BIBLIOGRAPHY OF TECHNICAL CONTRIBUTIONS TO THE YUCCA MOUNTAIN PROGRAM BY THE CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES, 1988–2011

Prepared for

U.S. Nuclear Regulatory Commission
Contract No. NRC 02–07–006

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September 2011

ABSTRACT

During its prelicensing activities to prepare for reviewing a license application for the proposed repository at Yucca Mountain, Nevada, and during subsequent licensing review activities, the U.S. Nuclear Regulatory Commission (NRC) sponsored more than 20 years of technical investigations that were conducted by the Center for Nuclear Waste Regulatory Analyses (CNWRA®). The prelicensing period ended in June 2008 when the U.S. Department of Energy (DOE) submitted a license application to NRC for authorization to construct a high-level waste geologic repository at Yucca Mountain, Nevada. Activities at CNWRA between 2008 and September 2010 focused on the technical analysis of DOE's license application materials. Subsequently, CNWRA staff prepared more than 45 technical and programmatic knowledge management reports to document previously unpublished information or to synthesize staff technical insights gained from years of experience in the program. This bibliography, which is one of these knowledge management reports, provides a summary of the main technical reports and journal publications that were prepared by CNWRA staff between the establishment of CNWRA in 1987 and the orderly closure of the Yucca Mountain program in 2011. The scope of the bibliography is limited, for practical reasons, to (i) the key technical reports transmitted as deliverables to NRC, either by letter report format or as numbered CNWRA-series reports; (ii) published journal articles or book chapters, and, in some cases, (iii) manuscripts that were prepared for journals but were unpublished in the open literature. Annotations are provided for many of the items to summarize their contents or note their significance, and NRC accession numbers are provided for the reports and papers that are available from the NRC Agencywide Documents Access and Management System (ADAMS).

CONTENTS

TABLES

ACKNOWLEDGMENTS

This report describes work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA®) and its contractors for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–07–006. The compilation of the bibliography is performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety. The technical activities reported in the bibliography listings were performed for the NRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety, in support of the technical and regulatory topics related to a geologic repository for high-level nuclear waste, and for the NRC Office of Nuclear Regulatory Research and the NRC Office of Federal and State Materials and Environmental Management Programs in support of topics related to the storage and disposal of high-level nuclear waste. The report is an independent product of the CNWRA and does not necessarily reflect the view or regulatory position of NRC.

The compilers of this bibliography gratefully acknowledge the advice and assistance of Maria Padilla, Laura Venhaus, and Leslie Gergen in collecting the reference information listed in the bibliography. The compilers also thank the many authors who provided annotations about their documents. Dr. James Rubenstone at the NRC initially suggested the preparation of a bibliography as a knowledge management activity, and he and other NRC staff provided helpful suggestions about how to organize the document. Dr. Bret Leslie at the NRC (and a former CNWRA scientist) has improved the usefulness of the bibliography by helping to identify many of the accession numbers for the CNWRA documents that are available for viewing in the NRC Agencywide Document Access and Management System (ADAMS). The compilers thank English Pearcy for the technical review, Budhi Sagar for the programmatic review, and L. Mulverhill for her editorial review. L. Selvey, A. Ramos, and B. Street are thanked for their administrative support.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: The CNWRA-generated data referenced in this bibliography meet quality assurance requirements described in the Geosciences and Engineering Division Quality Assurance Manual. Sources of other data should be consulted for determining the level of quality of those data.

ANALYSES AND CODES: None.

1 INTRODUCTION

1.1 Background

In the mid-1980s, the U.S. Department of Energy (DOE) was in the process of characterizing several locations in the United States as potential sites for a geologic repository for disposal of the nation's high-level radioactive waste. Anticipating the submission of a first-of-its-kind license application from DOE, perhaps as early as the mid-1990s, the U.S. Nuclear Regulatory Commission (NRC) recognized a need for support from a dedicated contractor that was free from conflict of interest to help NRC prepare to meet a statutory requirement to complete a review of the license application within the legislated 3-year period. To meet this need, the Center for Nuclear Waste Regulatory Analyses (CNWRA®) was established in October 1987 as a federally funded research and development center, sponsored by the NRC.[1] The main roles of CNWRA were to provide independent technical and scientific support to NRC (i) for the resolution of technical and regulatory issues related to a geologic repository for high-level nuclear waste and (ii) for other activities involved in the storage and disposal of high-level nuclear waste under the Nuclear Waste Policy Act.

In December of 1987, shortly after the establishment of CNWRA, the U.S. Congress amended the Nuclear Waste Policy Act to specify that DOE site characterization activities for a geologic repository were to continue at only one potential site, at Yucca Mountain, Nevada. The main component of CNWRA work in the first few years was largely programmatic in scope. Staff contributed to a comprehensive evaluation of 10 CFR Part 60, which was the federal regulation in effect at that time for disposal of high-level radioactive waste in geologic repositories, and staff used insights from that work to identify regulatory, institutional, and technical uncertainties related to the licensing of a repository. Insights gained from this approach helped support NRC development of 10 CFR Part 63, a regulation specific to the disposal of high-level radioactive wastes in a proposed geologic repository at Yucca Mountain, and helped to identify a set of key technical issues that, beginning in the 1990s, were the basis of many subsequent CNWRA technical investigations and prelicensing interactions involving NRC, CNWRA, and DOE staff (Table 1-1). To prepare for the review of a license application, CNWRA technical work activities were reorganized in 2005 by a set of integrated subissues that conformed to the structure of the NRC formal review plan guidance (Table 1-2).[2]

The prelicensing period ended in June 2008 when the DOE submitted a license application to NRC for authorization to construct a high-level waste geologic repository at Yucca Mountain, Nevada. Subsequent CNWRA activities focused on support for the NRC acceptance review of the license application and the detailed technical analysis of DOE's license application materials.

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[1]CNWRA is a separate business entity of Southwest Research Institute (SwRI®), a not-for-profit research and development organization in San Antonio, Texas, that provides an internationally recognized research, engineering, and testing resource for industry, government, and small businesses.

[2]NRC. NUREG–1804, "Yucca Mountain Review Plan, Revision 2." Washington, DC: NRC. July 2003.

Table 1-1. Key Technical Issues
• Igneous Activity • Structural Deformation and Seismicity • Evolution of the Near-Field Geochemical Environment • Container Life and Source Term • Thermal Effects on Flow • Repository Design and Thermal–Mechanical Effects • Unsaturated and Saturated Flow Under Isothermal Conditions • Radionuclide Transport • Total System Performance Assessment and Integration

Table 1-2. Integrated Subissues
• Preclosure Safety • System Description and Demonstration of Multiple Barriers • Scenario Analysis and Event Probability • Degradation of Engineered Barriers • Mechanical Disruption of Engineered Barriers • Quantity and Chemistry of Water Contacting Engineered Barriers and Waste Forms • Radionuclide Release and Solubility Limits • Climate and Infiltration • Flow Paths in the Unsaturated Zone • Radionuclide Transport in the Unsaturated Zone • Flow Paths in the Saturated Zone • Radionuclide Transport in the Saturated Zone • Volcanic Disruption of Waste Packages • Airborne Transport of Radionuclides • Concentration of Radionuclides in Groundwater • Redistribution of Radionuclides in Soil • Biosphere Characteristics

The technical analyses by NRC and CNWRA staff were documented in four NRC reports (NUREGs), one of which was published in 2010[3] and the remaining three in 2011.[4] During the technical analysis of DOE's license application materials between 2008 and 2010, few other CNWRA technical documents were published. However, when CNWRA staff completed their

[3]NRC. NUREG–1949, "Safety Evaluation Report Related to Disposal of High-Level Radioactive at Yucca Mountain, Nevada." Vol. 1, General Information. Washington, DC: NRC. August 2010.

[4]NRC. NUREG–2107, "Technical Evaluation Report on the Content of the U.S. Department of Energy's Yucca Mountain Repository License Application. Postclosure Volume: Repository Safety After Permanent Closure." Washington, DC: NRC. August 2011. ML11223A273.
NRC. NUREG–2108, "Technical Evaluation Report on the Content of the U.S. Department of Energy's Yucca Mountain Repository License Application." Preclosure Volume: Repository Safety Before Permanent Closure. Washington, DC: NRC. September 2011. ML11250A093.
NRC. NUREG–2109, "Technical Evaluation Report on the Content of the U.S. Department of Energy's Yucca Mountain Repository License Application." Administrative and Programmatic Volume. Washington, DC: NRC. September 2011. ML11255A002.

contributions to the NRC technical evaluation reports in 2010 and 2011, many of the staff went on to prepare more than 45 technical and programmatic knowledge management reports that either documented previously unpublished information or synthesized staff insights gained from years of technical experience in the Yucca Mountain program. The purpose of this bibliography, which was compiled as one of the knowledge management reports, is to list the main technical and scientific documents that CNWRA staff have written over the years for NRC, from CNWRA's establishment in 1987 through the NRC programmatic closeout of high-level waste activities related to Yucca Mountain in September 2011.

1.2 Bibliography Components and Format

Over more than two decades, CNWRA staff have transmitted literally thousands of draft and revised versions of programmatic and technical reports, journal manuscripts, conference papers, and workshop presentations to NRC. The scope of this bibliography is limited, for practical reasons, to a subset of these documents. The items selected for the bibliography are (i) the key technical reports transmitted as deliverables to NRC, either by letter report format or as numbered CNWRA-series reports; (ii) published journal articles or book chapters, and, in some cases, (iii) manuscripts that were prepared for journals but were unpublished in the open literature. Annotations are provided for many of the items, to summarize their content or note their significance.

Programmatic, operational, and planning documents were excluded from the bibliographic listings, as were many hundreds of CNWRA technical abstracts and papers published only as conference proceedings. Despite the high technical quality of many of these proceedings, time and resources were not available to screen them individually, and including all of them would have made the bibliography unwieldy.

The bibliography is organized by categories to facilitate its use as a technical resource. Several categories correspond closely to some of the programmatic divisions of work shown in Tables 1-1 and 1-2. Other bibliography categories are broader or more generic, to increase their usefulness for future investigators. A final category, Special Projects, is specific to sites besides Yucca Mountain, such as Hanford, Washington, and West Valley, New York, for which CNWRA supported radioactive waste-related topics for NRC. As an additional resource, an appendix to the bibliography provides a year-by-year listing of all CNWRA-series reports prepared for the high-level waste management repository safety program from 1988 to 2008.

In general, the documents listed in the bibliography that were transmitted from CNWRA to NRC as reports are also publicly available in the NRC official recordkeeping system, the Agencywide Documents Access and Management System (ADAMS). Access to ADAMS is available online at www.nrc.gov/reading-rm/adams.html. Each document in ADAMS is identified by a unique accession number. If a document has been split into sections electronically to facilitate downloads from a remote location, each section will have a unique accession number. All of the ADAMS accession numbers for the documents listed in the bibliography begin with the letters "ML" followed by 9 digits. In a few cases, the reports and papers transmitted to NRC that are listed in the bibliography had not been assigned ML-accesssion numbers by the time the bibliography was compiled. However, those items can be retrieved with an ADAMS search on the title or author name.

CNWRA maintains a separate document access system for internal use, the Electronic Library Facility (ELF), which contains a data record with a unique identifier for each project-related item transmitted from CNWRA to NRC. The ELF database was the primary resource used to

construct this bibliography, so the listed reports include a unique ELF identifier for each listing—beginning with the letter "Q" and followed by 12 numerals—which corresponds to a set of records about the document and, in most cases, links to an electronic copy of the document itself. For CNWRA staff, it is typically simpler to access documents using ELF than by downloading the document from ADAMS, so the "Q" number is also included in the bibliographic listings, plus the project number that supported the work.

Individual bibliography items are listed alphabetically by author name. Within each listing, the remainder of the formatting differs slightly depending on whether the item is a publication in the open literature or a document transmitted from CNWRA to NRC as a program deliverable. Table 1-3 provides an explanation of the format used in this bibliography for CNWRA reports and papers that were prepared for NRC as project-related items.

Published journal articles and book chapters are formatted in the bibliography according to the CNWRA style guide, in which the typical sequence is as follows:

Journal
Author(s). "Title of Article." *Title of Journal.* Volume number, issue number, page numbers. Year of publication.

Chapter in Book
Author(s). "Title of Chapter." *Title of Book.* Publisher City, Publisher State: Publisher Name. Year.

Table 1-3. Key to Bibliography Entries for Documents Transmitted to NRC

Entry	Explanation
Author(s)	
Transmittal date	Date the document was transmitted from CNWRA to NRC (*mm/dd/yyyy*)
Title	Title of report or unpublished manuscript
Report Number	Optional. Numbered CNWRA reports use one of two sequences: "CNWRA *yy-nnn*" or "CNWRA *yyyy-nnn*"
Status	Optional. Final, Revised, etc.
Publisher City and State	San Antonio, Texas
Publisher	Center for Nuclear Waste Regulatory Analyses
Publication Date	Year, or Month and Year
Annotation	Optional. Short description of report or its significance, or other notes
Project Number	Identifies the project milestone number represented by the document
ELF Identification Number	Unique electronic locator for the CNWRA in-house document record; format is "Q*yyyymmddnnnn*"
ADAMS Accession Number	Listed where available. Unique electronic locator(s) for the document in the NRC document management system; format is "ML*nnnnnnnnn*"

2 OVERVIEW AND BACKGROUND REPORTS

These are reports or papers that provide general information, cover a broad range of topics in a single document, or treat a specific topic (e.g., the Yucca Mountain Environmental Impact Statement) not covered elsewhere.

Ahola, M., R. Baca, A. Chowdhury, C. Connor, G. Cragnolino, F. Dodge, D. Dunn, A. Ghosh, R. Green, B. Hill, S. Hsiung, V. Kapoor, R. Manteufel, S. McDuffie, S. Mohanty, W. Murphy, R. Pabalan, E. Pearcy, N. Sridhar, G. Stirewalt, S. Stothoff, D. Turner, G. Wittmeyer, and S. Young. 02/01/1994. "U.S. Nuclear Regulatory Commission (NRC) High-Level Radioactive Waste Research at Center for Nuclear Waste Regulatory Analyses (CNWRA) for July through December 1993." B. Sagar, ed. CNWRA 93-02S. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: February 1994.
20.05704.004, Q199403180008, ML033650211

Ahola, M., R. Baca, A. Bagtzoglou, A.H. Chowdhury, C.B. Connor, G. Cragnolino, D. Dunn, A. Ghosh, R. Green, B. Henderson, B. Hill, S. Hsiung, B. Leslie, R. Manteufel, R. Martin, S. Mohanty, W. Murphy, R. Pabalan, E. Pearcy, N. Sridhar, D.R. Turner, G.W. Wittmeyer, and S.R. Young. 08/12/1993. "U.S. Nuclear Regulatory Commission (NRC) High-Level Radioactive Waste Research at the Center for Nuclear Waste Regulatory Analyses (CNWRA) for January through June 1993." B. Sagar, ed. CNWRA 93-01S. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: August 1993.
20.05704.004, Q199309200006, ML033650178

Ahola, M.P., P. Angell, R.G. Baca, A.C. Bagtzoglou, C.B. Connor, F.M. Conway, G.A. Cragnolino, D.S. Dunn, D.A. Ferrill, A. Ghosh, B.E. Hill, S.M. Hsiung, M.S. Jarzemba, P.C. Lichtner, R.D. Manteufel, S. Mohanty, W.M. Murphy, R.T. Pabalan, E.C. Pearcy, D.A. Pickett, J.D. Prikryl, N. Sridhar, J.A. Stamatakos, S.A. Stothoff, D.R. Turner, and G.W. Wittmeyer. 02/23/1996. "U.S. Nuclear Regulatory Commission (NRC) High-Level Radioactive Waste Research at Center for Nuclear Waste Regulatory Analyses (CNWRA) for July through December 1995." B. Sagar, ed. CNWRA 95-02S. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1996.
20.05708.463/473/563/573/671, Q199603220007, ML040230584

Ahola, M.P., R.G. Baca, F.P. Bertetti, A.H. Chowdhury, C.B. Connor, G.A. Cragnolino, D.S. Dunn, D.A. Ferrill, D.B. Henderson, B.E. Hill, S.M. Hsiung, D.D. Kana, R.V. Klar, P.C. Lichtner, R.H. Martin, S. Mohanty, A.P. Morris, W.M. Murphy, R.T. Pabalan, E.C. Pearcy, J.D. Prikryl, N. Sridhar, S.A. Stothoff, D.R. Turner, G.W. Wittmeyer, and B. Sagar. 02/01/1995. "U.S. Nuclear Regulatory Commission (NRC) High-Level Radioactive Waste Research at Center for Nuclear Waste Regulatory Analyses (CNWRA) for July through December 1994. B. Sagar, ed. CNWRA 94-02S. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: February 1995.
20.05704.002, Q199503060001, ML040210615

