

12 STRUCTURAL PERFORMANCE OF ENGINEERED MATERIALS CREEP, EMBRITTLEMENT, AND EARLY FAILURE MECHANISMS

Ankem, R. and T. Wilt. 10/24/2007. "A Literature Review of Low Temperature (<0.25T mp) Creep Behavior of α , α - β , and β Titanium Alloys." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2007.

20.14002.01.191, Q200710250006, ML072060401

This report surveys the current literature available in the public domain for information pertaining to the long-term, low temperature creep behavior of Titanium Grades 7 and 24 or reasonable surrogates. Specifically, this report investigates the creep mechanisms of slip, twinning, grain boundary sliding, alpha-beta interface sliding, Widmanstatten colony boundary sliding, and stress-induced martensite. Additional parameters such as the microstructure of phases, chemical composition, texture, stress type, and cold work are also evaluated.

Ankem, S., P.G. Oberson, R.V. Kazban, K.T. Chiang, L.F. Ibarra, and A.H. Chowdhury. 08/30/2007. "An Investigation of the Low Temperature Creep Deformation Behavior of Titanium Grade 7 and Grade 5 Alloys." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2007.

20.06002.01.342.740, Q200708300002, ML071900315

This study focuses on the creep deformation behavior of Titanium Grade 7 and Grade 5 at temperatures ranging from 25 to 250 °C [77 to 482 °F] and at stress levels ranging from 40 to 100 percent yield stress. In particular, the creep behavior of both titanium alloys is evaluated for a range of stress levels at the constant temperature of 150 °C [302 °F], and for a range of temperatures at the constant stress level of 85 percent yield stress of the corresponding material. This investigation includes: (i) analysis of the creep curves including determination of the activation energy for creep deformation, (ii) characterization of the as-received plate microstructures using optical and scanning electron microscopy, and (iii) transmission electron microscopy of the creep specimens.

Chan, K.S. 09/28/2007. "Revised Draft Journal Article: An Assessment of Delayed Hydride Cracking in Zirconium Alloy Cladding Tubes Under Stress Transients." *Journal of Nuclear Materials*. Elsevier Inc. 2007.

20.06002.01.222.740, Q200710010001

Hsiung, S.-M. and S. Mohanty. "An Abstracted Model for Assessing the Effect of Seismically Induced Rock Fall on the Waste Package Performance for High-Level Radioactive Waste Disposal." *PSAM 5-Probabilistic Safety Assessment and Management*. S. Kondo, K. Furuta, eds. *Frontiers Science Series 34*. Universal Academy Press, Inc. Tokyo, Japan: Vol. 3. pp. 1,581–1,588. 2000.

Ibarra, L., T. Wilt, G. Ofoegbu, and A. Chowdhury. 01/23/2007. "Structural Performance of Drip Shield Subjected to Static and Dynamic Loading." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2007.

20.06002.01.342.720, Q200701230005, ML070240131

The report presents the result of a modeling study in which the drip shield structure is modeled using both a finite element model (ABAQUS) and an equivalent frame model (SAP2000). The finite element model verifies the structural response obtained from the drip shield frame model, and it provides information about the moment-rotation relationships of the drip shield sections and equivalent spring constants to account for drip shield–rubble interaction. The frame model is then used to evaluate the structural performance of the drip shield based on sensitivity studies and seismic analyses.

Ibarra, L., T. Wilt, G. Ofoegbu, R. Kazban, F. Ferrante, and A.H. Chowdhury. 02/19/2007. "Drip Shield-Waste Package Mechanical Interaction." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2006.
20.06002.01.342.710, Q200702200001, ML070520335

This study evaluates the potential mechanical interaction between the drip shield and the waste package caused by a collapsed drip shield system. This interaction is evaluated by means of finite element models developed in ABAQUS. The models include (i) two-dimensional, plane strain models of simple geometry but a very refined mesh, and (ii) a three-dimensional model that reproduces the overall performance of the drip shield-waste package interaction. The three-dimensional modeling is used to verify some of the assumptions adopted in the plane strain models, and to estimate the contact length of the bulkhead. A sensitivity study is performed to evaluate the effect of demand and system parameter variation on the waste package capacity. The main results have been used to generate abstractions to update the Total-system Performance Assessment computer code.

Jain, V., D. Daruwalla, and C. Fairbanks. 04/03/2003. "Assessment of Mechanisms for Early Waste Package Failures." CNWRA 2003-05. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2003.
20.06002.01.081.310, Q200304090001, ML040350562

This report reviews the DOE methodology for estimating early waste package failures using simulation data from the expert-system based simulation RR-PRODIGAL code and event-tree analysis to quantify probabilities of failure for various manufacturing defects (CRVMS M&O, 2000a). In addition, this report provides a review of other available information, and an analysis of weld flaws for the outer-lid closure weld.

Sridhar N, G.A. Cragnolino, D.S. Dunn, and H.K. Manaktala. 04/21/1994. "Review of Degradation Modes of Alternate Container Designs and Materials." CNWRA 94-010. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1994
20.05704.045.201, Q199404280001, ML033630647

This report considered the performance of alternate container materials, including materials being considered for multipurpose canisters (MPCs), which would be a completely sealed canister containing spent fuel bundles that could be transferred within overpacks from the plants through intermediate storage sites to the eventual disposal site. The review focused on the structural characteristics of the MPC and noted that the mechanical integrity of the MPC materials, especially in the welds, can be impaired due to embrittlement under long-term exposure to temperatures of 200–300 °C.

Sridhar, N., B.E. Wilde, C. Manfredi, S. Kesavan, and C. Miller. 06/27/1991. "Hydrogen Absorption and Embrittlement of Candidate Container Materials." CNWRA 91-008. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1991.
20.03704.041, Q199107090036, ML40330594

Tszeng, T.C. 09/18/2008. "Review of Analysis of Mechanisms for Early Waste Package and Drip Shield Failure. Fifth Revision. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2008.

20.06002.01.322.630, Q200809180004, ML082630079

This report addresses possible mechanisms for early failure of waste packages and drip shields that may allow water ingress into the failed waste package and lead to early release of radionuclides. In particular, this report reviews the early failure analysis of the waste package outer container and drip shield related to manufacturing-induced defects presented in the U.S. Department of Energy report titled Analysis of Mechanisms for Early Waste Package/Drip Shield Failure.

Wilt, T., A. Chowdhury, and T. Ahn. 10/22/2010. "A Literature Review of the Structural Integrity of Analog Canisters." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2010.

20.14002.01.441, Q201010220001

This report documents a literature review used to evaluate the structural behavior of DOE standardized spent nuclear fuel canister, Idaho Spent Fuel Project canisters, multi-canister overpacks, and high-level waste canisters. These canisters can be considered analogous to the transportation, aging, and disposal (TAD) canister concept DOE has proposed. The primary objective was to investigate different types of canisters and their structural robustness when subjected to a drop event at a number of drop orientations and heights. The process used to develop structurally robust DOE canister designs includes (i) using limited small- or full-scale testing to evaluate the proposed canister design, (ii) using visual inspection and pressure testing of dropped canisters to verify structural integrity, and (iii) comparing small- and full-scale test results with the corresponding three-dimensional finite element analyses that provide detailed stress-strain distributions to further examine canister structural integrity.

13 ROCK MECHANICS AND EXCAVATION STABILITY

Ahola, M.A. 05/22/1997. "A Parametric Study of Drift Stability in Jointed Rock Mass–Phase II: Discrete Element Dynamic Analysis of Unbackfilled Drifts." CNWRA 97-007. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1997. 20.05708.761.740, Q199710210003, ML040200090

This report presents a discrete element analysis using the code UDEC (Version 3.0) to investigate the effect of repeated seismic loading, with peak underground accelerations ranging from 0.2 to 0.4g, on cumulative joint slip and failure around a heated and unsupported emplacement drift in the proposed repository at YM.

Ahola, M.P., R. Chen, H. Karimi, S. Hsiung, and A.H. Chowdhury. 09/01/1996. "A Parametric Study of Drift Stability in Jointed Rock Mass–Phase I: Discrete Element Thermal-Mechanical Analysis of Unbackfilled Drifts." CNWRA 96-009. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1996. 20.05708.671.640, Q199701230006, ML040230678

The objective of this study was to identify thermal and site specific natural phenomena and rock mechanical and thermal parameters that may significantly influence the pre- and postclosure performance of the repository under heated and seismic conditions. In Phase I, a distinct element computer code (UDEC) was used to conduct a parametric investigation of emplacement drifts without backfill, rock support, and seismic load for 100 yr of heating.

Brady, B.H.G., S.-M. Hsiung, and A.H. Chowdhury. 01/01/1990. "Qualification Studies on the Distinct Element Code Universal Distinct Element Code (UDEC) Against Some Benchmark Analytical Problems." CNWRA 90-004. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1990. No comments available. 20.03704.033, Q199112190002, ML040690187

This report presents the results of studies which assess the performance of the two-dimensional distinct element code, UDEC, in analysis of some benchmark problems in the mechanics of discontinuous rock.

Brandshaug, T., B. Dasgupta, B.H.G. Brady, S.-M. Hsiung, and A.H. Chowdhury. 02/01/1990. "Qualification Studies on the Finite Element Code HONDO II Against Some Benchmark Analytical Problems." CNWRA 90-006. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1990. 20.03704.033, Q199107230015, ML040690163

This report presents the results of studies that assess the performance of the two-dimensional finite element code, HONDO II, in analysis of some benchmark problems in the mechanics of discontinuous rock.

Fox, D.J., D.D. Kana, and S.M. Hsiung. "Influence of Interface Roughness on Dynamic Shear Behavior in Joint Rock." *International Journal of Rock Mechanics and Mining Sciences*. Vol. 35, No. 7. pp. 923–940. 1998.

Ghosh, A. and S. Hsiung. 07/29/2011. "Effects of Tilted and Faulted Strata on Seismic Ground Motion." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2011. 20.14002.01.441.160, Q201107290006, ML112130151

Draft knowledge capture report

Ghosh, A., S.-M. Hsiung, and A.H. Chowdhury. 06/27/1995. "Seismic Response of Rock Joints and Jointed Rock Mass." CNWRA 95-013. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1995.
20.05704.037.095.001, Q199507190003, ML040210700

This report summarizes one component of the activities conducted in the Rock Mechanics research project.

