

# **SANDIA REPORT**

SAND93-2675 • UC-814

Unlimited Release

Printed April 1994

## **Yucca Mountain Site Characterization Project**

# **Total-System Performance Assessment for Yucca Mountain - SNL Second Iteration (TSPA-1993)**

## **Executive Summary**

Michael L. Wilson, John H. Gauthier, Ralston W. Barnard, George E. Barr, Holly A. Dockery, Ellen Dunn, Roger R. Eaton, David C. Guerin, Ning Lu, Mario J. Martinez, Robert Nilson, Christopher A. Rautman, Thomas H. Robey, Benjamin Ross, Eric E. Ryder, Albert R. Schenker, Sharon A. Shannon, Lee H. Skinner, William G. Halsey, James D. Gansemer, Lynn C. Lewis, Alan D. Lamont, Inés R. Triay, Arend Meijer, David E. Morris

Prepared by  
Sandia National Laboratories  
Albuquerque, New Mexico 87185 and Livermore, California 94550  
for the United States Department of Energy  
under Contract DE-AC04-94AL85000

Approved for public release; distribution is unlimited.

*L/m - No*

**"Prepared by Yucca Mountain Site Characterization Project (YMSCP) participants as part of the Civilian Radioactive Waste Management Program (CRWM). The YMSCP is managed by the Yucca Mountain Project Office of the U.S. Department of Energy, DOE Field Office, Nevada (DOE/NV). YMSCP work is sponsored by the Office of Geologic Repositories (OGR) of the DOE Office of Civilian Radioactive Waste Management (OCRWM)."**

**Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.**

**NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors.**

**Printed in the United States of America. This report has been reproduced directly from the best available copy.**

**Available to DOE and DOE contractors from  
Office of Scientific and Technical Information  
PO Box 62  
Oak Ridge, TN 37831**

**Prices available from (615) 576-8401, FTS 626-8401**

**Available to the public from  
National Technical Information Service  
US Department of Commerce  
5285 Port Royal Rd  
Springfield, VA 22161**

**NTIS price codes  
Printed copy: A04  
Microfiche copy: A01**

SAND93-2675  
Unlimited Release  
Printed April, 1994

# Total-System Performance Assessment for Yucca Mountain — SNL Second Iteration (TSPA-1993)

## Executive Summary

Michael L. Wilson, John H. Gauthier<sup>†</sup>, Ralston W. Barnard,  
George E. Barr, Holly A. Dockery, Ellen Dunn, Roger R. Eaton, David C. Guerin<sup>‡</sup>,  
Ning Lu<sup>\*</sup>, Mario J. Martinez, Robert Nilson, Christopher A. Rautman,  
Thomas H. Robey<sup>†</sup>, Benjamin Ross<sup>\*</sup>, Eric E. Ryder, Albert R. Schenker<sup>‡</sup>,  
Sharon A. Shannon, Lee H. Skinner<sup>†</sup>  
(Sandia National Laboratories)

William G. Halsey, James D. Gansemer, Lynn C. Lewis, Alan D. Lamont  
(Lawrence Livermore National Laboratory)

Inés R. Triay, Arend Meijer<sup>§</sup>, David E. Morris  
(Los Alamos National Laboratory)

<sup>†</sup> Spectra Research, Inc.

<sup>‡</sup> Los Alamos Technical Associates, Inc.

<sup>\*</sup> Disposal Safety, Inc.

<sup>§</sup> Jacobs Engineering, Inc.

## Abstract

Sandia National Laboratories has completed the second iteration of the periodic total-system performance assessments (TSPA-93) for the Yucca Mountain Site Characterization Project (YMP). These analyses estimate the future behavior of a potential repository for high-level nuclear waste at the Yucca Mountain, Nevada, site under consideration by the Department of Energy. TSPA-93 builds upon previous efforts by emphasizing YMP concerns relating to site characterization, design, and regulatory compliance.

Scenarios describing expected conditions (aqueous and gaseous transport of contaminants) and low-probability events (human-intrusion drilling and volcanic intrusion) are modeled. The hydrologic processes modeled include estimates of the perturbations to ambient conditions caused by heating of the repository resulting from radioactive decay of the waste. Hydrologic parameters and parameter probability distributions have been derived from available site data. Possible future climate changes are modeled by considering two separate groundwater infiltration conditions: "wet", with a mean flux of 10 mm/yr, and "dry", with a mean flux of 0.5 mm/yr. Two alternative waste-package designs and two alternative repository areal thermal power densities are investigated. One waste package is a thin-wall container emplaced in a vertical borehole, and the second is a container designed with corrosion-resistant and corrosion-allowance walls emplaced horizontally in the drift. Thermal power loadings of 57 kW/acre (the loading specified in the original repository conceptual design) and 114 kW/acre (a loading chosen to investigate effects of a "hot repository") are considered.

TSPA-93 incorporates significant new detailed process modeling, including two- and three-dimensional modeling of thermal effects, groundwater flow in the saturated-zone aquifers, and gas flow in the unsaturated zone. The saturated-zone model is used to estimate travel times for contaminants through layered, dipping formations. Coupled calculations of gas and heat flow are used to estimate travel times for gaseous CO<sub>2</sub>. Time-dependent temperature distributions in the rock surrounding the potential repository are calculated, using the four repository layouts. A phenomenological model for waste-package degradation is implemented; the model includes temperature-dependent corrosion, fuel alteration, and dissolution.

Probabilistic analyses are performed for aqueous and gaseous flow and transport, human intrusion, and basaltic magmatic activity. Repository performance estimates are sensitive to assumptions made about unsaturated-zone water flow and contact with waste. Two conceptual models of unsaturated-zone water flow are considered — the composite-porosity model, which treats fracture and matrix flow as being strongly coupled; and the weeps model, which allows for flow only through locally saturated zones. The weeps aqueous releases and the human-intrusion direct releases are sensitive to the size of the waste packages that are affected: the larger horizontally-emplaced containers produce greater releases. Releases are generally insensitive to repository thermal effects: a hotter thermal loading protects parts of the repository from contact with liquid water, but other parts experience enhanced water flow due to condensation and diversion. The volcanic scenario, which investigates the effects of magmatic volatiles on the degradation of the waste packages, does not contribute significantly to releases.

Results of the calculations done for TSPA-93 lead to a number of recommendations concerning studies related to site characterization. Primary among these are the recommendations to obtain better information on percolation flux at Yucca Mountain, on the presence or absence of flowing fractures, and on physical and chemical processes influencing gaseous flow. Near-field thermal and chemical processes, and waste-container degradation are also areas where additional investigations may reduce important uncertainties. Recommendations resulting from TSPA-93 for repository and waste-package design studies are: 1) to evaluate the performance implications of large-size containers, and 2) to investigate in more detail the implications of high repository thermal power output on the adjacent host rock and on the spent fuel.

If future repository performance regulations are based on individual dose rather than cumulative release, results suggest that future site-characterization efforts should emphasize investigations of groundwater contact with waste packages in the unsaturated zone and examinations of saturated-zone flow paths. Because dose rates are dependent on the rate of radionuclide releases, it would be useful to investigate container designs that fail "slowly" over long periods of time.

**Volume 1**  
**contains Chapters 1 through 12**

**Volume 2**  
**contains Chapters 13 through 25**  
**and the Appendices**

**This report was prepared under the Yucca Mountain Site Characterization Project WBS 1.2.5.4.1. QAGR 1.2.3.4.1 was applied, however, the information and data documented in the report were not developed to meet quality-affecting standards. Not all the work activities were subject to QA controls. The information in this report is not qualified and is not to be used for licensing.**

7.2.1	Porosity ( $\phi$ ) .....	7-10
7.2.2	Matrix bulk density ( $\rho_b$ ) .....	7-10
7.2.3	Matrix saturated hydraulic conductivity ( $K_s$ ) .....	7-12
7.2.4	Matrix water-retention parameters (van Genuchten model) .....	7-14
7.3	Bulk hydraulic-parameter development .....	7-16
7.3.1	Bulk saturated hydraulic conductivity ( $K_{bs}$ ) .....	7-18
7.3.2	Gas conductivity ( $K_{bg}$ ) .....	7-19
7.3.3	Analog bulk saturated hydraulic conductivity .....	7-20
7.4	Fracture parameter development .....	7-22
7.4.1	Approach .....	7-22
7.4.2	Available fracture data .....	7-23
7.4.3	Derived parameters .....	7-25
7.5	Parameter correlations .....	7-31
7.6	Comparison of hydrogeologic parameters between TSPA-91 and TSPA-93 .....	7-32
7.6.1	Matrix porosity .....	7-33
7.6.2	Matrix saturated hydraulic conductivity .....	7-34
7.6.3	Water retention (van Genuchten) parameters .....	7-35
7.6.4	Fracture parameter comparisons .....	7-36
<b>Chapter 8</b>	<b>Infiltration and Percolation Rates .....</b>	<b>8-1</b>
8.1	Definitions .....	8-1
8.2	Strategy .....	8-3
8.3	Major differences with TSPA-91 .....	8-4
8.4	Climate-change timing .....	8-4
8.5	Infiltration rates for climate change .....	8-10
8.6	Dry-climate infiltration .....	8-10
8.7	Wet-climate infiltration .....	8-11
8.8	Water-table heights .....	8-13
8.9	Infiltration versus percolation for the composite-porosity model .....	8-14
<b>Chapter 9</b>	<b>Geochemistry: Solubility and Sorption Parameters .....</b>	<b>9-1</b>
9.1	Elicitation method .....	9-1
9.2	Solubility .....	9-2
9.2.1	Assumptions .....	9-2
9.2.2	Solubility values .....	9-6
9.2.3	Correlations .....	9-10
9.3	Sorption .....	9-11
9.3.1	Assumptions .....	9-11
9.3.2	Sorption coefficients .....	9-12
9.3.3	Correlations .....	9-16
9.4	Major differences from TSPA-91 .....	9-17
<b>Part III: Detailed Modeling and Abstraction</b>		
<b>Chapter 10</b>	<b>Thermal Effects .....</b>	<b>10-1</b>
10.1	Important thermally driven processes .....	10-1
10.2	Abstracted hydrothermal model .....	10-3
10.2.1	Dryout volume .....	10-5
10.2.2	Dryout fraction .....	10-6
10.2.3	Container-wall and fuel-rod temperature .....	10-6
10.3	Detailed thermal modeling .....	10-6
10.3.1	Background on repository thermal design .....	10-7
10.3.2	Thermal loading cases chosen for TSPA-93 .....	10-12

10.4	Implementation of conceptual hydrothermal model .....	10-31
10.4.1	Dryout volume and fraction dry .....	10-31
10.4.2	Container-wall and fuel-rod temperatures .....	10-35
10.5	Conclusions .....	10-36
<b>Chapter 11 Saturated-Zone Models .....</b>		
11.1	Three-dimensional geological model .....	11-1
11.1.1	Model thickness .....	11-2
11.1.2	Model stratigraphy .....	11-3
11.2	Calibration of the non-diversionary model .....	11-3
11.3	Transport calculations using the non-diversionary model .....	11-9
11.4	Calibration of the diversionary model .....	11-13
11.5	Transport calculations using the diversionary model .....	11-21
11.6	Abstraction of results for the TSA .....	11-27
11.6.1	Velocity and dispersivity .....	11-28
11.6.2	Transport area .....	11-35
11.6.3	Porosity, bulk density, and sorption coefficients .....	11-36
<b>Chapter 12 Gaseous Flow and Transport .....</b>		
12.1	The models .....	12-1
12.2	Inputs and assumptions .....	12-4
12.3	Simulation results .....	12-10
12.4	Abstraction of results for the TSA .....	12-19

## Contents of Volume 2

### Part IV: Probabilistic Modeling and Results

<b>Chapter 13 Source-Term Model .....</b>		
13.1	Functional description of the YMIM code .....	13-1
13.1.1	Comparison with TSPA-91 source term .....	13-3
13.2	Description of YMIM modules and model inputs .....	13-5
13.2.1	Near-field hydrology .....	13-6
13.2.2	Near-field geochemistry .....	13-7
13.2.3	Temperature .....	13-7
13.2.4	Container failure .....	13-8
13.2.5	Radionuclide properties .....	13-16
13.2.6	Internal-container flow .....	13-17
13.2.7	Waste-form dissolution .....	13-17
<b>Chapter 14 Nominal-Case Releases: Composite-Porosity Model .....</b>		
14.1	Similarities to and differences from TSPA-91 .....	14-1
14.1.1	Similarities .....	14-2
14.1.2	Differences .....	14-3
14.2	Dose calculation .....	14-4
14.3	Climate change .....	14-6
14.4	Radionuclide source term .....	14-9
14.4.1	YMIM capabilities not used .....	14-10
14.4.2	Container groups .....	14-11
14.4.3	Container wetting .....	14-13

14.5	Problem setup and parameter values .....	14-16
14.5.1	Repository layout, column stratigraphies, and SZ flow tubes .....	14-17
14.5.2	Dryout fraction and shedding volume .....	14-21
14.5.3	Inputs for YMIM .....	14-27
14.5.4	Inputs for TOSPAC .....	14-34
14.5.5	Inputs for GASTSA .....	14-38
14.6	Results .....	14-39
14.6.1	Aqueous releases .....	14-40
14.6.2	Gaseous releases .....	14-58
14.6.3	Parameter sensitivities .....	14-60
14.7	Conclusions/recommendations .....	14-70
Chapter 15 Nominal-Case Releases: Weeps Model .....		15-1
15.1	Brief description of the weeps model .....	15-1
15.2	Major differences with TSPA-91 .....	15-6
15.3	Incorporation of hydrothermal model and YMIM .....	15-7
15.3.1	YMIM implementation .....	15-8
15.3.2	Hydrothermal model implementation .....	15-10
15.4	Parameters .....	15-13
15.5	Results .....	15-17
15.5.1	Base case .....	15-18
15.5.2	Comparison of the four repository cases .....	15-42
15.5.3	Thermal modeling sensitivities .....	15-58
15.5.4	Parameter sensitivities .....	15-61
15.5.5	Assumptions and limitations .....	15-64
15.6	Conclusions/recommendations .....	15-66
15.6.1	Site characterization .....	15-68
15.6.2	Repository design .....	15-70
Chapter 16 Human Intrusion .....		16-1
16.1	Parameter definition .....	16-2
16.1.1	Probability of hitting a container .....	16-2
16.1.2	Analysis parameters .....	16-4
16.1.3	Measurements of performance .....	16-6
16.2	Waste-container lifetime studies .....	16-7
16.2.1	Analysis setup .....	16-8
16.2.2	Lifetime predictions .....	16-10
16.3	Release results .....	16-17
16.3.1	Results for borehole-emplacement, 57-kW/acre case .....	16-21
16.3.2	Results for borehole-emplacement, 114-kW/acre case .....	16-25
16.3.3	Results for in-drift-emplacement cases .....	16-26
16.4	Sensitivity studies .....	16-29
16.4.1	Amount of waste released by a drilling hit .....	16-29
16.4.2	Size of drill bit .....	16-30
16.5	Discussion .....	16-32
16.5.1	Lifetime studies .....	16-34
16.5.2	Drilling releases .....	16-35
Chapter 17 Magmatic Activity .....		17-1
17.1	Probability estimates .....	17-2
17.2	Analysis setup .....	17-3
17.2.1	Calculation of temperature excursion .....	17-4
17.2.2	Dike-waste-package interactions .....	17-7