Ahola, M.P., R.G. Baca, F.P. Bertetti, A.H. Chowdhury, C.B. Connor, G.A. Cragnolino, D.S. Dunn, R.T. Green, D.A. Ferrill, D.B. Henderson, B.E. Hill, S.M. Hsiung, R.C. Lichtner, S. Mohanty, A.P. Morris, W.M. Murphy, G.I. Ofoegbu, R.T. Pabalan, E.C. Pearcy, N. Sridhar, G.L. Stirewalt, S.A. Stothoff, D.R. Turner, G.W. Wittmeyer, and S.R. Young. 09/12/1994. "U.S. Nuclear Regulatory Commission (NRC) High-Level Radioactive Waste Research at the Center for Nuclear Waste Regulatory Analyses (CNWRA) for January through June 1994." B. Sagar, ed. CNWRA 94-01S. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1994.
20.05704.002, Q199410040003, ML040230547

Apps, J.A., J.W. Bradbury, R.E. Cady, R.C. Ewing, D.L. Gustafson, R.B. Hofmann, D.T. Hoxie, L.A. Kovach, M.B. McNeil, W.M. Murphy, W.R. Ott, E.C. Pearcy, B. Sagar, M.E. Shea, N. Sridhar, G.W. Wittmeyer, J.R. Wood, and S.R. Young. 09/05/1993. "The Role of Natural Analogs in Geologic Disposal of High-Level Nuclear Waste." CNWRA 93-020. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1993.
20.05704.002, Q199311300002, ML040360540

Baca, R.G., A.C. Bagtzoglou, D. Balin, F.P. Bertetti, C.B. Connor, F.M. Conway, D.A.Ferrill, C.J. Goulet, B.E. Hill, M.S. Jarzemba, R.V. Klar, P. LaFemina, P.C. Lichtner, A.P. Morris, W.M. Murphy, R.T. Pabalan, E.C. Pearcy, D.A. Pickett, J.D. Prikryl, K.H. Spivey, J.A. Stamatakos, S.A. Stothoff, D.R. Turner, and G.W. Wittmeyer. 08/01/1995. "U.S. Nuclear Regulatory Commission (NRC) High-Level Radioactive Waste Research at Center for Nuclear Waste Regulatory Analyses (CNWRA) January through June 1995 (Semi-Annual Report)." B. Sagar, ed. CNWRA 95-01S. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1995
20.5704.002, Q199601050013, ML040220368

Bryan, H. and D.R. Turner. 10/26/2007. "Nevada Demographic Survey Information on Low-Income and Minority Populations in the Vicinity of Yucca Mountain, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2007.
20.06002.01.151.720, Q200710260002,

Cragnolino, G.A. and N. Sridhar. 09/30/1995. "Expert-Panel Review of the Integrated Waste Package Experiments Research Project." CNWRA 95-020. San Antonio, Texas: Center for Nuclear Regulatory Analyses. September 1995.
20.05704.044, Q199601050014, ML040220371

This report documents the review of the Integrated Waste Package Experiments research project conducted at CNWRA, by an independent panel of five experts in materials science, combining expertise in the areas of localized corrosion, stress corrosion cracking, thermal stability and microbially influenced corrosion.

DeWispelare, A.R., L.T. Herren, E.J. Bonano, and R.T. Clemen. 09/30/1994. "Background Report on the Use and Elicitation of Expert Judgment." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. CNWRA 94-019. September 1994. 20.05704.712.405, Q199410110002, ML040230556

The report addresses the use of both informal and formal expert judgment techniques, with emphasis on the latter. The report surveys historical and current use of expert judgment in the nuclear programs. The report also presents criteria to assess the quality of a formal expert elicitation procedure and issues affecting the use of the results of a formal expert elicitation.

Hill, B.E. 03/01/1995. "Expert-Panel Review of CNWRA Volcanism Research Programs." (Revised). CNWRA 95-002. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1995.
20.05704.123.050, Q200605080002, ML040220371

This report describes how an independent panel of five experts in basaltic volcanology reviewed ongoing volcanism research programs at the CNWRA. The goals of this review were to (i) critically review the objectives and approaches of CNWRA volcanism research and its application to licensing issues at the proposed Yucca Mountain high-level waste repository site; (ii) recommend improvements to the research scope and methodologies, and investigate new issues that may not be part of the original research plans; and (iii) evaluate interpretations of the available data and explore alternative hypotheses.

Juckett, M. 09/28/2011. "Evolution of NRC and Public Attitudes Regarding Public Outreach." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011. 20.14002.01.441.112, Q201109280004, ML112710515

This knowledge management report, developed in collaboration with NRC staff, discusses the evolution of attitudes and technology over the duration of the NRC High-Level Waste Public Outreach Program.

Juckett, M. 09/28/2011. "Lessons Learned From Public Outreach Meetings." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011. 20.14002.01.441.110, Q201109280003

The public outreach program was vital to communication with stakeholders in the NRC license review process. The purpose of this knowledge management report is to retain, and make accessible for future use, a record of the approaches that were used in this program to convey information to the public. Much of this information is otherwise unrecorded because public outreach activities do not have the same formal documentation requirements as other technical activities.

Juckett, M. 09/28/2011. "Media Used by U.S. Nuclear Regulatory Commission in Conveying Information to the Public." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2010.
20.14002.01.441.104, Q201109280002

This knowledge management report describes the development and purpose of NRC public outreach materials and their reception by the public and stakeholders.

Juckett, M. 07/07/2006. "Safety Rules for a Potential High-Level Geologic Repository at Yucca Mountain, Nevada: What does the U.S. Nuclear Regulatory Commission Require?" 20.06002.01.161.610, Q200607070007

This publication is a public outreach document that provides background information about the Yucca Mountain licensing requirements. The NRC subsequently revised the document and produced the brochure under the title "Judging the Safety of a Repository at Yucca Mountain, Nevada" which is available at http://www.nrc.gov/waste/hlw-disposal/licensing/acceptance-safety/judging-safety.pdf

Mackin, P. 02/22/2011. "Using SharePoint to Support Development of a Technical Evaluation Report." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 2011. 20.14002.01.441.132, Q201102210003, ML110530163

Manteufel, R.D., M.S. Jarzemba, and R.G. Baca. 04/16/1996. "Relative Hazard of High-Level Waste Over Long Time Periods." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1996.
20.05708.771.615, Q199606140001, ML061370637

Mohanty, S. 06/11/2004. "High-Level Radioactive Waste Disposal." *Nuclear Technology.* Vol. 148, No.2. Page 103. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2004.
20.06002.01.112, Q200406170014

This article was prepared as the introduction for a special issue of Nuclear Technology.

Mohanty, S. 06/27/2003. " Safety in the (Very) Long Run Assessing Long-Term Performance of a Geologic Nuclear Waste Disposal Site." *Technology Today.* San Antonio, Texas: Southwest Research Institute. pp.10–15. July 2003.
20.06002.01.112.300, Q200306300010

Murphy, W.M. 08/21/1995. "Natural Analogs for Yucca Mountain." *Radwaste Magazine.* Vol. 2. pp. 44–50. 1995.
20.05704.064, Q199509210004

Murphy, W.M. 05/20/1992. "Natural Analog Studies for Geologic Disposal of Nuclear Waste." *Technology Today*. San Antonio, Texas: Southwest Research Institute. pp. 16–21. June 1992.
20.03704.063, Q199206160005

Nuclear Regulatory Commission. 12/16/2004. NUREG–1762, "Integrated Issue Resolution Status Report." Volumes 1 and 2. Rev. 1. Washington, DC: U.S. Nuclear Regulatory Commission. April 2005.
20.06002.01.181.410, Q200412200006, ML051360159 ML051360241

Numerous other "Issue Resolution Reports" were prepared during the prelicensing period and dealt with specific key technical issues (Table 1-1) that had been identified by NRC and CNWRA staff. Many of those items are listed under specific subject categories elsewhere in the bibliography. The report cited here, a two-volume NUREG, summarizes all the Key Technical Issue agreements that had been reached as of 2004, after DOE had recently published a large number of supporting technical reports about a potential repository at Yucca Mountain. This NUREG, which was prepared with input from CNWRA staff, provides an

overview of the available information and resolution status of the technical issue agreements. The report also documents the risk insights developed by NRC and CNWRA staffs, the results of reviews of DOE reports, independent confirmatory work by NRC and CNWRA staffs, information from published literature, and other publicly available information.

Nuclear Regulatory Commission. 07/08/2003. NUREG–1804, "Yucca Mountain Review Plan." Final Report, Rev. 2. Washington, DC: U.S. Nuclear Regulatory Commission July 2003.
20.06002.01.171.315, Q200307080006, ML032030389

This review plan, which was developed with input from CNWRA staff, provided guidance for the NRC staff to evaluate a U.S. Department of Energy license application for a geologic repository at Yucca Mountain. The principal purpose of the Yucca Mountain Review Plan was to ensure the quality, uniformity, and consistency of NRC staff reviews of the license application and any requested amendments. The Yucca Mountain Review Plan has separate sections for reviews of general information, repository safety before permanent closure, repository safety after permanent closure, the research and development program to resolve safety questions, the performance confirmation program, and administrative and programmatic requirements. Each section addresses determining compliance with specific regulatory requirements from 10 CFR Part 63. The guidance in the Yucca Mountain Review Plan is risk-informed and performance-based to the extent practical.

Pabalan, R.T. 09/28/1995. "Report on the Peer Review of the Sorption Modeling for High-Level Waste Performance Assessment Research Project." CNWRA 95-023. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1995.
20.05704.074, Q199510110003, ML040220328

An independent panel of five experts in sorption studies reviewed ongoing radionuclide sorption research conducted by the CNWRA under the Sorption Modeling for High-Level Waste (HLW) Performance Assessment Research Project. The goals of the review were to (i) critically review the objectives and approaches of the CNWRA Sorption Research Project and its application to licensing issues at the proposed Yucca Mountain HLW repository site; (ii) recommend improvements to the research scope and methodologies, and identify new issues that may not be part of the original research plan; (iii) evaluate interpretations of the available data and explore alternative hypotheses; and (iv) help prioritize future activities taking into consideration resource and time constraints imposed on the project and anticipated programmatic schedules. This report discusses the procedure used in selecting the review panel members, presents an outline which the panel used as a guide for the review process, and summarizes the comments and recommendations of the review panel.

Pabalan, R.T. 04/14/1994. "Summary Assessment of the Radionuclides Relevant to Research on the Geologic Disposal of High-Level Radioactive Wastes." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1994.
20.05704.074.165, Q200310080001, ML033640286

The potential release of radionuclides to the accessible environment is the key issue of concern in the design and licensing of a geologic repository. The HLW proposed to be emplaced in a geologic repository at Yucca Mountain comprised many different radionuclides. Limited programmatic resources and the expected complex chemistry and transport behavior of HLW radionuclides made it important to identify those radionuclides on which to focus research efforts. This summary assessment was conducted to consider what criteria should be used for selecting HLW radionuclides for NRC-sponsored research projects, and how this subset of

radionuclides could be used to screen (at least in a preliminary sense) relevant radionuclides for further study.

Sagar, B., J. Stamatakos, and A. Ghosh. 09/21/2011. "The Center for Nuclear Waste Regulatory Analyses (CNWRA) Perspective on Prelicensing Interactions and Information Gathering." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.182, Q201109210002, ML112640297

Tschoepe, E., F.F. Lyle, Jr., D.M. Dancer, C.G. Interrante, and P.K. Nair. 06/01/1994. "Field Engineering Experience with Structural Materials." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1994.
20.05702.551, Q199406140004, ML033650222

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3 CODE MANUALS, DESCRIPTIONS, AND USER GUIDES

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This report documents the underlying mathematical and numerical models, test problems, benchmarks, and applications of the BIGFLOW code. The report describes that the BIGFLOW software package is composed of a simulation code (BIGFLOW), and an interactive data processing code (DATAFLOW). The simulation code can be used for detailed modeling of transient or steady state flow systems in three-dimensional (3D) unsaturated, partially saturated, or saturated, heterogeneous porous media. BIGFLOW has been used for studying macroscale behavior of saturated and unsaturated flow processes in randomly heterogeneous media, for performance assessment of a high-level nuclear waste geologic repository in the presence of layers and faults, and for hydrologic simulations such as strip-source infiltration in layered soils or groundwater flow through lakes. A subsequent version (1.1) of BIGFLOW was documented in 1993 as NUREG/CR–6028, but that version was retired later the same year.

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Dasgupta, B., R. Benke, T. Maxwell, and N. Eisenberg. 07/08/2003. "Preclosure Safety Analysis (PCSA) Tool Version 2.0 User Guide." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2003.
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Freitas, C.J., N.A. Eisenberg, and R.G. Baca. 02/25/1994. "DRILLO Code: A Module for Simulation of Human Intrusion Scenarios, Model Description, and User Guide, IPA Phase 2." CNWRA 94-005. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1994.
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Gute, G.D., G. Ofoegbu, F. Thomassy, S.-M. Hsiung, G. Adams, A. Ghosh, B. Dasgupta, A.H. Chowdhury, and S. Mohanty. 04/30/2003. "Mechfail: A Total-System Performance Assessment Code Module for Evaluating Engineered Barrier Performance Under Mechanical Loading Conditions." CNWRA 2003-06. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 2003.
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Lozano, A.S., H. Karimi, J.P. Cornelius, R.D. Manteufel, and R.W. Janetzke. 07/28/1994. "INVENT: A Module for the Calculation of Radionuclide Inventories, Software Description and User Guide." CNWRA 94-016. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 1994.
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*(This report is publicly available at http://www.osti.gov/bridge/servlets/purl/204666-s85Ob5/webviewable/204666.pdf). Also published as CNWRA 94-020.***Torng, T.Y., P.C. Lichtner, and J.C. Walton**. 07/14/1994. "SCCEX: A Computer Code for Substantially Complete Containment Example Analysis of a Reference Container." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 1994.
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4 PRECLOSURE OPERATIONS AND SAFETY

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Gonzalez, S.H., J.A. Stamatakos, K.R. Murphy, and H.L. McKague. 06/28/2004. "Preliminary Evaluation and Analyses of the U.S. Department of Energy Geotechnical Data for the Waste Handling Building Site at the Potential Yucca Mountain Repository." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 2004. 20.06002.01.102.442, Q200406290004, ML083510555

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This report identifies the capabilities of five sets of commercially available computer codes, based on reported information, that could be used to support a safety review to determine the adequacy of the U.S. Department of Energy compliance demonstration of preclosure regulatory requirements. These requirements are relevant to radiation shielding evaluation, underground ventilation calculation, radiation dose assessment, criticality calculation, and structural and mechanical analysis.

Lesher, M., A. Ghosh, and B. Dasgupta. 08/21/2003. "Assessment of Subsurface Transporter System for the Proposed Repository at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2003. 20.06002.01.102.350, Q200308250009, ML040350694

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Annual radiation doses and risks to passengers and crew are calculated for shipments of radioactive materials in passenger aircraft under accident-free and incident-free conditions; (i.e., under normal transportation conditions). The 1982 database developed by Sandia National Laboratories is used, and calculations are made using RADTRAN 4.0. This paper is one of two papers estimating radiological risk associated with incident-free transportation of radioactive materials.

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Separate analyses were conducted for a hypothetical deep geologic repository in a fractured, granitic batholith and for a hypothetical deep geologic repository in a variably saturated, homogenous tuff unit underlain by a highly permeable, saturated carbonate unit. Each analysis was tailored to address different aspects of the proposed post-waste emplacement rule. The analyses performed for the granite test case are focused on the concept of 'fastest path,' and the analyses conducted for the variably saturated tuff test case are focused on the added computational difficulty posed by implementing a 'post-waste-emplacement' measure in the unsaturated zone.

Jarzemba, M.S. and F.J. Firth. 10/24/1996. "Background Information and Recommendations for a Stylized Human Intrusion Calculation at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1996.
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Jarzemba, M.S. and D.A. Pickett. 05/25/1995. "An Evaluation of the Important Radionuclides for Performance Assessment." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1995.
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Mohanty, S. and R. B. Codell. "Independent Postclosure Performance Estimates of the Proposed Repository at Yucca Mountain." *Nuclear Technology*. Vol. 148, No 2. pp 105–114. 2004.

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Mohanty, S., R. Benke, R. Codell, K. Compton, D. Esh, D. Gute, L. Howard, T. McCartin, O. Pensado, M. Smith, G. Adams, T. Ahn, P. Bertetti, L. Browning, G. Cragnolino, D. Dunn, R. Fedors, B. Hill, D. Hooper, P. LaPlante, B. Leslie, R. Nes, G. Ofoegbu, R. Pabalan, R. Rice, J. Rubenstone, J. Trapp, B. Winfrey, and L. Yang. 05/19/2005. "Risk Analysis for Risk Insights Progress Report." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 2005.
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The report documents 12 analyses that were conducted to enhance the staff understanding of features, events, and processes and associated uncertainties as identified in the Risk Insights Baseline Report. The specific areas identified for analysis included repository near-field environment, extrusive volcanism, radionuclide transport in the saturated zone, and radionuclide inventory.

Mohanty, S., R. Codell, J.M. Menchaca, R. Janetzke, M. Smith, P. LaPlante, M. Rahimi, and A. Lozano. 03/01/2004. Revision 2: "System-Level Performance Assessment of the Proposed Repository at Yucca Mountain Using the TPA Version 4.1 Code. Revised. CNWRA 2002-05. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2004.
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This report examines the consistency between the U.S. Department of Energy (DOE) TSPA-GoldSim code and the supporting documentation for particular submodels of the code. This report summarizes only review activities by the CNWRA staff.

