

2) lower concentrations of secondary minerals (such as calcite and opal) that record the integrated fluid flux history,

3) differences in flux as indicated by changes in uranium-series isotope systematics, and

4) reductions in fracture and matrix saturations. (Lack of large contrasts in simulated water saturations and measurement difficulties make this fourth method a less likely candidate.)

Field study of selected natural analogue site for drift shadow studies - Using the field site selected, analyses of samples from the flow diversion and drift shadow areas to determine the abundance of anthropogenic tracers in water and concentration of secondary minerals in fractures that record the integrated fluid flux history will be performed. The uranium-series disequilibrium and fracture and matrix water saturation measurements would only be conducted if significant contrasts in values between the flow diversion and drift shadow zones were predicted in numerical simulations.

Evaluation of lithophysal cavities as analogues for seepage and drift shadow processes - Lithophysal cavities at Yucca Mountain (Figure 4) provide the opportunity to evaluate the time-integrated effects of cavities on flow and transport processes at the proposed repository location. The deposition of secondary minerals such as calcite and opal on the floors of some cavities may in part result from the relatively low transport capacity beneath the cavity, caused by drift shadow effects. Flow and transport modeling, along with detailed study of these cavities and those without significant secondary minerals, will help determine whether a drift shadow

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[5] Houseworth, J.E., Finsterle, S.A., and Bodvarsson, G.S., 2003, Flow and transport in the drift shadow in a dual-continuum model. J. Contam. Hydrol. 62–63, 133–156.

[6] Whelan, J.F., J.B. Paces, and Z.E. Peterman, 2001. "Physical and stable-isotope evidence for formation of secondary calcite and silica in the unsaturated zone, Yucca Mountain, Nevada," Applied Geochemistry 17, pp. 735-750.

developed beneath these features. The use of cavity-specific parameters and geometry, with the same code used for larger openings, will account for scale differences.

Development of conceptual and numerical models for drift shadow zone - Using the results of these field measurements, revise existing conceptual and numerical models for the drift shadow zone at the natural analogue site. The refined conceptual model can then be applied to flow and transport models for the Yucca Mountain system.

BENEFITS TO OCRWM: The drift shadow has the potential of significantly retarding the transport of radionuclides within the proposed geologic repository, as suggested by the results of numerical flow and transport simulations around an emplacement drift[5]. These simulations indicate that diffusion is the primary mechanism for radionuclide migration from the drift through the drift shadow area into the surrounding rock, and that the absence of advective transport in this area will result in significantly longer predicted radionuclide travel times to the water table. Carefully selected natural analogues that record fluid flow around features that divert flow over long periods of time within the UZ, could provide key information to verify this model.

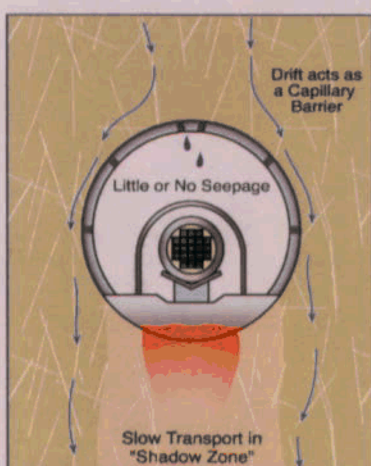

Figure 3: Drift shadow conceptual model

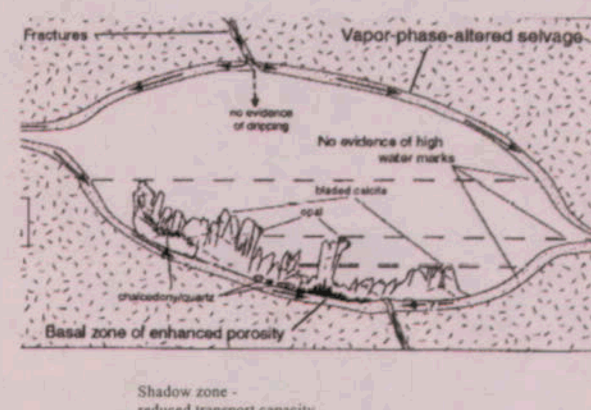

Figure 4: Lithophysal cavity conceptual model[6]