Ghosh, A., S.-M. Hsiung, and A.H. Chowdhury. 09/26/1995. NUREG/CR-6388, "Seismic Response of Rock Joints and Jointed Rock Mass." Washington, DC: U.S. Nuclear Regulatory Commission. 1995.
20.05704.037, Q199511070004

Also published as CNWRA 95-013.

Ghosh, A., S.-M. Hsiung, D.J. Fox, A.H. Chowdhury, and D.D. Kana. 09/28/1995. "Rock Joint Model Development for Cyclic Loads." CNWRA 95-022. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1995.
20.05702.623, Q199601050009

Hsiung, S.-M. and A.H. Chowdhury. 07/26/2011. "Seismic Effects on Soil-Structure Interactions." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2011.
20.14002.01.441.172, Q201107260005, ML112081622

Hsiung, S.-M., W. Blake, A.H. Chowdhury, and T.J. Williams. 03/01/1993. "Effects of Mining-Induced Seismic Events on a Deep Underground Mine." *Pure and Applied Geophysics*. Vol. 139, Nos. 3/4. pp. 741–762. 1992.
20.05704.034, Q199304140003

This paper assesses the performance of an underground excavation at the Lucky Friday Mine in the Coeur d'Alene Mining District of Idaho that was subjected to repetitive episodes of mining-induced seismic activities. Step changes in displacement or in excavation closures were explained by the concept of stick-slip on joints or bedding planes within the rock mass. Through this mechanism, joint displacement is accumulated at joints or along a bedding plane in a progressive fashion, weakening the rock mass around an excavation and making it more susceptible to seismic impacts.

Hsiung, S.-M., A.H. Chowdhury, W. Blake, M.P. Ahola, and A. Ghosh. 12/16/1992. "Field Site Investigation: Effect of Mine Seismicity on a Jointed Rock Mass." CNWRA 92-012. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 1992.
20.05704.034.031, Q199301200003, ML040200235

This field study at the Lucky Friday Mine in northern Idaho indicated that rock mass deformation around an excavation after repetitive episodes of mine seismic events was caused by an accumulation of joint shear displacement, which gradually weakens the rock mass. The mechanism of joint displacement accumulation is analogous to stress fatigue phenomena commonly observed for natural or artificial materials. This implies that similar, or even more, damage to an excavation may occur due to a number of seismic events with relatively smaller magnitudes, as opposed to the damage due to a single seismic event with a very strong motion.

Hsiung, S.-M., A. Ghosh, and A.H. Chowdhury. 01/31/1995. "Progress Toward a Fractal Representation of Rock Joint Roughness." CNWRA 95-004. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1995.
20.05702.623, Q199502070001, ML040210608

Hsiung, S.-M., A. Ghosh, A.H. Chowdhury, and M.P. Ahola. 11/19/1993. "Evaluation of Rock Joints Model and Computer Code Universal Distinct Element Code (UDEC) Against Experimental Results." CNWRA 93-024. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 1993.
20.05704.033, Q199401030007, ML033640188

Kana, D.D., D.J. Fox, S.-M. Hsiung, and A.H. Chowdhury. 06/27/1995. "An Experimental Scale-Model Study of Seismic Response of an Underground Opening in Jointed Rock Mass." CNWRA 95-012. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1995.
20.05704.034.095.001, Q199507190002, ML040210700

This report describes the design and implementation of simulated seismic experiments and results for a 1/15 scale model of a jointed rock mass with a circular tunnel in the middle.

Kana, D.D., D.C. Scheidt, B.H.G. Brady, A.H. Chowdhury, S.-M. Hsiung, and B.W. Vanzant. 01/01/1990. "Development of a Rock Joint Dynamic Shear Test Apparatus." CNWRA 90-005. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1990.
20.03704.032, Q199112190003, ML040780170

This report describes the design, assembly, calibration, and operation of a rock joint dynamic shear test apparatus, as part of the Seismic Rock Mechanics Project.

Ofoegbu, G. 07/12/2011. "Analysis of Spatial Variability of Rock-Mass Quality and Thermal-Mechanical Effects in Geologic Disposal of High-Level Nuclear Waste." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2011.
20.14002.01.441.178, Q201107120002, ML111930431

Ofoegbu, G.I., B. Dasgupta, and K.J. Smart. 04/20/2004. "Thermally Induced Rock Stress and Implications for Degradation of Emplacement Drifts at the Potential Yucca Mountain Nuclear Waste Repository. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 2004.
20.06002.01.001.441, Q200404270005

The report is a short summary of an analysis that was performed to investigate the development of thermally induced rock stress in lithophysal tuffs at the proposed Yucca Mountain nuclear waste repository and to assess the implications of the calculated stress distributions for rockfall and degradation of the emplacement drifts.

Ofoegbu, G., R. Fedors, C. Grossman, S. Hsiung, L. Ibarra, C. Manepally, J. Myers, M. Nataraja, O. Pensado, K. Smart, and D. Wyrick. 04/11/2007. "Summary of Current Understanding of Drift Degradation and Its Effects on Performance at a Potential Yucca Mountain Repository." Rev. 1. CNWRA 2006-02. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2007.
20.06002.01.342.650, Q200704120017, ML070650462

This report is a summary of information and evaluations regarding the degradation of emplacement drifts and the effects of drift degradation on long-term performance of a proposed Yucca Mountain nuclear waste repository.

Ofoegbu, G.I., R.V. Kazban, S. Painter, and C. Manepally. 11/29/2007. "Modeling Progressive Spallation of a Heated Underground Excavation." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2007.

(Manuscript prepared for an unspecified journal)

20.14002.01.191.810, Q200711300001

This paper demonstrates a continuum finite element modeling approach for coupled analysis of progressive roof spallation of a heated underground opening; rubble accumulation; and heat flow through the rubble, degrading opening, and surrounding rock. The analysis indicates that thermally induced spallation could be an important drift degradation mechanism because the driving stress tends to increase as roof spallation progresses and is sustained by a long-persisting far-field temperature distribution.

Ofoegbu, G.I., R.S. Read, and F. Ferrante. 02/28/2008. "Bulking Factor of Rock for Underground Openings." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 2008.

20.14002.01.191.820, 20.14002.01.121.830, Q200802290001

This draft report presents the results of a literature review, field work, and laboratory testing to examine ways of characterizing the bulking of rock when it breaks up to form rubble. The information reviewed includes data from underground excavations near Yucca Mountain, surface excavation of rock and soil, and underground mining. The data were statistically analyzed using techniques for summarizing expert opinions.

Ofoegbu, G.I., K.J. Smart, and B. Dasgupta. "Assessing Effects of Thermal Loading on the Stability of Emplacement Drifts." *Nuclear Technology*. Vol. 163. pp. 24–30. 2008.

ML060970233

Read, R.S. and G.I. Ofoegbu. 06/14/2006. "Review of Tools and Techniques to Monitor Repository Excavations." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2006.

20.06002.01.191.620, Q200606160002

The report provides a summary of tools and techniques for monitoring the stability of underground openings in rock that may be applicable to a potential Yucca Mountain repository. Monitoring methods typically used in and around underground openings and their suitability for monitoring in a repository environment of high temperature and radiation are reviewed. Means of interpreting measurements to identify and characterize damage around the underground openings are discussed, along with implications for developing a contingency plan for maintenance of the underground openings.

14 WASTE FORM PROPERTIES AND RADIONUCLIDE RELEASE

He, X., V. Jain, P.F. Bertetti, and D. Pickett. 01/10/2007. Revised: "Evolution of Fluid Chemistry Inside a Waste Package Due to Carbon Steel and Simulated High-Level Waste Glass Corrosion—Progress Report. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2007.

20.06002.01.222.630, Q200701100024

This report provides a summary of bench-scale experiments examining the chemical evolution of in-package solutions produced by corroding carbon steel samples in expected groundwater compositions. The experiments also studied neptunium sorption on the corrosion products. Results indicate that the corrosion processes increased the pH of the solution from near-neutral to alkaline (pH >9), accompanied by the formation of iron-bearing corrosion product precipitates. The addition of simulated high-level waste glass further increased the pH of the solution. The corrosion products showed substantial sorption of neptunium, however the presence of a small amount of calcite in the corrosion products is a complicating factor, which may also contribute to the sorption.

Jain, V., G. Cragolino, and L. Howard. 09/09/2004. "A Review Report on High Burnup Spent Nuclear Fuel—Disposal Issues." CNWRA 2004-08. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2004.

20.06002.01.081.410, Q200409170005, ML043020319

Jung, H., T. Ahn, K. Axler, R. Pabalan, and D. Pickett. 03/22/2011. "Corrosion of SIMFUEL in Aerated Carbonate Solution Containing Calcium and Silicate." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2011.

20.14002.01.441.124, Q201103230001, ML110820348

This report documents the results of a previously unpublished set of experiments that evaluated the corrosion behavior of simulated spent nuclear fuel (SIMFUEL). The purpose of the experiments was to confirm a range of dissolution rates of spent nuclear fuel (SNF) in a repository relevant environment, specifically under oxidizing conditions, and to assess the potential effect of radionuclide sorption onto the oxides formed on stainless steel.

Manaktala, H.K. "Standard Test Methods for Determining Chemical Durability of Nuclear Waste Glasses: The Product Consistency Test (PCT)." *American Society for Testing and Materials (ASTM) Nuclear Energy (I)*. ASTM Standard No. C1285-94. Vol. 12.01. pp. 1–18. 1995.

Manaktala, H. 03/01/1993. "Characteristics of Spent Nuclear Fuel and Cladding Relevant to High-Level Waste Source Term." CNWRA 93-006. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1993.

20.05702.013.295, Q199305110010, ML040200340

Manaktala, H.K. 09/01/1992. "An Assessment of Borosilicate Glass as a High-Level Waste Form." CNWRA 92-017. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1992.

20.03702.232, Q199209150002, ML033650021

Manaktala, H.K. 08/28/1992. "Leaching of Borosilicate Glass Using Draft ASTM Procedure for High-Level Waste." CNWRA 92-018. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1992.
20.03702.232, Q199209100003, ML033640056

Mohanty, S., R. Codell, T. Ahn, and G.A. Cragnolino. "An Approach to the Assessment of High-level Radioactive Waste Containment-II: Radionuclide Release from an Engineered Barrier System." *Nuclear Engineering and Design Journal*. Vol. 201 pp. 307–325. 2000.