17.3 Results .....	17-15
17.4 Discussion .....	17-20
<b>Part V: Summary and Conclusions</b>	
<b>Chapter 18 Discussion and Conclusions .....</b>	<b>18-1</b>
18.1 Discussion of results .....	18-1
18.1.1 Aqueous and gaseous releases based on composite-porosity model....	18-1
18.1.2 Aqueous and gaseous releases based on weeps model.....	18-2
18.1.3 Releases due to human intrusion .....	18-3
18.1.4 Releases due to magmatic activity .....	18-4
18.1.5 Supporting analyses .....	18-5
18.2 Comparison of results from the two flow models.....	18-8
18.3 Combination of CCDFs .....	18-12
18.4 Conclusions from the TSPA-93 study .....	18-18
<b>Chapter 19 Recommendations .....</b>	<b>19-1</b>
19.1 Site data .....	19-2
19.2 Waste-package data and near-field processes .....	19-5
19.3 Repository and waste-package design.....	19-6
19.4 Regulation .....	19-7
<b>Chapter 20 Future TSPA Work .....</b>	<b>20-1</b>
20.1 General .....	20-1
20.2 Thermal modeling .....	20-2
20.3 Source term .....	20-2
20.4 Aqueous flow and transport .....	20-3
20.5 Gaseous flow and transport .....	20-5
20.6 Human intrusion .....	20-5
20.7 Basaltic volcanism .....	20-6
<b>Part VI: Ancillary Calculations</b>	
<b>Chapter 21 Barometric Pumping of Contaminated Gases Through Unsaturated Fractured Rock .....</b>	<b>21-1</b>
21.1 Repository geometry and rock properties .....	21-3
21.2 Conceptual model .....	21-4
21.3 Governing equations .....	21-5
21.4 Numerical procedure .....	21-8
21.5 Numerical simulations .....	21-9
21.5.1 The baseline case .....	21-10
21.5.2 Comparison with Nevada Test Site experience .....	21-14
21.5.3 Retardation effects .....	21-16
21.6 Quasi-steady transport calculations .....	21-16
21.7 Single-horizon models .....	21-23
21.8 Summary .....	21-29
<b>Chapter 22 Barometric Pumping of Moisture Through Unsaturated Fractured Rock .....</b>	<b>22-1</b>
22.1 Maximum moisture transport .....	22-1
22.2 Vertical background gradients .....	22-2
22.3 Problem formulation .....	22-3
22.3.1 Fracture model.....	22-5
22.3.2 Matrix model .....	22-6
22.3.3 Constitutive relations .....	22-6

22.3.4	Mixture relations and thermodynamics .....	22-7
22.3.5	The single-horizon approximation .....	22-8
22.4	Numerical treatment .....	22-9
22.4.1	Test problems .....	22-11
22.5	Barometric pumping of water vapor .....	22-11
22.5.1	Figures of merit and characteristic material functions .....	22-11
22.5.2	General features of the motion .....	22-13
22.5.3	Factors controlling the net moisture respired .....	22-20
22.5.4	Effect of binary diffusion .....	22-21
22.5.5	Effect of matrix permeability .....	22-24
22.5.6	Effect of bulk permeability .....	22-25
22.5.7	Other parameter effects .....	22-26
22.6	Conclusions .....	22-27
Chapter 23	Appropriateness of One-Dimensional Calculations .....	23-1
23.1	Effect of material heterogeneity .....	23-2
23.1.1	Effect of low-conductivity obstructions on effective properties .....	23-2
23.1.2	Effects of unsaturated fractures on effective material properties .....	23-5
23.1.3	Effective conductivities for random material mixtures .....	23-6
23.2	Effect of boundary conditions on global-scale modeling .....	23-7
23.2.1	Unit-gradient boundary conditions .....	23-8
23.3	Nonisotropic hydraulic conductivity effects .....	23-12
23.3.1	Analytic model .....	23-13
23.3.2	Numerical approach .....	23-13
23.3.3	Results of nonisotropic-hydraulic conductivity effects .....	23-15
23.4	Summary of one-dimensional appropriateness studies .....	23-16
Chapter 24	Effect of Fractures on Repository Dryout .....	24-1
24.1	Problem description .....	24-1
24.2	Results .....	24-6
24.3	Conclusions regarding repository dryout .....	24-11
Chapter 25	References .....	25-1
Appendix A	TSPA-93 Column Stratigraphy .....	A-1
Appendix B	Probability Distribution Functions for Solubility and Sorption .....	B-1
Appendix C	Thermal Modeling Approaches .....	C-1

# Figures

		<u>Page</u>
1-1	Illustration of the purposes and users of iterative performance assessments .....	1-4
1-2	Elements of TSPA-93 analyses, showing chapters in report where they are discussed .....	1-13
2-1	Map showing location of Yucca Mountain region adjacent to the Nevada Test Site in southern Nevada.....	2-1
2-2	Schematic cross section of the potential Yucca Mountain repository region showing location of the repository horizon and static water table with respect to the thermal/mechanical stratigraphic units defined by Ortiz <i>et al.</i> (1985).....	2-4
2-3	Visualization of the potential Yucca Mountain repository and associated surface facilities .....	2-7
2-4	Release pathways arising from expected and unanticipated processes at Yucca Mountain .....	2-10
2-5	Map of region surrounding the potential repository at Yucca Mountain; the area outside the shaded region is the accessible environment .....	2-13
3-3	Condensed FEP diagram for nominal flow in the presence of a repository .....	3-8
3-4	Condensed FEP diagram for human intrusion.....	3-10
3-5	Condensed FEP diagram for basaltic volcanism .....	3-12
3-6	Flow chart showing computer programs used for calculation of nominal releases with the composite-porosity model .....	3-14
3-7	Flow chart showing computer programs used for calculation of nominal releases with the weeps model .....	3-15
3-8	Flow chart showing computer programs used for calculation of basaltic-volcanism releases .....	3-18
3-9	Flow chart illustrating the Monte Carlo method.....	3-21
4-1	SCP waste-package design .....	4-3
4-2	In-drift waste-package design .....	4-4
4-3	Borehole-emplacment configuration .....	4-5
4-4	In-drift emplacement configuration .....	4-6
4-5	SCP-CDR repository layout.....	4-11
4-6	Alternative repository layout based on tunnel-boring machine construction .....	4-12
4-7	Repository area for the 57-kW/acre borehole emplacement case .....	4-14
4-8	Repository area for the 114-kW/acre in-drift emplacement case .....	4-15
4-9	Repository area for the 57-kW/acre in-drift emplacement case .....	4-15
4-10	Repository area for the 114-kW/acre borehole emplacement case, showing extra area needed for high-level waste canisters .....	4-16
6-1	Correlation between matrix porosity and matrix permeability for non-zeolitic welded and nonwelded tuffs from Yucca Mountain .....	6-4
6-2	Map showing locations of deep drillholes used in developing the simulated stratigraphic models and of the desired stratigraphic columns at Yucca Mountain .....	6-5

6-3	Map showing the locations of the digitized cross sections used to develop the spatial continuity model of lithology .....	6-8
6-4	Sample variograms computed in the indicated directions from the digitized cross sections shown in Figure 6-3 .....	6-8
6-5	Conceptual representation in two directions of the fitted, two-part nested variogram model: (a) plan view; (b) cross-sectional view from west to east .....	6-10
6-6	Representative west-to-east cross section of Yucca Mountain illustrating the tendency of simulated welded and nonwelded lithologies to pinch and swell and to interfinger in a more complex fashion than is believed reasonable based on field observations .....	6-13
6-7	Composite vertical profile of Yucca Mountain showing approximate correspondence of indicator lithologic categories used in TSPA-93 with the thermal/mechanical units of Ortiz <i>et al.</i> (1985) and formal geologic nomenclature as modified from Scott and Bonk (1984) .....	6-15
6-8	Columns and associated areas for the 1139-acre (57-kW/acre) repository model .....	6-18
6-9	Columns and associated areas for the 575-acre (114-kW/acre) repository model .....	6-19
6-10	Ten simplified stochastic realizations of stratigraphic column 1 extracted from the three-dimensional indicator simulations .....	6-24
6-11	Ten simplified stochastic realizations of stratigraphic column 2 extracted from the three-dimensional indicator simulations. ....	6-25
6-12	Ten simplified stochastic realizations of stratigraphic column 3 extracted from the three-dimensional indicator simulations .....	6-26
6-13	Ten simplified stochastic realizations of stratigraphic column 4 extracted from the three-dimensional indicator simulations .....	6-27
6-14	Ten simplified stochastic realizations of stratigraphic column 5 extracted from the three-dimensional indicator simulations .....	6-28
6-15	Ten simplified stochastic realizations of stratigraphic column 6 extracted from the three-dimensional indicator simulations .....	6-29
6-16	Ten simplified stochastic realizations of stratigraphic column 7 extracted from the three-dimensional indicator simulations .....	6-30
6-17	Ten simplified stochastic realizations of stratigraphic column 8 extracted from the three-dimensional indicator simulations .....	6-31
6-18	Histograms summarizing the uncertainty associated with the upper contact of unit 5 at the location of (a) stratigraphic column 1 and (b) stratigraphic column 4.....	6-32
7-1	TSPA-93 unsaturated-zone hydrostratigraphy, from the top of the model domain to the water table. ....	7-3
7-2	Fit to limited data using the entropy-fit routine .....	7-6
7-3	Comparison of unscaled and scaled parameter distributions .....	7-9
7-4	PDF fit to the rock bulk density data for unit 3 .....	7-12
7-5	Log-transformed data and PDF for unit 2 .....	7-13
7-6	Distribution of fracture orientations for unit 5 .....	7-26
7-7	PDF for fracture orientations for unit 5 .....	7-26
7-8	Comparison of PDFs for matrix porosity in potential repository horizon .....	7-34
7-9	Comparison of PDFs for matrix saturated hydraulic conductivity in the potential repository horizon .....	7-35

8-1	Overview of infiltration and percolation at Yucca Mountain, including definitions of terms used in Chapter 8 .....	8-2
8-2	Oxygen isotope measurements made on two Indian Ocean cores by a CLIMAP research group showing size of the global ice sheets over the past half-million years .....	8-6
8-3	Oxygen isotope measurements made on ice core from central Greenland by a GRIP research group showing the average earth temperature over the past full glacial cycle .....	8-6
8-4	Distribution of northern-hemisphere ice sheets and modeled position of the jet stream. ....	8-8
8-5	Chronology of lake levels for Lake Lahontan, approximately 300 km northwest of Yucca Mountain.....	8-9
8-6	Probability distribution of $K_{sm}$ for the TSw unit .....	8-15
8-7	Infiltration and percolation flux under "dry" conditions .....	8-16
8-8	Infiltration and percolation flux under "wet" conditions .....	8-16
8-9	Distribution of the ratio of composite-porosity percolation to matrix conductivity ( $q/K_{sm}$ ) .....	8-17
10-1	Possible thermally driven effects at a potential Yucca Mountain repository .....	10-2
10-2	Conceptual hydrothermal model used in TSPA-93 .....	10-4
10-3	Characteristics of double-blended waste stream for 21/40 waste packages .....	10-9
10-4	Youngest-fuel-first waste stream for 21/40 waste packages .....	10-11
10-5	Representation of unit cell to calculate LAPD; Heated drift length used to calculate design-basis areal power density .....	10-13
10-6	Isothermal plot for 5-m plane, 50 years following waste emplacement for the 114-kW/acre in-drift case. ....	10-18
10-7	Isothermal plot for 5-m plane, 50 years following waste emplacement for the 57-kW/acre in-drift case .....	10-18
10-8	Isothermal plot for 5-m plane, 50 years following waste emplacement for the 114-kW/acre vertical-borehole case .....	10-19
10-9	Isothermal plot for 5-m plane, 50 years following waste emplacement for the 57-kW/acre vertical-borehole case.....	10-19
10-10	Fraction dry calculated using V-TOUGH for 114-kW/acre case .....	10-20
10-11	Fraction dry calculated using V-TOUGH for 57-kW/acre case .....	10-20
10-12	Sampling lines used in V-TOUGH estimations of volume dry .....	10-22
10-13	Dryout volume calculated using V-TOUGH for 114-kW/acre case .....	10-23
10-14	Dryout volume calculated using V-TOUGH for 57-kW/acre case .....	10-23
10-15	COYOTE and analytical waste-package surface temperatures for the 57-kW/acre, in-drift case .....	10-26
10-16	Composite container surface temperature for the 114-kW/acre, in-drift case .....	10-26
10-17	Composite container surface temperature for the 57-kW/acre, in-drift case .....	10-27
10-18	Composite container surface temperature for the 114-kW/acre, vertical-borehole case .....	10-27
10-19	Composite container surface temperature for the 57-kW/acre, vertical-borehole case .....	10-28
10-20	Fuel-rod temperatures for the 114-kW/acre, vertical-borehole case .....	10-29
10-21	Fuel-rod temperatures for the 57-kW/acre, vertical-borehole case .....	10-29
10-22	Fuel-rod temperatures for the 114-kW/acre, in-drift case .....	10-30
10-23	Fuel-rod temperatures for the 57-kW/acre, in-drift case .....	10-31

11-1	Geologic units intercepted by the water table .....	11-4
11-2	A three-dimensional view of the Topopah Springs unit as constructed by translation .....	11-5
11-3	A schematic diagram showing the three-dimensional relationship among the potential repository, the stratigraphic units, and the major faults .....	11-6
11-4	The approximate location of the potential repository, Solitario Canyon Fault Zone, and Drill Hole Wash Fault Zone on the calculational grid of Figure 11-1 .....	11-7
11-5	The revised potentiometric surface map from Ervin <i>et al.</i> (1993) .....	11-8
11-6	The potentiometric surface map based on calculated values of head for the case described in Table 11-2 .....	11-11
11-7	Approximate location of the 5-km fence at which breakthroughs are calculated .....	11-12
11-8	Locations of the three contaminant sources for transport calculations, shown as filled elements .....	11-13
11-9	Breakthrough curves along the 5-km fence for a source of unit concentration located at the water table in the Prow Pass .....	11-14
11-10	Breakthrough curves along the 5-km fence for a source of unit concentration located at the water table in the Bullfrog .....	11-15
11-11	Breakthrough curves along the 5-km fence for a source of unit concentration located at the water table in the Calico Hills .....	11-16
11-12	Concentration contours at the water table at 4,700 years for a continuous source of unit concentration, with retardation = 1, located in the Prow Pass at the water table .....	11-17
11-13	Concentration contours at the water table at 4,700 years for a continuous source of unit concentration, with retardation = 1, located in the Bullfrog at the water table .....	11-18
11-14	Concentration contours at the water table at 4,700 years for a continuous source of unit concentration, with retardation = 1, located in the Calico Hills at the water table .....	11-19
11-15	The potentiometric surface map based on calculated values of head for the case described in Table 11-4 .....	11-22
11-16	Breakthrough curves along the 5-km fence for a source of unit concentration located at the water table in the Prow Pass .....	11-23
11-17	Breakthrough curves along the 5-km fence for a source of unit concentration located at the water table in the Bullfrog .....	11-24
11-18	Breakthrough curves along the 5-km fence for a source of unit concentration located at the water table in the Calico Hills .....	11-25
11-19	Concentration contours at 4,700 years for a continuous source of unit concentration, with retardation = 1, located in the Prow Pass at the water table .....	11-26
11-20	Distribution of effective velocities for Prow Pass source, no drain .....	11-29
11-21	Distribution of effective velocities for Bullfrog source, no drain .....	11-30
11-22	Distribution of effective velocities for Calico Hills source, no drain .....	11-30
11-23	Distribution of effective velocities for Prow Pass source, with drain .....	11-31
11-24	Distribution of effective velocities for Bullfrog source, with drain .....	11-31
11-25	Distribution of effective velocities for Calico Hills source, with drain .....	11-32
11-26	Comparison of SZ transport times for TSPA-91 and TSPA-93 .....	11-34
12-1	Retardation factor as a function of temperature for the modeled units .....	12-4
12-2	Repository layout used for gas-flow calculations. ....	12-5
12-3	Geometry of the three modeled cross sections .....	12-6