Project Title	Peña Blanca Natural Analogue
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, University of Tennessee Knoxville, University of Texas El Paso, Framatome, Inc. (Subcontracts to Autonomous University of Chihuahua, University of Southern California, University of California Santa Barbara)
Principal Investigators	A. Simmons, P. Dobson, M. Murrell , M. Fayek, P. Goodell, G. Saulnier
FY 2004 Funding	$765,000

Abstract **BACKGROUND:** In the 1970s, the Peña Blanca district, approximately 50 km north of the city of Chihuahua, Mexico, was a major target of uranium exploration and mining by the Mexican government. Since that time, the Nopal I uranium deposit has been studied by numerous researchers as an analogue for the long-term decay of spent fuel in a geologic nuclear waste repository. The Nopal I uranium deposit at Peña Blanca presents an environment that closely approximates that of the planned high-level waste repository at Yucca Mountain, Nevada in the following ways:

- Both are located in semi-arid regions
- Both are situated in a basin-and-range horst structure composed of Tertiary rhyolitic tuffs overlying limestones
- Both are located in a chemically oxidizing, unsaturated zone 100 m or more above the water table
- The alteration of uraninite to secondary uranium minerals at Nopal I may be similar to the eventual alteration sequence of uranium fuel rods in a geologic repository like that planned for Yucca Mountain.

Since 1999, investigators have conducted studies to extend knowledge gained by previous surface investigations into the vertical direction.

OBJECTIVES: Natural analogues offer the opportunity to observe processes over the long term. Analogues can also be used to determine the range of applicability of models and to assure qualitatively that the appropriate processes and subprocesses are included. In these ways, natural analogues provide corroborating information that can enhance the defensibility of the Yucca Mountain models.

The Nopal I site at Peña Blanca affords a setting to test models of unsaturated flow and transport, saturated flow and transport, and waste form degradation. Although the Yucca Mountain Project has used supporting information from a number of natural analogue sites to corroborate such processes as, for example, the rate of matrix diffusion, the role of colloids in facilitating radionuclide transport, and sequestration of uranium in secondary minerals within the waste form, no analogue has been studied to test an entire process model nor to test a total system

performance.

APPROACH: This project will build on previous studies that characterized the Nopal I site geology and studies of uranium-series disequilibrium. The project includes field investigations, laboratory experiments, conceptual model refinement, and numerical modeling. Some of the specific topics that will be investigated are: identity, quantity, and stability of colloids in the unsaturated zone; filtration of colloids in the saturated zone; active fractures and fracture/matrix interaction; location of uranium in secondary minerals; transport of uranium and daughter products in unsaturated and saturated environments; seasonal variations in transport conditions; local changes in redox conditions; and transport of technetium, if detectable. Tracer tests are planned for both unsaturated and saturated environments.

BENEFITS TO OCRWM: Peña Blanca is the only analogue site thus far identified that possesses numerous similar attributes to Yucca Mountain in geology, hydrologic setting, climate, mineralogy, and size of the uranium deposit (or source term). Of all the analogue sites explored to date, Peña Blanca is the closest to being a total system analogue. Of benefit will be the confidence gained by the expected demonstration of conservatism in the current Yucca Mountain TSPA, and identification of any features detected at Peña Blanca that could be negative contributors to performance within the similar Yucca Mountain setting.