Murphy, W.M. 05/07/1991. "Calculated Solubilities of Radioelements at 25 C in J-13 Well Water." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1991.
20.03702.065, Q199107160023, ML040210573

Murphy, W.M. and R.T. Pabalan. 06/28/1995. "Review of Empirical Thermodynamic Data for Uranyl Silicate Minerals and Experimental Plan." CNWRA 95-014. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1995.
20.05704.153.501, Q199507240003, ML040210708

Experimental and natural analog data indicate that uranyl silicate minerals are likely to form as oxidation products of spent nuclear fuel in a high-level radioactive waste repository at Yucca Mountain, Nevada. Although these minerals would control releases of uranium and possibly much of the radionuclide inventory of high-level waste, the fundamental thermodynamic properties of these minerals required for predictive modeling of their behavior are poorly known. This report describes an experimental plan that was developed to determine thermodynamic properties of uranyl silicate minerals through original experimentation and data interpretation. The plan involved the study of uranophane, soddyite, and schoepite solubilities at 25, 60, and 900 °C. This document also described experiments designed to determine the importance of coprecipitation reactions as mechanisms for limiting the release and transport of actinides such as plutonium and neptunium.

Murphy, W.M. and E.C. Percy. 09/01/1991. "Source-Term Constraints for the Proposed Repository at Yucca Mountain, Nevada, Derived from the Natural Analog at Peña Blanca, Mexico." (Manuscript prepared for unspecified journal)
20.03704.063, Q199110140001

Murphy, W.M. and E.L. Shock. "Environmental Aqueous Geochemistry of Actinides." *Uranium: Mineralogy, Geochemistry, and the Environment, Reviews in Mineralogy*. P.C. Burns and R. Finch, eds. Washington, DC: Mineralogical Society of America. Vol. 38. pp. 221–253 1999.

Pan, Y.-M., V. Jain, and O. Pensado-Rodriguez. "Degradation of High-Level Waste Glass Under Simulated Repository Conditions." *Journal of Non-Crystalline Solids*. Vol. 319, No. 1–2. pp. 74-88. May 2003.

Percy, E.C., W.M. Murphy, and P.C. Goodell. 05/23/1990. "Element Mobility in Uranium Deposits of the Sierra Peña Blanca as a Natural Analog of Radionuclide Migration in a High-Level Nuclear Waste Repository." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1990.
20.03704.062, Q199107170009, ML062430425

This manuscript was prepared for the El Paso Geological Society.

Pearcy, E.C, J.D. Prikryl, W.M. Murphy, and B.W. Leslie. 05/25/1993. "Alteration of Uraninite From the Nopal I Deposit, Peña Blanca District, Chihuahua, Mexico, Compared to Degradation of Spent Nuclear Fuel in the Proposed U.S. High-Level Nuclear Waste Repository at Yucca Mountain, Nevada." *Applied Geochemistry*. Vol. 9. pp. 713–732. 1994.

Pearcy, E.C., J.D. Prikryl, W.M. Murphy, and B.W. Leslie. 06/01/1993. "Uranium Mineralogy of the Nopal I Natural Analog Site, Chihuahua, Mexico." CNWRA 93-012. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1993.
20.05704.065, Q199307080003, ML033650119

Pickett, D.A. 12/01/2005. "Effects of Spent Nuclear Fuel Uranyl Alteration Phases on Radionuclide Dissolved Concentration Limits." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 2005.
20.06002.01.222.520, Q200512010005, ML053480220

Prikryl, J.D. "Uranophane Dissolution and Growth in CaCl₂-SiO₂(aq) Test Solutions." *Geochimica et Cosmochimica Acta*. Vol. 72. Pp. 4,508–4,520. 2008.
ML070800453

This paper examines the dissolution and growth of uranophane [Ca(UO₂)₂(SiO₃OH)₂ · 5H₂O] in Ca- and Si-rich test solutions. Uranium-bearing experimental solutions undersaturated and supersaturated with uranophane were reacted with synthetic uranophane and analyzed periodically over a 10 week period. Interpretation of aqueous solution data permitted extraction of a solubility constant for the uranophane dissolution reaction and a standard state Gibbs free energy of formation for uranophane.

Yang, L., O. Povetko, and S. Hsiung. 07/24/2003. "Predecisional for Official Use Only: Characteristics of Fuels to be Stored at the Proposed Idaho Spent Fuel Facility: Final Report." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2003.
20.06002.02.031.340, Q200307280001

15 FLOW AND TRANSPORT

Radionuclide transport is affected by many mechanisms, including sorption and matrix diffusion. Those topics are included in this section, as are hydrogeological models of isothermal groundwater flow in unsaturated and saturated rocks.

Ababou, R. 08/01/1991. NUREG/CR-5743, "Approaches to Large Scale Unsaturated Flow in Heterogeneous Stratified, and Fractured Geologic Media." Washington, DC: U.S. Nuclear Regulatory Commission. 1991.
20.03704.051, Q199107160004

This report develops a broad review and assessment of quantitative modeling approaches and data requirements for large-scale subsurface flow in a radioactive waste geologic repository. The data review includes discussions of controlled field experiments, existing contamination sites, and site specific hydrogeologic conditions at Yucca Mountain. Local-scale constitutive models for the unsaturated hydrodynamic properties of geologic media are analyzed, with particular emphasis on the effect of structural characteristics of the medium. The report further reviews and analyzes large-scale hydrogeologic spatial variability from aquifer data, unsaturated soil data, and fracture network data gathered from the literature. Finally, various modeling strategies toward large-scale flow simulations are assessed, including direct high-resolution simulation, and coarse-scale simulation based on auxiliary hydrodynamic models such as single equivalent continuum and dual-porosity continuum.

Ahola, M. and B. Sagar. 01/10/1992. "Regional Groundwater Modeling of the Saturated Zone in the Vicinity of Yucca Mountain, Nevada, Iterative Performance Assessment—Phase II." CNWRA 92-001. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1992.
20.03702.065, Q199201210006, ML040630369

As one of the auxiliary analyses in this iterative performance assessment, it was decided to simulate the flow field in the saturated unconfined region that contains Yucca Mountain. The specific objective of this analysis is to study the fluctuations in the water table in response to postulated changes in recharge rates and other modifications in geohydrologic structures.

Armstrong, A., D.A. Farrell, S.L. Painter, and D.R. Turner. "Review of the Saturated Zone Flow and Transport Models Used to Support the Viability Assessment of the Proposed High-Level Waste Repository at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 1999.

Baca, R.G., G.W. Wittmeyer, and R.W. Rice. 09/27/1996. "Analysis of Contaminant Dilution in Groundwater." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1996.
20.05708.771, Q199612160001, ML040230658

In this scoping analysis, large-scale groundwater flow and transport models were used to study dilution characteristics of the proposed repository site for two basic purposes: (i) to gain insight into site specific factors that may affect groundwater mixing and attendant dilution of dissolved radionuclides at the YM site; and (ii) to determine if there are any methodology issues that may impact implementation of a dose or risk-based standard as proposed by the National Academy of Sciences.

Bagtzoglou, A.C. and M. Muller. 06/01/1994. "Stochastic Analysis of Large-Scale Unsaturated Flow and Transport in Layered, Heterogeneous Media." CNWRA 94-012. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1994. 20.05704.053, Q199407050005, ML040160540

Bagtzoglou, A.C., R. Ababou, and B. Sagar. 02/14/1992. "Effects of Layering, Dipping Angle, and Faulting on Two-Dimensional Variably Saturated Flow, Iterative Performance Assessment—Phase II." CNWRA 92-004. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1992. 20.03702.065, Q199202210001, ML033640017

This report documents results of unsaturated flow simulations undertaken as an auxiliary analysis for the Iterative Performance Assessment (IPA) Phase 2 Project. The primary objective of the simulations is to study the effect on flow of common geological features, such as nonhorizontal stratification and vertical or near-vertical fault zones intersecting the strata, in a two-dimensional or thin "slice" domain.

Bagtzoglou, A.C., S. Mohanty, A. Nedungadi, T.-C. Jim Yeh, and R. Ababou. 03/24/1994. "Effective Hydraulic Property Calculations for Unsaturated, Fractured Rock with Semi-Analytical and Direct Numerical Techniques: Review and Applications." CNWRA 94-007. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 1994. 20.05704.056.094.003, Q199403310005, ML033630442

Basagaoglu, H. 06/05/2008. "Status of Colloid Release Evaluations. Final Report." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2008. 20.14002.01.083.840, Q200806050004, ML081890318

This report summarizes the current CNWRA understanding of the DOE abstraction for colloid-facilitated radionuclide transport in the wastefrom and engineered barrier systems. The report focuses on (i) type, mass concentrations, and stability of colloids; (ii) underlying assumptions of the abstraction and the relevant features, events, and processes; and (iii) importance of irreversible and reversible colloid types to radionuclide transport.

Basagaoglu, H., S. Succi, C. Manepally, R. Fedors, and D.Y. Wyrick. "Sensitivity of the Active Fracture Parameter to Fracture Network Orientation and Injection Scenarios." *Hydrogeology Journal*. Vol. 17. pp. 1,347–1,358. 2009.

Bertetti, F.P. "Laboratory and Modeling Studies of Neptunium Uptake on Calcite." CNWRA 2002-04. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2002. Q200207050001, 06/26/2002, 20.01402.871.210

This report summarized laboratory batch sorption experiments to evaluate neptunium sorption onto calcite. Results indicated that calcite was an effective sorber of neptunium. The results were modeled using a combination of ion exchange and surface complexation models.

Bertetti, F.P. "Laboratory Experiments of Neptunium Uptake on Calcite." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2001. Q200107030001, 06/27/2001, 20.01402.871.210

Bertetti, F.P., R.T. Pabalan, D.R. Turner, and M.G. Almendarez. "Studies of Neptunium(V) Sorption Onto Montmorillonite, Clinoptilolite, Quartz, and α -alumina." Chapter 4. E. Jenne, ed. San Diego, California: *Adsorption of Metals by Geomedia*. Academic Press. pp. 131–148. 1998.

Bertetti, F.P. and B. Werling. 09/22/2005. "Predecisional for Official Use Only: Sorption of Neptunium-237 on Alluvium Collected from Fortymile Wash, Nye County, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2005. 20.06002.01.242.520, Q200509220006

This report provides the status and a brief summary of CNWRA experiments conducted to evaluate Np-237 sorption on alluvium collected from Fortymile Wash. The report includes a comparison of Np-237 sorption on alluvium and important single mineral phases, (e.g., montmorillonite) to the results of previous sorption experiments.