Sridhar, N. 09/24/1992. "Selection and Evaluation of Models for Substantially Complete Containment Example Problem. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1992.
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This report evaluates models for corrosion potential; pit initiation, growth and repassivation; crevice corrosion initiation, growth and repassivation; stress corrosion cracking; buckling; and fast fracture. Simple parametric equations for the critical potentials associated with these phenomena are suggested.

Stirewalt, G.L, B.E. Hill, C.B. Connor, and C. Lin. 01/13/1995. "A Critical Review of Data in the Center for Nuclear Waste Regulatory Analyses (CNWRA) Volcanism Geographic Information System (GIS) Database." CNWRA 95-003. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1995.
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Stirewalt, G.L., S.M. McDuffie, R.D. Manteufel, and R.W. Janetzke. 06/15/1995. "Technical Specifications for a Fault Displacement Module." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1995.
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Walton, J.C., P.K. Nair, and T. Torng. 02/11/1993. "Calculational Approach for Substantially Complete Containment Example Problem." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1993.
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This report describes an approach for calculation of waste package lifetime related to the "Substantially Complete Containment" requirement in 10 CFR 60.

Weldy, J.R. 06/12/1997. "Comparison of Reference Input Parameter Values for the Total System Performance Assessment of the Proposed Yucca Mountain Repository." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1997.
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Weldy, J. and J. Peckenpaugh. 02/26/2003. "Response to the External Peer Review of the Total-System Performance Assessment Version 3.2 Code." CNWRA 2001-002. Rev. 1. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: September 2001 (REVISED February 2003).
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This report documents the responses of CNWRA and NRC staff to comments from an independent peer review panel of eight scientists and engineers with expertise in materials science, volcanology, hydrology, rock mechanics, geochemistry, radiation health physics, scenario analysis, and performance assessment. The peer review examined the performance assessment methodology in the Total-system Performance Assessment (TPA) Version 3.2 code. This report also describes modifications to the TPA code that have been made subsequently or that are under consideration for future versions of the code.

Wilt, T., A. Chowdhury, and P.A. Cox. 09/23/2011. "Response of Reinforced Concrete Structures to Aircraft Crash Impact." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
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Winkler, R.L. S.C. Hora, and R.G. Baca. 09/18/1992. "The Quality of Expert Probabilities Obtained Through Formal Elicitation Techniques." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1992.
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This report focuses on the issue of the quality of experts' probability estimates as obtained through a formalized elicitation process. A broad survey of the scientific literature was performed to examine studies where expert judgment was compared with actual data."

6 SITE CHARACTERIZATION

These publications describe field and literature studies, at Yucca Mountain and elsewhere, and methods and databases used to obtain site information.

Basse, B. 08/03/1990. "Water Resources in Southern Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1990.
20.03702.002.305.604, Q199107170012, ML003755474

A review of available information on long-term projections of regional groundwater needs in southern Nevada. The report reviews water resources in southern Nevada and the current and projected water demands on these resources.

Bertetti, F.P., and J.D. Prikryl. 07/23/2003. "Mineralogy and Geochemistry of Well Cuttings from Selected Early Warning Drilling Project Wells in Fortymile Wash." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2003.
20.06002.01.141.320, Q200307240002, ML040350688

This is a report that describes detailed studies of the mineralogy and chemistry of cuttings from two Nye County Early Warning Drilling Program wells. Wells, NC-EWDP-02D and NC-Washburn-1X, which are located in the southern part of Fortymile Wash along the potential groundwater flow path from Yucca Mountain. The cuttings were analyzed using semiquantitative x-ray diffraction, thin-section petrography, scanning electron microscopy, x-ray fluorescence, and inductively coupled plasma mass spectrometry.

Connor, C.B., R.H. Martin, P.G. Hunka, J.A. Stamatakos, D.B. Henderson, and R.V. Klar. 11/22/1995. "Ground Magnetic Survey of the Little Cones, Crater Flat, Nevada." CNWRA 96-002. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 1995.
20.05702.425, Q199602290013, ML040220433.

The Little Cones survey was conducted to evaluate the utility of ground magnetic data for characterizing igneous intrusions and related structures at small-volume basaltic volcanoes in the Yucca Mountain region.

Dinwiddie, C.L. "The Small-Drillhole Minipermeameter Probe for In-Situ Permeability Measurement." Society of Petroleum Engineers *SPE Reservoir Evaluation & Engineering*. Vol. 8, No. 6. pp. 491–501. DOI:10.2118/84595-PA. December 2005.

This paper presents an innovative technique for measuring permeability in situ. The design of a new minipermeameter probe is discussed, as well as the accompanying analytical technique, and the size and shape of the instrument's averaging volume. Some data are presented from a Bishop Tuff analog to nonwelded units at Yucca Mountain.

Dinwiddie, C.L., K.K. Bradbury, R.N. McGinnis, R.W. Fedors, and D.A. Ferrill. "Fault Zone Deformation Overprints Permeability of Nonwelded Ignimbrite: Chalk Cove Fault, Bishop Tuff, Bishop, California." *Vadose Zone Journal.* No. 5. pp. 610–627. (May 2006): DOI: 10.2136/vzj2005.0062.

Dinwiddie, C.L., K.K. Bradbury, R.N. McGinnis, D.A. Ferrill, and R.W. Fedors. 01/02/2007. "Lithological, Structural, and Hydrological Characteristics of Reworked Tuffaceous Sedimentary Rock and Interbedded Ashfall Deposits Near Bishop, California: Implications for Lateral Flow." (Manuscript prepared for *Vadose Zone Journal*)
20.06002.01.262.630, Q200701020016, ML071690539

The paper describes how lithological, structural, and in-situ gas permeability data were collected and used as a natural analog for nonwelded tuffs of the Paintbrush and Calico Hills tuffs at Yucca Mountain to examine the hypothesis that these conditions could laterally divert downward flow of water in a sequence of poorly consolidated, reworked tuffaceous rock.

Dinwiddie, C.L., K.K. Bradbury, R.N. McGinnis, and D.E. Stillman. 09/07/2011. "Hydrogeologic Heterogeneity of Faulted and Fractured Glass Mountain Bedded Tuffaceous Sediments and Ashfall Deposits: The Crucifix Site Near Bishop, California." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.147, Q201109070003, ML112510093

Dubreuilh, P., D.J. Waiting, C. Cardenas, and K. Overby. 10/13/2008. "Internet-Based Interactive Maps and Satellite Images of the Yucca Mountain Area." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2008. 20.14002.01.141.804, Q200810130001, ML082880161,

This report describes an internet-based tool of interactive maps and satellite images of the Yucca Mountain area that was developed on a dedicated internet site accessible to the public from any location at http://gedinfomaps.swri.org/YMmaps/.

Farrell, D. and S.K. Sandberg. 01/05/2004. "Electrical Resistivity Studies of Fortymile Wash, Nye County, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2004.
20.06002.01.131.330, Q200401080005, ML040270033.

This report provides a summary of direct current electrical resistivity, induced polarization, and time-domain electromagnetic studies performed in southern Fortymile Wash and neighboring northern Amargosa Valley, Nevada, in 1998 and 1999 by Center for Nuclear Waste Regulatory Analyses (CNWRA). For the level of accuracy required for groundwater flow models in the Yucca Mountain region and given the shallow groundwater gradients, the errors in the inferred elevations of the water table were generally too large to support detailed modeling of groundwater flow in the region.

Farrell, D.A., J. Winterle, W. Illman, and R.W. Fedors. "Review of Porosity Distributions in the Yucca Mountain Region." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2000.
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Green, R.T., K. Meyer, and G. Rice. 10/01/1994. "Hydraulic Characterization of Hydrothermally-Altered Nopal Tuff." CNWRA 94-027. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 1994.
20.05704.191, Q199505080001, ML040220209.

Hill, B.E., B.W. Leslie, and C.B. Connor. 09/27/1993. "A Review and Analysis of Dating Techniques for Neogene and Quaternary Volcanic Rocks." CNWRA 93-018. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1993.
20.05704.123, Q199310140006, ML040200609.

Hooper, D.M., and D. M. Necsoiu. 09/07/2011. "Spectroscopic Analysis of Tephra as a Site Characterization Tool." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.176, Q201109070001,ML112500246.

A knowledge management report that summarizes the current understanding of the physical properties of volcanic tephra and its spectral response in the visible and near-infrared regions. These relationships support investigations on the extent of tephra deposit remobilization and redistribution, resuspension, weathering and erosion rates, and grain-size characteristics.

LaFemina, P.C., C.B. Connor, J.A. Stamatakos, and D.A. Farrell. "Imaging an Active Normal Fault in Alluvium by High-Resolution Magnetic and Electromagnetic Surveys." *Environmental & Engineering Geoscience.* Vol. 8, No. 3. pp. 193–207. 2002.

Leslie, B.W. 02/11/1994. "An Annotated Analysis of Logic in the 1992 Report, The Origin and History of Alteration and Carbonization of the Yucca Mountain Ignimbrites, by J.S. Szymanski." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1994.
20.05702.442.421.001, Q199403180021, ML033640282

This report provides a systematic analysis of the logic used in the 1992 report listed in the title, which asserted that field evidence of mineralization in the shallow subsurface, among other factors, supported a conclusion that potential upwelling of hydrothermally derived waters and auxiliary gas-assisted processes posed a significant safety hazard for a geologic repository at Yucca Mountain. The report provides an annotated logical deconstruction of the premises, arguments, and logical analysis of the 1992 report. It examines the current geodynamic configuration of the Yucca Mountain region; outcrop and rock core features; and geochemical, mineralogical, and isotopic evidence.

McGinnis, R.N., A.P. Morris, D.A. Ferrill and C.L. Dinwiddie. "Deformation Analysis of Tuffaceous Sediments in the Volcanic Tableland Near Bishop, California." *Lithosphere*, 1. pp. 291–304. 2009. DOI: 10.1130/L43.1.

McKague, L., P.S. Justus, D. Waiting, A. Morris, R. Pabalan, and J. Stamatakos. 10/01/2009. "Yucca Mountain Region Field Guide." Rev. 1. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2009.
20.14002.01.401, Q200910050007, ML102770339.

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.

Murphy, W.M. and R.T. Pabalan. 03/16/1994. "Geochemical Investigations Related to the Yucca Mountain Environment and Potential Nuclear Waste Repository." CNWRA 94-006. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1994.
20.05704.014, Q199405030005, ML033630657

This report presents the final results of the Geochemistry Research Project conducted at the CNWRA for the Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research. The study focused on experimental determinations and theoretical interpretations of fundamental thermodynamic and kinetic properties of minerals and reactions that characterize geochemical processes at the proposed nuclear waste repository site at Yucca Mountain and that could affect the capacity of the site to isolate nuclear waste. Technical results are

presented in three major sections covering (i) cation exchange studies on clinoptilolite, (ii) kinetic and solubility studies on analcime and Na-clinoptilolite, and (iii) conceptual and numerical geochemical modeling of natural and repository systems. Also published as NUREG/CR–6288.

Necsoiu, M., D. Hooper, and R. Benke. 08/13/2008. "Summary of the Relationship Between Known Tephra Deposits, Tephra Isopachs, and Topography at Lathrop Wells Volcano, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2008.
20.14002.01.161.803, Q200808150001, ML082280310

This report correlates a CNWRA topographic analysis of the region surrounding the Lathrop Wells Volcano, developed from a digital elevation model, with existing information such as tephra-fall deposit thickness from U.S. Department of Energy (DOE) isopach maps and field measurements. The analysis was developed to prepare CNWRA and NRC staff for a September 2007 Appendix 7 meeting about fluvial redistribution of radionuclides.

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.

This paper reports the results of ion exchange experiments that were conducted between clinoptilolite, which is the predominant zeolite mineral in altered pyroclastic and volcaniclastic rocks, and aqueous mixtures of Na^+/K^+ and Na^+/Ca^{2+} to provide a thermodynamic basis for understanding zeolite-water interactions in geologic systems. 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. This investigation contributed to a better understanding of how zeolites might influence groundwater chemistry at Yucca Mountain.

Painter. S.L. 01/22/2001 "Statistical Characterization of Spatial Variability in Sedimentary Rock." *Heterogeneity in the Crust and Upper Mantle: Nature, Scaling and Seismic Properties*. J.A. Goff and K. Holliger, eds. New York, New York: Kluwer Academic/Plenum Publishers. pp. 187–206. 2003.
20.01402.861/20.01402.471, Q200101290007

This paper detailed an examination and evaluation of four different statistical methods that may be used to represent spatial variability in sedimentary rocks. Results indicated a model based on a mixture of two Laplace distributions and a model based on subordination of a Gaussian process both outperformed models based on a Levy-stable distribution and a generalized Gaussian distribution.

Pearcy, E.C. and W.M. Murphy. 10/01/1990. "Geochemical Natural Analogs Literature Review." CNWRA 90-008. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1991.
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Pickett, D.A., J. D. Prikryl, B.W. Leslie, and E.C. Pearcy. 09/28/2011. "Radionuclide Mobility at the Nopal I Natural Analog." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.164, Q201109280007

This knowledge management report summarizes NRC-sponsored Peña Blanca natural analog work—centered on the Nopal I uranium ore deposit—with emphasis on understanding radionuclide mobility. The report discusses the beginnings of NRC-sponsored Peña Blanca work and Nopal I site selection, hydrologic characterization, fracture characterization, uranium

mineralogy, radionuclide mobility studies, and performance assessment applications. The report provides references to all available reports and publications, and describes in more detail the results of studies that were unpublished and appeared only in posters or presentations.

Prikryl, J.D., D.A. Pickett, and E.C. Pearcy. 12/27/2002. "Natural Analog Studies at the Nopal I Uranium Deposit, Peña Blanca District, Chihuahua, Mexico." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2002.
20.06002.01.141, Q200301140015, ML061310294

This paper, which was prepared as a chapter for the unpublished book Geology and Mineralogy of Radioactive Waste Repositories, summarizes results of natural analog studies at the Nopal I uranium deposit and their use in support of performance assessment modeling for the proposed Yucca Mountain repository. These studies focused on the mechanisms and timing of uraninite alteration and secondary uranium mineral formation, controls on groundwater and secondary mineral composition, and processes affecting elemental migration.

Ressler, T.R., J.A. Stamatakos, K.D. Ridgeway, and J. Winterle. 09/28/2000. "Preliminary Hydrostratigraphy of the Valley-Fill Aquifer in Fortymile Wash and the Amargosa Desert." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2000.
20.01402.471.060, Q200010240001, ML020100101

This report describes a detailed investigation of outcrops and evaluation of the sedimentary architecture and hydraulic properties of the alluvium of Fortymile Wash. The outcrop investigations indicated that the alluvium consists of predominantly conglomerate and sandstone. Seven diagnostic sedimentary lithofacies were identified based on grain size, sedimentary features, and geometry. Laboratory permeability tests of alluvium samples were completed to investigate the variation in permeability between the different lithofacies. The results of this report were utilized in several subsequent modeling efforts designed to evaluate the effects of heterogeneity and scale on flow and transport.

Ressler, T.R., K.D. Ridgway, J.A. Stamatakos, and J.M. Sharp, Jr. 11/23/2004. "Facies Architecture, Hydrostratigraphy, and Aquifer Characterization of Quaternary Alluvium Adjacent to Yucca Mountain, Nevada."
20.06002.01.291, Q200412270001 ML061700336.

Unpublished manuscript prepared for Geological Society of America Bulletin.

Smart, K.J., D.Y. Wyrick, P.S. Landis, and D.J. Waiting. 03/07/2006. "Summary and Analysis of Subsurface Fracture Data From the Topopah Spring Tuff Upper Lithophysal, Middle Nonlithophysal, Lower Lithophysal, and Lower Nonlithophysal Zones at Yucca Mountain, Nevada." CNWRA 2005-04. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2006.
20.06002.01.292.510, Q200603230005, ML060660009.

This report summarizes subsurface fracture data collected by DOE from the Topopah Spring Tuff (upper lithophysal through lower nonlithophysal zones) at Yucca Mountain and analyzes the data to provide a revised characterization of key fracture characteristics (e.g., fracture orientations and spacings). The analyses were undertaken to assist NRC and CNWRA staff with technical reviews in the areas of drift degradation, and unsaturated zone flow and radionuclide transport.

Stamatakos, J., S. Biswas, and M. Silver. 08/15/2007. "Supplemental Evaluation of Geophysical Information Used to Detect and Characterize Buried Volcanic Features in the Yucca Mountain Region." Second Revision. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2007.
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Stirewalt, G.L., S.R. Young, and K.D. Mahrer. 09/01/1992. "A Review of Pertinent Literature on Volcanic-Magmatic and Tectonic History of the Basin and Range." CNWRA 92-025. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1992.
20.03704.121, Q199210050003, ML033650055.

Stirewalt, G.L., S.R. Young, and A.P. Morris. 06/19/1992. "Use of Balanced Two-Dimensional Geological Cross-Sections in Development of Scenarios for Performance Assessment Analyses at Yucca Mountain, Nevada.
20.03702.132, Q199206250003. ML061370259

This is an unpublished journal manuscript. This document describes computerized cross-section balancing that were applied to define a viable geologic framework for geometric representation of major faults beneath Yucca Mountain. The derived two-dimensional model consists of a linked listric-detachment fault system with the predicted detachment at a depth of 5.5 to 5.6 km below sea level.