12-4	Finite-difference mesh for cross section N765000 .....	12-8
12-5a	Retarded travel times of $^{14}\text{C}$ particles from the repository to the atmosphere for particles released at 1,000 years. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-11
12-5b	Retarded travel times of $^{14}\text{C}$ particles from the repository to the atmosphere for particles released at 5,000 years. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-11
12-5c	Retarded travel times of $^{14}\text{C}$ particles from the repository to the atmosphere for particles released at 10,000 years. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-12
12-5d	Retarded travel times of $^{14}\text{C}$ particles from the repository to the atmosphere for particles released at 15,000 years. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-12
12-6a	Calculated temperature field ( $^{\circ}\text{C}$ ) at 1,000 years for cross section N765000. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-13
12-6b	Calculated temperature field ( $^{\circ}\text{C}$ ) at 5,000 years for cross section N765000. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-13
12-6c	Calculated temperature field ( $^{\circ}\text{C}$ ) at 10,000 years for cross section N765000. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-14
12-6d	Calculated temperature field ( $^{\circ}\text{C}$ ) at 15,000 years for cross section N765000. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-14
12-7a	Calculated gas-flow field at 5,000 years for cross section N765000. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-15
12-7b	Calculated gas-flow field at 10,000 years for cross section N765000. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-16
12-7c	Calculated gas-flow field at 15,000 years for cross section N765000. Welded-tuff bulk permeability of $10^{-11} \text{ m}^2$ .....	12-16
12-8a	Retarded travel times of $^{14}\text{C}$ particles from the repository to the atmosphere for particles released at 2,000 years. Welded-tuff bulk permeability of $10^{-12} \text{ m}^2$ .....	12-17
12-8b	Retarded travel times of $^{14}\text{C}$ particles from the repository to the atmosphere for particles released at 5,000 years. Welded-tuff bulk permeability of $10^{-12} \text{ m}^2$ .....	12-18
12-8c	Retarded travel times of $^{14}\text{C}$ particles from the repository to the atmosphere for particles released at 10,000 years. Welded-tuff bulk permeability of $10^{-12} \text{ m}^2$ .....	12-18
12-9	$^{14}\text{C}$ travel times for welded-tuff permeability of $10^{-12} \text{ m}^2$ compared to $^{14}\text{C}$ travel times for welded-tuff permeability of $10^{-11} \text{ m}^2$ .....	12-19
12-10	Comparison of retardation/permeability factor for TSPA-91 and TSPA-93 .....	12-21
12-11	$^{14}\text{C}$ travel-time distributions for TSPA-91 .....	12-22
12-12	$^{14}\text{C}$ travel-time distributions for TSPA-93 .....	12-23
12-13	$^{14}\text{C}$ travel-time distributions for steady-state gas flow, with welded-tuff permeability of $10^{-11} \text{ m}^2$ and nonwelded permeability of $10^{-12} \text{ m}^2$ .....	12-24
13-1	Functional structure of the YMIM model .....	13-5
13-2	Generalized aqueous corrosion rate as a function of temperature .....	13-9
13-3	Illustration of pitting growth rates for three growth conditions .....	13-11
13-4	Probability of failure as a function of number of pits .....	13-14

13-5	Fuel oxidation rates .....	13-18
14-1	Distributions of UZ transport time for an unretarded tracer, for TSPA-91 and TSPA-93 .....	14-9
14-2	Fraction of containers wet, for vertical-borehole containers .....	14-15
14-3	Fraction of containers moist, for vertical-borehole containers .....	14-15
14-4	Fraction of containers dry, for vertical-borehole containers .....	14-16
14-5	Column stratigraphies for the composite-porosity calculations .....	14-19
14-6	Saturated-zone flow tubes for 57-kW/acre cases .....	14-20
14-7	Saturated-zone flow tubes for 114-kW/acre cases .....	14-20
14-8	Dryout-fraction curves for 57 kW/acre, vertical emplacement .....	14-22
14-9	Dryout-fraction curves for 114 kW/acre, vertical emplacement .....	14-22
14-10	Dryout-fraction curves for 57 kW/acre, in-drift emplacement .....	14-23
14-11	Dryout-fraction curves for 114 kW/acre, in-drift emplacement .....	14-23
14-12	Shedding-volume curves for 57 kW/acre, vertical emplacement .....	14-25
14-13	Shedding-volume curves for 114 kW/acre, vertical emplacement .....	14-25
14-14	Shedding-volume curves for 57 kW/acre, in-drift emplacement .....	14-26
14-15	Shedding-volume curves for 114 kW/acre, in-drift emplacement .....	14-26
14-16	Neptunium-solubility distributions for TSPA-91 and TSPA-93 .....	14-29
14-17	CCDFs for individual columns, plus the combination CCDF .....	14-42
14-18	CCDFs of normalized cumulative aqueous release over 10,000 years for the four cases and for TSPA-91 .....	14-43
14-19	Comparison of normalized cumulative aqueous release over 10,000 years for TSPA-91, TSPA-93, and a test case in which percolation flux is the same as for TSPA-91 but everything else is the same as for TSPA-93 .....	14-44
14-20	CCDFs of normalized cumulative aqueous release over 10,000 years, divided into two parts: one part with a climate change within the period and the other part with no climate change within the period .....	14-45
14-21	CCDFs of peak individual drinking-water dose rate over 1,000,000 years for the four cases.....	14-45
14-22	Mean distributions of container-failure time for the four repository cases and for TSPA-91 .....	14-47
14-23	Distributions of potential dilution factor for dry and wet climates .....	14-50
14-24	CCDFs of peak individual drinking-water dose rate over 1,000,000 years with fluctuating water table and with fixed water table .....	14-51
14-25	CCDFs of normalized cumulative aqueous release over 10,000 years with fluctuating water table and with fixed water table .....	14-52
14-26	Distributions of time of peak individual drinking-water dose rate for the four cases.....	14-52
14-27	CCDFs for three time periods .....	14-54
14-28	CCDFs for individual radionuclides .....	14-55
14-29a	CCDFs for normalized cumulative aqueous release over 10,000 years from the EBS, from the unsaturated zone, and to the accessible environment (57 kW/acre, vertical emplacement) .....	14-56
14-29b	CCDFs for normalized cumulative aqueous release over 100,000 years from the EBS, from the unsaturated zone, and to the accessible environment (57 kW/acre, vertical emplacement) .....	14-57
14-29c	CCDFs for normalized cumulative aqueous release over 1,000,000 years from the EBS, from the unsaturated zone, and to the accessible environment (57 kW/acre, vertical emplacement) .....	14-57

14-30	CCDFs of normalized cumulative gaseous release over 10,000 years for the four cases and for TSPA-91 .....	14-59
14-31	CCDFs of normalized cumulative gaseous release from the EBS over 10,000 years for the four cases and for TSPA-91 .....	14-59
14-32	CCDFs of normalized cumulative nominal release over 10,000 years for the four cases and for TSPA-91 .....	14-61
14-33	Scatter plot of normalized cumulative aqueous release over 10,000 years vs. "dry" percolation flux .....	14-63
14-34	Scatter plot of normalized cumulative aqueous release over 10,000 years vs. first climate-change time .....	14-63
14-35	Scatter plot of peak individual drinking-water dose rate over 1,000,000 years vs. saturated-zone transport area .....	14-65
14-36	Scatter plot of peak individual drinking-water dose rate over 1,000,000 years vs. "dry" percolation flux .....	14-65
14-37	Scatter plot of peak individual drinking-water dose rate over 1,000,000 years vs. TSw matrix saturated conductivity .....	14-66
14-38	Scatter plot of peak individual drinking-water dose rate over 1,000,000 years vs. 100°C pitting increment .....	14-66
14-39	Scatter plot of peak individual drinking-water dose rate over 1,000,000 years vs. neptunium solubility .....	14-67
14-40	Scatter plot of normalized cumulative gaseous release over 10,000 years vs. TSw matrix saturated conductivity .....	14-68
14-41	Scatter plot of normalized cumulative gaseous release over 10,000 years vs. 100°C pitting increment .....	14-68
14-42	Scatter plot of normalized cumulative gaseous release over 10,000 years vs. "dry" percolation flux .....	14-69
14-43	Scatter plot of normalized cumulative gaseous release over 10,000 years vs. TSw bulk permeability .....	14-69
14-44	Mean distributions of container-failure time for some alternative two-walled containers .....	14-72
15-1	Overview of potential weep flow through the unsaturated zone at Yucca Mountain. ....	15-2
15-2	Illustration of adjacent containers, one contacted by a weep and suffering degradation, the other not contacted and remaining intact .....	15-3
15-3	Overview of the method used by the weeps model to calculate probability of a weep contacting a container .....	15-4
15-4	Container numbering scheme used by the weeps model for determining container-wall and fuel-rod temperatures .....	15-9
15-5	Illustration of flow-pattern changes calculated by the weeps model when the dryout zone is expanding .....	15-11
15-6	Illustration of flow-pattern changes calculated by the weeps model when the dryout zone is contracting. ....	15-12
15-7	Calculation of the area in which a weep can intercept a container ( $A_{contact}$ ). ....	15-15
15-8	Layout of the one-dimensional flow tube used to describe the saturated zone for a weeps-model calculation .....	15-17
15-9	Overview of a typical realization of the weeps model for a 57-kW/acre repository with vertically emplaced containers .....	15-19
15-10	Distribution of containers contacted by weeps over a 1,000,000-year period .....	15-21
15-11	Distribution of containers that have aqueous releases of radionuclides over a 1,000,000-year period .....	15-22

15-12	Distribution of initial times at which containers have aqueous releases of radionuclides .....	15-22
15-13	Distribution of containers that experience corrosion-induced failure over a 1,000,000-year period .....	15-24
15-14	Distribution of juvenile failures specified as an input parameter .....	15-24
15-15	Distribution of the ratio of aqueous-releasing containers that experience corrosion-induced failures to all aqueous-releasing containers over a 1,000,000-year period .....	15-25
15-16	Distribution of the times of corrosion-induced failures .....	15-25
15-17	Distribution of the durations that weeps contact containers before corrosion-induced failure occurs .....	15-26
15-18	Distribution of the total durations that weeps contact containers .....	15-27
15-19	Conditional CCDFs of cumulative aqueous releases to the accessible environment, normalized by the EPA limits .....	15-28
15-20	Conditional CCDFs of cumulative aqueous releases to the accessible environment, at 10,000 years, normalized by the EPA limits, for specified radionuclides and their combination .....	15-30
15-21	Conditional CCDFs of cumulative aqueous releases from the EBS, normalized by the EPA limits .....	15-31
15-22	Conditional CCDFs of cumulative aqueous releases from the EBS, at 10,000 years, normalized by the EPA limits, for specified radionuclides and their combination .....	15-32
15-23	Conditional CCDFs of peak radiation doses from drinking water to a maximally exposed individual .....	15-33
15-24	Conditional CCDFs of peak radiation doses from drinking water to a maximally exposed individual, for specified radionuclides and their combination .....	15-34
15-25	Conditional CCDFs of the times of peak radiation doses .....	15-35
15-26	Scatter plot of peak dose vs. time of occurrence .....	15-35
15-27	Distribution of containers contacted by weeps over a 10,000-year period .....	15-37
15-28	Distribution of containers that have gaseous releases of radionuclides over a 10,000-year period .....	15-38
15-29	Distribution of initial times at which containers have gaseous releases of radionuclides .....	15-38
15-30	Distribution of containers that experience corrosion-induced failure over a 10,000-year period .....	15-39
15-31	Conditional CCDFs of cumulative gaseous releases to the accessible environment, at 10,000 years, normalized by the EPA limits .....	15-40
15-32	Combined conditional CCDFs of cumulative aqueous and gaseous releases to the accessible environment, at 10,000 years, normalized by the EPA limits .....	15-41
15-33	Comparison of the distributions of containers contacted by weeps over a 1,000,000-year period, for the four repository cases .....	15-42
15-34	Comparison of the distributions of containers that have aqueous releases of radionuclides over a 1,000,000-year period, for the four repository cases ..	15-44
15-35	Comparison of the distributions of initial times at which containers have aqueous releases of radionuclides, for the four repository cases .....	15-44
15-36	Comparison of the distributions of containers that experience corrosion-induced failure over a 1,000,000-year period, for the four repository cases ..	15-46
15-37	Comparison of the distributions of the times of corrosion-induced failures for the four repository cases .....	15-46
15-38	Comparison of the distributions of the durations that weeps contact containers before corrosion-induced failure occurs, for the four repository cases .....	15-48

15-39	Comparison of the distributions of the total durations that weeps contact containers, for the four repository cases .....	15-49
15-40	Comparison of the conditional CCDFs of cumulative aqueous releases to the accessible environment, at 10,000 years, normalized by the EPA limits, for the four repository cases .....	15-50
15-41	Comparison of the conditional CCDFs of cumulative aqueous releases from the EBS, at 10,000 years, normalized by the EPA limits, for the four repository cases .....	15-51
15-42	Comparison of the conditional CCDFs of peak radiation doses from drinking water to a maximally exposed individual, for the four repository cases .....	15-52
15-43	Comparison of the conditional CCDFs of the times of peak radiation doses for the four repository cases .....	15-53
15-44	Comparison of the distributions of containers contacted by weeps over a 10,000-year period, for the four repository cases .....	15-54
15-45	Comparison of the distributions of containers that have gaseous releases of radionuclides over a 10,000-year period, for the four repository cases .....	15-55
15-46	Comparison of the distributions of initial times at which containers have gaseous releases of radionuclides, for the four repository cases .....	15-55
15-47	Comparison of the distributions of containers that experience corrosion-induced failure over a 10,000-year period, for the four repository cases .....	15-57
15-48	Comparison of the conditional CCDFs of cumulative gaseous releases to the accessible environment, at 10,000 years, normalized by the EPA limits, for the four repository cases .....	15-57
15-49	Comparison of the combined conditional CCDFs of cumulative aqueous and gaseous releases to the accessible environment, at 10,000 years, normalized by the EPA limits, for the four repository cases .....	15-58
15-50	Comparison of the conditional CCDFs of cumulative aqueous releases to the accessible environment, at 10,000 years, normalized by the EPA limits, for the four repository cases .....	15-60
16-1	Possible orientations of drill and in-drift HLW containers .....	16-7
16-2	Standardized container-wetting conditions used for lifetime studies .....	16-9
16-3	Air-oxidation rates for alloy 825 and carbon steel .....	16-11
16-4	Container failure profile for 50% container wetting conditions .....	16-12
16-5	Container failure profile for 50% container wetting conditions .....	16-13
16-6	Container failure profile for 20% container wetting conditions .....	16-13
16-7	Range of container failures for 57-kW/acre, borehole case .....	16-14
16-8	Range of container failures for 114-kW/acre, borehole case .....	16-15
16-9	Range of container failures for 57-kW/acre, in-drift case .....	16-16
16-10	Range of container failures for 114-kW/acre, in-drift case .....	16-16
16-11	Nonlinear entropy fit to histogram of releases .....	16-17
16-12	Mean values of release peaks for times to 1,000,000 years .....	16-18
16-13	Contributions to releases from components of source term for 57-kW/acre borehole case .....	16-22
16-14	Conditional CCDFs for 10,000-year cumulative releases after various starting times for 57-kW/acre borehole case .....	16-23
16-15	Conditional CCDFs for cumulative releases over 1,000,000 years for 57-kW/acre borehole case .....	16-23
16-16	Comparison of CCDFs for similar TSPA-91 and TSPA-93 analyses .....	16-24
16-17	Conditional CCDF for releases for 114-kW/acre, borehole case .....	16-25
16-18	Conditional CCDF for cumulative releases over 1,000,000 years for 114-kW/acre, borehole case .....	16-26