Project Title	Planning for Large-Scale Drawdown Test in Volcanics
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	Los Alamos National Laboratory, U.S. Geological Survey, Sandia National Laboratories, Lawrence Berkeley National Laboratory
Principal Investigators	Paul Reimus, Robert C. Roback, Ed Kwicklis, M. J. Umari, John Earle, Michael Chornak, Richard L. Beauheim, Randall M. Roberts, Susan J. Altman, Bill Arnold, Stephanie Kuzio, Chin-Fu Tsang, Hui-Hai Liu, Kenzi Karasaki
FY 2004 Funding	$360,000

Abstract **BACKGROUND:** Evidence from field and laboratory tests indicates large variability in permeability and hydraulic conductivity in saturated tuff at Yucca Mountain. Although it is likely that much of the bulk groundwater flow occurs in high permeability zones, there is uncertainty in the degree of groundwater channelization in the fractured volcanic rocks remains. The role of laterally continuous faults on groundwater flow at Yucca Mountain also has uncertainty that could be reduced with additional data.

OBJECTIVES: It is important for modeling capability of natural barriers to understand to what extent high permeability zones influence groundwater flow and elemental transport. For example, highly channelized flow in a few, widely separated fracture zones would result in little matrix diffusion and faster radionuclide migration; whereas, groundwater flow distributed among numerous, closely spaced fractures would result in greater matrix diffusion and slow radionuclide migration.

APPROACH: This project is a multidisciplinary, multiphase approach aimed at providing a detailed plan for enhancing understanding of physical and chemical heterogeneity of groundwater flow near the proposed repository at Yucca Mountain. Much of the investigation plan will focus on testing discrete vertical intervals with different physical and chemical properties. Currently envisioned is the selection of one well (possibly H-4) for long-term pumping and several wells surrounding the pumping well as observation wells. The plan will include pre-test activities such as cleaning selected wells and instrumenting. *In-situ* flow and hydrochemical profiles will aid in final selection and instrumentation of wells that will ultimately be used for long-term pumping and/or tracer tests.

BENEFITS TO OCRWM: The multiple benefits of the project include:

- Detailed flow surveys will yield information on the spatial distribution of flowing intervals in the fractured volcanics and on the distribution of volumetric flow rates between these intervals. This information will reduce uncertainty in effective flow porosity and groundwater travel time estimates in the volcanics, and it will also reduce uncertainty in predicting radionuclide attenuation in the saturated zone (SZ) due to matrix diffusion.
- Detailed hydrochemical profiles and discrete-interval geochemistry sampling will

provide information on the spatial distribution of major ions, natural isotopic tracers, Eh/pH conditions, and colloids in the SZ. This information will reduce uncertainties in predictions of flow pathways, vertical mixing, colloid-facilitated transport, and Eh/pH variability (which could result in significant attenuation of key radionuclides, such as technetium, uranium, and neptunium). Geochemistry data from both high- and low-permeability zones will also yield information on fracture-matrix interactions and on the potential role of "fast pathways" such as faults or fracture zones in the SZ, thus leading to refinement and uncertainty reduction in flow and transport models.

- Large-scale drawdown testing will yield information on anisotropy and heterogeneity of horizontal hydraulic conductivity in the saturated volcanics near Yucca Mountain. This information will reduce uncertainty in the prediction of flow pathways and groundwater travel times.
- Single-well tracer tests in observation wells conducted in selected intervals prior to and at the end of large-scale drawdown testing will yield information on ambient and induced flow velocities as well as on matrix diffusion. This information will provide local estimates of groundwater flux, estimates of flow porosity, and constraints for interpreting the large-scale drawdown test, which will reduce uncertainty in the parameters estimated from the test.
- The SZ Site-Scale flow model will be used to help interpret information obtained from flow surveys, tracer testing, and geochemical sampling. The influence of fault zones as flow boundaries or conduits will be explored through sensitivity analyses. Additional modeling will simulate and characterize probabilistically the nature and effects of channeling on large-scale flow and transport throughout the SZ.