Bertetti, P., R.V. Klar, and M.M. Vaught. 09/26/2006. "Colloid-Facilitated Transport of Radionuclides in Natural Groundwater Systems—Literature Review." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2006.

20.06002.01.242.620, Q200609260003

This report discusses transport-related issues such as colloid stability, colloid retention, sorption of radionuclides onto colloids, and colloid deposition and mobilization. Based on a review of the collected literature, several topics are identified as potential areas of detailed work to address uncertainties in the Yucca Mountain performance assessment abstractions of colloid transport.

Bertetti, P., R. Pabalan, D. Pickett, and D. Turner. 05/26/2011. "Radionuclide Sorption Technical Assistance Activities at the Center for Nuclear Waste Regulatory Analyses." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2011. 20.14002.01.441.150, Q201105270001, ML111510235

This report provides a summary of experimental, modeling, and performance assessment activities undertaken at CNWRA since the initial sorption projects in the late 1980s.

Bertetti, P., J. Prikryl, and B. Werling. 09/23/2004. "Development of Updated Total-System Performance Assessment (TPA) Parameter Distributions for Radionuclide Transport in the Saturated Zone." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2004.

20.06002.01.141.420, Q200410010007

This report updates the TPA code probability distribution for parameters associated with the retardation processes in the saturated alluvium based on an examination of water chemistry and sediment samples from the Yucca Mountain vicinity.

Browning, L.B. and W.M. Murphy. "Reactive Transport Modeling in the Geosciences." *Computers and Geosciences*. Vol. 29, No. 3. p. 245. April 2003.

This short paper is a guest editorial to introduce a special issue of the journal.

Browning, L.B., W.M. Murphy, C. Manepally, and R.W. Fedors. "Reactive Transport Model for the Ambient Unsaturated Hydrogeochemical System at Yucca Mountain, Nevada." *Computers and Geosciences*. Vol. 29, No. 3. pp. 247–263. April 2003.

The primary focus of this paper is to present a calibrated reactive transport model for the ambient system at YM, as developed from petrologic observations and thermodynamic and kinetic interpretations of pore water chemistry. The model predictions permitted evaluations of origins of dissolved silica in YM groundwater and hydrogeochemical controls on fracture and matrix groundwater compositions.

Colton, S., A. Sun, J.A. Stamatakos, and D. Sims. 07/05/2007. "Three-Dimensional Hydrogeologic Model of the Amargosa Desert, Version 2.0." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2007.
20.06002.01.272.621, Q200707060003, ML071900243

This report documents major updates and improvements made in Version 2.0 of the model. Version 1.0 of the model was developed by CNWRA as a conceptual framework for analysis of groundwater flow in the vicinity of Yucca Mountain, Nevada. Although the model was originally (Version 1.0) identified as Three-Dimensional Structural Model of the Amargosa Desert, the title was revised in Version 2.0 because the model was developed for use in hydrogeologic process modeling. It is more accurately described as a hydrogeologic framework model because the model layers are hydrogeologic units, not structural units. Version 2.0 incorporates newly published data and supports the independent review of the DOE site-scale, saturated zone flow model.

Contardi, J.S., D.R. Turner, and T.M. Ahn. "Modeling Colloid Transport for Performance Assessment." *Journal of Contaminant Hydrology*. Vol. 47. pp. 323–333. 2001.

Cvetkovic, V., S.L. Painter, D.R. Turner, D.A. Pickett, and F.P. Bertetti. "Parameter and Model Sensitivities for Colloid-Facilitated Transport on the Field Scale." *Water Resources Research*. Vol. 40, No. 6. June 2004. W06504, doi: 10.1029/2004WR003048.

Farrell, D.A., V. Rankin, and A. Buseman-Williams. 10/31/2007. "Development and Application of Models to Simulate Saturated Zone Transport Under a Wetter Climate at Yucca Mountain." Final. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2007.
20.06002.01.282.631, Q200711010001, ML073480160

Farrell, D.A., A. Armstrong, J.R. Winterle, D.R. Turner, D.A. Ferrill, J.A. Stamatakos, N.M. Coleman, M.B. Gray, and S.K. Sandberg. 07/08/1999. "Structural Controls on Groundwater Flow in the Yucca Mountain Region." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 1999.
20.01402.861.960, Q199907130002

Farrell, D.A., V. Rankin, and A. Buseman-Williams. 12/07/2005. "Final Development and Application of a Model to Simulate Saturated Zone Transport From the Location of the Proposed Repository Footprint at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2005.
20.06002.01.282.531, Q200512080001, ML053480229

Fedors, R.W., J.R. Winterle, W.A. Illman, C.L. Dinwiddie, and D.L. Hughson. "Unsaturated Zone Flow at Yucca Mountain, Nevada: Effects of Fracture Heterogeneity and Flow in the Nonwelded Paintbrush Tuff Unit." San Antonio, Texas: CNWRA. April 2002.
20.01402.861.200, Q200204190005, ML022460157

This report evaluates several key topics in unsaturated zone flow, including the potential development of preferential flow paths and the potential for lateral flow. The authors review recent DOE unsaturated zone flow models and present independent results from CNWRA modeling and field studies, particularly with respect to limited effects of lateral flow,

Ferrill, D.A., J.R. Winterle, G.W. Wittmeyer, D.W. Sims, S. Colton, A. Armstrong, and A.P. Morris. "Stressed Rock Strains Groundwater at Yucca Mountain, Nevada." *GSA Today*. Vol. 9, No. 5. pp. 1–8. 1999.

Greathouse, J.A., G. Bemis, and R.T. Pabalan. “Molecular Dynamics Simulation of the Uranyl Ion Near Quartz Surfaces.” *Water-Rock Interaction*. R. Cidu, editor. Lisse, The Netherlands: A.A. Balkema Publishers. pp. 173–176. 2001.

The effectiveness of sorption processes as a mechanism to retard radionuclide migration from nuclear waste repositories depends on the physicochemical characteristics of mineral sorbents and the chemistry of radionuclide-bearing groundwater. This paper describes the use of molecular simulation techniques to study the structure and dynamics of an aqueous uranium (VI) species, the uranyl ion, near a quartz crystallographic surface.

Greathouse, J.A., R.J. O'Brien, G. Bemis, and R.T. Pabalan. “Molecular Dynamics Study of Aqueous Uranyl Interactions with Quartz (010).” *Journal of Physical Chemistry*. Vol. B 106. pp. 1,646-1,655. 2002.

In this study, molecular dynamics simulations were used to study the structure and dynamics of the uranyl ion and its aquo, hydroxy, and carbonato complexes in bulk water and near the hydrated quartz (010) crystallographic surface.

Green, R.T., A.C. Bagtzoglou, G.W. Wittmeyer, B. Sagar, and R.G. Baca. 10/15/1992. “Computational Analysis of Groundwater Travel Time—A Preliminary Study.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 1992. 20.03702.131, Q199210200001, ML033650083

This report identifies three uncertainties related to groundwater travel time: (i) in a variably-saturated, fractured, layered, heterogeneous medium, it may not be possible to uniquely define the fastest path of radionuclide travel; (ii) the definition of disturbed zone is not precise; and (iii) it is not clear how much, if any, mass of water is to be associated with the flow tube used in computing the travel time. The report examines the need for clarification (and possible resolution) of the technical uncertainties associated with the geologic setting performance measure.

Gureghian, A.B., Y.-T. Wu, and B. Sagar. 08/23/1991. “Sensitivity and Uncertainty Analyses Applied to One-Dimensional Transport in a Layered Fractured Rock, Part 1: Analytic Solutions and Local Sensitivities.” CNWRA 91-010. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1991. 20.03702.065, Q199109160002 ML040220140

Gureghian, A.B., Y. Wu, B. Sagar, and R.B. Codell. 09/01/1992. NUREG/CR-5917, “Sensitivity and Uncertainty Analyses Applied to One-Dimensional Transport in a Layered Fractured Rock, Volume 1: Analytic Solutions & Local Sensitivities, Iterative Performance Assessment—Phase 2.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: November 1992. 20.03702.065, Q199211190002, ML040220140

Also published as CNWRA 91-010.

Jarzemba, M.S. 09/07/1995. “An Improved Method for Modeling Sorption of Radionuclides During Liquid Phase Transport for Performance Assessments of High-Level Waste Repositories.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1995. (Manuscript prepared for *Nuclear Technology*) 20.05704.191, Q199509210002

Kapoor, V. 05/20/1994. "Water Film Flow in a Fracture in Unsaturated Porous Medium." CNWRA 94-009. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1994.
20.05704.191, Q199405310007, ML033630684

Lenhard, R. 10/12/2007. "Summary of the Matrix Diffusion Workshop." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2007.
20.06002.01.262.780, Q200710150002

This brief report summarizes a two-day workshop by NRC and CNWRA staff in July 2007 that was aimed at promoting a common understanding of the conceptualization and importance of the matrix diffusion process. The workshop examined test data, process-level models, and performance assessment abstractions for matrix diffusion and related fracture-matrix interactions.

Lichtner, P.C. 10/24/1994. "Multi-Phase Reactive Transport Theory." CNWRA 94-018. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 1994.
20.05704.191, Q199411030002, ML040160645

Manepally, C., K. Bradbury, S. Colton, C. Dinwiddie, R. Green, R. McGinnis, D. Sims, K. Smart, and G. Walter. 04/19/2007. "The Nature of Flow in the Faulted and Fractured Paintbrush Nonwelded Hydrogeologic Unit." Revised. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 2007.
20.06002.01.262.640, Q200704230001, ML071410138

Manaktala, H., D. Turner, T. Ahn, V. Colten-Bradley, and E. Bonano. 09/27/1995. "Potential Implications of Colloids on the Long-Term Performance of a High-Level Waste Repository." CNWRA 95-015. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1995.
20.05702.523.415, Q199704100016 ML040160817

McMurry, J. 10/31/2007. "Overview of Field and Laboratory Studies of Unsaturated-Zone Matrix Diffusion and Related Fracture-Matrix Interactions." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: October 2007.
20.06002.01.232.620, Q200710310002, ML073050347

This report provides an overview of current published research that describes field and laboratory studies of matrix diffusion and other examples of fracture-matrix interaction in unsaturated flow regimes, particularly in terms of pertinent DOE field experiments at Yucca Mountain. In addition to the relatively few studies that have explicitly investigated unsaturated zone matrix diffusion, the report summarizes other field and laboratory studies that have documented related unsaturated zone flow and transport processes.