Waiting, D.J., L. McKague, and D. Sims. 07/30/2007. "Yucca Mountain Stratigraphic and Model Unit Correlation Chart." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2007.
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Wittmeyer, G., R. Klar, G. Rice, and W. Murphy. 04/28/1995. "The Center for Nuclear Waste Regulatory Analyses (CNWRA) Regional Hydrogeology Geographic Information System Database." CNWRA 95-009. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1995.
20.05704.131, Q199505180007, ML040220222

This report describes a Geographic Information System (GIS) database for the Research Project on Regional Hydrogeologic Processes of the Death Valley Region that was developed to facilitate the evaluation of existing conceptual models and the construction of alternative conceptual models of the regional flow system.

Wyrick, D., R. Fedors, K. Smart, R. Lenhard, R. McGinnis, D. Bannon, and C. Manepally. 09/27/2011. "Field and Laboratory Experiments to Estimate Bulking Factor for a Lithophysal Tuff, Fran Ridge, Yucca Mountain, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
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Zhu, C. and W.M. Murphy. "On Radiocarbon Dating of Ground Water." *Ground Water.* Vol. 38. pp. 802–804. 2000.

7 IGNEOUS ACTIVITY

Basu, D., N.K. Adams, J.A. Stamatakos, S. Sparks, and A. Woods. 01/10/2007. "Review of Two Electric Power Research Institute Technical Reports on the Potential Igneous Processes Relevant to the Yucca Mountain Repository." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2007.
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Basu, D., K. Das, and N. Adams. 09/19/2008. "Simulations of Magma-Waste Package Interactions Using Computational Fluid Dynamics." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2008.
20.14002.01.151.802, Q200809220006, ML082670317

This summary report, which is specific to the igneous intrusion scenario, explains the technical aspects and results of computational analyses conducted to investigate the flow of magma into a subsurface tunnel, including obstacles.

Basu, D., K. Das, and S. Self. 09/23/2011. "Review of Numerical Analyses for Magma Dynamics at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
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A knowledge management report that documents the important technical aspects and results of computational analyses carried out to study magma dynamics and the possible interaction between a rising basaltic magma and a hypothetical horizontal repository at Yucca Mountain.

Bokhove, O., A.W. Woods, and A. de Boer. "Magma Flow Through Elastic-Walled Dikes." *Theoretical and Computational Fluid Dynamics.* Vol. 22. pp. 261–286. 2005.

The article describes a first-order numerical model to evaluate the likely relationships between wall-rock stress and magma flow processes. The numerical model is developed using convective-diffusive flow relationships, which are coupled to elastic wall-rock responses to stress.

Condit, C.D. and C.B. Connor. 06/30/1995. "Recurrence Rates of Volcanism in Basaltic Volcanic Fields: An Example from the Springerville Volcanic Field, Arizona." *Geological Society of America Bulletin.* Vol. 108. pp. 1,225–1,241. 1996.

Connor, C.B. and F.M. Conway. "Basaltic Volcanic Fields." *Encyclopedia of Volcanology*, *Academic Press*. pp. 331–343. 2000.

Connor, C.B. and B.E. Hill. "Three Nonhomogenous Poisson Models for the Probability of Basaltic Volcanism: Application to the Yucca Mountain Region, Nevada." *Journal of Geophysical Research.* Vol. 100, B6. pp. 10,107–10,125. 1995.

Connor, C.B., and B.E. Hill. 06/29/1994. "Strategy for the Evaluation and Use of Probability Models for Volcanic Disruptive Scenarios." CNWRA 94-015. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1994.
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Connor, C.B. and C.O. Sanders. 06/23/1994. "Geophysics Review Topical Report: Application of Seismic Tomographic and Magnetic Methods to Issues in Basaltic Volcanism." CNWRA 94-013. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1994. 20.0571998 04.145, Q199406280011 ML040160528

Connor, C.B., B. Hill, P. La Femina, M. Navarro, and M. Conway. "Soil ^{222}Rn Pulse During the June 1995 Phreatic Eruption of Cerro Negro, Nicaragua." *Journal of Volcanological and Geothermal Research.* Vol. 73. pp. 119–127. 1996.

This paper documented post-eruption soil–gas surveys that were conducted to determine the extent of shallow degassing.

Connor, C.B., B.E. Hill, B. Winfrey, N. Franklin, and P.C. LaFemina. "Estimation of Volcanic Hazards from Tephra Fallout." *Natural Hazards Review.* Vol. 2, No. 1. pp. 33–42. 2001.

C.B. Connor, P.C. Lichtner, **F.M. Conway, B.E. Hill**, **A.A. Ovsyannikov, I. Federchenko, Y. Doubik, V.N. Shapar, and Y.A. Taran**. "Cooling of an Igneous Dike 20 Years After Intrusion." *Geology.* Vol. 25. pp. 711–714. 1997.

This article documents a modeling study of the cooling rates of a shallow volcanic dike emplaced during the 1975 Talbachik eruption in Russia, illustrating how rock thermophysical properties and water in the unsaturated zone influenced the cooling rates.

Connor, C.B., S.B.L. Magsino, J.A. Stamatakos, R.H. Martin, P. LaFemina, B.E. Hill, **S. Lieber**. "Magnetic Surveys Help Reassess Volcanic Hazards at Yucca Mountain." *EOS, Transactions of the AGU.* Vol. 78. pp. 73–78. 1997.

Connor, C.B., J.A. Stamatakos, D.A. Ferrill, B.E. Hill, G.O. Ofoegbu, M.F. Conway, B. Sagar, and J. Trapp. "Geologic Factors Controlling Patterns of Small-Volume Basaltic Volcanism: Application to a Volcanic Hazard Assessment at Yucca Mountain, Nevada." *Journal of Geophysical Research.* Vol. 105. pp. 417–432. 2000.

Conway, F.M., C.B. Connor, B.E. Hill, C.D. Condit, K. Mullaney, and C.M. Hall. "Recurrence Rates of Basaltic Volcanism in SP Cluster, San Francisco Volcanic Field, Arizona." *Geology.* Vol. 26. pp. 655–658. 1998.

Conway, F.M., D.A. Ferrill, C.H. Hall, A.P. Morris, J.A. Stamatakos, C. Connor, A.N. Halliday, and C. Condit. "Timing of Basaltic Volcanism Along the Mesa Butte Fault in the San Francisco Volcanic Field, Arizona From ^{40}Ar/^{39}Ar Ages: Implications for Longevity of Cinder Cone Alignments." *Journal of Geophysical Research.* Vol. 102. pp. 815–824. 1997.

Doubik, Y.P. and B.E. Hill. "Magmatic and Hydromagmatic Conduit Development During the 1975 Tolbachik Eruption, Kamchatka, with Implications for Hazards Assessment at Yucca Mountain, Nevada." *Journal of Volcanology and Geothermal Research.* Vol. 91. pp. 43–64. 1999.

Ferrill, D.A, C.B. Connor, J.A. Stamatakos, H.L. McKague, B.E. Hill, G.I. Ofoegbu, and R. Terhune. 09/18/1997. "Modeling Fault-Dike Interaction: Implications for Lateral Diversion Dikes and Alignment of Volcanos in the Yucca Mountain (Nevada) Region." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1997. 20.05708.471.760, Q199709300004, ML040200083

This paper uses a summary of a diverse set of analyses for fault and dike interaction to illustrate and describe the control of magma ascent by faults. Included are discussions of the

geologic record of fault-dike interaction at Yucca Mountain, theoretical constraints on fault-dike interaction, analog modeling results, numerical modeling results, in situ stress controls, and volcano cone alignment.

Hill, B. 11/06/1996. "Constraints on the Potential Subsurface Area of Disruption Associated with Yucca Mountain Region Basaltic Volcanos." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 1997.
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This report summarizes results of Center for Nuclear Waste Regulatory Analyses (CNWRA) research at Tolbachik volcano in Kamchatka, Russia, where the process of subsurface disruption was well documented during the 1975 eruption.

Hill, B.E. 03/01/1995. "Expert-Panel Review of CNWRA Volcanism Research Programs." (Revised). CNWRA 95-002. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1995.
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This document provides a useful example of how to implement an independent peer review.

Hill, B.E., C.B. Connor, M.S. Jarzemba, P.C. LaFemina, M. Navarro, and W. Strauch. "1995 Eruptions of Cerro Negro Volcano, Nicaragua, and Risk Assessment for Future Eruptions." *Geological Society of America Bulletin.* Vol. 10. pp. 1,231–1,241. 1998.
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Jarzemba, M.S. "Stochastic Radionuclide Distribution After a Basaltic Eruption for Performance Assessment of Yucca Mountain." *Nuclear Technology.* Vol. 118, No. 2. pp.132–141. 1997.

This paper describes the initial model for post-eruption dose calculations.

La Femina, P.C., C.B. Connor, B.E. Hill, W. Strauch, and J. Armando Saballos. "Magma-Tectonic Interactions in Nicaragua: The 1999 Seismic Swarm and Eruption of Cerro Negro Volcano." *Journal of Volcanology and Geothermal Research.* Vol. 137 Nos. 1–3. pp. 187–199. DOI:10.1016/j.volgeores.2004.05.006. 2004.
20.06002.01.051.375, Q200304280001

The study simulates a 1999 eruption of the Cerro Negro volcano in Nicaragua and concludes that the temporal and spatial patterns of earthquake swarms, surface ruptures, and the eruption location can be explained by using a model in which an eruption is triggered by tectonically induced changes in the regional stress field, rather than being initiated by magmatic overpressure.

Magsino, S.L., C.B. Connor, B.E. Hill, J.A. Stamatakos, P.C. La Femina, D.A. Sims, and R.H. Martin. 01/27/1998. "CNWRA Ground Magnetic Surveys in the Yucca Mountain Region, Nevada (1996–1997)." CNWRA 98-001. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1998.
20.01402.461.840, Q199803040001, ML032890330

This report describes basic methods for identification and characterization of buried igneous bodies.

Menand, T. and J. C. Phillips. "Gas Segregation in Dykes and Sills." *Journal of Volcanology and Geothermal Research*. Vol. 159, No. 4. pp. 393-408. 2007.
20.06002.01.302.610, Q200512080007

This paper investigates 1) how the geometry and connectivity of the plumbing system affect the circulation of magma and 2) how this circulation impacts gas segregation. The investigation is restricted to the geometry of a vertical conduit connected to a horizontal magma body.

Menand, T., J.C. Phillips, and R.S.J. Sparks. "Circulation of Bubbly Magma and Gas Segregation Within Tunnels for the Potential Yucca Mountain Repository." *Bulletin of Volcanology*. Vol. 70, No. 8. pp. 947–960. 2008.

This article describes igneous activity analog experiments designed to simulate sustained flow of ascending magma and exsolved volatiles from a vertical dike into a hypothetical drift at the potential Yucca Mountain repository. These models help bound uncertainties in predicting the eruptive style of an actively degassing magmatic system and the subsequent effects in the event that basaltic magma was to entrain nuclear waste material.

Phillips, J.C., T. Menand, R.S.J. Sparks, A.J. Hogg, J.A. Stamatakos, and N.K. Adams. 05/29/2008. "Final Revision of the Steady State Interaction of Rising Magma Within Drifts: Summary Report of Magma Flow Dynamics in the Potential Yucca Mountain Repository From Experimental Studies Performed at the University of Bristol, Bristol, United Kingdom." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 2008.
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Stamatakos, J., S. Biswas, and M. Silver. 04/13/2007. "Supplemental Evaluation of Geophysical Information Used to Detect and Characterize Buried Volcanic Features in the Yucca Mountain Region." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2007.
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Woods, A.W., O. Bokhove, A. de Boer, and B.E. Hill. "Compressible Magma Flow in a Two-Dimensional Elastic-Walled Dike." *Earth and Planetary Science Letters.* Vol. 246, Nos. 3-4. pp. 241–250. 2006.

Woods, A.W., S. Sparks, O. Bokhove, A-M. LeJeune, C.B. Connor, and B.E. Hill. "Modeling Magma–Drift Interaction at the Proposed High-Level Radioactive Waste Repository at Yucca Mountain, Nevada, U.S.A." *Geophysical Research Letters.* Vol. 29, No. 13. pp.19-1–19-4. DOI: 10.1029/2002GL014665. 2002.

Young, S.R., H.L. McKague, and R.W. Terhune. 10/07/1994. "Influence of Faults on Ascent of Mafic Magma by Dike Intrusion." CNWRA 94-025. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 1994.
20.05702.425, Q199410190001 ML040160563

This report describes and analyzes a preliminary numerical study of the effects of intersection depth and fault dip on the upward transport of magma.

8 STRUCTURAL GEOLOGY AND SEISMICITY

Bennett, R.A., J.L. Davis, P. Elosegui, B.P. Wernicke, J.K. Snow, M.J. Abolins, M.A. House, G.L. Stirewalt, and D.A. Ferrill. 09/18/1997. "Global Positioning System constraints on Fault Slip Rates in the Death Valley, Region, California and Nevada." *Geophysical Research Letters.* Vol. 24. 3,073–3,076. 1997.

Biswas, S. and J. Stamatakos. 12/14/2007. "Evaluation of the Regional Scale Geologic Cross Section Interpretations at Yucca Mountain Based on Modeling of U.S. Department of Energy (DOE) Aeromagnetic Anomalies Data." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 2007.
20.06002.01.292.730, Q200712140016, ML073510141

This report describes modeling analyses obtained using 2004 DOE aeromagnetic data to evaluate uncertainties in four existing regional-scale geologic cross section interpretations.

Connor, C.B., J.A. Stamatakos, D.A. Ferrill, B.E. Hill. "Technical Comment on 'Anomalous Strain Rates in the Yucca Mountain Area, Nevada,' by Wernicke, et al." *Science.* Vol. 282. pp. 1007b–1009b. 1998.

Dunne, W.M., D.A. Ferrill, J.G. Crider, B. Hill, P. La Femina, D. Waiting, A.P. Morris, and R. Fedors. 2003. "Orthogonal Jointing During Coeval Igneous Degassing and Normal Faulting, Yucca Mountain, Nevada." *Geological Society of America Bulletin.* Vol. 115. pp. 1,492–1,509. 2003.

Ferrill, D.A. "Critical Re-evaluation of Differential Stress Estimates From Calcite Twins." *Tectonophysics.* Vol. 285 pp. 77–84. 1998.

Ferrill, D.A. and A.P. Morris. "Geometric Considerations of Deformation Above Curved Normal Faults and Salt Evacuation Surfaces." *The Leading Edge.* Vol. 16. pp. 1,129–1,133. 1997.

Ferrill, D.A. and A.P. Morris. "Displacement Gradient and Deformation in Normal Fault Systems." *Journal of Structural Geology.* Vol. 23. pp. 619–638. 2001.

Ferrill, D.A., A.P. Morris, S.M. Jones, and J.A. Stamatakos. "Extensional Layer-Parallel Shear and Normal Faulting." *Journal of Structural Geology.* Vol. 20. pp. 355–362. 1998.

Ferrill, D.A., A.P. Morris, J.A. Stamatakos, D.J. Waiting, R.A. Donelick, and A.E. Blythe. 09/19/2011. "Fission Track Constraints on Exhumation and Extensional Faulting in Southwest Nevada and Eastern California, U.S.A." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.145, Q201109190005, ML112630153

This report presents the entire fission-track data set collected from the Yucca Mountain region by the Center for Nuclear Waste Regulatory Analyses since 1993, as well as other published data from the region, and provides a summary of results and the constraints provided by the data on the timing and rate of lower crustal exhumation in the Yucca Mountain region.

Ferrill, D.A., J.A. Stamatakos, **S.M. Jones, B. Rahe, H.L. McKague, R.H. Martin, and A.P. Morris**. "Quaternary Slip History of the Bare Mountain Fault (Nevada) from the Morphology and Distribution of Alluvial Fan Deposits." *Geology.* Vol. 24. pp. 559–562. 1996. 20.05704.164, Q199603060008

Ferrill, D.A., J.A. Stamatakos, and H.L. McKague. "Quaternary Slip History of the Bare Mountain Fault (Nevada) From the Morphology and Distribution of Alluvial Fan Deposits: Reply." *Geology.* Vol. 25. p. 190. 1997.

Ferrill, D., J. Stamatakos, A.P. Morris, R.A. Donelick, A.E. Blythe, S.M. Jones, and K. Spivey. 07/14/1997. "Geometric, Thermal, and Temporal Constraints on the Tectonic Evolution of Bare Mountain, Nevada."
20.05708.471.731, Q199709030009, ML061070270
Unpublished manuscript prepared for Geological Society of America Bulletin

Ferrill, D.A., J.A. Stamatakos, and D.W. Sims. "Normal Fault Corrugation: Implications for Growth and Seismicity of Active Normal Faults." *Journal of Structural Geology.* Vol. 21. pp. 1,027–1,038. 1999.