Project Title	Pore Connectivity, Episodic Flow, and Unsaturated Diffusion in Fractured Tuff
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	Lawrence Livermore National Laboratory, Iowa State University.
Principal Investigators	Qinhong Hu, Robert Ewing, Liviu Tomutsa
FY 2004 Funding	$260,000

Abstract **BACKGROUND:** Recent research has shown that rocks whose pores are poorly interconnected display anomalous scaling behaviors that strongly impact long-term net diffusion. Specifically, most rocks with poorly connected pores have a cross-over length below which diffusivity decreases with distance, and above which diffusivity appears constant but with a diffusion coefficient less than that measured at small sample sizes.

Preliminary work indicates that Yucca Mountain devitrified welded tuff is poorly interconnected at the pore scale. These results are consistent with theoretical work that shows how diffusion at low phase saturations and/or pore connectivity can be characterized as a percolation problem. Use of a percolation paradigm for diffusion suggests both specific mathematical tools for upscaling from laboratory to in-situ scales, and the use of a pore-scale random walk modeling approach to help understand and interpret the experiments.

Infiltration and water seepage through unsaturated fractured rocks of low matrix permeability are episodic and intermittent in nature. With episodic flow of varying rate and intensity, the matrix is constantly imbibing or drying, and this fluctuating wetness both drives two-way advective movement of radionuclides, and alters the matrix diffusivity.

OBJECTIVES: This work is designed to improve understanding of diffusive retardation of radionuclides due to fracture/matrix interactions, particularly in light of recent discoveries. Results from this combined experimental and modeling work will:

1) provide insights into the upscaling of laboratory-scale diffusion experiments, and
2) evaluate the impact on diffusive retardation of episodic fracture flow and pore connectivity in Yucca Mountain tuffs.

APPROACH:

- Acquire and characterize the three major tuff types (zeolitic, vitric, and devitrified) encountered below the potential waste emplacement drifts at Yucca Mountain.
- Measure steady-state argon gas diffusion coefficients for each tuff type at three sample scales (2, 20, and 200 mm) to examine scaling effect.
- Determine the imbibition rate over time of a tracer solution into the samples, to

provide further information on pore connectivity.

- Measure the fine-scale distribution of tracer concentration with distance from the wetted face, following both imbibitions (above) and vacuum-saturation, using laser ablation interfaced with inductively coupled plasma-mass spectrometry (LA / ICP-MS).
- Analyze the shape of iso-concentration surfaces, which is indicative of pore connectivity, in the three tuff types obtained from three-dimensional images using the synchrotron microtomography system at the Advanced Light Source facilities of Lawrence Berkeley National Laboratory.
- Compare long-term net tracer movement and concentration profiles between episodic and steady-state boundary conditions.
- Predictively simulate the above experiments using a pore-scale network model using both classical and anomalous diffusion, in conjunction with advective/dispersive wetting and drying processes where appropriate.

BENEFITS TO OCRWM: Matrix diffusion and imbibition processes, by moving radionuclides away from the flowing fracture and exposing the tuff matrix for retardation of sorbing radionuclides, greatly contribute to the effectiveness of the natural geological barrier. But there are uncertainties about how pore connectivity of tuff matrix, scaling issues, water saturation, and episodic flow events affect the matrix diffusion and imbibition processes. This work integrates experimental and simulation approaches, using new experimental methods, state-of-the-art synchrotron microtomography, and pore-scale network modeling. It is anticipated that the results from this work will directly address these uncertainties to matrix/fracture interaction and the related potential contribution to dose estimates.

Project Title	Seismic Ground Motion Evaluation Workshop
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	U.S. Geological Survey
Principal Investigators	Tom Hanks
FY 2004 Funding	$230,000

Abstract The U.S. Geological Survey (USGS) will organize and coordinate a group of five seismicity experts to address the topic of extreme ground motions (large amplitude, low probability ground motions) at Yucca Mountain. The experts will collectively determine the approach to be taken to select a group of about 25 topical specialists to provide information on specific aspects of the topic. The experts will convene a workshop in which the specialists will present their knowledge and understanding to the expert group. After the workshop, the expert group will collectively determine their recommendations on a set of technical topics to enhance understanding of potential extreme ground motions at Yucca Mountain and write a final report. Dr. Thomas Hanks will chair the group.