McMurry, J., and F.P. Bertetti. 12/03/2007. "Selection of Sorption-Related Values for Unsaturated Zone and Saturated Zone Transport in Total-System Performance Assessment." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2007.
20.06002.01.232.520, Q200712030001, ML073370866

Mohanty, S. and S.-M. Hsiung. 06/27/2011. "An Experimental Investigation of Single Fracture Flow Behavior Under Normal and Shear Loads." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2011.
20.14002.01.441.155, Q201106270010, ML111780625, ML111780594.

Mohanty, S., A.H. Chowdhury, S.-M. Hsiung, and M.P. Ahola. 10/07/1994. "Single Fracture Flow Behavior of Apache Leap Tuff Under Normal and Shear Loads." CNWRA 94-024. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 1994. 20.05704.039, Q199410180001, ML040360547

Mohanty, S., R.T. Green, and K.A. Meyers-James. 10/30/1995. "Study of Flow in a Fracture Under Shear: Progress Report." CNWRA 96-001. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 1995. 20.05704.039.095.005, Q199602290014, ML040330888

Murphy, W.M. NUREG/CP-0040, "Technical Issues Related to Groundwater Flow and Radionuclide Transport in Unsaturated Fractured Rock." D.D. Evans and T.J. Nicholson, eds. Proceedings of Workshop V: Flow and Transport Through Unsaturated Fractured Rock-Related to High-Level Radioactive Waste Disposal. Washington, DC: U.S. Nuclear Regulatory Commission. p. 230–232. 1993.

Murphy, W.M. and D.A. Pickett, D.A. "Isotope Fractionation Effects on Radionuclide Transport in Geologic Disposal of Nuclear Waste." *Radionuclide Retention in Geologic Media*. Nuclear Energy Agency, Organisation for Economic Co-operation and Development. p. 113–118. 2002.

Murphy, W.M., E.C. Percy, R.T. Green, J.D. Prikryl, S. Mohanty, B.W. Leslie, and A. Nedungadi. "A Test of Long-Term, Predictive, Geochemical Transport Modeling at the Akrotiri Archaeological Site." *Journal of Contaminant Hydrology*. Vol. 29, Issue 3. pp. 245–279. 1998.

Murphy, W.M., E.C. Percy, R.T. Green, J.D. Prikryl, S. Mohanty, and B.W. Leslie. 05/26/1995. "A Test of Long Term, Predictive Geochemical, Transport Modeling at the Akrotiri Archaeological Site." (Manuscript prepared for an unspecified journal) 20.05704.064, Q199505310002

Or, D. and C. Dinwiddie. 06/28/2007. "Sensor and Measurement Considerations for Long-Term Hydro-Environmental Monitoring of Vadose Zone Processes." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2007. 20.06002.01.191.710, Q200706290001, ML071800385

This report describes how long-term monitoring during performance confirmation may require the advancement of hydro-environmental sensor technology. Ideally, monitoring should include measurement redundancy (multiple sensors and methods), built-in self-calibration and quality assurance measures (e.g., failure detection capabilities), staged and upgradable monitoring network design and sensor software, and the potential for capitalization on advanced enabling technologies (e.g., wireless underground communication and robotic and semi-autonomous monitoring and sensor-calibrating systems).

Or, D., T. Markus, and S. Stothoff. 07/13/2006. Revised: "Review of Vadose Zone Measurement and Monitoring Tools for Yucca Mountain Performance Confirmation Program Performance Confirmation Program." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2006. 20.06002.01.191.610, Q200607130014, ML062060514, ML062060516

This review of vadose zone monitoring methods identified shortcomings in current technological solutions, such that most presently available hydro-environmental sensors may not be suitable for long-term, deep-subsurface, fractured rock monitoring activities.

Pabalan, R.T., D.R. Turner, F.P. Bertetti, and J.D. Prikryl. "Uranium(VI) Sorption Onto Selected Mineral Surfaces: Key Geochemical Parameters." Chapter 3. E. Jenne, ed. San Diego, California: *Adsorption of Metals by Geomedia*. Academic Press. pp. 99–130. 1998.

Pabalan, R.T. "Thermodynamics of Ion-exchange Between Clinoptilolite and Aqueous Solutions of Na⁺/K⁺ and Na⁺/Ca²⁺." *Geochimica et Cosmochimica Acta*. Vol. 58, No. 21. pp. 4,573–4,590. 1994.

To provide a thermodynamic basis for understanding zeolite-water interactions in geologic systems, ion-exchange experiments were conducted between clinoptilolite, which is the predominant zeolite mineral in altered pyroclastic and volcanoclastic rocks, and aqueous mixtures of Na⁺/K⁺ and Na⁺/Ca²⁺. Isotherm points were obtained by equilibrating Na-clinoptilolite and chloride solutions having different ionic concentration ratios, but constant total normalities of 0.5, 0.05, or 0.005 N. The experimental data were interpreted using a Margules thermodynamic formulation for zeolite solid solutions, coupled with the Pitzer model for aqueous activity coefficients. The isotherm data were used to derive equilibrium constants and Gibbs free energies for the ion-exchange reactions.

Pabalan, R.T. and F.P. Bertetti. "Experimental and Modeling Study of Ion Exchange Between Aqueous Solutions and the Zeolite Mineral Clinoptilolite." *Journal of Solution Chemistry*. Vol. 28. pp. 367–393. 1999.

Ion-exchange experiments were conducted between the zeolite mineral clinoptilolite and aqueous solutions of Na⁺/Sr²⁺, K⁺/Sr²⁺, and K⁺/Ca²⁺. The isotherm data were used to derive equilibrium constants and Gibbs energies for the ion-exchange reactions and Margules parameters for the zeolite solid solution.

Pabalan, R.T. and F.P. Bertetti. "Cation-Exchange Properties of Natural Zeolites." *Reviews in Mineralogy and Geochemistry*. Vol. 45. D. Bish and D. Ming, editors. Washington, DC: The Mineralogical Society of America. pp. 453–518. 2001.

This paper summarizes information from the open literature about the cation-exchange properties of natural zeolites.

Pabalan, R.T. and W.M. Murphy. 01/01/1990. "Progress in Experimental Studies on the Thermodynamic and Ion Exchange Properties of Clinoptilolite." CNWRA 89-006. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1990. 20.03704.013, Q199112190005, ML040690193

This report provides the theoretical bases for ion exchange and phase equilibrium studies in the Geochemistry Research Program at CNWRA, reviews experimental work reported in the literature on ion exchange between aqueous solutions and clinoptilolite, and presents the results of characterization work performed on experimental materials. The report identifies important factors to be considered or constrained in conducting ion exchange studies, as well as procedures for ion exchange experiments that take these factors into account, and various other procedures relevant to the conduct of this work.

Pabalan, R.T. and D.R. Turner. “Uranium (6+) Sorption on Montmorillonite: Experimental and Surface Complexation Modeling Study.” *Aquatic Geochemistry*. Vol. 2. pp. 203–226. 1997.

This paper describes batch experiments that were conducted to determine the effects of varying pH, solid-mass to solution-volume ratio, and solution concentration on U(6+) sorption onto montmorillonite. The results show that U(6+) sorption on montmorillonite is a strong function of pH, reaching a maximum at near-neutral pH (~6 to ~6.5) and decreasing sharply towards more acidic or more alkaline conditions. The experimental results were used to develop a thermodynamic model based on a surface complexation approach to permit predictions of U(6+) sorption at differing physicochemical conditions.

Painter, S. and V. Cvetkovic. 06/23/2004. “Colloid-Facilitated Transport in the Saturated Zone: Process-Level Sensitivity Analysis.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2004.
20.06002.01.141.430, Q200406280002, ML042160183

Painter, S.L., V. Cvetkovic, D.A. Pickett, and D.R. Turner. “Significance of Kinetics for Sorption on Inorganic Colloids: Modeling and Experiment Interpretation Issues.” *Environmental Science Technology*. Vol. 36. pp. 5,369–5,375. 2002.

This paper utilized a two-site kinetic sorption model to explore and reinterpret colloid sorption data derived by DOE investigators. Modeling results and sensitivity analyses suggested that the significance of colloid associated transport was most important for slow desorption rates.

Painter, S.L., V. Cvetkovic, and D.R. Turner. “Effect of Heterogeneity on Radionuclide Transport in the Alluvial Aquifer near Yucca Mountain, Nevada.” *Groundwater*. Vol. 37, No. 3. pp. 326–338. May 2001.
Q200003020001, 02/11/2000, 20.01402.871.010

This paper included process-level analyses to quantify the effects of physical heterogeneity (hydraulic conductivity) and chemical heterogeneity (K_d) on radionuclide retardation in the alluvial aquifer near Yucca Mountain. The hydraulic conductivity, K , was modeled using a unimodal lognormal distribution with exponential spatial covariance function. The spatial variability of K_d for Np was modeled in a similar fashion, based on a saturated zone geochemistry data set collected from 238 sample locations in the vicinity of Yucca Mountain (Turner and Pabalan, 1999). Uncertainty associated with mass transport was quantified using a two-site, mobile-immobile mass transfer model formulated in the stochastic streamtube framework, and an instantaneous point source was assumed. The authors concluded that the effect of physical heterogeneity is important; however, chemical heterogeneity and the correlation between K and K_d have minimal effect. They also found that treating K_d as a spatially constant but uncertain parameter greatly overemphasizes the effect of K_d variability.

Painter, S.L., J.R. Winterle, and A. Armstrong. “Using Temperature to Test Models of Flow Near Yucca Mountain, Nevada.” *Ground Water*. Vol. 41, No. 5. pp. 657–666. 2003.

Pearcy, E.C. 05/30/1994. “Fracture Transport of Uranium at the Nopal I Natural Analog Site.” CNWRA 94-011. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1994.
20.05704.065.094.006, Q199405310006, ML033630674

Pearcy, E.C., J.D. Prikryl, and B.W. Leslie. “Uranium Transport Through Fractured Silicic Tuff and Relative Retention in Areas with Distinct Fracture Characteristics.” *Journal of Applied Geochemistry*. Vol. 10. pp. 685–704. 1995.

Pickett, D.A. and W.L. Dam. "Approach to Assessing the Potential Effects of Colloidal Radionuclide Transport on Nuclear Waste Repository Performance." *Nuclear Science and Engineering*. Vol. 151, No. 1. pp. 114–120. September 2005.