Ferrill, D.A., G.L. Stirewalt, D. Brent Henderson, J.A. Stamatakos, A.P. Morris, B.P. Wernicke, and K.H. Spivey. 08/25/1995. "Faulting in the Yucca Mountain Region: Critical Review and Analyses Tectonic Data from the Central Basin and Range Region. CNWRA 95-017. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1995.
20.05704.167.504, Q199509050028, ML040330873

Gray, M.B., J.A. Stamatakos, D.A. Ferrill, and M.A. Evans. 2005. "Fault Zone Deformation Process in Miocene Tuffs at Yucca Mountain, Nevada." *Journal of Structural Geology.* Vol. 27. pp. 873–1891. 2005.

Gonzalez, S.H., A.P. Morris, G.I. Ofoegbu, K.J. Smart, and J.A. Stamatakos. 08/22/2006. "Review of Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada." Rev. 2 San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2006.
20.06002.01.352.610, Q200608220001, ML062510008
This report provides an evaluation of the U.S. Department of Energy (DOE) report "Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada". This evaluation includes a comprehensive review of the technical bases used by the DOE to support the proposed bounding value for horizontal peak ground velocity, and a summary of current and ongoing research in the field of earthquake mechanics with particular emphasis on current or future research that could be used to support or refute the proposed bounding value for horizontal peak ground velocity.

Huyse, L., R. Chen, and J.A. Stamatakos. "Application of Generalized Pareto Distribution to Constrain Uncertainty in Low-Probability Peak Ground Accelerations." *Bulletin of the Seismological Society of America.* Vol. 100. pp 87–101. 2010.

McKague, H.L. 06/11/1996. "Identification of Type II Faults in the Yucca Mountain Region." (Supplement). San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1996.
20.05708.471.620, Q200310210002, ML040220060

*This report examined more than 400 faults within 100 km [60 mi] of the proposed Yucca Mountain repository site to identify faults as candidates for more detailed investigations. This report is a revision of a report that was first transmitted 04/12/1996. Note that some figures, on pages 11 through 18, were not included in this version of the report due to technical difficulties in retransmitting the images. However, the missing figures can be viewed on pages 11 through 18 in the April 1996 version of the report (*20.05708.471.620, Q199604230008, ML040220033).

McKague, L., D. Ferril, K. Smart, J. Stamatakos, and D. Waiting. 12/15/2010. "Synthesis Report for Yucca Mountain Region Tectonic Models." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 2010.
20.14002.01.441.102, Q201012150001, ML103500198

This report provides a review of the tectonic models proposed for the Yucca Mountain region.

McKague, H.L., J.A. Stamatakos, and D.A Ferrill. 01/30/1997. "Type I Faults in the Yucca Mountain Region." Rev. 1. CNWRA 96-007. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 1996.
20.05708.471, Q200310210003, ML040220051

Morris, A.P. and D.A. Ferrill. "Constant Thickness Deformation Above Curved Normal Faults." *Journal of Structural Geology.* Vol. 21. pp. 67–83. 1999.

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Morris, A.P., D.A. Ferrill, D.W. Sims, N. Franklin, D.J. Waiting. "Patterns of Fault Displacement and Strain at Yucca Mountain, Nevada." *Journal of Structural Geology*. Vol. 26. pp.1,707–1,725. 2004.

Morris, A.P., S.R. Young, and W.L. Stirewalt. 09/29/1992. "Geometric Analysis of Alternative Models of Tectonic Faulting at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1992.
20.03702.132, Q199210050008, ML033650067

Newman, A.V., T.H. Dixon, G.I. Ofoegbu, and J.E. Dixon. "Geodetic and Seismic Constraints on Recent Activity at Long Valley Caldera, California: Evidence for Viscoelastic Rheology." *Journal of Volcanology and Geothermal Research.* Vol. 105. pp.183–206. February 2001.

G.I. Ofoegbu and D.A. Ferrill. "Mechanical Analyses of Listric Normal Faulting with Emphasis on Seismicity Assessment." *Tectonophysics.* Vol. 284. pp. 65–77. 1998.

Ofoegbu, G.I., D.A. Ferrill, K.J. Smart, and J.A. Stamatakos. 06/22/1998. "Patterns of Ground Motion Amplitudes From Numerically Simulated Earthquakes."
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Unpublished manuscript prepared for the Bulletin of the Seismological Society of America.

Rahe, **B., D.A. Ferrill, and A.P. Morris**. "Physical Analog Modeling of Pull-Apart Basin Evolution." *Tectonophysics.* Vol. 285. pp. 21–40. 1998.

The paper documents modeling results that constrain the sequence of structural evolution of pull-apart basins and factors controlling their overall model geometry. The results provide conceptual constraints for identifying the stage and development of pull-apart basins and characterizing earthquakes associated with the controlling strike slip systems.

Ridgway, K., J. Stamatakos, M. Gutenkunst, and P. Dubreuilh. 07/31/2011. "Stratigraphic Analysis and Regional Correlation of Oligocene and Early Miocene Strata in the Yucca Mountain Area." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2011.
20.14002.01.441.108, Q201108010001, ML112140240

Sims, D.W., D.A. Ferrill, and J.A Stamatakos. "Role of a Ductile Décollement in the Development of Pull-Apart Basins." *Journal of Structural Geology.* Vol. 21. pp. 533–554. 1999.

Sims, D.W., H.L. McKague, D.J. Waiting, and S.L. Colton. 10/16/2008. "Reconsideration of Geomorphic Evidence Regarding the Neotectonic Setting of Fortymile Wash, Nye County, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2008.
20.06002.01.292.700, Q200810160001, ML083030516

Sims, D.W., J.A. Stamatakos, D.A. Ferrill, H.L. McKague, D.A. Farrell, and A. Armstrong. 12/03/1999. "Three-Dimensional Structural Model of the Amargosa Desert, Version 1.0: Report to Accompany Model Transfer to the Nuclear Regulatory Commission." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 1999.
20.01402.471.040, Q199912080003, ML033630387

The report describes a three-dimensional structural model developed by CNWRA staff to analyze groundwater flow in the Amargosa Desert region. It provided the basic regional structural framework for abstraction into regional groundwater flow models. As more structural data became available, the model was revised and renamed as the Three-Dimensional Hydrogeologic Model of the Amargosa Desert (see 20.06002.01.272.621, Q200707060003, ML071900243 for Version 2.0).

Smart, K.J. 02/20/2004. "Examination of Effects of Geologic Features on Thermally Induced Stress at Yucca Mountain, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2004.
20.06002.01.051.470, Q200402240005, ML041670379

This report summarizes the assumptions and results of previous DOE thermal stress studies and considers how thermal stress distribution potentially may be affected by aspects of geology not fully explored in previous DOE work.

Stamatakos, J.A. and D.A. Ferrill. "Strike-Slip Fault System in Amargosa Valley and Yucca Mountain, Nevada." *Tectonophysics.* Vol. 294. pp. 151–160. 1998.

Stamatakos, J.A., D.A. Ferrill, and K.A. Spivey. "Paleomagnetic Constraints on the Tectonic History of Bare Mountain, Nevada." *Geological Society of America Bulletin.* Vol. 110 pp. 1,530–1,546. 1998.

Stamatakos, J., D.A. Ferrill, and A.P. Morris. 09/15/2011. "Age and Timing of Extensional Faulting and Basin Growth at Crater Flat, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.120, Q201109150005, ML112580263

Waiting, D.L., R. Chen, J.G. Crider, W.M. Dunne, R.W. Fedors, D.A. Ferrill, M.B. Gray, B.E. Hill, P.C. La Femina, H.L. McKague, A.P. Morris, D.W. Sims, and J.A. Stamatakos. 09/21/2001. "Technical Assessment of Structural Deformation and Seismicity at Yucca Mountain, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2001.
20.1402.471.120, Q20011004005, ML033630629

This report provides a summary of tectonic information relevant to understanding effects on igneous processes.

Young, S.R., A.P. Morris, and G.L. Stirewalt. 11/13/1992. "Preliminary Structural Interpretation of Reflection Seismic Line AV-1." CNWRA 92-024. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 1992.
20.05702.003, Q199211180014, ML040200192

Young, S.R. and G.L. Stirewalt. 09/28/1990. "Evaluation of Computer-Assisted Cross Section Balancing Methods of Analysis of Subsurface Fault Geometry in the Vicinity of Yucca Mountain, Nevada: A Pilot Study." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1990.
20.03702.002, Q199107230004, ML040220081

This pilot study evaluated the usefulness of computer-assisted geological cross section balancing methods in the geometric and kinematic analysis of subsurface structures in the vicinity of Yucca Mountain, including underlying listric normal fault and detachment fault geometries and their relationships in a linked fault system.

Young, S.R., G.L. Stirewalt, and A.P. Morris. 10/23/1992. "Geometric Models of Faulting at Yucca Mountain." CNWRA 92-008. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 1992.
20.05702.132, Q199210260004, ML033650105, ML033650108, ML033650111

9 CLIMATE AND INFILTRATION

Ababou, R. 06/12/1990. "High-Resolution Modeling of Strip Source Infiltration: Three-Dimensional Synthetic Experiment Analogous to Las Cruces Trench Experiment." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1990.
20.03704.051, Q199107160019 ML040210558

The paper describes how a high-resolution, three-dimensional finite difference model (BIGFLO) was used to model strip source infiltration and natural drainage in a randomly heterogeneous and imperfectly stratified soil. The flow regime, soil properties, and boundary conditions used were similar to those associated with a vadose zone hydrology experiment at the Las Cruces Trench Site in southern New Mexico.

Bagtzoglou, A.C., S.A. Stothoff, and M.A. Muller. 10/30/1995. "Progress Towards Estimating Infiltration and Deep Percolation at the Yucca Mountain Site." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1995.
20.05702.723, Q199601050012, ML040220364

This is a numerical modeling study that used a ten-year sequence of weather data. The simulations indicated that alluvial covers with higher values of permeability allow less liquid water to percolate in the deeper parts of the rock due to rate-limiting evaporation. Deep percolation simulations were conducted to address the effect of spatial and temporal averaging of infiltration and to develop an improved probability density function for percolation through the proposed repository horizon at two cross sections, including the Solitario Canyon fault area.

DeWispelare, A.R., L. Tandy Herren, M.P. Miklas, and R.T. Clemen. 08/30/1993. "Expert Elicitation of Future Climate in the Yucca Mountain Vicinity—Iterative Performance Assessment Phase 2.5." CNWRA 93-016. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1993.
20.05702.065.850.001, Q199309140002, ML033630407

Groeneveld, D.P., R.W. Fedors, and S.A. Stothoff. "Weedy Brome Grasses and Their Potential Effect on the Infiltration and Recharge Rates in the Vicinity of Yucca Mountain, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1999.
20.01402.861.985, Q199908260001, ML033630380

This report includes a brief botanical guide to plant species in the Yucca Mountain region.

Stothoff, S. 11/10/2009. "Subsurface Observations Related to Infiltration at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 2009.
20.14002.01.111.860, Q200911100001, ML093160095

This report summarizes geochemical and thermal information that the U.S. Department of Energy (DOE) used to estimate net infiltration and deep percolation fluxes at Yucca Mountain.

Stothoff, S. 08/21/2008. "Infiltration Tabulator for Yucca Mountain: Bases and Confirmation." CNWRA 2008-001. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2008.
20.14002.01.111.820, Q200808210003, ML082350701

This report is the third in a series of three reports assessing the role of climate change on infiltration at Yucca Mountain. This report describes the Infiltration Tabulator for Yucca Mountain (ITYM), a mathematical model that provides estimates of mean annual infiltration

and that was developed specifically to consider the potential effects of terrain and climate at Yucca Mountain, Nevada, under present and potential future conditions.

Stothoff, S.A. 09/29/2011. "Uncertainty and Variability: Water Flow Through Yucca Mountain Over the Next Million Years." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.130, Q201109290004

Stothoff, S.A. "Sensitivity of Long-Term Bare-Soil Infiltration Simulations to Hydraulic Properties in an Arid Environment." *Water Resources Research*. Vol. 33, No. 4. pp. 547–558. 1997.

This paper assesses the impact of hydraulic properties in two idealized simulations of infiltration through deep colluvium and alluvium to fractured, densely welded tuff.

Stothoff, S. and M. Musgrove. 11/14/2006. "Literature Review and Analysis: Climate and Infiltration." CNWRA 2007-002. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 2006.
20.06002.01.252.720, Q200611140002, ML063190115

This report is the first in a series of three reports assessing the role of climate change on infiltration at Yucca Mountain. The report documents a review of literature from outside of the Yucca Mountain program related to infiltration under climates analogous to climates that may occur at Yucca Mountain.

Stothoff, S. and G. Walter. 09/20/2007. "Long-Term Average Infiltration at Yucca Mountain, Nevada: Million-Year Estimates." CNWRA 2007-003. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2007.
20.06002.01.252.730, Q200709210002, ML072760607

This report is the second in a series of three reports assessing the role of climate change on infiltration at Yucca Mountain. In this report, the authors constructed potential future climate sequences based on orbital mechanics and paleoclimatic inferences, and used an infiltration tabulator model to estimate million-year-average net infiltration at Yucca Mountain for specified climatic sequences.

Stothoff, S.A, D. Or, D.P. Groeneveld, and S.B. Jones. 07/29/1997. "The Effect of Vegetation on Infiltration in Shallow Soils Underlain by Fissured Bedrock." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 1997.
20.05708.861.730, Q199709300002, ML040200076

The report describes field and modeling studies that were performed to achieve insight into the hydrologic behavior of a semi-arid environment characterized by shallow, permeable soils overlying bedrock with soil-filled fissures. Particular attention is given to the impact of vegetation on the hydrologic system, including the observation that widely spaced soil-filled fissures appear to be conducive to plant growth even when fissures are buried below soils as deep as 30 cm.

Walter, G. 12/09/2005. Revised: "Analysis of Factors Contributing to Uncertainty in Estimating Future Climates at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 2005.
20.06002.01.252.531, Q200512090004, ML053470163

This report summarizes the approach taken by the DOE to estimate the nature and sequence of future climate, and discusses the uncertainties that may affect those estimates.

Wittmeyer, G.W., M.P. Miklas, R.V. Klar, D. Williams, and D. Balin. 08/26/1996. "Use of Groundwater in the Arid and Semi-Arid Western United States: Implications for Yucca Mountain Area." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1996. 20.05708.771.640, Q199704250002, ML040160822

The report summarizes a survey of water well practices in four arid and semi-arid southwestern states: Arizona, Nevada, New Mexico, and Texas. Water wells drilled deeper than 150 m are tabulated, located, and described by intended use. Wells which provide water from more than 240 m depth are discussed individually. Representative costs of typical public water supply and agricultural deep wells are presented.

Woolhiser, D.A., R.W. Fedors, R.E. Smith, and S.A. Stothoff. "Estimating Infiltration in the Upper Split Wash Watershed, Yucca Mountain, Nevada." *Journal of Hydrologic Engineering. Vol. 11, No. 2. pp. 123-134.* 2006.

The authors used a distributed rainfall-runoff model (KINEROS2) and precipitation measurements to estimate the spatial distribution of storm and mean annual infiltration into soils and bedrock on hillslopes and channels of a small watershed on Yucca Mountain , Nevada. The objective was to examine the impact of the runoff-runon phenomenon on the possible spatial focusing of net infiltration.

10 EVOLUTION OF THE NEAR-FIELD ENVIRONMENT

These are reports or papers that focus primarily on coupled processes (thermal, hydrological, mechanical, and chemical) that are expected to change over time in the repository near-field.

Ahola, M. P. 09/27/1995. "Expert-Panel Review of Center for Nuclear Waste Regulatory Analyses (CNWRA) Coupled Thermal-Mechanical-Hydrological Processes Research Project." CNWRA 95-021. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1995.
20.05704.036, Q199511070005, ML040220346

An independent panel of five experts reviewed the ongoing research on coupled thermal-mechanical-hydrological (TMH) processes at the Center for Nuclear Waste Regulatory Analyses (CNWRA). The goals of the review were to (i) critically review the objectives and approaches of CNWRA coupled TMH research and its application to licensing issues at the proposed Yucca Mountain high-level waste repository site, (ii) recommend improvements to the research scope and methodologies, and (iii) investigate new issues that may not be part of the original research plans. This report includes the individual summary reports and responses to each reviewer's comments and recommendations.

Ahola, M.P., S.-M. Hsiung, L.J. Lorig, and A.H. Chowdhury. 04/01/1992. "Thermo-Hydro-Mechanical Coupled Modeling: Multiple Fracture Model, BMT2; Coupled Stress-Flow Model, TC1, DECOVALEX Phase 1." CNWRA 92-005. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1992.
20.03704.039, Q199204150012, ML040330769

Ahola, M.P., A. Thoraval, and A.H. Chowdhury. "Distinct Models for the Coupled T-M-H Processes: Theory and Implementation." Chapter 7, *Coupled Thermo-Hydro-Mechanical Processes of Fractured Media*. O. Stephansson, L. Jing, and C-F. Tsang, eds. Developments in Engineering, 79. Amsterdam, The Netherlands: Elsevier Science. pp. 181–211. 1996.

Ahola, M.P., S.-M. Hsiung, and D.D. Kana. "Experimental Study on Dynamic Behavior of Rock Joints." Chapter 18, *Coupled Thermo-Hydro-Mechanical Processes of Fractured Media*. O. Stephansson, L. Jing, and C-F. Tsang, eds. Developments in Engineering, 79. Amsterdam, The Netherlands: Elsevier Science. pp. 467–494. 1996.