The work to be completed in fiscal year 2004 is in preparation for the writing and publishing in fiscal year 2005 of a USGS Open File Report and a shorter version for publication in a peer-reviewed journal. To prepare for this report and other writings, these seismicity experts will define an *integrated long-term technical program* (e.g., as a set of technical topics to investigate) designed to provide the technical basis for a "next-generation" hazard analysis of extreme ground motions relevant for a proposed Yucca Mountain repository. In particular, the expert group will identify and recommend a suite of relevant technical studies (e.g., nonlinear effects and new ways to quantify energy release and propagation through rock), as well as the hazard analysis tools and methodology that would need to be developed in order to incorporate the results.

Project Title	Seismic Strong Motion Generated by Dynamic Slip on Rough Faults
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	Itasca Consulting Group
Principal Investigator	Peter Cundall
FY 2004 Funding	$132,000

Abstract

BACKGROUND: The Probabilistic Seismic Hazard Analysis (PSHA) developed by the Yucca Mountain Project is over-conservative. It greatly overstates the annual likelihoods for the very largest earthquakes.

OBJECTIVE: This project studies the near-field, strong motion that may be produced by a slipping non-uniform rough fault. The ultimate objective is to reduce the conservatism in the PSHA by building a numerical model of fault rupture that has been calibrated against the actual rock at the earthquake faults of interest for the Yucca Mountain site.

APPROACH: The approach is to employ a numerical simulation technique, with appropriate boundary conditions, using a bonded-particle model (BPM) to represent brittle rock. The numerical fault model will be calibrated to match rock likely to exist in the actual fault locations of interest. The softening behavior that governs dynamic fault motion derives not from a simple weakening assumption but from the intrinsic properties of the synthetic material (i.e., the brittle rock represented by BPM), which must be independently calibrated.

The large-scale rough-fault simulations are based on a hybrid model. The hybrid model consists of a near-field BPM, to reproduce nonlinear rock response in the near-fault region, coupled to a far-field continuum model that allows waves to propagate away from a fault source efficiently and without reflection. The concept of the coupled model draws from the fields of both continuum and discrete particle mechanics. The codes use an explicit finite-difference, time-marching solution scheme to deal with the nonlinear aspects of inelastic response (plasticity, particle-to-particle contact bond breakage and sliding.) In the simulations each micro-crack event within the larger energy-release event releases a dynamic pulse of kinetic energy. Several related crack events can produce elastic waves that resemble those from real seismic sources. It is necessary to assure the appropriate boundary conditions are used, extending to the elastic region outside the immediate near-field region. In this way, the fault is able to extend dynamically (e.g., due to an increased applied shear stress), and the resulting waves are able to propagate into the near field region without artificial boundary reflections.

BENEFITS TO OCRWM: This project has the potential to enhance understanding of the seismic-source aspects of the overall seismic hazard analysis at the Yucca Mountain site. If the project's prospects can be realized, it will lead to reduction of conservatism in the PSHA. Since seismic hazard is used both to analyze the response of the underground engineered system at Yucca Mountain and to design and analyze the surface facilities, this work can potentially lead to substantial cost reduction.

Project Title	Testing the Concept of Drift Shadow
OCRWM S&T Program Thrust	Natural Barriers
Project Performers:	U.S. Geological Survey, Lawrence Berkeley National Laboratory
Principal Investigators	James Paces, Zell Peterman, Patrick Dobson
FY 2004 Funding	$910,000

Abstract **BACKGROUND:** The presence of open drifts may provide a capillary barrier mechanism to divert seepage away from waste canisters and invert areas below any failed canisters. This process is expected to create a drift shadow effect resulting in increased unsaturated zone (UZ) flow on the sides of a cavity and a zone of low flow beneath the cavity. This effect has the attribute of limiting the amount of UZ flow capable of transporting radionuclides away from any compromised waste packages. However, this conceptual effect has not been demonstrated by field data obtained under natural flow conditions within the proposed repository horizon.