Prikryl, J.D., A. Jain, D.R. Turner, and R.T. Pabalan. "Uranium(VI) Sorption Behavior on Silicate Mineral Mixtures." *Journal of Contaminant Hydrology*. Vol. 47, Issues 2–4. pp. 241–253. February 2001.

This paper presents the results of uranium(VI) sorption experiments involving quartz and clinoptilolite conducted to evaluate the ability of surface complexation models to predict uranium(VI) sorption onto mineral mixtures based on parameters derived from single mineral experiments. Data from the sorption experiments were used in a diffuse-layer surface complexation model (DLM) to predict sorption of uranium(VI) onto clinoptilolite/quartz mixtures. The DLM reproduced many aspects of the pH-dependent sorption behavior of both quartz and clinoptilolite.

Prikryl, J.D., R.T. Pabalan, D.R. Turner, and B.W. Leslie. "Uranium Sorption on Alpha-Alumina: Effects of pH and Surface- Area/Solution-Volume Ratio." *Radiochimica Acta*. Vol. 66/67. pp. 291–296 1994.

This paper examined the effects of solution pH and the sorbent surface area on the sorption behavior of uranium(VI). The sorbent phased used in the experiments was alpha-alumina with surface areas of 2.09, 0.229, and 0.0686 m²/g, respectively. Experimental results indicated that uranium(VI) sorption on alpha-alumina occurs at near-neutral pH and increases as the sorbent-surface area/solution-volume ratio increases.

Prikryl, J.D., D.A. Pickett, W.M. Murphy, and E.C. Percy. "Migration Behavior of Naturally Occurring Radionuclides at the Nopal I Uranium Deposit." *Journal of Contaminant Hydrology*. Vol. 26. pp. 61–69 1997.

This paper presents the results of petrographic, electron microprobe, and U-series isotopic data on secondary Fe-oxides/hydroxides formed in a fracture that crosscuts the Nopal I uranium deposit. Mobilization and transport of U away from the deposit was indicated by decreasing U concentrations in fracture-filling materials and minerals with distance from the deposit and greater than unity ²³⁴U/²³⁸U activity ratios measured in fracture-filling materials.

Reeder, R.J., M. Nugent, and R.T. Pabalan. "Local Structure of Uranium (VI) Sorbed on Clinoptilolite and Montmorillonite." *Water-Rock Interaction*. R. Cidu, editor. Lisse, The Netherlands: A.A. Balkema Publishers. pp. 423–426. 2001.

In this study, X-ray absorption fine-structure (XAFS) spectroscopy was used to elucidate the structure of uranium(VI) sorbed onto the zeolite clinoptilolite and the clay montmorillonite. The solids were reacted with uranyl nitrate solutions either at pH-3.3, which favors sorption at fixed ion-exchange sites, or at pH -6.3, which favors sorption onto amphoteric surface hydroxyl sites. The results suggest that uranyl forms inner-sphere complexes with montmorillonite and clinoptilolite at near-neutral pH. At low pH, uranyl sorbs onto montmorillonite via an outer-sphere complex. Uranyl likely forms an outer-sphere complex when sorbed onto clinoptilolite at low pH, but steric limitations imposed by the zeolite structure probably cause the observed distortion of the equatorial shell.

Sagar, B. "Flow Modeling in Heterogeneous Media in the Context of Geologic Nuclear Waste Repositories." *Nuclear Science and Engineering*. Vol. 123. p. 443. 1996.

Sagar, B., A.C. Bagtzoglou, R.T. Green, and S.A. Stothoff. “Measurement and Modeling of Flow Through Unsaturated Heterogeneous Rock in the Context of Geologic Disposal of Nuclear Waste.” *Heat, Mass, and Momentum Transfer in Environmental Flows*. ASME. HTD-Vol. 321/FED-Vol. 233. pp. 271–284. 1995.

Sagar, B., A.B. Gureghian, R. Codell, and Y.-T. Wu. 10/01/1992. “Sensitivity and Uncertainty Analysis Applied to One-Dimensional Radionuclide Transport in a Layered Fractured Rock: Part 1: Analytical Solutions and Local Sensitivities, Part 2: Probabilistic Methods Based on the Limit State Approach.” (Manuscript prepared for *The Journal of Nuclear Technology*) 20.05702.065, Q199210260003, ML033170030

Stirewalt, G.L. and D.B. Henderson. 09/28/1995. “A Three-Dimensional Geological Framework Model for Yucca Mountain, Nevada, with Hydrologic Application: Report to Accompany 1995 Model Transfer to the Nuclear Regulatory Commission, Revision 1.” CNWRA 94-023. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1995. 20.05702.425, Q199601050011, ML040220357

Stirewalt, G.L., S.R. Young, and D. Brent Henderson. 09/29/1994. “A Preliminary Three-Dimensional Geological Framework Model for Yucca Mountain Nevada.” CNWRA 94-023. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1994. 20.05704.425, Q199410170002, ML040160555

This report accompanied transfer of the three-dimensional geological framework modeling software to NRC.

Sun, A.Y. 03/21/2008. “State-of-the-Art Multiscale Approaches for Flow and Transport Modeling: A Literature Review.” Final Report. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2008. 20.14002.01.131.820, Q200803240001, ML080850416, ML080850416

Sun, A.Y. and P. Bertetti. 10/26/2007. “Evaluation of the Effects of Physical and Chemical Heterogeneities on Flow and Transport in the Saturated Alluvium of Fortymile Wash, Nevada.” Final Report. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2007.

20.06002.01.272.760, Q200710260001, ML073470857

This report summarized numerical experiments conducted to quantify the effects of subgrid physical and chemical heterogeneities. Monte Carlo simulations were performed using realizations of a fine-scale block model for which the properties are generated stochastically based on a hierarchical alluvium facies model developed in previous work. The statistics of neptunium sorption parameters were derived from field data. Transport was solved in a Lagrangian framework in which the solute mass is divided into a large number of particles, which are then displaced using an efficient random walk algorithm. The results indicated that the upscaled block hydraulic conductivities have similar magnitudes as those assigned to the alluvium in site-scale models. The simulated longitudinal macrodispersivities are on the order of 10 m [32.8 ft], depending on the variance of hydraulic conductivities. The results of reactive transport modeling show that retardation introduces at most a two-fold increase in solute spread in the longitudinal direction.

Sun, A.Y., R. Ritzi, and D. Sims. “Characterization and Modeling of Spatial Variability in a Complex Alluvial Aquifer: Implications On Solute Transport.” *Water Resources Research*. Vol. 44. 2008. doi:10.1029/2007WR006119. ML071640028

This paper modeled the sedimentary architecture of the alluvium deposits in Fortymile Wash, Nevada, using a hierarchical transition probability geostatistical approach. A three-dimensional hierarchical hydrofacies model was developed through fusion of multiple geologic data types and sources. Markov chain models of transition probabilities were employed to represent complex patterns of spatial variability at each hierarchical level in a geostatistical fashion and to impose realistic constraints to such variations through conditioning on existing data. The link between the alluvium spatial variability and solute dispersion at different spatiotemporal scales was demonstrated using the stochastic-Lagrangian transport theory. The authors concluded that the longitudinal macrodispersivity can be on the order of hundreds to thousands of meters, and it may not reach its asymptotic value until after 1,000 years of travel time.

Sun, A., R. Ritzi, and D. Sims. 10/19/2006. Revised: “Characterization of Modeling of the Alluvium Beneath Fortymile Wash, Nevada.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2006. 20.06002.01.272.631, Q200610190006, ML071630488

Turner, D.T. 12/19/1991. “Effects of Variable Hydrologic Saturation on Sorption Modeling for High-Level Waste Performance Assessment: A Literature Review.” CNWRA 91-016. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 1991. 20.03704.071, Q199201030004, ML003755802

Turner, D.R. 08/01/1991. “Sorption Modeling for High-Level Waste Performance Assessment: A Literature Review.” CNWRA 91-011. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: August 1991. 20.03704.071, Q199109160004, ML040220147

Turner, D. R. 01/12/1995. “A Uniform Approach to Surface Complexation Modeling of Radionuclide Sorption.” CNWRA 95-001. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1995. 20.05704.074, Q199501180001 ML040160669

Turner, D.R. 09/01/1993. “Mechanistic Approaches to Radionuclide Sorption Modeling.” CNWRA 93-019. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1995. 20.05704.074, Q199310140033, ML040200620

Turner, D.R. and R.T. Pabalan. “Abstraction of Mechanistic Sorption Model Results for Performance Assessment Calculations at Yucca Mountain, Nevada.” *Waste Management*. Vol. 19. pp. 375–388. 1999.

Turner, D.R. and S.A. Sassman. “Approaches to Sorption Modeling for High-Level Waste Performance Assessment.” *Journal of Contaminant Hydrology*. Vol. 21. pp. 311–332. 1996.

Turner, D.R., F.P. Bertetti, and R.T. Pabalan. “Applying Surface Complexation Modeling to Radionuclide Sorption.” *Surface Complexation Modeling*. Munich, Germany: pp. 553–604. September 2006.

Turner, D.R., F.P. Bertetti, and R.T. Pabalan. “Role of Radionuclide Sorption in High-Level Waste Performance Assessment: Approaches for the Abstraction of Detailed Models.” *Geochemistry of Soil Radionuclides*. Soil Science Society of America Special Publication. Vol. 59. pp. 211–252. 2002.

Turner, D.R., R.T. Pabalan, and F.P. Bertetti. “Neptunium(V) Sorption on Montmorillonite: An Experimental and Surface Complexation Modeling Study.” *Clays and Clay Minerals*. Vol. 46. pp. 256–269. 1998.