Ahola, M.P., L.J. Lorig, A.H. Chowdhury, and S.-M. Hsiung. 08/30/1993. "Thermo-Hydro-Mechanical Coupled Modeling: Near Field Repository Model, BMT3." CNWRA 93-002. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1993. 20.05704.039.020, Q199311090002, ML040200648

The report presents results of a distinct element analysis as part of the Phase II activities of the international cooperative project DECOVALEX (acronym for the DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation). The analysis was conducted for the benchmark test problem identified as the Near-Field Repository Model (BMT3), using the Universal Distinct Element Code (UDEC). The test problem was designed to compare modeling results based on both continuum and discontinuum approaches for simulating coupled thermal-hydrological-mechanical (THM) behavior for a near-field repository.

Ahola, M.P., S. Mohanty, and A. Makurat. "Coupled Mechanical Shear and Hydraulic Flow Behavior of Natural Rock Joints." Chapter 15, *Coupled Thermo-Hydro-Mechanical Processes of Fractured Media*. O. Stephansson, L. Jing, and C-F. Tsang, eds. Developments in Engineering, 79. Amsterdam, The Netherlands: Elsevier Science. pp. 393–423. 1996.

Ahola, M.P., G.I. Ofoegbu, A.H. Chowdhury, and S.-M. Hsiung. 09/29/1994. "Thermo-Hydro-Mechanical Coupled Modeling: Big-Ben Experiment, TC3—Decovalex-Phase III." CNWRA 94-021. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1994.
20.05704.039, Q199410140002, ML040230574

Angell, P., J.A. Apps, G.A. Cragnolino, S.M. Hsiung, P.C. Lichtner, W.M. Murphy, P. Pabalan, D.A. Pickett, N. Sridhar, S.A. Stothoff, and D.A. Turner. 06/27/1996. "Evolution of the Near-Field Environment in the Proposed High-Level Waste Repository at Yucca Mountain—A Review of Hypotheses." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1996.
20.05708.561.620, Q199607160004, ML040230602

This report presents a review of hypotheses on the evolution of the near-field environment, primarily gleaned from the literature. An effort is made to evaluate the set of processes and the environmental parameters that may have important impacts on performance. Specifically, the report addresses thermal-hydrologic effects, hydrothermal-chemical effects, radiolysis effects on radionuclide mobilization, thermal-mechanical effects, cementitious materials, corrosion of container materials, waste form alteration products, microbiological effects, and near-field transport processes.

Baca, R.B. and M.S. Seth. 02/27/1996. "Benchmark Testing of Thermohydrologic Computer Codes." CNWRA 96-003. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1996.
20.05708.661, Q199603220008, ML040220029

Three major objectives of this benchmark testing study were to (i) compare and contrast the simulation capabilities of the U.S. Nuclear Regulatory Commission (NRC)/CNWRA codes with those of the U.S. Department of Energy (DOE), (ii) identify and understand any significant differences that may arise between DOE and NRC/CNWRA code applications, and (iii) assess the robustness and computational efficiencies of the codes. Four thermohydrologic codes (CTOUGH, MULTIFLO, TOUGH2, and FEHMN) were evaluated and compared in terms of capability to simulate diverse conditions and overall computational efficiency.

Basagaoglu, H., K. Das, R. Fedors, R. Green, C. Manepally, S. Painter, O. Pensado, S. Stothoff, J. Winterle, and D. Wyrick. 10/24/2007. "Seepage Workshop Report." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2007.
20.06002.01.262.760, Q200710250004, ML072980846 ["Part A"], ML072980851 ["Part B"], ML072980850 ["Part C"]

This report documents updates to the CNWRA staff's technical basis for the seepage factors used in abstractions in TPA Version 5.1. Discussions include conceptualizations related to seepage such as ambient and thermal seepage, seepage-related parameters, and the technical basis for fluid and heat flow parameters used in TPA Version 5.1.

Das, K., C. Manepally, R. Fedors, and D. Basu. 09/16/2011. "Numerical and Experimental Study of In-Drift Heat and Mass Transfer Processes". San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.136, Q201109160001, ML112590142

Fedors, R., S. Green, D. Walter, D. Farrell, S. Svedeman, F. Dodge, and R. Hart. 03/18/2004. "Environmental Conditions in Drifts." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2000.
20.06002.01.091.410, Q200403220002, ML061310419

This report presents in-drift temperature and relative humidity estimates for two scenarios, with drift degradation and without drift degradation. Environmental conditions along a typical drift are assessed to support estimates of the onset and duration of conditions conducive to corrosion, and to provide input for computational fluid dynamics models of in-drift air flow and moisture redistribution to model natural convection in heated drifts.

Green, R.T. and S.L. Painter. 09/21/2007. Revised: "Numerical Simulation of the Drift-Scale Heater Test at Yucca Mountain: September 2002 Status Report." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: September 2007.
20.06002.01262.709, Q200709240001, ML072670518

This report documents the CNWRA thermohydrological modeling analysis of the Drift-Scale Heater Test to predict the temperature and saturation distribution in the rock during the heating and cooling phases of the test. The outcome of these predictive analyses is compared with temperatures measured during 4 years of heating. A CNWRA-developed multiphase code (MULTIFLO) was used in all simulations.

Green, R.T., F.T. Dodge, and G. Rice. 12/15/1994. "Prediction of Thermally-Driven Flow at Different Scales." 1994.
20.05704.023, Q199412270001, ML061370333

This unpublished journal manuscript describes work conducted to assess fluid flow regimes at different scales, to assess work performed by DOE in their coupled Thermal-Hydrologic-Mechanical-Chemical tests.

Green, R.T., F.T. Dodge, S.J. Svedeman, R.D. Manteufel, G. Rice, K.A. Meyer, and R.G. Baca. 05/25/1995. "Thermally Driven Moisture Redistribution in Partially Saturated Porous Media." CNWRA 95-05. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1995.
20.05704.027, Q199505300001, ML040160742

Also published as NUREG/CR-6348

Green, R.T., C. Manepally, R.W. Fedors, and M.M. Roberts. 10/28/2008. "Examination of Thermal Refluxing in In-Situ Heater Tests."
20.14002.01.121.840, Q200810280007, ML083030097

The report summarizes experimental data, theoretical developments, and evaluation of scaling relationships from studies conducted over a two-year period in the Thermohydrology Research Project. During the studies, a series of laboratory experiments was conducted in a variety of media to study the physics of thermally driven moisture redistribution. Principles of similarity theory were applied to develop dimensionless parameters to be used to predict thermohydrologic behavior at the field and repository scales from that observed at the laboratory scale. Numerical modeling of two-phase flow phenomena was used to evaluate the scaling theories and interpret the experimental results.

Green, R., R Manteufel, S. Svedeman, and F. Dodge. 04/08/1992. "Theoretical and Experimental Investigation of Thermo-Hydrologic Processes in a Partially Saturated, Fractured Porous Medium: A Summary of Work Through December 1991." CNWRA 92-006. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 1992. 20.03704.023, Q199204130001, ML040330762

The Thermohydrology Research Project was undertaken in 1989 by CNWRA to assess coupled interactions, identify a representative elementary volume for unsaturated fractured rock, assess the role of fractures with regard to impeding or augmenting groundwater flow, identify those parameters critical to understanding the heat and mass transfer in the geologic system, extrapolate laboratory and field data and model validation. The purpose of the project was to expand the knowledge base of thermohydrologic phenomena, primarily derived from studies of geothermal systems, soil physics, and the drying of porous media, to conditions more applicable to the proposed high-level waste repository in a zone of highly fractured, low-permeability rock. This report summarizes the activities conducted and results of the program in its first year or so. (Also published as NUREG/CR-6026.)

Green, R., S. Painter, B. Fratesi, C. Manepally, and G. Walter. 08/28/2003. "Status Report for Multiphase Numerical Simulation." CD-ROM includes Appendixes A thru G. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 2003. 20.06002.01.091.330, Q200309020006, ML040350704

This report documents analyses conducted by the CNWRA to evaluate conceptual models and key property value assignments in numerical models used to simulate heat and mass transfer processes. The assessment used results from two experiments, one of which was conducted at laboratory scale by CNWRA staff and the other by the DOE at the field scale at the Exploratory Studies Facility at Yucca Mountain. The objective of the analyses was to evaluate the importance and effects of conceptual model selection, boundary condition prescription, and property value assignment. A CNWRA-developed multiphase modeling code (MULTIFLO, Version 1.5.2) was used to perform all the simulations.

Hsiung, S.-M. and A.H. Chowdhury. 03/27/2003. "Final Report for DECOVALEX III Task 2C: Thermal-Mechanical Modeling of the Drift-Scale Heater Test at Yucca Mountain." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2003. 20.06002.01.101.310, Q200304010005, ML033640578

Hsiung, S.-M., A.H. Chowdhury, and M.S. Nataraja. "Numerical Simulation of Thermal-Mechanical Processes Observed at the Drift-Scale Heater Test at Yucca Mountain, Nevada, USA." *International Journal of Rock Mechanics and Mining Sciences*. Vol. 42. No. 5–6. pp. 652–666. July–September 2005.

Hughson, D.L. and F.T. Dodge. "The Effect of Cavity Wall Irregularities on Seepage Exclusion from Horizontal Cylindrical Underground Openings. *Journal of Hydrology.* Vol. 228. pp. 206–214. 2000.

Lichtner, P.C. and J.C. Walton. 12/30/1994. "Near-Field Liquid-Vapor Transport in a Partially Saturated High-Level Nuclear Waste Repository." CNWRA 94-022. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 1994. 20.05702.723450, Q199411010003, ML040160575

The report describes an auxiliary CNWRA analysis conducted to estimate the time to wetting and fluid fluxes in the proposed repository at Yucca Mountain. The heat transfer and two-phase flow conditions in the repository were analyzed for the various heat loadings, with calculations performed using a CNWRA version (CTOUGH) of the VTOUGH computer code.

Manepally, C., S. Green, F. Viana, and R. Fedors. 04/16/2007. "Evaluation of In-Drift Heat Transfer Processes." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 2007.
20.06002.01.262.720, Q200704170002, ML071070508

This report summarizes CNWRA investigations of the combined effect of the thermal processes and moisture redistribution in drifts using laboratory and numerical models. In particular, this report describes an intermediate scale (20-percent of drift scale) experiment and a related numerical model that were developed to provide confidence in the modeling capabilities. The experimental setup simulates the effects of uniform and nonuniform heat load distributions between the waste packages.

Manepally, C., A. Sun, R. Fedors, and D. Farrell. 06/30/2004. "Drift-Scale Thermohydrological Process Modeling—In-Drift Heat Transfer and Drift Degradation." CNWRA 2004-05. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2004.
20.06002.01.091.420, Q200407020002, ML042160447

This report describes a coupled thermohydrological detailed process model that integrates in-drift and near-field heat transfer processes. Such process models provide the in-drift and near-field thermohydrological conditions that are needed to determine the composition of pore water that may contact the waste package and to evaluate the potential of corrosion of waste packages, and they serve as a basis for model abstractions used in performance assessment. A two-dimensional drift-scale model using the MULTIFLO code (Version 2.0) was developed as part of this study. In addition, a separate two-dimensional drift-scale model was developed to incorporate the effects of drift degradation. The report also contains results of sensitivity analyses of significant parameters and a comparison of results with previous model conclusions.

Manteufel, R.D. "Effects of Ventilation and Backfill on a Mined Waste Disposal Facility." *Nuclear Engineering and Design*. Vol. 172, No. 1–2. pp. 205–219. 1997.

Manteufel, R., M. Ahola, D. Turner, and A. Chowdhury. 03/04/1993. NUREG/CR–6021, "A Literature Review of Coupled Thermal-Hydrologic-Mechanical-Chemical Processes Pertinent to the Proposed High-Level Nuclear Waste Repository." CNWRA 92-011. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 1993.
20.05702.023.010.001, Q199303080003, ML012750463

The literature review focuses on identifying coupling mechanisms between individual processes and assessing their importance (i.e., if the coupling is important, potentially important, or negligible). The significance of considering thermal-hydrologic-mechanical-chemical coupled processes lies in whether or not the processes impact the design and/or performance objectives of the repository.

Phillips, O.M.. . "Infiltration of a Liquid Finger Down a Fracture Into Superheated Rock." *Water Resources Research.* Vol. 32, No. 6. pp. 1660–1670. 1996.

This article describes an analysis conducted to estimate the thermal protection from focused liquid infiltration in fractures. The model accounts for the heat transfer and two-phase vaporization expected to control focused liquid infiltration into hot dry rock. The rate of liquid penetration and the maximum stable penetration depth are estimated using both scaling principles and numerical calculations.

Mintz, T., R. Pabalan, and C. Manepally. 09/23/2011. "Bench-Scale Tests of a Yucca Mountain Heated Drift Environment." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.153, Q201109230001, ML112660404

Mohanty, S. "Effect of Multiphase Fluid Saturation on the Thermal Conductivity of Geologic Media." *Journal of Physics D. Applied Physics.* Vol. 30. p. L80–L84. 1997.

Mohanty, S. and G. Adams. 01/13/2006. "An Abstracted Model for Estimating Temperature and Relative Humidity in the Proposed Repository at Yucca Mountain." (unpublished manuscript)
20.06002.01.352.609, Q200601190001, ML071690513

The paper describes an analysis conducted to estimate the thermal protection from focused liquid infiltration in fractures. The model accounts for the heat transfer and two-phase vaporization expected to control focused liquid infiltration into hot dry rock. The rate of liquid penetration and the maximum stable penetration depth are estimated using both scaling principles and numerical calculations.

Murphy, W.M., C.J. Freitas, and P.C. Lichtner. 12/12/1995. "A Numerical Model for the Evolution of the Carbon System Geochemistry at the Proposed Nuclear Waste Repository at Yucca Mountain, Nevada, USA." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1995.
20.05702.723.545, Q199603060014, ML061370439

This paper summarizes the theoretical framework developed to describe liquid and gas phase transport coupled with the local equilibrium carbon system chemistry and near-field thermohydrologic conditions. The paper presents some simulation results for the proposed high-level waste repository.

Murphy, W.M., R.T. Pabalan, J.D. Prikryl, and C.J. Goulet. "Reaction Kinetics and Thermodynamics of Aqueous Dissolution and Growth of Analcime and Na-Clinoptilolite at 25 degrees C." *American Journal of Science.* Vol. 296. pp. 128–186. 1996.

This paper describes low-temperature (25 °C), long-term (up to 2.6 yr) batch-type dissolution and precipitation experiments that were conducted to examine reaction kinetics and thermodynamics of aqueous dissolution and growth of analcime and Na-clinoptilolite at pH values close to 9.

Ofoegbu, G.I., A.C. Bagtzoglou, R.T. Green, and M. Muller. "Effects of Perched Water on Thermally Driven Moisture Flow at the Proposed Yucca Mountain Repository for High Level Waste." *Nuclear Technology*. Vol. 125, No. 2. pp. 235–253. 1999.
20.05708.661, Q199709030002

Ofoegbu, G.O., S. Painter, R. Chen, R.W. Fedors, D.A. Ferrill. "Geomechanical and Thermal Effects on Moisture Flow at the Proposed Yucca Mountain Nuclear Waste repository." *Nuclear Technology.* Vol. 134. p. 241–262. 2001.

Ofoegbu, G.I., A. Ghosh, M.P. Ahola, S.-M. Hsiung, and A.H. Chowdhury. 08/30/1995. "Evaluation of ABAQUS as a Compliance Determination Computer Code." CNWRA 95-016. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1995.
20.05702.623, Q199509210012, ML040330880

This work evaluated the computer code ABAQUS to determine whether the code would be suitable as a compliance-determination computer code to assess the impact of

thermal-mechanical effects on near-field fluid flow and, in turn, on the capability of the proposed repository to provide effective isolation of the proposed types and quantities of radioactive waste. Therefore, the code was evaluated with respect to its capabilities to model coupled thermal, mechanical, and hydrologic processes in a fractured rock mass.

Shukla, P.K., B. Dasgupta, S. Chocron, W. Li, and S. Green. 05/07/2007. "Thermal Modeling of a Storage Cask System: Capability Development." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 2007.
20.06002.01.332.640, Q200705070003, ML071280826

The report examines how the use of transportation, aging, and disposal canisters in a repository could affect the thermal regimes.

Vidal, O. and W.M. Murphy. "Calculation of the Effect of Gaseous Thermodiffusion and Thermogravitation Processes on the Relative Humidity Surrounding a High Level Nuclear Waste Canister." *Waste Management.* Vol. 19. pp. 189–198. 1999.

11 CORROSION OF ENGINEERED MATERIALS

Most of these reports and papers deal with waste package container corrosion processes; a few involve corrosion of drip shield materials and other metals.

Agarwal, S. and P. Shukla. 09/15/2011. "Critical Crack Dimensions for Advective Flow of Aqueous Solutions Through Elliptical Stress Corrosion Cracks" September 2011. 20.14002.01.441.188, Q201109150002, ML112580209

Ahn, T., H. Jung, X. He, and O. Pensado. "Understanding Long-Term Corrosion of Alloy 22 Container in the Potential Yucca Mountain Repository for High-Level Nuclear Waste Disposal." *Journal of Nuclear Materials.* Vol 379, No. 1–3. pp. 33-41. 2008.