16-19	Contributions to releases from components of source term for 114-kW/acre, in-drift case .....	16-27
16-20	Conditional CCDF for 10,000-year releases for the two in-drift cases .....	16-27
16-21	Conditional CCDFs for cumulative releases over 1,000,000 years for 57-kW/acre, in-drift case .....	16-28
16-22	Conditional CCDF for cumulative releases over 1,000,000 years for 114-kW/acre, in-drift case .....	16-29
16-23	Alternative distribution of waste released from in-drift waste package .....	16-30
16-24	Comparison of 10,000-year CCDFs for two assumptions for distributions of waste-package releases .....	16-31
16-25	Comparison of 1,000,000-year CCDFs for two assumptions for distributions of waste-package releases .....	16-31
16-26	Comparison of CCDFs for two drill-bit diameters .....	16-33
16-27	Comparison of CCDFs for different drill-bit diameters .....	16-33
16-28	Container lifetime profile for low corrosion rate assumption .....	16-35
17-1	Interaction between waste packages and magmatic intrusion .....	17-1
17-2	Time-temperature surface for rock temperatures adjacent to a 0.75-m (half-width) dike.....	17-5
17-3	Time-temperature surface for rock temperatures adjacent to a 2.25-m (half-width) dike.....	17-6
17-4	Distribution of dike widths .....	17-6
17-5	Distribution of dike orientations .....	17-8
17-6	Examples of dikes crossing drifts for 57-kW/acre repository area .....	17-8
17-7	Dike-induced temperature excursion for 57-kW/acre repository .....	17-9
17-8	Dike-induced temperature excursion for 114-kW/acre repository .....	17-10
17-9	Comparison of rock-temperature excursions for a dike in host rock at 50°C and 500°C ambient temperatures .....	17-10
17-10	Cumulative releases to the accessible environment, with magmatic intrusion .....	17-16
17-11	Releases due to magmatic intrusion .....	17-16
17-12	Releases due to magmatic intrusion .....	17-18
17-13	Comparison of direct and indirect releases over 10,000 years .....	17-19
17-14	Releases due to magmatic intrusion, scaled by probability of occurrence .....	17-19
17-15	Releases due to magmatic intrusion, scaled by probability of occurrence .....	17-20
17-16	Comparison of peak doses with and without magmatic intrusion .....	17-21
18-1	CCDFs of normalized cumulative release over 10,000 years for nominal aqueous releases .....	18-9
18-2	CCDFs of normalized cumulative release over 10,000 years for nominal gaseous releases .....	18-10
18-3	CCDFs of normalized cumulative release over 10,000 years for nominal aqueous releases .....	18-10
18-4	CCDFs of peak individual drinking-water dose over 1,000,000 years for nominal aqueous releases .....	18-11
18-5	Distribution of time of peak dose for nominal aqueous releases .....	18-12
18-6	Combination of nominal and human-intrusion CCDFs. Composite-porosity model used for UZ flow and transport .....	18-14
18-7	Combination of nominal and human-intrusion CCDFs. Weeps model used for UZ flow and transport .....	18-14
18-8	Combination of nominal and human-intrusion CCDFs. Weeps model used for UZ flow and transport .....	18-15

18-9	Combination of nominal and human-intrusion CCDFs. Composite-porosity model used for UZ flow and transport .....	18-16
18-10	Combination of nominal and human-intrusion CCDFs. Weeps model used for UZ flow and transport .....	18-16
18-11	CCDFs of normalized cumulative release over 10,000 years. Composite-porosity model used for UZ flow and transport .....	18-17
18-12	CCDFs of normalized cumulative release over 10,000 years. Weeps model used for UZ flow and transport .....	18-17
21-1	Schematic of barometric pumping in a fractured permeable medium .....	21-2
21-2	Schematic of proposed Yucca Mountain repository .....	21-4
21-3	Concentration profiles for typical Yucca Mountain parameters .....	21-11
21-4	Normalized outflows for typical Yucca Mountain parameters .....	21-12
21-5	Concentration profiles for typical Nevada Test Site parameters .....	21-15
21-6	Normalized outflows for typical Nevada Test Site parameters .....	21-15
21-7	Concentration profiles for typical Nevada Test Site parameters with retardation .....	21-17
21-8	Normalized outflows for typical Nevada Test Site parameters with retardation .....	21-17
21-9	Concentration profiles for quasi-steady analysis with typical Yucca Mountain parameters .....	21-18
21-10	Normalized outflows for quasi-steady analysis with typical Yucca Mountain parameters .....	21-19
21-11	Influence of retardation factor on quasi-steady outflow of contaminant .....	21-20
21-12	Influence of matrix permeability on quasi-steady outflow of contaminant .....	21-21
21-13	Influence of fracture spacing on quasi-steady contaminant outflow .....	21-22
21-14	Influence of diffusion strength of quasi-steady contaminant outflow .....	21-22
21-15	Comparison of analytical and numerical solutions for quasi-steady contaminant transport through a uniform gradient in a semi-infinite medium .....	21-25
21-16	Comparison of single-horizon model with numerical calculations which take account of finite height and nonuniform gradients .....	21-27
21-17	Concentration histories at three elevations for $\Delta L/L=1/2$ .....	21-28
21-18	Concentration profiles at various times during typical cycle with $\Delta L/L=1/2$ .....	21-28
21-19	Concentration histories at three elevations for $\Delta L/L=2$ .....	21-28
21-20	Concentration profiles at various times during typical cycle with $\Delta L/L=2$ .....	21-28
22-1	Conceptual model of the fractured permeable medium .....	22-4
22-2	Profiles of gas pressure in the matrix during a 5-day barometric cycle .....	22-14
22-3	Profiles of capillary pressure in the matrix during a 5-day barometric cycle .....	22-15
22-4	Profiles of vapor mass fraction in the matrix during a 5-day barometric cycle .....	22-15
22-5	Profiles of gas mass flux in the matrix during a 5-day barometric cycle .....	22-16
22-6	Profiles of liquid mass flux in the matrix during a 5-day barometric cycle .....	22-17
22-7	Profiles of vapor mass flux in the matrix during a 5-day barometric cycle .....	22-18

22-8	Profiles of moisture (liquid and vapor) mass flux in the matrix during a 5-day barometric cycle .....	22-19
22-9	Gas displacement in the fracture as a function of diffusive strength and matrix permeability .....	22-22
22-10	Net annual outflow of moisture as a function of diffusive strength and matrix permeability .....	22-22
22-11	Illustration of time-phase shifts and optimal moisture respiration with respect to diffusive strength .....	22-23
22-12	Gas displacement and net annual outflow as function of matrix permeability .....	22-24
22-13	Gas displacement and annual net outflow as a function of fracture spacing .....	22-25
23-1	(a) Nonhomogeneous material concept, (b) assumed idealized symmetric array, and (c) numerical mesh .....	23-3
23-2	Material hydraulic conductivity .....	23-3
23-3	Nondimensional fluxes for three geometric configurations .....	23-4
23-4	(a) Schematic of the periodic global fracture/matrix system, (b) representative unit cell of the periodic fracture model .....	23-6
23-5	Flow path lines for material mixes: (a) 25%, (b) 50%, and (c) 75% .....	23-7
23-6	Two-dimensional computational domain .....	23-9
23-7	Darcy velocity vectors, using unit-gradient boundary conditions, $q = 0.01$ mm/yr .....	23-11
23-8	Darcy velocity vectors, using no-flow boundary conditions, $q = 0.01$ mm/yr .....	23-11
23-9	Particle path lines, 0.01 mm/yr .....	23-12
23-10	Problem geometry and numerical boundary conditions .....	23-14
23-11	Hydraulic conductivity ratio as a function of boundary capillary pressure for an average of eleven realizations, $\text{downdip} = 10$ degrees .....	23-15
23-12	Hydraulic conductivity ratio as a function of capillary pressure for an average of eleven realizations, $\text{dip} = 70$ degrees .....	23-16
24-1	Two-dimensional axisymmetric geometry of repository and surrounding geologic media for 114-kW/acre, 30-yr-old fuel, Buscheck and Nitao (1993) .....	24-2
24-2	(a) One-dimensional approximation to repository and surrounding layered geologic media (b) Initial temperature and saturation profiles .....	24-2
24-3	Vertical liquid saturation profiles along the repository centerline, 30-yr-old SNF, 114 kW/acre .....	24-3
24-4	Vertical temperature profiles along the repository centerline, 30-yr-old SNF, 114 kW/acre .....	24-4
24-5	Vertical liquid saturation profiles along the repository centerline for 30-yr-old SNF, 114 kW/acre, $t = 0, 100, 600,$ and 10,000 yr .....	24-7
24-6	Vertical liquid saturation profiles along the repository centerline for 30-yr-old SNF, 114 kW/, $t = 0, 100, 600,$ and 10,000 yr .....	24-8
24-7	Vertical extent of dryout as a function of fracture permeability .....	24-9
24-8	Vertical extent of perched water above the repository as a function of permeability .....	24-9
24-9	Permeability as a function of capillary pressure, TSw2 .....	24-10
24-10	Liquid saturation as a function of capillary pressure, TSw2 .....	24-10

# Tables

		<u>Page</u>
1-1	Information sources for TSPA-93 analyses .....	1-10
2-1	Generalized stratigraphy at Nevada Test Site/Yucca Mountain region .....	2-2
4-1	Waste-receipt schedule based on the DOE Mission Plan Amendment .....	4-7
4-2	Waste-acceptance schedule for borehole-emplacement waste packages .....	4-8
4-3	Waste-acceptance schedule for in-drift-emplacement waste packages .....	4-9
4-4	Emplacement/thermal loading cases analyzed .....	4-10
4-5	Repository areas and waste-package spacings for four emplacement configurations .....	4-17
5-1	Weighted-average age and burnup of spent fuel .....	5-1
5-2	Spent-fuel inventory and characteristics .....	5-2
5-3	Description of reactor fuel assemblies .....	5-4
5-4	Numbers of fuel rods per package .....	5-4
5-5	Fuel rod parameters .....	5-4
5-6	Sources of high-level waste .....	5-5
5-7	HLW waste stream used for TSPA analyses .....	5-6
5-8	Comparison of HLW inventories at two burnups .....	5-7
5-9	High-level waste radionuclides with EPA limits not included in TSPA inventory .....	5-8
5-10	Combined high-level waste inventory .....	5-9
5-11	Combined (spent-fuel and high-level waste) inventory .....	5-10
5-12	Radionuclides and modified inventories used for aqueous and gaseous analyses .....	5-11
5-13	Illustration of adjustment of inventory for <sup>237</sup> Np .....	5-11
5-14	Comparisons of TSPA-91 and TSPA-93 inventories .....	5-13
5-15	Comparison of spent-fuel and HLW inventories .....	5-14
6-1	Summary of modeled variogram parameters .....	6-9
6-2	Descriptions of the ten hydrogeologic units used in TSPA-93 .....	6-16
6-3	TSPA-93 column locations .....	6-20
7-1	Hydrogeologic properties used to determine PDFs for TSPA-93 .....	7-4
7-2	Hydrogeologic units and their mean thicknesses .....	7-9
7-3	Matrix porosity statistics, unscaled beta and scaled beta distribution parameters .....	7-11
7-4	Rock bulk density statistics, and beta and scaled beta distribution parameters .....	7-11
7-5a	Matrix saturated hydraulic conductivity statistics, and log <sub>10</sub> statistics .....	7-14
7-5b	Matrix saturated hydraulic conductivity entropy fit parameters, and scaled beta probability distribution parameters .....	7-14
7-6a	Matrix air-entry parameter statistics and log <sub>10</sub> statistics .....	7-15
7-6b	Matrix air-entry parameter entropy fit parameters, and scaled beta-distribution parameters .....	7-15
7-7a	Matrix saturation/desaturation statistics and log <sub>10</sub> statistics .....	7-16

7-7b	Matrix saturation/desaturation entropy fit, and scaled beta-distribution parameters .....	7-16
7-8	Matrix residual degree of saturation statistics, and beta and scaled beta distribution parameters .....	7-17
7-9a	Bulk saturated hydraulic conductivity basic statistics and log <sub>10</sub> statistics ..	7-18
7-9b	Bulk saturated hydraulic conductivity probability-distribution parameters from an entropy fit .....	7-19
7-10a	Barometric pumping statistics expressed as bulk conductivities for units 2 and 3 .....	7-19
7-10b	Barometric pumping beta probability distribution parameters from an entropy fit.....	7-20
7-11	Hydrogeologic unit matrix, bulk-hydraulic, and fracture parameters comparison for analog bulk saturated hydraulic conductivity .....	7-21
7-12	Bulk saturated hydraulic conductivity parameters for units 1, 4, and 5 .....	7-22
7-13	Summary of $K_{bs}$ parameters .....	7-22
7-14	Fracture frequency statistics and beta distribution approximation of the exponential .....	7-24
7-15	Analog units used for fracture orientation missing units .....	7-24
7-16	Fracture angle/orientation statistics and beta-distribution parameters .....	7-25
7-17	Fracture spacing statistics and beta-distribution parameters .....	7-28
7-18	Hydraulic aperture statistics and beta-distribution parameters .....	7-29
7-19	Fracture porosity statistics, log <sub>10</sub> statistics, and beta distribution parameters .....	7-30
7-20	Fracture hydraulic conductivity statistics, log <sub>10</sub> statistics, and beta distribution parameters .....	7-30
7-21	Fracture air-entry parameter basic statistics and beta-distribution parameters .....	7-31
7-22	Spearman rank correlations for matrix porosity and saturated hydraulic conductivity.....	7-32
7-23	Corresponding hydrogeologic units in TSPA-91 and TSPA-93 .....	7-33
7-24	Comparison of expected values for matrix-porosity between TSPA-91 and TSPA-93 .....	7-33
7-25	Comparison of expected values for matrix saturated hydraulic conductivity between TSPA-93 and TSPA-91 .....	7-34
7-26	Comparison of expected values for matrix air-entry between TSPA-93 and TSPA-91 .....	7-36
7-27	Comparison of expected values for matrix saturation/desaturation between TSPA-93 and TSPA-91 .....	7-36
7-28	Comparison of matrix residual saturation expected values between TSPA-93 and TSPA-91 .....	7-37
7-29	Comparison of expected values for fracture parameters between TSPA-93 and TSPA-91 .....	7-37
8-1	Distributions used for climate/percolation parameters .....	8-5
8-2	Recharge for various precipitation zones in Ash Meadows groundwater system as predicted by the Maxey-Eakin method .....	8-11
9-1	Ground water chemistry at Yucca Mountain .....	9-3
9-2a	Elicited solubilities for elements with linear PDFs (moles/l).....	9-7
9-2b	Elicited solubilities for elements with logarithmic PDFs (moles/l) .....	9-7
9-3	Stratigraphy vs. rock type .....	9-12

9-4	Elicited sorption-coefficients ( $K_d$ ) distributions (ml/g) .....	9-16
10-1	Summary of thermal loading cases examined in TSPA-93 .....	10-14
10-2	Time at which the composite container surface temperatures change from the COYOTE to the analytical predictions .....	10-25
11-1	Parameters and boundary conditions used for calibration, non-diversionary model .....	11-9
11-2	Comparison of calculated heads to data for heads measured in various wells .....	11-10
11-3	The fit of calculated heads to data for the diversionary model without Solitario Canyon and Drill Hole Wash faults .....	11-20
11-4	The fit of calculated heads to data for the diversionary model with Solitario Canyon and Drill Hole Wash faults .....	11-21
11-5	Parameters and boundary conditions used for calibration diversionary model .....	11-22
11-6	Effective velocity and dispersivity for the six SZ cases .....	11-33
11-7	Velocity and dispersivity distributions for TSA simulations .....	11-35
12-1	Coefficients used in Equation (12.5) .....	12-9
12-2	Fixed parameter values used in the simulations.....	12-9
13-1	Principal mechanisms included in YMIM .....	13-1
13-2	Geochemistry parameters used in YMIM .....	13-7
13-3	Air-oxidation rates used for TSPA-93 .....	13-9
13-4	Generalized aqueous corrosion rates for mild steel .....	13-10
13-5	Estimates of corrosion rates for high-nickel alloy .....	13-11
13-6	Parameters used in YMIM alloy 825 pitting model .....	13-13
13-7	Parameters of YMIM fuel-rod cladding failure model .....	13-16
13-8	Parameters for YMIM fuel-oxidation model .....	13-17
13-9	Fuel-oxidation parameters used in TSPA-93 .....	13-19
14-1	Total-body dose-conversion factors for ingestion .....	14-5
14-2	Areas for the UZ columns .....	14-17
14-3	Number of containers in each column.....	14-17
14-4	Flow-tube dimensions for saturated-zone transport .....	14-19
14-5	Summary of radionuclide properties .....	14-28
14-6	Summary of hydrothermal parameters .....	14-30
14-7	Summary of physical dimensions and geochemistry .....	14-31
14-8	Summary of parameters for container and fuel-rod failure .....	14-32
14-9	Summary of parameters for $UO_2$ alteration and pulse releases .....	14-33
14-10	Summary of parameters for unsaturated-zone flow .....	14-35
14-11	Summary of parameters for saturated-zone flow .....	14-37
14-12	Summary of transport parameters .....	14-37
14-13	Summary of parameters for gaseous flow and transport .....	14-38
14-14	Nuclide mean releases and dose rates in relation to total .....	14-56
14-15	Parameters important to composite-porosity aqueous EPA releases .....	14-62
14-16	Parameters important to composite-porosity aqueous peak dose rates .....	14-64
14-17	Parameters important to composite-porosity gaseous EPA releases .....	14-67
15-1	Weeps-model parameters used for flow calculation .....	15-14
15-2	Repository-related parameters required by the weeps model .....	15-14