Walter, G. 03/23/2011. Revised: “The Role of Matrix Diffusion as a Retardation and Attenuation Process at Yucca Mountain and Other Geologic Environments.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2011.
20.14002.01.441.114, Q201103230002, ML110820364

Winterle, J.R. 04/16/2003. “Evaluation of Alternative Concepts for Saturated Zone Flow: Effects of Recharge and Water Table Rise on Flow Paths and Travel Times at Yucca Mountain.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 2003.
20.06002.01.131.320, Q200304170004, ML040350576

Winterle, J. 08/25/2005. “Simulation of Spring Flows South of Yucca Mountain, Nevada, Following a Potential Future Water Table Rise.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analysis. August 2005.
20.06002.01.272.521, Q200509200002, ML052630242

Winterle, J. and L. Gergen. 07/14/2011. “Summary of Groundwater Flow Models of the Death Valley Regional Aquifer System and Yucca Mountain Area.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: July 2011.
20.14002.01.441.152, Q201107120001, ML111930420

Winterle, J.R., R.W. Fedors, D.L. Hughson, and S.A. Stothoff. 02/25/1999. “Review of the Unsaturated Zone Models Used to Support the Viability Assessment of a Repository at Yucca Mountain.” San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1999.
20.01402.861.930, Q199903030004

Wittmeyer, G.W. and D.R. Turner. 09/27/1995. “Conceptual and Mathematical Models of The Death Valley Regional Groundwater Flow System.” CNWRA 95-019. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1995.
20.05704.132, Q199601050015, ML040220379

Wu, Y.-T., A.B. Gureghian, and B. Sagar. 03/12/1992. "Sensitivity and Uncertainty Analyses Applied to One-Dimensional Transport in a Layered, Fractured Rock. Part 2: Evaluation of Limit State Approach, Iterative Performance Assessment—Phase II." CNWRA 92-002. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 1992. 20.03702.065, Q199203180005, ML040330673

Zaidan, O.F., J.A. Greathouse, and R.T. Pabalan. "Monte Carlo and Molecular Dynamics Simulation of Uranyl Adsorption on Montmorillonite Clay." *Clays and Clay Minerals*. Vol. 51. pp. 372–381. 2003.

In this study, Monte Carlo and molecular dynamics simulations were conducted to investigate the interlayer structure of a uranyl-substituted smectite clay.

16 AQUEOUS AND VOLCANIC DOSE (BIOSPHERE)

The main biosphere dose pathways of interest in Yucca Mountain studies were those resulting from radionuclides released to the surface environment from groundwater and from volcanic ash (tephra).

Benke, R. and D. Hooper. 05/11/2011. "Airborne Particle Resuspension and Inhalation Radiological Dose Estimation Following Volcanic Events." Draft. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 2011.
20.14002.01.441.142, Q201105110002, ML111320257

For extrusive volcanism at a geologic repository, the inhalation of resuspended radionuclides is expected to dominate other potential exposure pathways in long-term performance assessments. The purpose of this knowledge capture report is to describe, in a single document, the concepts and factors that influence the radiological dose calculation for the inhalation of resuspended particles contaminated with high-level waste.

Benke, R.R., B.E. Hill, and D.M. Hooper. 01/31/2006. "Fluvial Redistribution of Contaminated Tephra: Description of an Abstracted Model". 2006 International High Level Radioactive Waste Management Conference. Las Vegas, Nevada: April 30–May 4. 2006.
20.06002.01.362.602, Q200601310004

An abstracted model was developed for a total-system performance assessment model to gain fundamental insights into tephra redistribution processes and risk to the reasonably maximally exposed individual. An abstracted sediment yield approach was used to model the long-term fluvial redistribution of potential tephra deposits in Fortymile Wash, in southern Nevada. Results of this model for fluvial redistribution are used with other inputs to estimate airborne particle concentrations, which are important factors for calculating inhalation dose to the reasonably maximally exposed individual.

Benke, R.R., D.M. Hooper, J.S. Durham, D.R. Bannon, K.L. Compton, M. Necsoiu, and R.N. McGinnis. "Measurement of Airborne Particle Concentrations Near the Sunset Crater Volcano, Arizona." *Health Physics*. Vol. 96, Issue 2. pp. 97–117. 2009.

Airborne particle mass concentrations were measured using a personal sampler under a variety of surface-disturbing activities within different depositional environments at both volcanic and nonvolcanic sites near the Sunset Crater volcano in northern Arizona. The level of surface-disturbing activity was found to be the most influential factor affecting the measured airborne particle concentrations, which increased over three orders of magnitude relative to ambient conditions. Overall, the ground surface material type, depositional environment, and percentage of near-surface mass that is resuspendible were not as influential as other factors.

Benke, R., B. Hill, D. Hooper, and R. Nes. 03/30/2006. "Draft Description of Abstracted Models for Tephra Redistribution and Resuspension in the Total-System Performance Assessment (TPA) Version 5.1 Beta Code." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2006.
20.06002.01.362.610, Q200603310001

Two separate approaches are available in the TPA Version 5.1 beta code for modeling the airborne transport of tephra, tephra redistribution and resuspension, and inhalation of airborne particulates in the biosphere following a potential volcanic eruption. This report describes the two abstracted models for tephra redistribution and resuspension for estimating inhalation doses to the reasonably maximally exposed individual. Having two separate approaches is intended to provide more realistic estimates of volcanic eruption consequences by accounting for (i) wind-field variations along the height of the eruption column, which affect the initial deposition of tephra, and (ii) first-order processes affecting fluvial and eolian redistribution of tephra.

Hooper, D.M. 10/17/2005. "Modeling the Long -Term Fluvial Redistribution of Tephra in Fortymile Wash, Yucca Mountain, Nevada." Revised. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2005.
20.06002.01.362.530, Q200510180001, ML052910334

This report communicates the current understanding of tephra redistribution analyses independently developed by Center for Nuclear Waste Regulatory Analyses (CNWRA) staff. The report describes a sediment budget approach to analyze the potential posteruption redistribution of tephra in the Fortymile Wash drainage system at Yucca Mountain, Nevada. Fortymile Wash is an ephemeral stream; hydrologic data are minimal, and sediment transport data are lacking. Rates of erosion in arid regions are not well-constrained, but a suitable range of values can be entered into a sediment budget to demonstrate the quantitative or mass flux relationship between such components as sediment yield, discharge to the depositional fan, balance of remaining tephra, dilution by mixing with ambient sediment, and associated changes in transient sediment storage.

Hooper, D.M. 03/17/2004. "First-Order Conceptual Model for Fluvial Remobilization of Tephra Along Fortymile Wash, Yucca Mountain, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2004.
20.06002.01.051.465, Q200403220009, ML041320668

This report described a first-order conceptual model that focuses on a simplified mass-balance approach to analyze the remobilization or redistribution of tephra in the Fortymile Wash drainage system at Yucca Mountain, Nevada. The methodology is first tested by applying it to the tephra deposit from the 1943–1952 eruption of Parícutin volcano (Mexico), the primary analog for this study. Erosional processes are mostly simplified in this first-order approach, but model refinements are incorporated. Results for the Fortymile Wash watershed are dependent upon the erosion rate as well as the area, thickness, and volume of dispersed tephra within the watershed.

Hooper, D.M. and R.R. Benke. 01/31/2006. "Fluvial Redistribution of Contaminated Tephra: Process Level Modeling and Parameter Estimation." Proceedings, 2006 International High Level Radioactive Waste Management Conference. Las Vegas, Nevada. April 30–May 4. 2006.

20.06002.01.362, Q200601310002,

This paper describes how the modeling approach supports the abstracted fluvial redistribution model for the Total-system Performance Assessment code through the determination of values for the five local input parameters of the abstracted model, as developed for expected dryland conditions in the Fortymile Wash drainage system following a potential volcanic eruption.

Hooper, D.M., N.J. Franklin, B.L. Winfrey, and B.E. Hill. 03/30/2006. "Realistic Modeling of Volcanic Eruption Plumes with the Tephra Code." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2006.

20.06002.01.312.620, Q200603310006

The objective of this report is to present the progress of modeling volcanic eruption plumes with the TEPHRA code. TEPHRA is an improvement over the previous ASHPLUME model and allows the user to calculate expected tephra (ash) and uranium (fuel) accumulation as areal mass density (variable thickness over a two-dimensional grid) by sedimentation out of the volcanic plume. The code calculates tephra accumulation using measured eruption data as input parameters and incorporates the effects of realistic, stratified wind fields on tephra dispersal. Illustrative applications of the TEPHRA code, focusing on Yucca Mountain consequences, are presented in this report.

Hooper, D.M., M. Necsoiu, and R.R. Benke. 02/27/2008. "Final Status Report of Field Observations From Sunset Crater, Arizona." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 2008.

20.06002.01.312.640, Q200802270003, ML080720615, ML080720613

This report summarizes CNWRA field activities conducted at Sunset Crater, Arizona. Because Sunset Crater volcano is a relatively young basaltic cinder cone that now exists in the semi-arid climate of Northern Arizona, it is used as an analog for future basaltic volcanism at Yucca Mountain. The work at Sunset Crater thus provides staff with important constraints on the surficial geologic processes that control redistribution of ash and tephra following an eruption.

Jarzemba, M.S. 09/28/1995. "Stochastic Radionuclide Distribution After a Basaltic Eruption for Performance Assessment of Yucca Mountain." *Nuclear Technology*. Vol. 118. pp. 132–141. 1995.

The paper describes a stochastic modeling approach for simulating the airborne release of radioactive particulates associated with a volcanism scenario. The modeling approach considers such factors as the eruption energetics, eruption duration, wind velocity, and particle properties to compute the activity areal density of particles as a function of spatial location. Various components of the model are based on empirical relationships and data report in the volcanology literature. Illustrative applications of the stochastic model are presented for the cases of single and multiple event eruptions.

Jarzemba, M.S. and P.A. LaPlante. 05/14/1996. "Preliminary Calculations of Expected Dose from Extrusive Volcanic Events at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1996.

20.05708.771.610, Q199606140002 ML040220041

This report, which was prepared in consideration of the revision of the EPA standard, describes a set of scoping calculations: (i) volcanism scenario, (ii) hazards comparison, and (iii) plume dilution.

Jarzemba, M. and J. Weldy. 05/08/1997. "A Summary of Information Relevant to Defining Critical Groups and Reference Biospheres." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1997.

20.05708.771.730, Q199710290001

The information in this report was prepared as an attachment to a Commission paper written by the NRC staff. The report is a summary of information to facilitate the selection of appropriate critical groups and reference biospheres for use in dose/risk assessments of the proposed repository. The report identifies climate (current and pluvial), depth to groundwater, and land slope as primary factors that could be used in defining critical group locations and reference biospheres.

LaPlante, P. 08/29/2006. Revised: "Preliminary Description of Abstracted Models for Biosphere Pathways and Dose in the Total-System Performance Assessment (TPA) Version 5.1 Beta Code." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses.

August 2006.