Brossia, C.S. and G.A. Cragnolino. "Effect of Environmental Variables on Localized Corrosion of Carbon Steel." *Corrosion.* Vol. 56. pp. 505–514. May 2000.

Brossia, C.S. and G.A. Cragnolino. "Effect of Palladium on the Corrosion Behavior of Titanium." *Corrosion Science.* Vol. 46, No. 7. pp. 1,693–1,711. July 2004.

Brossia, C.S. and G.A. Cragnolino. "Effects of Environmental and Metallurgical Conditions on the Passive and Localized Dissolution of Ti-0.15%Pd." *Corrosion.* Vol. 57, No. 9. pp. 768–776. 2001.

Chiang, K. 09/02/2011. "Interactions Between Magma and Waste Containers." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011. 20.14002.01.441.106, Q201109020014, ML112450439

Chiang, K. 09/02/2011. "Stress Corrosion Cracking of Weldment of Nuclear Waste Outer Container Material." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.134, Q201109020012, ML112450432

Chiang, K. and L. Yang. 09/23/2011. "Techniques for Monitoring Localized Corrosion at High Temperatures." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.174, Q201109230002, ML112660316

Chiang, K.T., D.S. Dunn, and G.A. Cragnolino. "Effect of Simulated Groundwater Chemistry on Stress Corrosion Cracking of Alloy 22." *Corrosion.* Vol. 63. pp. 940–950. 2007.

Chiang, K.-T., D.S. Dunn, Y.-M. Pan, O. Pensado, and P.K. Shukla. 12/21/2006. "Stress Corrosion Cracking for Waste Package Materials—Modeling and Experiments." CNWRA 2007-01. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 2006.
20.06002.01.322.620, Q200701020001, ML070030061

Cragnolino, G.A. and N. Sridhar. "Localized Corrosion of a Candidate Container Material for High-Level Nuclear Waste Disposal." *Corrosion.* Vol. 47. pp. 464–472. June 1991.

Cragnolino, G. and N. Sridhar. 02/19/1993. "Long-Term Stability of High-Level Waste Container Materials: I-Thermal Stability of Alloy 825." CNWRA 93-003. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1993.
20.05704.043.103, Q199303020004, ML040200291

Cragnolino, G. and N. Sridhar. 08/01/1992. "A Review of Stress Corrosion Cracking of High-Level Nuclear Waste Containers Materials—I." CNWRA 92-021. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1992.
20.03704.042, Q199209140004, ML033640122

This report reviews the literature on stress corrosion cracking (SCC) of the candidate container materials for the proposed Yucca Mountain repository site, including Fe-Cr-Ni alloys and copper-based alloys. The advantages and limitations of different stress corrosion cracking (SCC) test methods are discussed in terms of their suitability for determining parameters that can be used for long-term prediction of SCC resistance performance, followed by a detailed review of investigations conducted by various laboratories and a review of results available in the general literature for the materials considered.

Cragnolino, G.A., D.S. Dunn, S. Brossia, Y.-M. Pan, O. Pensado, and L. Yang. "Corrosion Behavior of Waste Package and Drip Shield Materials." *Nuclear Technology*. Vol. 148, No. 2. pp. 166–173. 2004.

Cragnolino, G.A., D.S. Dunn, N. Sridhar. "Environmental Factors in the Stress Corrosion Cracking of Type 316L Stainless Steel and Alloy 825 in Chloride Solutions." *Corrosion.* Vol. 52, No. 3. pp. 194–203. 1996.

Cragnolino, G.A., D.S. Dunn, and N. Sridhar. 11/02/1994. "Environmental Effects on Stress Corrosion Cracking of Type 316L Stainless Steel and Alloy 825 as High-Level Nuclear Waste Container Materials." CNWRA 94-028. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 1994.
20.05704.042.255, Q199411150002, ML040360661

Cragnolino, G.A., H.K. Manaktala, and Y.-M. Pan. 05/23/1996. "Thermal Stability and Mechanical Properties of High-Level Radioactive Waste Container Materials: Assessment of Carbon and Low-Alloy Steels." CNWRA 96-004. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1996.
20.05708.571, Q199607160007, ML040230612

Cragnolino, G.A., S. Mohanty, D.S. Dunn, N. Sridhar, and T. Ahn. "An Approach to the Assessment of High-Level Radioactive Waste Containment I-Waste Package Degradation." *Nuclear Engineering and Design Journal.* Vol. 201 pp. 289–306. September 2000.

Cragnolino, G.A., Y.-M. Pan, D. Turner, and E. Pearcy. 01/15/2004. "Natural Analogs of High-Level Container Materials—Experimental Evaluation of Josephinite." CNWRA 2004-02. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2004.
20.06002.01.081.340, Q200401190012, ML041390323

Cragnolino, G.A., H. Pennick, N. Sridhar, and T.Y. Torng. "Application of a Transient Crevice Corrosion Model to the Prediction of Performance of High-Level Nuclear Waste Container Materials." *Life Predictions of Corrodible Structures.* R.N. Parkins, ed. Houston, Texas: NACE International. Vol. 1. pp. 429–453. 1994.
Q199203100004, 20.03702.013

The initiation of crevice corrosion of austenitic container materials is examined through an extension of the Watson-Postlethwaite model to higher temperatures. The model predicts that increasing the temperature will lower the crevice corrosion initiation time, mainly through its effect on the hydrolysis equilibria.

Cragnolino, G., N. Sridhar, J. Walton, R. Janetzke, T. Torng, J. Wu, and P. Nair. 12/17/1994. "Substantially Complete Containment–Example Analysis of a Reference Container." CNWRA 94-003. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 1994.
20.05702.551.410, Q199403160011, ML033640232

This report presents the analyses and results of an example problem conducted in support of evaluating the "substantially complete containment" rule for waste packages in 10 CFR Part 60. Several models representing the repository thermal fields, near-field environment, corrosion of container materials, including localized corrosion and stress corrosion cracking, as well as mechanical failures were coupled to calculate the time-to-wetting and the time-to-failure of waste packages for an unsaturated repository site. A probabilistic method was adapted to generate cumulative distribution functions (CDFs) for failures of multiple waste packages arranged in a simulated square repository. For evaluating the various corrosion processes, the corrosion potential is used as a key parameter in conjunction with critical potentials for localized corrosion. This concept is shown to be a generally powerful approach for evaluating waste package lifetimes in a geologic repository.

Csontos, A., T. Ahn, A. Passarelli, Y.-M. Pan, D.S. Dunn, and L. Yang. "The Evaluation of Corrosion Processes for Engineered Barrier Systems." *JOM.* Vol. 57, No. 1. pp. 36-42. 2005.

Csontos, A.A., Y.-M. Pan, D.S. Dunn, L. Yang, and G.A. Cragnolino. "The Effect of Potential and Aging on the Pb-Assisted Stress Corrosion Cracking Susceptibility of Alloy 22 Gas Tungsten Arc-Welded Weldments." *Metallurgical and Materials Transactions A—Physical Metallurgy and Materials Science.* Vol. 36A, No. 5. pp. 1,169–1177. 2005.

Dunn, D.S. and G.A. Cragnolino. 08/01/1997. "An Analysis of Galvanic Coupling Effects on the Performance of High-Level Waste Container Materials." CNWRA 97-010. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. August 1997.
20.05708.761.730, Q199709240002, ML040200062

Dunn, D.S., M.B. Bogart, C.S. Brossia, and G.A. Cragnolino. "Corrosion of Iron Under Alternating Wet and Dry Conditions." *Corrosion*. Vol. 56. pp. 470–481. May 2000.

Dunn, D.S., G.A. Cragnolino, and N. Sridhar. "An Electrochemical Approach to Predicting Long-Term Localized Corrosion of Corrosion-Resistant High-Level Waste Container Materials." *Corrosion.* Vol. 56. pp. 90–104. January 2000.

Dunn, D.S., G.A. Cragnolino, and N. Sridhar. "Effect of Galvanic Coupling Between Overpack Materials of High-Level Nuclear Waste Containers." *Corrosion.* Vol. 56. pp. 598–610. June 2000.

Dunn, D.S., G.A. Cragnolino, and N. Sridhar. 06/13/1997. "An Electrochemical Approach to Predicting Long-Term Localized Corrosion of Corrosion Resistant Container Materials." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1997. 20.05708.561, Q199708150002, ML040200176

This report identifies corrosion potential and the repassivation potential as useful parameters to predict the long-term localized corrosion susceptibility for corrosion resistant candidate container materials such as type 316L stainless steel and alloy 825. This conclusion is based on laboratory tests that have demonstrated that pitting and crevice corrosion are initiated when the corrosion potential of the material exceeds the repassivation potential for localized corrosion. Once initiated, the propagation rate for the localized attack will result in rapid penetration of the waste packages. However, no localized corrosion can be initiated and all active corrosion sites repassivate when the corrosion potential of the material is lower than the repassivation potential.

Dunn, D., D. Daruwalla, and Y.-M. Pan. 10/28/2003. "Effect of Fabrication Processes on Material Stability—Characterization and Corrosion." CNWRA 2004-01. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2003. 20.06002.01.081.320, Q200311060005, ML040480532

This report presents results of CNWRA experiments, as well as a review of DOE evaluations, on the effects of fabrication processes such as welding and annealing on the microstructure, uniform corrosion rate, localized corrosion susceptibility, and stress corrosion cracking resistance of Alloy 22.

Dunn, D.S., Y.-M. Pan, and K.T. Chiang. 03/30/2005. "Microstructural Analyses and Mechanical Properties of Alloy 22." CNWRA 2005-03. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2005. 20.06002.01.102.420, Q200503310003, ML050910074

Dunn, D.S., Y.-M. Pan, K.T. Chiang, L. Yang, G.A. Cragnolino, and X. He. "The Localized Corrosion Resistance and Mechanical Properties of Alloy 22 Waste Package Outer Containers." *JOM.* Vol. 57, No. 1. pp. 49–54. January 2005.

Dunn, D.S., Y.-M. Pan, L. Yang, and G.A. Cragnolino. "Localized Corrosion Susceptibility of Alloy 22 in Chloride Solutions: Part 1—Mill-Annealed Condition." *Corrosion.* Vol. 61. pp. 1,078–1,085. November 2005.

Dunn, D.S., O. Pensado, Y.-M. Pan, R.T. Pabalan, L. Yang, X. He, and K.T. Chiang. 12/19/2005. "Passive and Localized Corrosion of Alloy 22 —Modeling and Experiments, Revision 1." CNWRA 2005-02. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses: December 2005 20.06002.01.322.500, Q200512190006, ML071560057

Dunn, D., N. Sridhar, and G. A. Cragnolino. "Effects of Surface Chromium Depletion on Localized Corrosion of Alloy 825 as a High-Level Nuclear Waste Container Material." *Corrosion.* Vol. 51, No. 8. pp. 618–624. 1995.

Dunn, D.S.. N. Sridhar, and G.A. Cragnolino. "Long-Term Prediction of Localized Corrosion of Alloy 825 in High-Level Nuclear Waste Repository Environments." *Corrosion*. Vol. 52, No. 2. pp. 115–124. 1996.

Geesey, G. 06/20/1993. "A Review of the Potential for Microbially Influenced Corrosion of High-Level Waste Containers." CNWRA 93-014. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1993.
20.05704.044.101, Q199306300001, ML040230184

He, X. 09/27/2011. "Electrochemical Behavior and Passivity of Titanium Drip Shield Materials Under Immersion Conditions." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.151, Q201109270006, ML112700443

This report documents the results of a previously unpublished set of experiments that evaluated the fundamental difference in corrosion behavior between Titanium Grades 7 and 29 under immersion conditions. Cathodic and anodic polarization results show that both palladium in Titanium Grade 7 and ruthenium in Titanium Grade 29 influence the cathodic reaction kinetics and enhance the crevice corrosion resistance; however, palladium and ruthenium appeared not to influence much of the anodic dissolution behavior. Both materials showed high passivity and the passive film resistance appeared to be independent of temperature. Compared to Titanium Grade 7, Titanium Grade 29 showed lower passive film resistance however, the difference is not significant.

He, X. and D.S. Dunn. 12/21/2005. "Crevice Corrosion Penetration Rate of Alloy 22 in Chloride-Containing Waters." CNWRA 2006-001. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. December 2005.
20.06002.01.322.500, Q200512280002, ML062440377

This progress report presents the experimental results of the crevice corrosion propagation rates of Alloy 22 in chloride-containing waters. The results of the investigation indicate that, the stifling and arrest of crevice corrosion significantly decrease the actual values of crevice corrosion propagation rates even under the aggressive environmental conditions used in these laboratory tests.

He, X. and D.S. Dunn. "Crevice Corrosion Penetration Rates of Alloy 22 in Chloride-Containing Waters." *Corrosion.* Vol. 63. pp. 145–158. 2007.

He, X. and T. Mintz. "Localized Corrosion of Alloy 22 in the Yucca Mountain Repository Environment." *Journal of Metals.* Vol. 60. pp. 44–51. 2008.

The main purpose of this paper is to summarize work conducted to evaluate (i) the effects of environmental conditions relevant to the potential Yucca Mountain repository, metallurgical states (e.g., mill-annealed and welded plus solution annealed), and similar and dissimilar metal crevices on the crevice corrosion susceptibility of Alloy 22, and (ii) crevice corrosion propagation behavior by contacting to Alloy 22 or Titanium Grade 7. The results have shown that crevice corrosion susceptibility of Alloy 22 increased with increasing chloride concentration, temperature, and chloride-to-nitrate concentration ratios. Fabrication processes such as welding plus solution annealing also increased the localized corrosion susceptibility of Alloy 22.

He, X. and T. Mintz. "Quantitative Characterization of Alloy 22 Crevice Corrosion Damage Profiles." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 2011.
20.14002.01.441.156, Q200909230002, ML092660562

Three- and two-dimensional (3-D and 2-D) laser profilometry scans were performed to accurately and quantitatively characterize the corrosion damage profiles. Laser scans are more sensitive to variations in penetration sites, leading to larger maximum crevice corrosion penetration depths measured than those previously obtained by optical microscope. For Alloy

22, crevice corrosion attack may have initially followed metallurgical features such as grain boundaries.

He, X. , T. Ahn, and T. Sippel. 09/06/2011. "Corrosion of Borated Stainless Steel in Liquid Water and Vapor." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.138, Q201109060002, ML112490365

In this study, borated 304B4 and 304B5 stainless steels were exposed to the liquid and vapor phases of simulated ground water at 60, 75, and 90 °C [140, 167, and 194 °F] for about 3 months. It was found that some specimens exposed to vapor at 75 and 90 °C [167 and 194 °F] suffered pitting corrosion, but pitting corrosion was not observed at 60 °C [140 °F] or from the liquid exposure at 75 and 90 °C [167 and 194 °F]. At all three temperatures, the general corrosion rates of 304B4 were less than 80 nm/yr [0.0032 mil/yr] and those of 304B5 were less than 600 nm/yr [0.024 mil/yr].

He, X., B. Brettmann, and H. Jung. "Effects of Test Methods on Crevice Corrosion Repassivation Potential Measurements of Alloy 22." *Corrosion.* Vol. 65. pp. 449–460. 2009.

The relative susceptibility of Alloy 22 to crevice corrosion is evaluated through the measurement of crevice corrosion repassivation potential (E_{rcrev}) using electrochemical test methods. The main purpose of the work described in this paper is to verify some E_{rcrev} values reported in the literature and investigate the effects of different electrochemical test methods on the measurement of E_{rcrev}. .

He. X., D.S. Dunn, and A.A. Csontos. 01/08/2008. "Crevice Corrosion Initiation and Propagation of Similar and Dissimilar Metal Couples in the Engineered Barrier System of the Potential Yucca Mountain Repository." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. November 2007.
20.06002.01.322.720, Q200801080001, ML080080465

The report describes the corrosion performance of the engineered barrier system materials in sodium chloride and magnesium chloride solutions at 95 °C [203 °F]. Five types of crevices were evaluated: (i) Type 316L stainless steel to mill-annealed Alloy 22, (ii) mill-annealed Alloy 22 to mill-annealed Alloy 22, (iii) welded plus solution annealed Alloy 22 to mill-annealed Alloy 22, (iv) mill-annealed Alloy 22 to Titanium Grade 7, and (v) welded plus solution annealed Alloy 22 to Titanium Grade 7. Except for Type 316L stainless steel, all other metal-to-metal crevices were less susceptible to crevice corrosion than the corresponding metal-to-polytetrafluoroethylene crevices.

He, X., D.S. Dunn, and C.S. Csontos. "Corrosion of Similar and Dissimilar Metal Crevices in the Engineered Barrier System of a Potential Nuclear Waste Repository." *Electrochimica Acta*. Vol. 52. pp. 7,556–7,569. 2007.