15-3	Parameters used by the weeps model for calculating saturated-zone flow .....	15-16
15-4	Weeps-model mean releases and doses in relation to total .....	15-36
15-5	Parameters important to weeps-model aqueous EPA releases .....	15-61
15-6	Parameters important to weeps-model aqueous peak doses .....	15-63
15-7	Parameters important to weeps-model gaseous EPA releases .....	15-64
16-1	Drilling analysis probabilities and parameters .....	16-3
16-2	Repository-related parameters for drilling analyses .....	16-4
16-3	Source-term parameters for drilling analyses .....	16-5
16-4	Times to cool to 100°C and 70°C for various analysis cases .....	16-9
16-5	Range of container failure times .....	16-15
16-6	Scaling factors for 1,000,000-year releases .....	16-19
16-7	Probabilities of hits for 0.21-m drill bit diameter .....	16-32
16-8	Waste-package failure times for various analysis cases .....	16-34
17-1	Probabilities of occurrence for magmatic events .....	17-3
17-2	Thermal properties of tuff and dike .....	17-7
17-3	Container half-spacings and range of distances from dikes .....	17-11
17-4	Magma-induced sulfidation rates used for TSPA-93 .....	17-13
17-5	Fractions of undistributed releases at various probability levels .....	17-17
17-6	Fractions of undistributed releases at various probability levels .....	17-17
21-1	Parameters used in base case calculation of contaminant transport at Yucca Mountain .....	21-10
22-1	Standard problem parameters, $k_b = 10D$ .....	22-13
23-1	Material properties .....	23-10
24-1	Material matrix properties .....	24-5
24-2	Fracture properties for all units .....	24-5
24-3	Parametric variation in material properties .....	24-6

**(This page left intentionally blank)**

# Executive Summary

## 1 Introduction

Yucca Mountain is being investigated by the U.S. Department of Energy (DOE) as the potential site for the permanent disposal of spent fuel from nuclear reactors and high-level radioactive waste generated by the U.S. Department of Defense. Yucca Mountain is located in a sparsely populated, arid region of the U.S., approximately 120 km northwest of Las Vegas, Nevada, on the border of the DOE's Nevada Test Site. To take advantage of less groundwater, a potential repository at the site would be mined in the unsaturated zone of the mountain, about 300 m below the surface, but over 200 m above the water table (Figure ES-1).

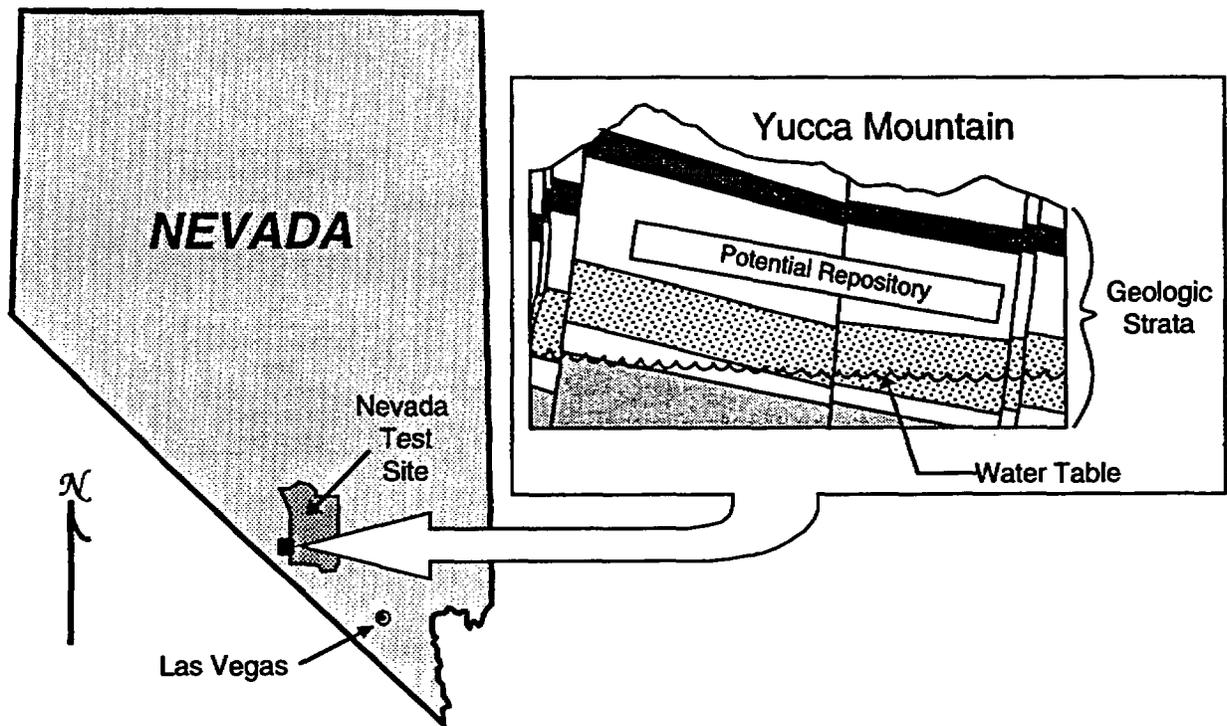


Figure ES-1. Location of Yucca Mountain and a potential high-level radioactive-waste repository.

A repository at Yucca Mountain will have to meet a number of Federal regulations, including regulations concerning long-term waste isolation promulgated by the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission. To determine long-term waste isolation, the Yucca Mountain Site Characterization Project (YMP) of DOE has begun a series of total-system performance assessments (TSPAs). The work described in this report—TSPA-93—is part of the second full iteration in the series (Figure ES-2).

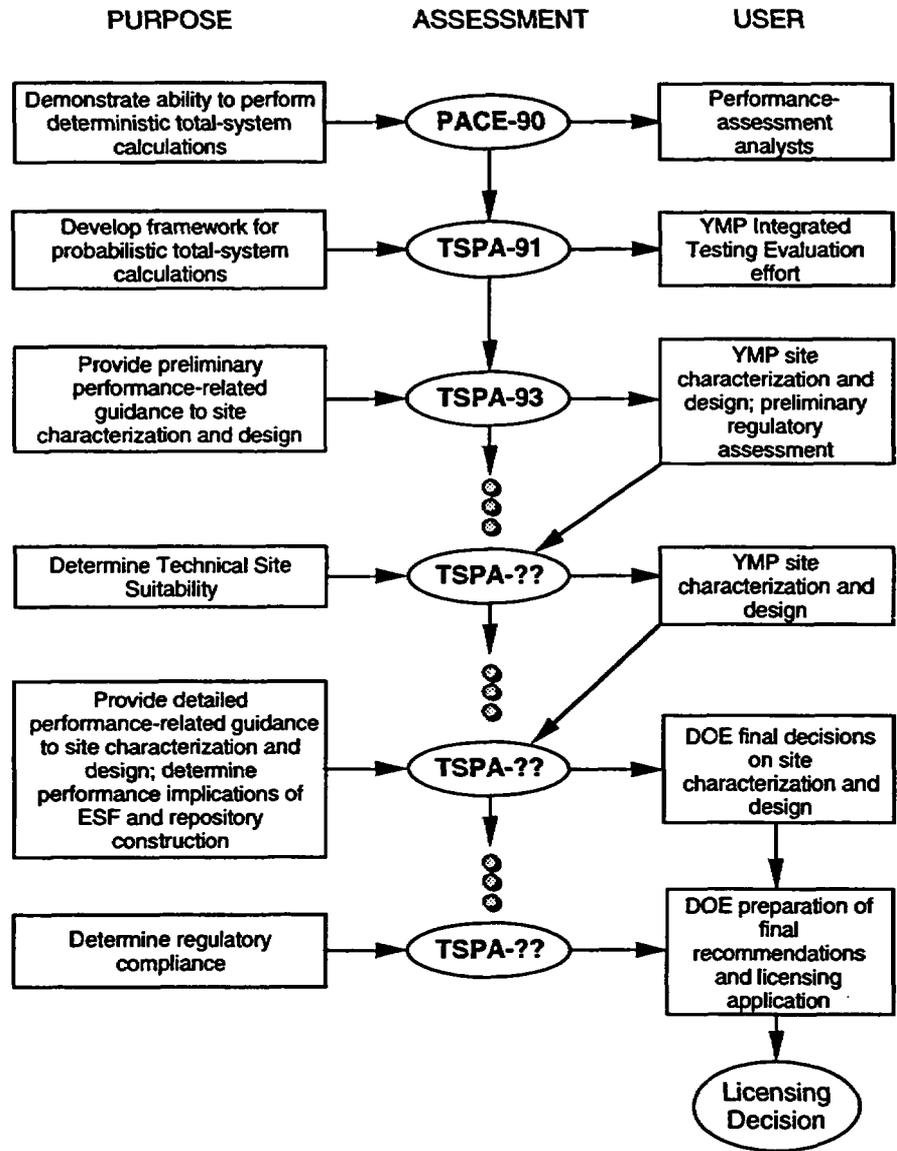


Figure ES-2. Progression of TSPA analyses.

TSPA-93 differs from previous analyses in several important respects. Significant new detailed modeling is undertaken, including three-dimensional geostatistical modeling of the stratigraphy, three-dimensional modeling of the saturated zone, and modeling of repository thermal effects. A phenomenological source term developed by Lawrence Livermore National Laboratory (LLNL) and climate change extrapolated from the paleoclimatic record are included in the probabilistic models. Several different repository designs with different containers and different thermal loadings are evaluated.

Two performance measures are considered in this TSPA iteration: normalized cumulative release, as defined by the EPA in 40 CFR 191.13, and radiation dose to a maximally exposed individual. The Energy Policy Act of 1992 dictates that 40 CFR Part 191 no longer

applies to Yucca Mountain, and sets a course of action for specifying a new standard. Individual dose is examined in TSPA-93 to determine the potential impact of such a standard on the performance assessment. To study the impact of longer time periods on repository performance, both cumulative-releases and dose results were calculated for a million-year time period in addition to the typical 10,000-year period.

In one respect, the results of TSPA-93 tend to confirm previous work: cumulative releases from all investigated sources are generally below the EPA standard (40 CFR 191.13), except for gaseous releases of  $^{14}\text{C}$ . However, a significant new result is that future peak doses from drinking water in the area could be substantially above background radiation levels. Also, some of the models indicate that larger containers (e.g., the multipurpose container) and hotter repository configurations could lead to worse long-term performance, although a great deal of uncertainty is associated with these results.

### **1.1 TSPA-93 purpose**

The ultimate goal of the TSPA process is to determine compliance of a repository with applicable regulations and to support a license application for construction and operation of a repository. However, at this point in the process, the primary goal of TSPA-93 is to provide feedback to YMP participants on the significance of design and site-characterization information to regulatory compliance. Secondary goals of TSPA-93 involve progress toward performance assessments that are scientifically justified and acceptable for a license application, including refinement of mathematical models of physical processes, features, and events that could influence repository performance; consideration of an individual-dose performance measure; and calculation of conditional estimates of compliance with performance measures for scientific review. A final goal of TSPA-93 is to involve several different organizations within the project in production of a TSPA for Yucca Mountain. Table ES-1 shows the participants who provided input to TSPA-93. In addition, researchers from the Waste Isolation Pilot Project (WIPP) contributed to an independent review of this work.

### **1.2 Scenarios**

A TSPA is based on a risk-assessment methodology that contains the following major steps: (1) develop and screen scenarios, (2) develop models of important features, events, and processes, (3) estimate parameter values and uncertainties, (4) make calculations using the models and parameter values, and (5) interpret results. A summary of models, parameters, and results is contained in the following sections. Development and screening of scenarios are independent efforts and are described in separate documents; a brief discussion follows.

Table ES-1. Information sources for TSPA-93 analyses.

Component	Contributors
Stratigraphy and Hydrogeologic Parameters	<i>LBL</i> (C. Wittwer, G. Bodvarsson) <i>USGS</i> (A. Flint, L. Flint, R. Spengler, E. Weeks, R. Luckey, A. Geldon, D. Appel, D. Hoxie) <i>SNL</i> (A. Schenker, T. Robey, C. Rautman, D. Guerin)
Climate Change	<i>USGS</i> (A. Flint, L. Flint, D. Hobson, R. Forester, Z. Peterman) <i>WIPP</i> (P. Swift) <i>SNL</i> (J. Gauthier, M. Wilson)
Geochemistry	<i>LANL</i> (I. Triay, D. Morris, A. Meijer, M. Ebinger) <i>SNL</i> (M. Siegel)
Thermal Effects	<i>LLNL</i> (G. Johnson, T. Buscheck, L. Lewis) <i>TRW</i> (J. King) <i>B&amp;W Fuel</i> (T. Doering, R. Bahney, A. Thompson) <i>SNL</i> (E. Ryder, E. Dunn, J. Holland)
Saturated Zone	<i>USGS</i> (R. Luckey) <i>SNL</i> (G. Barr)
Gas Flow	<i>DSI</i> (B. Ross, N. Lu) <i>SNL</i> (M. Wilson)
Source Term and EBS Processes	<i>LLNL</i> (A. Lamont, J. Gansemer, W. Halsey, L. Lewis, R. Stout, D. McCright) <i>Iowa State University</i> (D. Bullen) <i>ORNL</i> (A. Croff) <i>SNL</i> (R. Barnard, J. Gauthier, M. Wilson)

A scenario consists of an organized list of features, events, and processes (FEPs) that could lead to releases of radionuclides to the accessible environment—either the ground surface or a subsurface boundary 5 km from the repository. Scenario categories consist of groupings of similar scenarios. The general scenario categories considered in TSPA-93 include cases with an undisturbed repository (the “nominal” case), and with a disrupted repository (the “disturbed” cases).

For TSPA-93, the nominal case consists of a heat-generating repository that is subjected to climate-dependent groundwater flow. Two alternative conceptual models of groundwater flow in the unsaturated zone are considered. Waste containers within the repository degrade by a variety of mechanisms, but the most important mechanism is aqueous-induced corrosion. If and when containers fail, radionuclides are available for gaseous or aqueous transport to the accessible environment. For gaseous transport, radionuclides move upward through the unsaturated zone to the ground surface. For aqueous transport, radionuclides

move downward through the unsaturated zone, then laterally through the saturated zone past the 5-km subsurface boundary. Radionuclides are tracked in terms of (1) cumulative releases to the accessible environment and (2) the dose an individual might receive by drinking contaminated water pumped from the saturated zone at the accessible environment.

For TSPA-93, two disturbed cases are investigated: (1) inadvertent human intrusion by exploratory drilling, and (2) volcanic activity that introduces corrosion-enhancing heat and volatiles into the repository. For human intrusion, radionuclides exhumed with the drill core and the drilling fluids contribute to releases. For indirect volcanic effects, magmatic-induced corrosion of containers allows earlier releases of radionuclides that are transported in groundwater flowing as described in the nominal case. (Direct volcanic releases were evaluated in TSPA-91.)