20.06002.01.372.630, Q200608290007, ML062420097

LaPlante, P.A. and K. Poor. 07/25/1997. "Information and Analyses to Support Selection of Critical Groups and Reference Biospheres for Yucca Mountain Exposure Scenarios."

CNWRA 97-009. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses.

August 1997.

20.05708.761, Q199709240001, ML040200056

The purpose of this study was to enhance the NRC capability to estimate radiologic risks from HLW disposal at YM. This report provides updated dose conversion factors, summarizes and documents the site-specific characteristics and parameters used in modeling the environmental pathways, and presents the results of a sensitivity analysis to identify the model parameters that have the greatest effect on the dose calculations.

LaPlante, P.A., M.S. Jarzemba, R.B. Neel, and C.A. McKenney. 06/10/1996. "An Initial Approach for Defining Potential Site-Specific Reference Biospheres and Critical Groups for Exposure Scenarios. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1996.

20.05708.771.620, Q199607160008 ML040230619

LaPlante, P.A., S.J. Maheras, and M.S. Jarzemba. 10/02/1995. "Initial Analysis of Selected Site-Specific Dose Assessment Parameters and Exposure Pathways Applicable to a Groundwater Release Scenario at Yucca Mountain." CNWRA 95-018. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1995.

20.05702.723.602, Q199602290017, ML040330891

Simpkins, A.A. 09/05/2007. Revised: "Summary of Near-Field Methods for Atmospheric Release Modeling." San Antonio, Texas: Center For Nuclear Waste Regulatory Analyses. June 2007.

20.06002.01.332.790, Q200709070003

This report summarizes existing methods used for near-field atmospheric release modeling, including building wake effects, and gives example calculations of various models.

17 SPECIAL PROJECTS

17.1 Aluminum-Based Fuel Characteristics

Brossia, S.C. 09/08/1999. "Review of the U.S. Department of Energy Evaluation of the Disposability of Aluminum-Based Spent Nuclear Fuel Final Report." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1999.
20.01407.001.930, Q200310010002, ML040350730

Brossia, C.S. and G.D. Gute. 08/25/2000. "Review of the U.S. Department of Energy Evaluation of Thermal Performance Analysis and Dissolution Rates of Melt and Dilute Aluminum-Based Nuclear Spent Nuclear Fuel." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2000.
20.01407.001.940, Q200008290004 ML033640495

Sridhar, N., A. Chowdhury, L. Deere, V. Jain, D. Pickett, and J. Weldy. 05/29/1998. "Review of the Technical Issues Related to Interim Storage and Disposal of Aluminum Based Spent Nuclear Fuel." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1998.
20.01407.001.810, Q199806050001

Weldy, J., D. Pickett, N. Sridhar, and S. Brossia. 03/29/1999. "Evaluation of the U.S. Department of Energy Aluminum-Based Fuel Criticality Analyses." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1999.
20.01407.001.905, Q200309300040, ML040350722, ML040350722

17.2 West Valley

Cragnoilino, G.A. 04/29/1993. "Review of Corrosion Aspects of High-Level Waste Storage Tanks at West Valley." CNWRA 93-008. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1993.
20.05706.004, Q199305030002, ML033630389

Cragnoilino, G.A. 09/23/1994. "Review of the West Valley THOREX Waste Neutralization Process." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1994.
20.05706.003.100, Q199410140004

Pomerening, D.J., C. Tschoepe, and P.K. Nair. 04/29/1993. "Seismic/Tornado Analysis Review for the Vitrification Facility at West Valley." CNWRA 93-007. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1993.
20.05706.003, Q199305030003, ML040200332

Tschoepe, E. 01/17/1995. "Report on Vitrification Operations Readiness Review—Waste Solidification Systems." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1995.
20.05706.001.600, Q199705310005, ML040200115

Tschoepe, E., P.C. Mackin, D.J. Pomerening, D.J. Stevens, D.E. Ketchum, H. Manaktala, H. Karimi, P.J. Mayo, and D. Williams. 08/27/1996. "Review of Draft Environmental Impact Statement for Completion of the West Valley Demonstration Project and Closure or Long-Term Management of Facilities at the Western New York Nuclear Service Center." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1996.
20.05706.003.605, Q199610140002, ML040230632

Tschoepe, E., D.J. Pomerening, and P.K. Nair. 04/14/1995. "Draft Safety Evaluation Report on the Vitrification Process and High-Level Waste Interim Storage, Review of WVNS-SAR-003." Rev. 2, Draft D. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1995.
20.05706.002, Q199506070001, ML040220304

17.3 Hanford Tank Waste Project

Cragolino, G.A., M.S. Jarzempa, J. Ledbetter-Ferrill, W.M. Murphy, R.T. Pabalan, D.A. Pickett, J.D. Prikryl, and N. Sridhar. 07/24/1997. CNWRA 97-001, "Hanford Tank Waste Remediation System Familiarization Report." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. Revised July 1997.
20.05709.101.730, Q199709030018, ML040200047

Daruwalla, D.D., J. Weldy, and R.F. Vance. 06/28/2000. "Classification of Process Systems Used in the Tank Waste Remediation System-Privatization Design." Letter Report. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2000.
20.01403.104.001, Q200006290002

Deere, L. and P. LaPlante. 02/03/1999. "(1) Viability Assessment Review: Location and Lifestyle of Critical Group KESA and (2) Dilution of Radionuclides in Soil KESA." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1999.
20.01403.771.910, Q199905050018, ML033640472

Frank, M. 09/16/1998. "A Survey of Risk Assessment Methods from the Nuclear, Chemical, and Aerospace Industries for Applicability to the Privatized Vitrification of Hanford Tank Waste." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1998.
20.01403.103.810, Q199809090002, ML033640266

Jain, V. 04/24/1998. "Survey of Solidification Process Technologies." CNWRA 98-005. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1998.
20.01403.102.810, Q199805050002, ML033640242

Jain, V. 01/25/1999. "Technical Manual for TWRS-Type Facilities (Final)." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1999.
20.01403.202.930, Q199902010004, ML033640279

Jain, V. 10/16/2000. "Chemical Durability of Nuclear Waste Glasses—A Review." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2000.
(Manuscript prepared for *Journal of Materials Science & Technology*)
20.01403.106, Q200310010001, ML061310303

Jain, V. 03/23/1999. "Technical Manual for TWRS-Type Facilities." Rev. 1. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1999.
20.01403.202.930, Q200310020001, ML040350737

Jain, V. 05/29/1997. "Survey of Solidification Process Technologies—Interim Report." CNWRA 97-005. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1997—August 1997.
20.05709.102.710, Q199710300016, ML040780182

Jain, V. and Y.-M. Pan. 09/01/2000. "Glass Melt Chemistry and Product Qualification." CNWRA 2000-05. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2000. (In storage—Building 139)
20.01403.106.030, Q200012270001 ML033640523

Moghissi, O., Y.-M. Pan, D.D. Daruwalla, and J. Weldy. 07/14/2000. "Ultrafiltration in Low-Activity and High-Level Waste Processes: A Critical Review." Letter Report. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2000.
20.01403.102.002, Q200007170002

Murphy, W.M. "Problems in the Study of Water-Rock Interactions Related to Geologic Disposal of Nuclear Waste at Hanford, Washington, Yucca Mountain, Nevada, and Vienne, France." *Bulletin de Liaison de la Societe Francaise de Mineralogie et de Cristallographie*. Vol. 11. pp. 94–95. 1999.

Pabalan, R.T. 06/23/1997. "High Level Waste Chemistry Manual, Preliminary Report." CNWRA 97-008. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1997.
20.05708.106.705, Q199709030017

Pabalan, R.T., V. Jain, R.F. Vance, S. Ioannidis, D.A. Pickett, C.S. Brazel, J.T. Persyn, E. Jennings Taylor, and M.E. Innman. 12/14/2000. NUREG/CR-6714, "Hanford Tank Waste Remediation System Pretreatment Chemistry and Technology." September 2001.
20.01403.106.020, Q200012180003, ML012690529

Pabalan, R., M. Jarzempa, T. Abrajano, D. Pickett, D. Moulton, N. Sridhar, J. Weldy, C. Brazel, J. Persyn, B. Li, J.-P. Hsu, and J. Erwin. 02/24/1999. NUREG/CR-5751, "Hanford Tank Waste Remediation System High-Level Waste Chemistry Manual." Rev. 2. May 1999.
20.01403.106.930, Q199903010001, ML033640258
Also published as CNWRA 97-008.

Pickett, D. and R. Fedors. 03/05/1999. "Review of the Hanford Immobilized Low-Activity Tank Waste Performance Assessment." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 1999.
20.01403.201.930, Q199903090002, ML033640464

Sridhar, N., R.T. Pabalan, M.S. Jarzempa, and W.M. Murphy. 12/17/1996. "Hanford Tank Waste Remediation System Familiarization Report." CNWRA 97-001. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 1996.
20.05709.101.710, Q199705310007, ML040200118, ML040200138, ML040200141
ML040200047

Yang, L. and R.T. Pabalan. 02/24/2000. "PRETREAT: A Spreadsheet-Based Mass-Balance Model for Hanford Tank Waste Remediation System (TWRS) Pretreatment Processes."
San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2000.
20.01403.106.010, Q200008290005, ML033640503

APPENDIX
CNWRA-Series Reports: 1988–2008

APPENDIX

CNWRA-Series Reports: 1988–2008

The first bound and numbered CNWRA-series reports were issued in 1988, soon after the Center for Nuclear Waste Regulatory Analyses (CNWRA[®]) was established. With few exceptions, the CNWRA reports between 1988 and 2008 dealt with high-level nuclear waste management topics, with a particular focus on technical and programmatic issues for evaluating the safety of a proposed geologic repository at Yucca Mountain, Nevada. For completeness, all numbered CNWRA reports that were published between 1988 and 2008 (including technical, planning, and quality assurance topics) are listed here.

When the U.S. Department of Energy submitted a license application for a geologic repository at Yucca Mountain in mid-2008, CNWRA technical activities transitioned from pre-licensing to license review support for the U.S. Nuclear Regulatory Commission. No CNWRA-series reports specific to the Yucca Mountain activities were issued after 2008.

2008

CNWRA 2008-001

Infiltration Tabulator for Yucca Mountain: Bases and Confirmation

Stothoff, S.

August 2008

2007

CNWRA 2007-003

Long-Term Average Infiltration at Yucca Mountain, Nevada: Million-Year Estimates

Stothoff, S. and G. Walter

August 2007

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