Jung, H., T. Ahn, and T. Mintz. 09/06/2011. "Corrosion of Stainless Steel Type 316L in a Seepage Water Dripping Environment." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.186, Q201109060003, ML112490377

Jung, H., X. He, T. Ahn, T. Mintz, and R. Pabalan. 09/02/2011. "Corrosion of Alloy 22 and Titanium Alloys Under Seepage Water Dripping Condition." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.118, Q201109020011, ML112450427

Jung, H., T. Mintz, D.S. Dunn, O. Pensado, and T. Ahn. 10/12/2007. "A Review of the Long-Term Persistence of the Passive Film on Alloy 22 in Potential Yucca Mountain Repository Environments." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2007.
20.14002.01.171.735, Q200710150003, ML072880595

Jung, H., T. Mintz, L. Yang, and T. Ahn. 01/13/2009. "Long-Term Persistence of the Passive Film on Alloy 22 at Elevated Temperatures in the Potential Yucca Mountain Repository Environment." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2009
20.14002.01.171.820, Q200901130004, ML090220175
This report documents an evaluation of the long-term persistence of the passive film on Alloy 22 (Ni-22Cr-13Mo-4Fe-3W) at elevated temperatures {e.g., above 100 °C [212 °F]}. Two conditions are evaluated: (i) passive film stability with respect to composition and structure and (ii) the effects of anodic sulfur segregation on stability.

Jung, H., L. Yang, and T. Ahn. 09/23/2011. "An Electrochemical Study on Passivation of Alloy 22 in Chloride-Containing Solutions With and Without Sulfur." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.012.020, Q201109230010, ML112660508

Larose, S. and R.A. Rapp. 03/07/1997. "Review of Low-Temperature Oxidation of Carbon Steels and Low-Alloy Steels for Use as High-Level Radioactive Waste Package Materials." CNWRA 97-003. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1997.
20.05708.571.775, Q199705310004, ML040200112

Pan, Y.-M., C.S. Brossia, G.A. Cragnolino, D.S. Dunn, G.D. Gute, and L. Yang. 10/29/2002. "Stress Corrosion Cracking and Hydrogen Embrittlement of Container and Drip Shield Materials." CNWRA 2003-02. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2002.
20.06002.01.081, Q200210300002, ML033640096

Pan, Y.-M., K.T. Chiang, D.S. Dunn, X. He, O. Pensado, P. Shukla, and L. Yang. "Independent Evaluation of Waste Package Corrosion Performance Under Potential Repository Conditions." *Nuclear Technology*. Vol. 163, No. 1. pp. 85–91. July 2008.
This paper summarizes the results of laboratory measurements and model analyses focused on uniform, localized, and microbially influenced corrosion, and stress corrosion cracking of Alloy 22.

Pan, Y.-M., D.S. Dunn, and G.A. Cragnolino. 02/20/2004. "Topologically Close-Packed Phase Precipitation and Thermal Stability in Alloy 22." *Metallurgical and Materials Transactions A*. Vol. 36. pp. 1143–1151. 2005.
This study evaluated the effects of fabrication processes such as short-term thermal aging, welding, and postweld solution annealing on the phase stability of Alloy 22.

Pan, Y.-M., D.S. Dunn, and G.A. Cragnolino. "Effects of Environmental Factors and Potential on Stress Corrosion Cracking of Fe-Ni-Cr-Mo Alloys in Chloride Solutions." *Environmentally Assisted Cracking: Prediction Methods for Risk Assessment and Evaluation of Materials, Equipment, and Structures.* ASTM STP 1401. R.D. Kane, ed. ASTM. West Conshohocken, Pennsylvania. pp. 273–288. 2000.

Pan, Y.M., D.S. Dunn, G.A. Cragnolino, and N. Sridhar. "Grain Boundary Chemistry and Intergranular Corrosion in Alloy 825." *Metallurgical and Materials Transactions A.* Vol. 31A. pp. 1,163–1,173. 2000.

Pan, Y.-M., N. Sridhar, D.S. Dunn, and G.A. Cragnolino. 05/04/1995. "Effect of Specimen Preparation Procedures on Chromium Depletion and Precipitation Chemistry in Alloy 825 by Analytical Electron Microscopy." *Journal of Materials Science Letter*s. Vol. 15, No. 6. pp. 522-524. 1996.

Pensado, O. and R. Pabalan. "Probabilistic Methodology to Estimate Environmental Conditions for Localized Corrosion and Stress Corrosion Cracking of Alloy 22 in a High-Level Radioactive Waste Repository Setting." *Journal of Nuclear Materials.* Vol. 381, Issue 3, 15. Pp 231–241. November 2008.

Pensado, O. and R.T. Pabalan. 09/15/2011. "Assessment of Probability of Localized Corrosion of Alloy 22 Waste Package Material in a Proposed High-Level Waste Geologic Repository at Yucca Mountain, Nevada." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.146, Q201109150004, ML112580219

Pensado, O., D.S. Dunn, G.A. Cragnolino, and V. Jain. 10/25/2002. "Passive Dissolution of Container Materials—Modeling and Experiments." CNWRA 2003-01. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2002.
20.06002.01.081.230, Q200210300001 ML033640090

Shukla, P., R. Pabalan, and X. He. 09/21/2011. "Crevice Chemistry Model Development for Nickel-Based Alloys and Analysis of Model Results In View of Literature Information." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.166, Q201109210001, ML112640376

Sridhar, N. 09/28/1992. "A Preliminary Assessment of Pitting Corrosion Models." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1992.
20.03702.013, Q199210120007, ML033650080

Sridhar, N. and G. A. Cragnolino. "Effects of Environment on Localized Corrosion of Copper-Based, High-Level Waste Container Materials." *Corrosion.* Vol. 79, No 12. pp. 967–976. 1993.

This paper examined the effects of environmental factors on localized corrosion of copper-based materials. The environmental factors examined were those present in the groundwater near Yucca Mountain: bicarbonate, chloride, and sulfate.

Sridhar, N. and G. A. Cragnolino. "Applicability of Repassivation Potential for Long-Term Prediction of Localized Corrosion of Alloy 825 and Type 316L Stainless Steel." *Corrosion*. Vol. 49, No 11. pp. 885–894. 1993.

Sridhar, N. and G.A. Cragnolino. "Stress Corrosion Cracking of Nickel-Base Alloys. *Stress Corrosion Cracking: Materials Performance and Evaluation*." Russell H. Jones, ed. Materials Park, Ohio: ASM International. pp. 131–179. 1992.

Sridhar, N. and G. Cragnolino. "Stress Corrosion Cracking of Nickel-Base Alloys." Chapter 5 (pp 131–179) in *Stress-Corrosion Cracking: Material Performance and Evaluation.* R.H. Jones, ed. Materials Park, Ohio: American Society of Metallurgists (ASM) International. 1992.

Sridhar, N. and D.S. Dunn. "Effect of Applied Potential on Changes in Solution Chemistry Inside Crevices on Type 304L Stainless Steel and Alloy 825." *Corrosion.* Vol. 50, No. 11. pp. 847–872. 1994.

Sridhar, N. and D.S. Dunn. "*In-Situ* Study of Salt Stability in Simulated Pits of Nickel by Raman and Electrochemical Impedance Spectroscopies." *Journal of the Electrochemical Society.* Vol. 144, No. 12. pp. 4,243–4,253. 1997.

Sridhar, N., G.A. Cragnolino, and D. Dunn. 02/01/1993. "Experimental Investigations of Localized Corrosion of High-Level Waste Container Materials." CNWRA 93-004. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. February 1993. 20.05704.041, Q199303020001, ML040200255

Sridhar, N., G.A. Cragnolino, and D.S. Dunn. 05/19/1995. "Experimental Investigations of Failure Processes of High-Level Radioactive Waste Container Materials." CNWRA 95-010. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. May 1995. 20.05704.041, Q199506060001, ML040220295

This report presents the results of five years of research activities in the Integrated Waste Package Experiments Research Project. Experiments focused on localized corrosion, stress corrosion cracking, materials thermal stability, and hydrogen embrittlement of austenitic Fe-Cr-Ni-Mo alloys selected as candidate materials for the construction of high-level radioactive waste containers.

Walton, J.C., G.A. Cragnolino, and S.K. Kalandros. "A Numerical Model of Crevice Corrosion for Passive and Active Metals." *Corrosion.* Vol. 38, No. 1. pp. 1–18. 1996.

Yang, L. 04/21/2006. "Corrosion of Alloy 22 in Concentrated Nitrate and Chloride Salt Environments at Elevated Temperatures—Progress Report." CNWRA 2006-02. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. April 2006. 20.06002.01.322.610, Q200604250001, ML061430298

The objectives of this work were to (i) study the chemistry of the liquid formed by the nitrate-chloride salt mixtures and the vapor above the liquid, and (ii) investigate the localized and general corrosion behavior of Alloy 22 in the liquid and vapor environment in an ambient-pressure system that was not deaerated to simulate the potential Yucca Mountain drift conditions at elevated temperatures.

Yang, L., R.T. Pabalan, and M.R. Juckett. "Deliquescence Relative Humidity Measurements Using an Electrical Conductivity Method." *Journal of Solution Chemistry.* Vol. 35. pp. 583–604. 2006.

Yang, L., R. Pabalan, P. Shukla, M. Juckett, X. He, K.T. Chiang, H. Gonzalez, and T. Ahn. 03/14/2011. "Corrosion of Alloy 22 Induced by Dust Deliquescence Brines." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. March 2011. 20.14002.01.441.830, Q201103140001 ML110730489

During the preclosure period of a potential Yucca Mountain repository, the repository drift would be ventilated and atmospheric aerosols and tunnel dusts could be deposited onto the waste package surfaces by the ventilation, leading to the accumulation of small amounts of

hygroscopic salts on the waste package surfaces. The hygroscopic salts could deliquesce and form a brine solution on the waste package surfaces when the relative humidity of the in-drift environment is near or above the salt's deliquescence relative humidity. This report evaluates Alloy 22 corrosion by the deliquescence brines under potential repository conditions.

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 a, a-ß, and ß Titanium Alloys." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. October 2007.
20.14002.01.191, Q200710250006, ML072980893, ML072980894, ML072980897

This report surveys the current literature pertinent 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.

Chan, K.S. 09/28/2007. "An Assessment of Delayed Hydride Cracking in Zirconium Alloy Cladding Tubes Under Stress Transients."
20.06002.01.222.740, Q200710010001, ML112650048

This document is an unpublished manuscript.

Chan, K.S. and Y. Lee. "A Fracture Mechanics-Based Model for Assessing the Mechanical Failure of Nuclear Fuel Rods Due to Rock Fall." *Nuclear Engineering and Design*, Vol. 201, pp. 209-226. 2000.

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 U. S. Department of Energy (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. 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 [392–572 °F].

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. June 1991.
20.03704.041, Q199107090036, ML040330594

Tszeng, T.C. 09/18/2008. "Review of Analysis of Mechanisms for Early Waste Package and Drip Shield Failure. 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, ML112650310

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 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 Yucca Mountain.

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. 09/29/2011. "Effects of Tilted and Faulted Strata on Seismic Ground Motion." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011. 20.14002.01.441.160, Q201109290003

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.

Hsiung, S.-M. and A.H. Chowdhury. 09/15/2011. "Seismic Effects on Soil-Structure Interactions." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.172, Q201109150001, ML112580204

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.

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, ML040210691

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. 09/23/2011. "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. September 2011.
20.14002.01.441.178, Q201109230003,ML112660328

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., 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.

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, ML061740535

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

Jain, V., G. Cragnolino, 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, ML043020321

Jung, H., T. Ahn, K. Axler, R. Pabalan, and D. Pickett. 09/08/2011. "Corrosion of SIMFUEL in Aerated Carbonate Solution Containing Calcium and Silicate." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.124, Q201109080001, ML112520488

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 in a repository relevant environment, specifically under oxiding 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 90 °C [77, 140, and 194 °F]. 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.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.

Pearcy, 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." P.C. *Energy Resources of the Chihuahua Desert Region.* El Paso, Texas: El Paso Geological Society, pp. 192-296. 1994. .

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 [$Ca(UO_2)_2(SiO_3OH)_2 \cdot 5H_2O$] 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.

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. (This report is publicly available at http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=138205.)

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. ML033630097

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 Yucca Mountain 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 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." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. July 2008. 20.14002.01.083.840, Q200806050004, ML081890318

This letter report summarizes the current Center for Nuclear Waste Regulatory Analyses (CNWRA) understanding of the U.S. Department of Energy (DOE) abstraction for colloid-facilitated radionuclide transport in the wasteform 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, ML033640040

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., 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. "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, ML052660288

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, ML062690355

This report discusses transport-related issues such as colloid stability, colloid retention, and 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. 09/06/2011. "Radionuclide Sorption Technical Assistance Activities at the Center for Nuclear Waste Regulatory Analyses." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.150, Q201109060004, ML112490545

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

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 Yucca Mountain, 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 Yucca Mountain 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." 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, ML033630356

Farrell, D.A., V. Rankin, and A. Buseman-Williams. 12/07/2005. "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. December 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, B. Sagar, and R.B. Codell. 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

Also published as NUREG/CR-5917.

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

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 2005.
20.06002.01.232.520, Q200712030001, ML073370866

Mohanty, S. and S.-M. Hsiung. 09/23/2011. "An Experimental Investigation of Single Fracture Flow Behavior Under Normal and Shear Loads." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.155, Q201109260001, ML112690142

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. 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. Pearcy, 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.

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., M. Tuller, 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, ML062060477, 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 volcaniclastic rocks, and aqueous mixtures of Na^+/K^+ and Na^+/Ca^{2+}. 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^+/Sr^{2+}, K^+/Sr^{2+}, and K^+/Ca^{2+}. 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.

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. 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). 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. Pearcy. "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 Uranium-series isotopic data on secondary iron-oxides/hydroxides formed in a fracture that crosscuts the Nopal I uranium deposit. Mobilization and transport of uranium (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 $^{234}U/^{238}U$ 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.

Gureghian, A.B., Y.T. Wu, B. Sagar, and R.B. Codell. "Sensitivity and Uncertainty Analyses Applied to One-Dimensional Radionuclide Transport in a Layered Fractured Rock. 1. Analytical Solutions and Local Sensitivities." *Nuclear Technology*. Vol. 104. pp. 272–296. 1993.

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." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. January 2008.
20.14002.01.131.820, Q200803240001, 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." 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.

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.

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 1993.
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, ML110820365

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. 09/23/2011. "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: September 2011.
20.14002.01.441.152, Q201109230004, ML112660339

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, ML033630074

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. 09/02/2011. "Airborne Particle Resuspension and Inhalation Radiological Dose Estimation Following Volcanic Events." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 2011.
20.14002.01.441.142, Q201109020013, ML112450435

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 management 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., 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.

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

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. February 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., 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, ML080720613 (Part 1), ML080720615 (Part 2)

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 U.S. Environmental Protection Agency standard, describes a set of scoping calculations: (i) volcanism scenario,(ii) hazards comparison, and (iii) plume dilution.

LaPlante, P. 08/29/2006. "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

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. June 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

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

Chowdhury, D. Deere, V. Jain, D. Pickett, N. Sridhar, 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, ML033640251

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

17.2 West Valley

Cragnolino, 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

Cragnolino, G.A. 09/23/1994. "Review of the West Valley THOREX Waste Neutralization Process." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. September 1994.
20.05706.003.100, Q199410140004, ML040230579

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

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

This is the final version of a report that summarizes a large volume of information available regarding the Hanford site, tank farms, and activities pertaining to the Tank Waste Remediation System (TWRS). The report includes a description of tank waste contents, types of hazards posed by the tanks and TWRS activities. See Sridhar, et al., December 1996–April 1997, in this bibliography for references to detailed earlier parts of this report.

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. August 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. 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. "Radioactive Waste Treatment/Nuclear Material Production Facility Integrated Design Inspection Program" "San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 1999.
20.01403.202.930, Q200310020001, ML040350737

This document describes an inspection program methodology to be used for performing multidisciplinary integrated design inspections at radioactive waste treatment and nuclear material processing plants.

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. September 2000.
20.01403.106.030, Q200012270001 ML033640523

Pabalan, R.T., M.S. Jarzemba, T.A. Abrajano, Jr., D.A. Pickett, D. S. Moulton, N. Sridhar, J. Weldy, C.S. Brazel, J.T. Persyn, B. Li, J.P. Hsu, and J. Erwin. . "High Level Waste Chemistry Manual." CNWRA 97-008. Revision 1. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. June 1998.
20.05708.106.705, Q199709030017, ML033640258.

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

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. Jarzemba, 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–April 1997.
20.05709.101.710, Q199705310007, ML040200118, ML040200138, ML040200141
This report, published in several parts, summarizes the large volume of information available regarding the Hanford site, tank farms, and ongoing activities pertaining to the Tank Waste Remediation System (TWRS). The report includes a description of tank waste contents, types of hazards posed by the tanks and TWRS activities.

Yang, L. and R.T. Pabalan. 02/24/2000. "PRETREAT: A Spreadsheet-Based Mass-Balance Model for Hanford Tank Waste Remediation System 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. Where available, accession numbers are provided for those CNWRA documents that are publicly available for viewing in the U.S. Nuclear Regulatory Commission (NRC) Agencywide Document Access and Management System (ADAMS).

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 NRC. No CNWRA-series reports specific to the Yucca Mountain activities were issued after 2008.

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Stothoff, S. and M. Musgrove
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Chiang, K.-T., D.S. Dunn, Y.-M. Pan, O. Pensado, and P.K. Shukla
December 2006
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