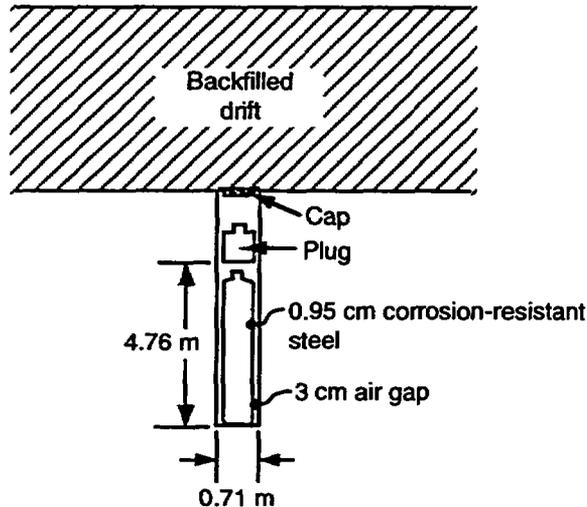
## **2 Data development**

### **2.1 Repository**

The design limit for a repository at Yucca Mountain is 70,000 metric tons of radioactive waste. The approximately 63,000 metric tons of spent fuel emplaced in the repository is considered to be aged 25 years, with burnups of 30,000 MWd/MTU for boiling-water-reactor fuel and 40,000 MWd/MTU for pressurized-water-reactor fuel. The approximately 7,000 metric tons of defense high-level waste is considered to have many of the heavy metal products removed and to be encased in a vitrified waste form. A study performed in conjunction with TSPA-93 examined the significance of each radionuclide contained in the wastes in terms of its potential for contributing to contamination at the accessible environment. Based on this study, the human-intrusion analyses in TSPA-93 consider a broad suite of 43 radionuclides. Nominal case and indirect volcanic effects consider 8 radionuclides, chosen for their transport characteristics (low retardation) or their potential contribution to individual dose.

The waste forms are enclosed in containers; container designs have not been finalized, but those investigated to date consist of cylindrical metal containers with gas-tight closures. Two container types are considered in TSPA-93 (Figure ES-3): (1) a smaller, "vertically emplaced" container proposed in the Site Characterization Plan (SCP) Conceptual Design of 1987, and (2) a larger, "in-drift" container which approximates the multipurpose container (MPC) presently being considered by the Yucca Mountain Project. Vertically emplaced containers are modeled with a surrounding air gap that is sometimes filled with rubble. In-drift containers are modeled with a surrounding backfill, provided to prevent drift collapse. (Consequences of adding a backfill are an increased potential for water pathways to the waste container, and higher container temperatures caused by the backfill acting as a thermal

**Thin-wall, SCP-type  
container  
vertically emplaced  
in borehole**



**Robust container  
horizontally emplaced  
in drift**

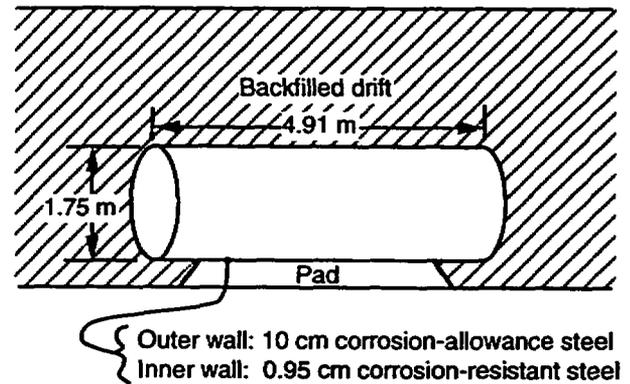


Figure ES-3. The two container types and emplacement strategies considered in TSPA-93.

insulator.) A 70,000-metric-ton repository requires the use of about 35,000 of the vertically emplaced containers or about 8,500 of the in-drift containers.

The repository layout incorporated in TSPA-93 consists of a series of emplacement drifts that run perpendicular to a main access drift. Length and proximity of the drifts to one another depend on the rock mass and the thermal characteristics of the repository. Decay of the radioactive waste produces heat: approximately 1 kW of heat for every metric ton (at emplacement—heat generation decreases over time). While the heat output depends primarily on the spent-fuel burnup and on the waste-acceptance schedule, the temperatures within the repository depend on the local areal power density (LAPD, expressed in terms of kW/acre), which is primarily a function of the waste-container spacing. It has been proposed that temperatures above boiling could produce a dry environment that would enhance the long-term performance of the repository. The SCP Conceptual Design specified an LAPD of 57 kW/acre (Figure ES-4). More recently, LAPDs up to 114 kW/acre have been considered by the YMP in order to attempt to induce a larger dryout zone.

Four combinations of container/thermal loadings are examined in TSPA-93. A 57-kW/acre repository with vertically emplaced containers is the baseline analysis case for TSPA-93, and most like the design described in the SCP and evaluated in TSPA-91. Also

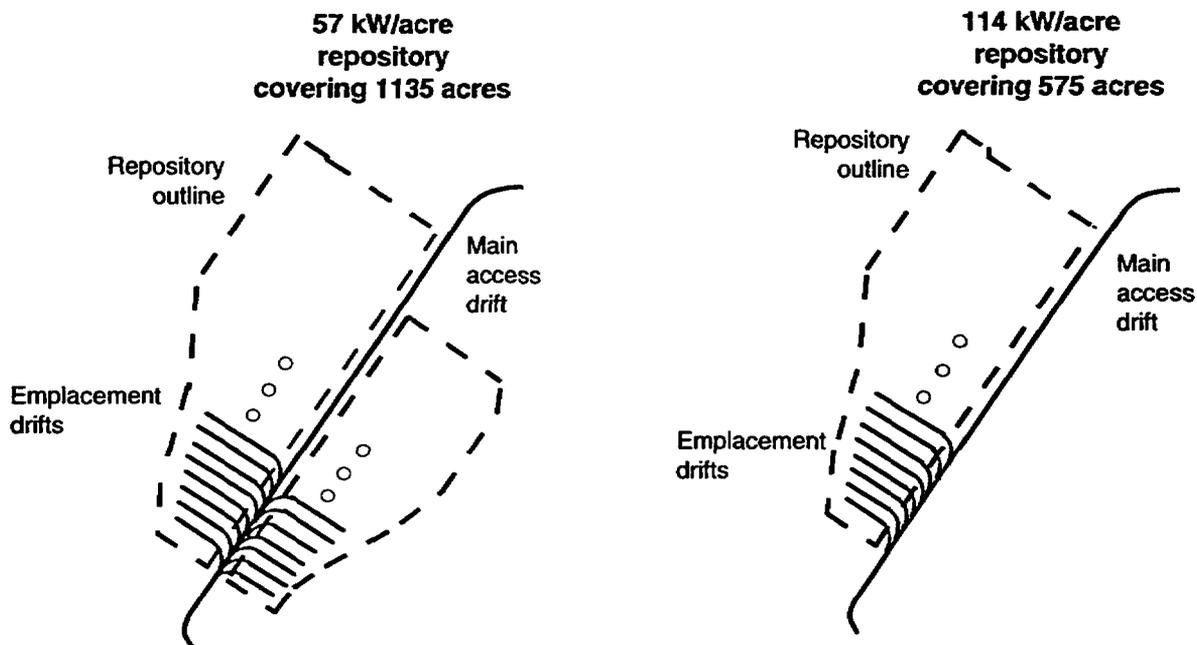


Figure ES-4. Repository layouts for the two thermal loadings considered in TSPA-93.

examined are a 114-kW/acre repository with vertically emplaced containers, a 57-kW/acre repository with in-drift containers, and a 114-kW/acre repository with in-drift containers.

## 2.2 Stratigraphy

A fully three-dimensional stratigraphic model of the potential repository region is developed for TSPA-93. The model uses geostatistics to reduce dependence on qualitative approaches by incorporating as much site-specific information as possible. The model was developed with the long-term goal of determining whether the thicknesses of the strata at the site are important to the modeled performance. For TSPA-93, probabilistic calculations (see below) are conducted using a reference stratigraphy selected from 10 geostatistical simulations performed with this approach.

The model incorporates lithologic data from 22 deep drillholes within or near the potential repository region in an indicator simulation to determine boundaries between welded and nonwelded layers of tuff. More regular structures—the Topopah Spring vitrophyre and the boundary between the vitric and zeolitized Calico Hills layers—are added separately.

Despite the welded/nonwelded indicator having horizontal correlation lengths on the order of kilometers, significant variation is seen in the strata contacts within the repository block for the 10 geostatistical outcomes. The implication is that the lithologic-data drillholes are not spaced closely enough for accurate predictions.

### **2.3 Hydrogeologic parameters**

A performance-assessment data base is produced for TSPA-93 for the purpose of standardizing available data and generating probability distributions of parameters used in both the detailed and the probabilistic models. Data are categorized for 15 hydrologic properties (e.g., porosity, hydraulic conductivity, etc.) in 10 strata, both in the unsaturated and saturated formations. Each of the 10 modeled strata is considered homogeneous, and one probability density function (PDF) is developed for each hydrologic property in each layer. Each PDF is either derived directly from available data (where data are abundant), or is derived based on maintaining maximum informational entropy (where data are sparse), in order to minimize the chance of biasing the results. PDFs are also adjusted from lab scale to site scale to make them more representative.

A new accomplishment with this effort is the development of a method for determining fracture characteristics that are consistent with site data. Distributions of bulk-permeability, fracture-frequency, and fracture-dip data from drillholes are used as input to a parallel-plate model, allowing calculation of fracture apertures, hydraulic conductivities, porosities, etc.

### **2.4 Climate change**

Groundwater flow could be the most important process affecting the performance of a repository at Yucca Mountain (analysis of TSPA-91 and TSPA-93 results show a significant sensitivity to the groundwater-flux parameter). Although the present groundwater flow through Yucca Mountain is thought to be relatively insignificant, few quantitative data are available. The strategy for TSPA-93 is to examine the paleoclimatic record and data from analog sites, then extrapolate future infiltration and percolation at Yucca Mountain. The paleoclimatic record shows that an ice-age cycle of 100,000 years has existed during the recent Pleistocene, and researchers have noted that Yucca Mountain experienced probably 40% but perhaps up to 200% more annual precipitation during the last ice age. Recent data from the U. S. Geological Survey (USGS) has also indicated that the water table under Yucca Mountain was higher by 85 m or more during the last ice age.

For TSPA-93, a series of "wet" (ice-age) and "dry" (interglacial) climates are specified, with a cycle of 100,000 years, but with the dividing time between wet and dry selected at random. Flow is modeled as a sequence of steady states. Infiltration rates average 10 mm/yr for wet climates, and 0.5 mm/yr for dry climates. The water table is allowed to rise up to 120 m during wet climates. These values are greater than what often is believed for the region. Percolation from meteoric sources is assumed to equal infiltration in the TSPA model that describes groundwater flow in fractures (the weeps model) but, for the model that describes

flow in both matrix and fractures (the composite-porosity model), percolation is reduced to account for lateral diversion of flow above the repository. For TSPA-93, groundwater mobilized by a repository thermal pulse (see below) is added onto the direct meteoric influx and both are diverted around the dried region where temperatures are above boiling.

## **2.5 Solubility and sorption parameters**

Distributions of solubility and sorption parameters for TSPA-93 were obtained through elicitation of experts from Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL). Their decisions are based primarily on laboratory data, while keeping in mind that solubility and sorption characteristics of radionuclides are especially dependent on site-specific groundwater chemistry and somewhat dependent on temperature. The experts reaffirmed that most of the actinides are relatively insoluble and highly sorbing in conditions typical of Yucca Mountain. However, neptunium does not adsorb well to tuffs and under oxidizing conditions is relatively soluble. The solubility and sorption values offered by the experts resulted in neptunium often being a major contributor to aqueous releases and doses for the nominal-case scenarios.

## **3 Detailed calculations**

### **3.1 Thermal effects**

It has become increasingly apparent over the last few years that heat generated by radioactive decay within a repository will influence the environment around it. For TSPA-93, thermal effects related to the thermal dryout, perturbation of the flow field, container corrosion, and spent-fuel alteration are considered.

For TSPA-93, three-dimensional heat-flow calculations were performed to determine parameters thought to be the most critical in defining the impact of the repository thermal pulse. Only heat conduction was considered in the calculations; hydrologic and mechanical effects were not explicitly modeled. All four repository configurations were explicitly modeled, however, accounting for each container location, container thermal output, and container emplacement time. In addition, LLNL supplied TSPA-93 with results of two-dimensional hydrothermal calculations with a smeared heat source for comparison (see below).

Critical parameters that are produced relate to the extent that the thermal pulse protects the repository from groundwater by forming a region above boiling temperature (called the protected, or "dryout fraction," of the repository), as well as the extent that it perturbs the environment by displacing vaporized water (water is displaced from the "dryout volume") and diverting meteoric water. In addition, container-wall temperatures and internal waste

temperatures are produced. The parameters are used in the probabilistic calculations to redistribute groundwater flow and to adjust the source term. For example, the source term used in the probabilistic calculations allows aqueous corrosion of a container only when liquid water is contacting the container and the container-wall temperature is below 100°C.

Some major results of the thermal modeling are as follows. The boiling isotherm, and therefore the perturbation in the environment, reaches substantial proportions around both the 57-kW/acre repositories and the 114-kW/acre repositories, although more so for the higher thermal loading (Figure ES-5). (For a period, at 114-kW/acre, the entire repository is dried out.) Comparison of the SNL and LLNL thermal modeling shows that repository geometry and the discrete nature of the heat sources are important: the center of 114-kW/acre repositories drops below boiling at around 5000 years with a discretely modeled repository, but at around 9000 years when the repository is modeled as a smeared heat source. Also, the in-drift containers are large discrete heat sources that produce a nonuniform dryout zone at early times. Thermal loading, backfill, and container size have a significant effect on container temperatures: the in-drift containers could see temperatures well above 500°C under certain conditions in a 114 kW/acre repository; the vertically emplaced containers reach temperatures slightly above 200°C in a 57 kW/acre repository.

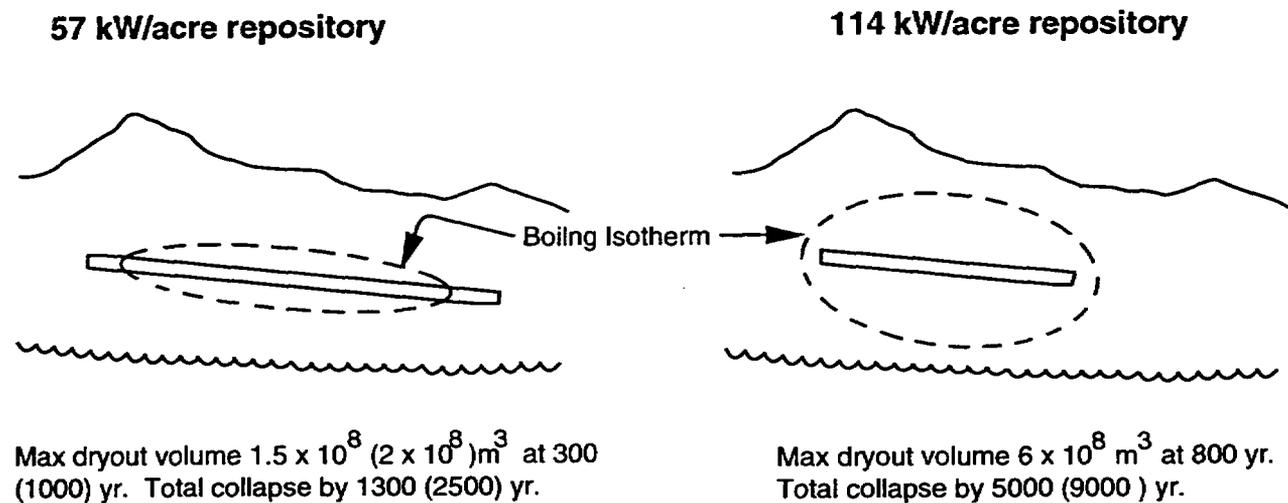


Figure ES-5. Extent and duration of the volume encompassed by the boiling isotherm (the dryout volume). Where different, the values calculated with a smeared heat source are shown in parentheses.