OBJECTIVES: The proposed work will address the concept of the drift shadow effect in Yucca Mountain through an evaluation and testing of natural cavities within the repository units that have been affected by UZ flow for the last 12.8 million years. The identification of isotopic and chemical differences in rock and pore water from samples adjacent and subjacent to the natural cavities would demonstrate that long term fluxes beneath cavities are reduced relative to flow through the rock mass outside of the shadow zone.

APPROACH: Several meter-scale lithophysal cavities are intersected by the Exploratory Studies Facility and Expanded Characterization of Repository Block Cross Drift. This study will target several cavities present in the wall rock beyond the limit of ventilation dry-out. Geophysical methods, such as seismic tomography, will be used to locate potential near-drift cavities. Once located, small-diameter dry-drilled boreholes will provide rock samples both adjacent and subjacent to target cavities.

Both whole rock and extracted pore water will be analyzed for chemical and isotopic tracers of flow. Uranium-series isotopes in whole rock samples respond to differences in long-term matrix percolation fluxes. Higher fluxes outside of the shadow zone would exhibit greater degrees of radioactive disequilibrium whereas more-stagnant flow conditions beneath the cavity would yield isotopic results closer to secular equilibrium. Precise analyses of thorium-230/uranium-238 and uranium-234/238 ($^{230}Th/^{238}U$ and $^{234}U/^{238}U$) ratios on the new U.S. Geological Survey thermal ionization mass spectrometer will allow identification of the subtle differences expected in samples from these different zones. Uranium-series isotopes are also advantageous because the presence of radioactive disequilibrium indicates that water-rock interactions have occurred in the last several hundred thousand years.

Strontium isotopic compositions of whole-rock leachates are also likely to show

evidence of long-term stagnation by having values closer to whole-rock compositions compared to unrestricted percolation. Similarly, pore water samples extracted from within and outside of the drift shadow are expected to show differences if flow rates are substantially different beneath a cavity. An advantage of using natural cavities for this study is that no scaling of percolation rates is necessary to demonstrate the presence or absence of the drift-shadow effect.

Data associated with natural cavities will be used to calibrate numerical models of flow diversion and drift shadow development in the Yucca Mountain system using computer code at Lawrence Berkeley National Laboratory. This phase of the study will be coordinated with similar studies at analogue sites to reach the most comprehensive understanding of this hydrologic effect.

Products will include interpretive reports describing significant findings and results of modeling.

BENEFITS TO OCRWM: Demonstration that the drift shadow concept is effective would likely result in predictions of reduced radionuclide transport through the unsaturated zone. This work has a strong potential for identifying significant drift shadow effects, if they are present.

Project Title	Unsaturated Zone Workshop/AGU Monograph
OCRWM S&T Program Thrust	Natural Barriers
Project Performers	Lawrence Berkeley National Laboratory, DOE Office of Science
Principal Investigators	Bo Bodvarsson
FY 2004 Funding	$195,000

Abstract: The goal of the workshop is to bring together experts to discuss the state of knowledge of unsaturated zone flow and transport processes that are potentially applicable to Yucca Mountain. The primary area of interest is flow focusing and means of reducing uncertainty in estimates of its behavior. A report summarizing the consensus of the workshop will be prepared and will identify promising areas of further research that may enhance understanding of unsaturated zone processes, especially flow focusing.

A book describing the groundwater flow and transport in the unsaturated zone fracture networks is under preparation. The publication will describe the current status of the technical work in the evolution of field and laboratory testing, the ambient processes, the thermally driven coupled processes, the unsaturated zone and the natural analogues. The monograph will be published by the American Geophysical Union.