### 3.2 Saturated zone

A three-dimensional model of steady-state groundwater flow in the saturated zone is constructed for TSPA-93. Geometry for the model consists of an approximately 8-km square

section extending from the water table down 200 m. Five strata are included, which because of the tilt of the units intersect the water table at an angle. Two different flow models are superimposed on this geometry: nondiversionary flow, where all fluid entering the “high-gradient region” (to the northeast of the repository block) in the tuff aquifers continues to move through the tuff aquifers; and diversionary flow, where part of the fluid entering the high-gradient region is diverted from the saturated tuff downward to continue its flow path in the carbonate aquifers. Flow boundary conditions are taken from a regional saturated-zone flow model. Both the nondiversionary and the diversionary models calibrate to within a meter of water-table elevation at almost all drillholes.

Tracer transport times through the complicated three-dimensional structure are estimated for both models by transport calculations. The calculations involve a nonsorbing tracer released at various points under the repository block. Transport-time distributions are changed to velocity distributions for use in the probabilistic models.

Model calculations indicate that tracer transport times over the 5 km to the accessible environment tend to be less than 1000 years, and they tend to be shorter for the diversionary flow model than for the nondiversionary model. The short transport times, as well as the structure exhibited by the tracer concentrations during transport, indicate that three-dimensional modeling is important in the saturated zone. Accurate calibration of the flow systems required that reduced hydraulic conductivities be assigned to the Solitario Canyon fault and the Drill Hole Wash fault; these faults should be investigated for these properties.

### 3.3 Gas flow

A two-dimensional, nonisothermal, transient model of gas flow and  $^{14}\text{CO}_2$  transport provide gaseous-transport-time distributions for use in the TSPA-93 probabilistic models. Geometry for the model is taken from three parallel east-west cross sections that incorporate the latest information about site topography and stratigraphy. Only a 57-kW/acre repository is considered. For each calculation, transport times are determined for gas particles traveling from points distributed throughout the repository area to the ground surface. Transport-time distributions for  $^{14}\text{CO}_2$  particles are output at 1000-year intervals.

Major results of the gas-flow calculations indicate that  $^{14}\text{CO}_2$  transport times are short enough to have only marginal effect on cumulative releases. Gas flow depends primarily on temperature and the bulk-permeability distribution within the mountain. Retardation by exchange of  $^{14}\text{CO}_2$  with bicarbonate in the groundwater is included in the model, and significantly slows transport—typically by an order of magnitude or more. Adsorption onto minerals in the rock is not included, but is potentially important.

## **4 Probabilistic modeling**

The models for probabilistic analyses are abstractions of process models. The input parameters for these models come primarily from the data development and detailed modeling activities discussed above. To address uncertainty in parameters, the probabilistic models are used to perform thousands of calculations with parameters picked from probability distributions (the Monte Carlo method). To address uncertainty in models, two alternative conceptual models of groundwater flow in the unsaturated zone are analyzed. To simplify the process, aqueous, gaseous, human-intrusion, and basaltic-volcanism releases are modeled separately.

### **4.1 Nominal-case models**

Two alternative conceptual models of flow in the unsaturated zone form the foundation of the nominal-case calculations. These two models were used in TSPA-91, but are refined for TSPA-93 to include an abstracted thermal-effects model (based on the results of the detailed thermal-effects calculations discussed above) and climate change. To calculate aqueous releases and doses, each of these models incorporates: (1) a phenomenological source-term model to calculate radionuclide releases from containers, (2) a transport model to calculate spread of radionuclides through the groundwater, (3) a simplified saturated-zone model (using parameters from the detailed saturated-zone calculations discussed above), (4) a simple drinking-water-dose model, and (5) a simplified gas-flow model (based on the detailed gas-flow modeling discussed above).

#### **4.1.1 The composite-porosity model**

The composite-porosity model (also known as the equivalent-continuum model) describes flow through an equivalent porous medium of matrix and fractures using Darcy's law. The major assumption in the model is that a local pressure equilibrium tightly couples flow in the matrix and flow in the fractures; thus, groundwater flow is dominated by capillary forces and only occurs in the fractures when the matrix is saturated. The result is a relatively uniform flow (Figure ES-6). Radionuclide transport also is modeled assuming tight coupling between matrix and fracture transport; thus, when fracture flow does occur in the calculations, diffusion of radionuclides into the matrix slows the transport considerably. At the onset of a climate change, the water table is modeled to rise abruptly, and all radionuclides in the inundated part of the unsaturated zone are transferred immediately to the saturated zone, shortly thereafter forming a spike in the releases at the accessible environment.

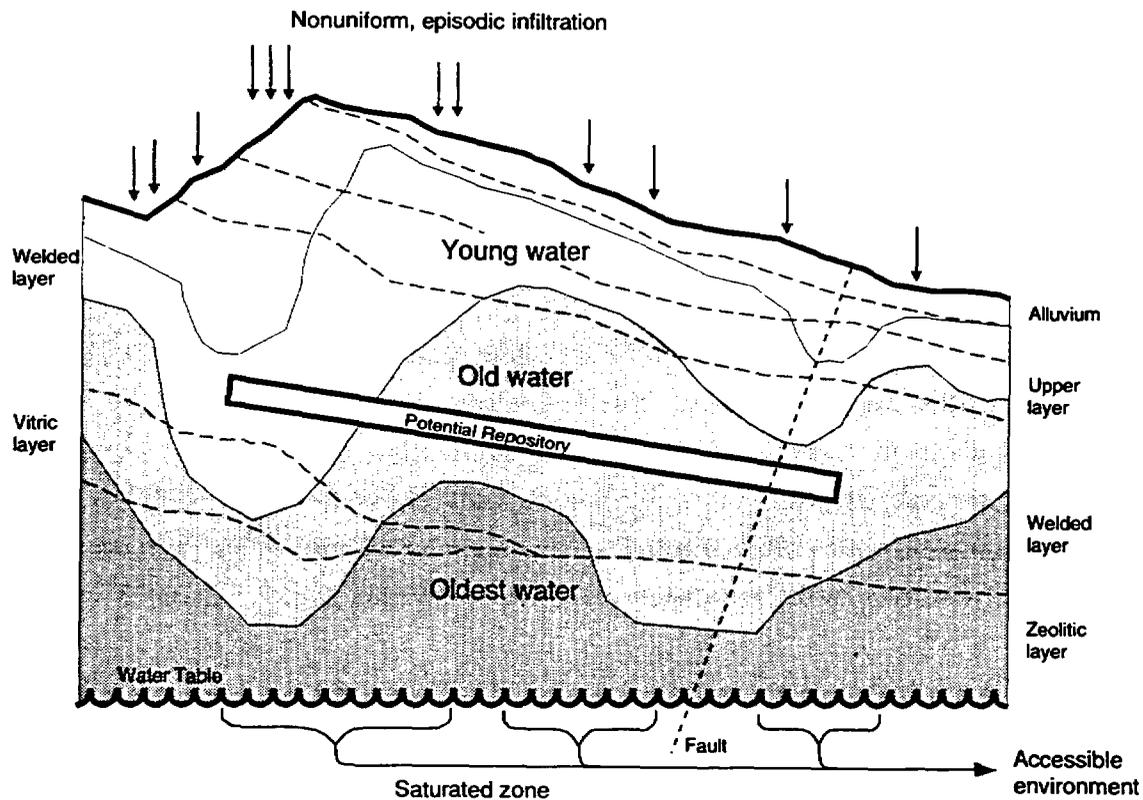


Figure ES-6. The composite-porosity model (large-scale regular percolation).

For TSPA-93, flow and transport through the unsaturated zone is modeled in 8 (for the 57-kW/acre repositories) or 5 (for the 114-kW/acre repositories) vertical flow tubes. Each unsaturated-zone flow tube is matched with a horizontal flow tube in the saturated zone.

Calculations using the composite-porosity model indicate that a relatively uniform flow pattern causes a large number of containers to be in a moist or a wet environment. Subsequent aqueous corrosion of these containers leads to widespread failure. (With the source-term being used, most aqueous corrosion occurs during the collapse of the repository thermal pulse, when water contacts containers that are near 100°C—see below.) Slow, constant percolation causes slow, constant leaching of waste from the failed waste containers. Long travel times afforded by the slowly percolating water in the unsaturated zone limit cumulative releases over 10,000 years, but are not sufficient to significantly limit peak doses that could occur in a 1,000,000-year period.

The parameters most important to performance depend on the performance measure applied, i.e., cumulative releases or individual dose. For the EPA measure from 40 CFR 191.13, percolation flux is the dominant parameter; when cumulative releases are measured at 10,000 years, the leading edge of a long-term pulse of releases is being measured, and the percolation flux determines how much of that leading edge crosses the boundary to

the accessible environment within 10,000 years. For the individual-dose measure, without any time limit, dilution in the environment is most important, but parameters relating to releases from containers are also important. For example, backfill allows more water contact with in-drift containers, causing a substantial number of failures and subsequent radioactive releases.

#### 4.1.2 The weeps model

The weeps model describes groundwater flow restricted to locally saturated fractures, which only contact the repository at discrete points (Figure ES-7). Weep location in time and space depends on thermal effects and climate change, and is treated as an inherently probabilistic process. Degradation of containers and releases of radionuclides are limited to the intersections of weeps and containers. Transport of radionuclides through the unsaturated zone is assumed to be instantaneous. The saturated zone is modeled with a single flow tube.

Weeps-model calculations indicate that flowing fractures contacting containers are relatively rare occurrences, and that many containers within a repository remain relatively dry

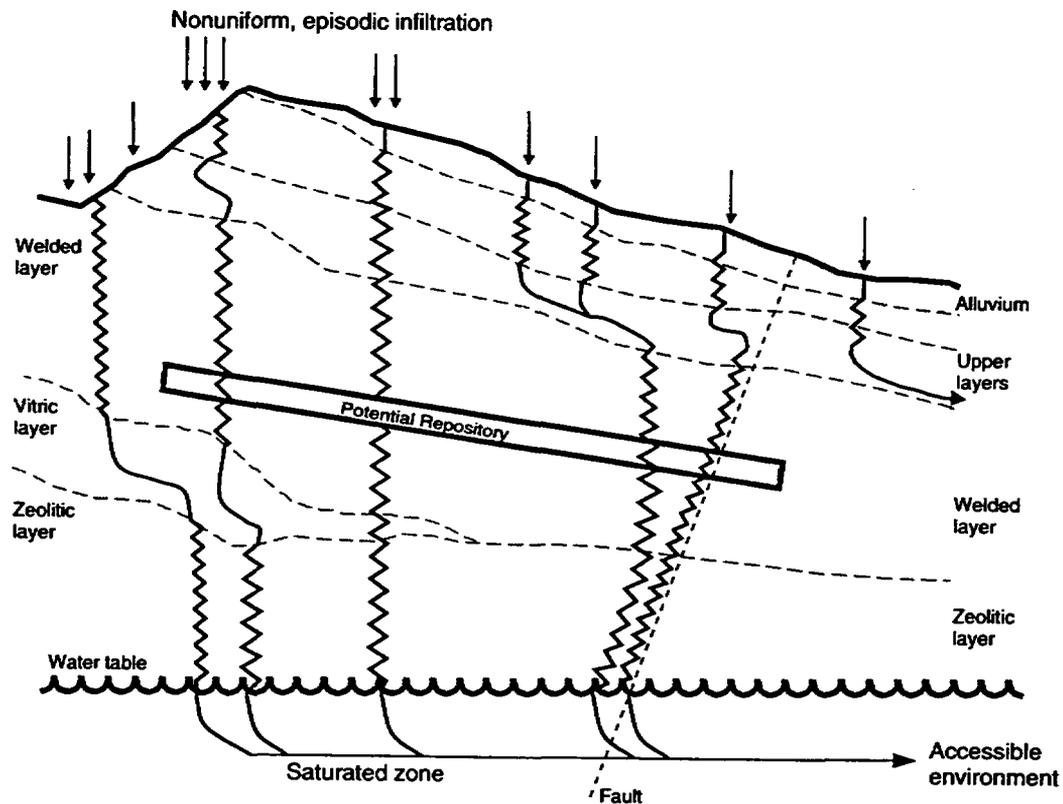


Figure ES-7. The weeps model (episodic pulses of flow in locally saturated zones, e.g. fractures).

and intact. In-drift containers present a larger cross section to vertical weeps than vertically emplaced containers, and are more readily contacted. Most contacts occur because of the flow perturbation from repository thermal effects or during a wet climate. Although it is typically of shorter duration, the flow perturbation caused by thermal effects is more significant in terms of releases than the increased flow caused by a wet climate. The reason is because the waste containers are susceptible to corrosion primarily when their temperature is above ambient (about 25°C), and especially when near 100°C, which occurs during the collapse of the thermal pulse. At later times when climate change is most often modeled to occur, container temperatures have fallen to levels where the corrosion rates are insignificant. Releases during wet climates typically only occur from a few previously failed containers. Consequently, peak doses occur most often within the first 20,000 years of repository life, and cumulative releases do not increase much after this time.

#### **4.1.3 Radionuclide source-term model**

For TSPA-93, the YMIM source-term model, developed at LLNL, is directly incorporated into the nominal-case probabilistic models. YMIM is a phenomenological model that calculates container corrosion (including oxidation, general aqueous corrosion, and localized corrosion—pitting), oxidation alteration of spent fuel, and dissolution of radionuclides within spent fuel. Temperature dependence of these processes is included in the model, although the temperature dependence of solubility is not considered in TSPA-93. Inputs include near-field hydrology, container and fuel-rod temperature, and water chemistry. Defective or mechanically failed containers (known as juvenile failures) are considered probabilistically. Several important processes (e.g., steam corrosion and cathodic protection of containers) are not yet included in YMIM.

Use of YMIM within the composite-porosity and weeps models provides two important results: (1) dry oxidation destroys the corrosion-allowance steel outer wall of the in-drift containers during the high-temperature period following backfill, and (2) aqueous corrosion is only significant while container temperatures are above ambient (about 25°C), and it can be especially rapid while temperatures are near 100°C.

## **4.2 Disturbed-case models**

### **4.2.1 Human intrusion**

The human-intrusion analysis is based on a FEP sequence involving exploratory drilling, waste container breakage, and radionuclide release via extracted drill core and entrainment in the drilling fluid. Extraction of contaminated rock from a near miss of a failed container is also considered. Present-day drilling technology is assumed. Drilling

frequency is based on guidance given in 40 CFR Part 191. A more comprehensive source term that distinguishes between spent-fuel and defense-high-level-waste containers is used in TSPA-93 than was used in TSPA-91. The only performance measure calculated is normalized cumulative release—individual doses are not considered.

Because of the more detailed source term, more variation is seen in the results when compared with the results for TSPA-91. As with TSPA-91, drilling frequency is the most important parameter (and one of the most difficult to predict). The in-drift containers, being larger, are more often hit by drilling and lead to greater releases; however, if it is assumed that only part of the container is exhumed commensurate with the size of the drill, then releases from in-drift containers are similar to releases from vertically emplaced containers.

#### **4.2.2 Indirect volcanic effects**

For TSPA-91, direct releases of radionuclides caused by intrusion of a basaltic dike into the repository were investigated; for TSPA-93, indirect releases are investigated. The FEP sequence modeled addresses magma intruding rock units near the repository and accelerating waste-container degradation because of the effects of heat and aggressive volatiles. These effects result in changes to the aqueous-transport source term. Dike length, location, and thickness are calculated probabilistically. The temperature of rock adjacent to a magmatic intrusion is calculated as a function of basaltic dike temperature and thickness, distance into the rock, and time. Waste-container corrosion rates are adjusted  $10^4$  higher to account for aggressive magmatic volatiles. This value is consistent with sulfidization rates.

Analysis results show penetration of heat from a dike only on the order of a few meters. Magmatic volatiles are assumed to intrude only the same distance. Also, the probability of magmatic intrusion, based on geologically realistic values for the volcanic recurrence rate in the Yucca Mountain region and scaled for the two possible areas of the repository, is extremely low over 10,000 years ( $\sim 10^{-4}$  probability of occurrence), and even when extrapolated to 1,000,000 years ( $\sim 10^{-2}$  probability of occurrence). Thus, little contribution from indirect volcanic effects to the nominal-case aqueous releases is observed.

## **5 Results**

Results of the TSPA-93 probabilistic modeling are in the form of conditional complementary cumulative distribution functions (CCDFs). The CCDFs show the probability of exceeding a given value of either the EPA sum (i.e., the cumulative release normalized as specified in 40 CFR 191.13) or peak individual dose for a given realization of a probabilistic model. The distributions are conditional because they do not as yet include all possible scenarios.

Figure ES-8 shows calculated CCDFs of 10,000-year normalized cumulative release using the composite-porosity model, for all modeled release mechanisms. Only results for a 57-kW/acre repository with vertically emplaced containers are shown; however, with the composite-porosity model, all repository configurations produce similar results (see below). Gaseous releases are predicted to be the most significant, exceeding the EPA standard. Several factors contribute to the large gaseous releases: relatively uniform flow causes a large number of containers to be contacted by water when they are warm (near 100°C) and susceptible to corrosion; upon container failure,  $^{14}\text{CO}_2$  is readily released (there is a sizable prompt fraction of  $^{14}\text{C}$ , but also, when temperatures are elevated, oxidation alteration of spent fuel proceeds rapidly and allows  $^{14}\text{C}$  to escape); and  $^{14}\text{CO}_2$  has a short transport time to the ground surface. Releases caused by human intrusion and nominal-case aqueous releases are important, but do not violate the standard. Indirect releases caused by volcanism are both few and low; direct releases caused by volcanism (a TSPA-91 result) are low primarily because the probability of a basaltic dike intruding in the repository in 10,000 years is very low.

As mentioned, the composite-porosity model predicts little influence of the four repository designs on performance. Container size is immaterial because slow, uniform percolation

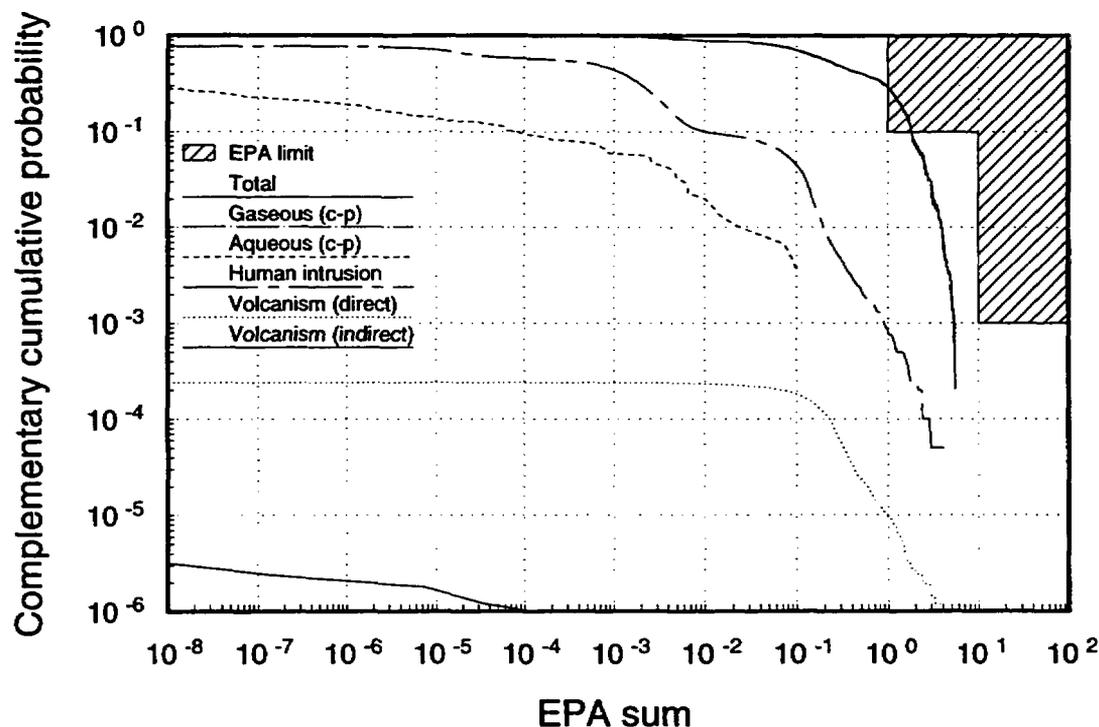


Figure ES-8. Base-case normalized cumulative release predicted by the composite-porosity model.

of groundwater leads to widescale contact irrespective of size. A slight effect is seen in the normalized cumulative releases over 10,000 years, where the dryout zone created by the hotter repositories results in a several thousand year increase in container lifetime. But for dose calculations over 1,000,000 years, container lifetime and thermal perturbations are too short to make much difference.

The CCDFs of 10,000-year normalized cumulative release calculated using the weeps model are shown in Figure ES-9. Normalized cumulative releases are predicted to be lower for the weeps model than for the composite-porosity model (compare total releases in Figure ES-8 with those shown in Figure ES-9). Releases caused by human intrusion are often predicted to be greater than the nominal-case releases predicted by the weeps model. The reason is that weeps rarely contact waste containers. And within 10,000 years, most weep contacts are caused by groundwater shed around the dryout volume onto unprotected parts of the repository (although many of the resulting contacts are for short periods of time). Gaseous releases are greater than aqueous releases at the highest probabilities because of juvenile failures that release  $^{14}\text{CO}_2$  without weep contact. Indirect releases caused by volcanism are not calculated for the weeps model and do not appear in the figure. (This figure only represents the base-case design; repository design does influence releases predicted by the weeps model, as discussed below.)

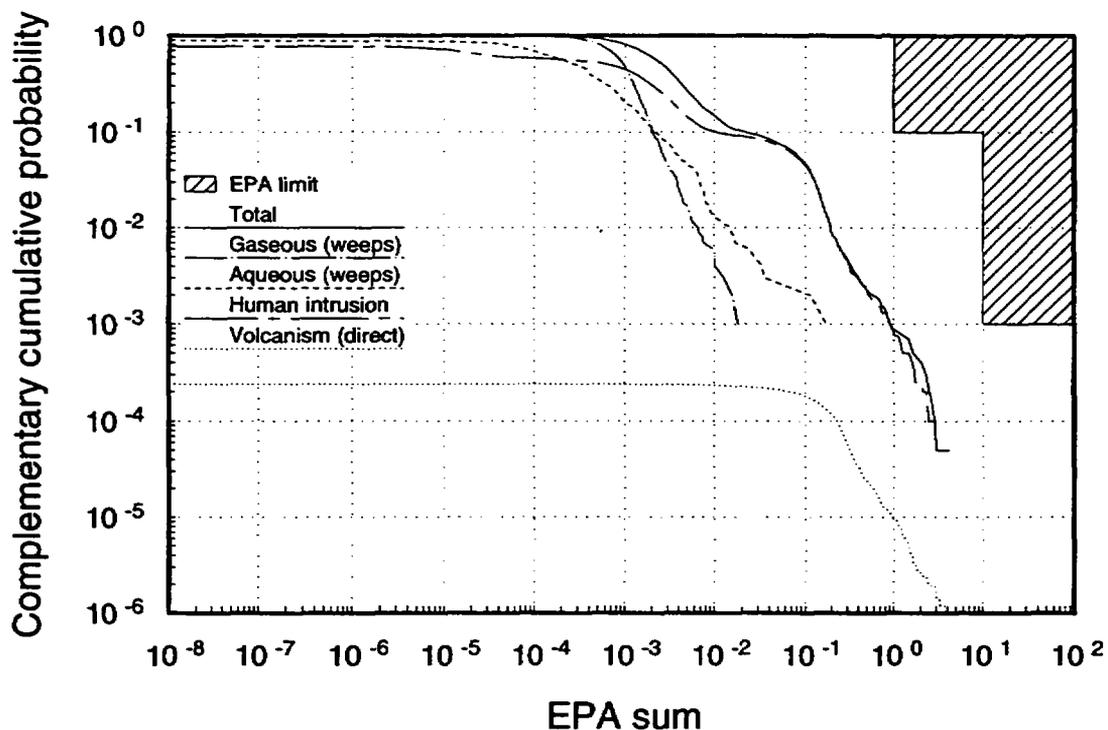


Figure ES-9. Base-case normalized cumulative release predicted by the weeps model.

A comparison of peak individual doses for the two unsaturated-zone flow models is shown in Figure ES-10. The doses shown are for drinking water only and are the peak doses realized within a 1,000,000-yr period. The figure shows that both models predict doses from the repository at levels above background dose (approximately 300 mrem/yr): over 90% of the composite-porosity realizations and about 1% of the weeps model realizations exceed background. These doses are primarily caused by neptunium. Peak doses predicted by the composite-porosity model typically occur because of high percolation rates and water-table rise of a wet climate; those predicted by the weeps model typically occur because of water shed on easily corroded containers (the number of containers contacted by water is a probabilistic result) as the repository thermal perturbation dissipates.

Because transport time is not an issue (except that some actinides decay away before they reach the accessible environment), peak doses are primarily a function of radionuclide release rate from the repository and dilution in the environment. Arid environments typically have little dilution. The release rate is greater, and thus the doses are greater, for the composite-porosity model than for the weeps model because of the larger number of containers that are contacted by water and fail.

Figure ES-11 presents weeps-model peak doses calculated for the four repository designs. The weeps model predicts that larger containers, because of the larger cross section

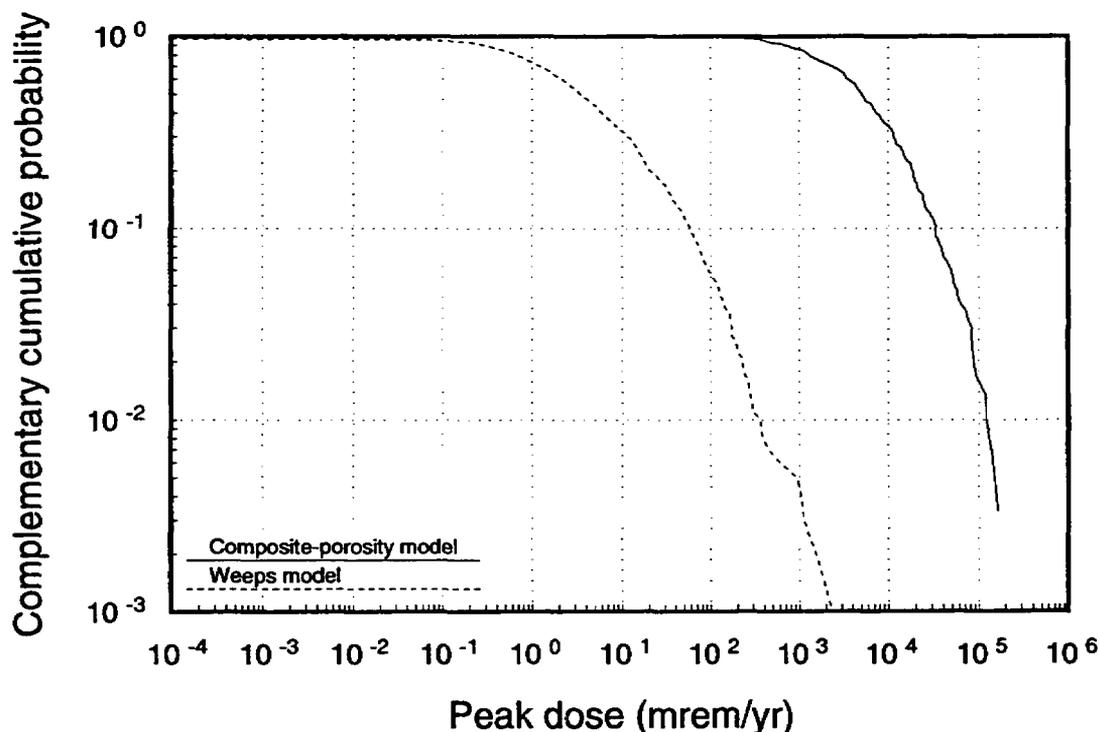


Figure ES-10. Peak drinking-water dose within 1,000,000 years.

they offer for vertical weeps, have worse performance. A secondary effect is that hotter repositories cause worse performance, because hotter repositories cause a greater perturbation in groundwater flow and an increased probability of containers being contacted by weeps. (These findings are predicated on a number of factors, including that the repository drifts do not divert or concentrate weep flow, that flow returns to the dryout volume coincident with its collapse, etc.) The weeps model predicts similar behavior with the EPA performance measure, although none of the repository designs violate this standard.

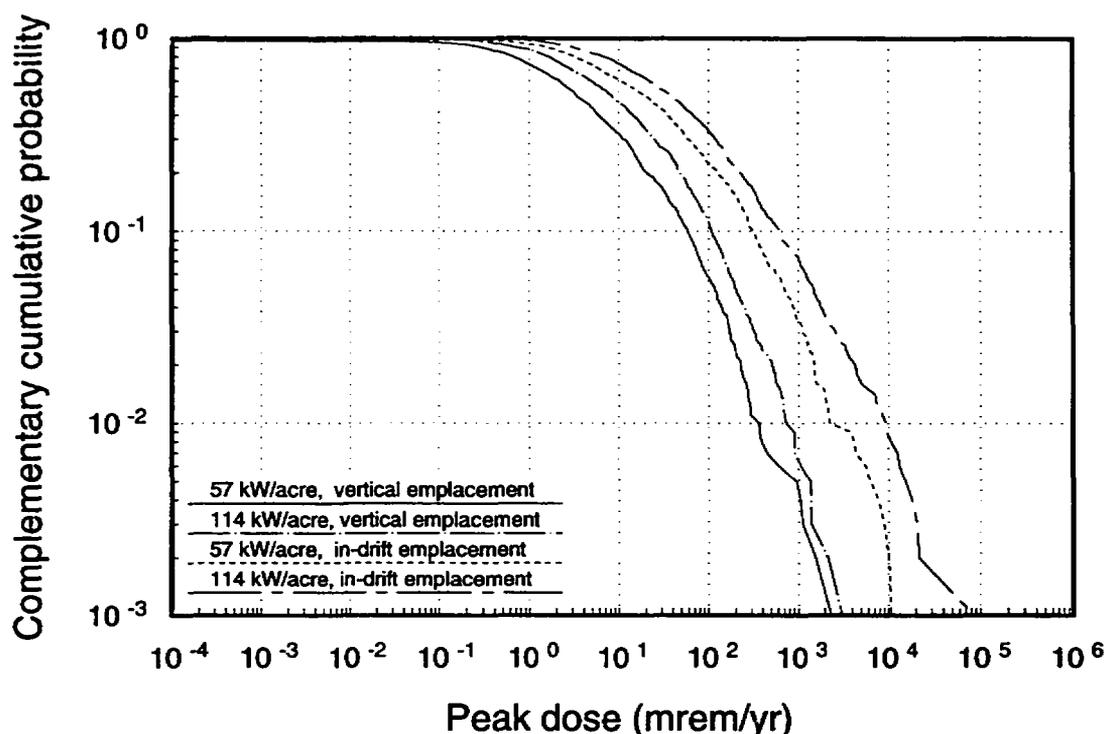


Figure ES-11. Peak doses for four repository configurations as predicted by the weeps model.

## 6 Conclusions and recommendations

The large difference in the results of the alternative conceptual models leads to questions about what model best approximates the behavior of the groundwater flow system. Calculations of peak individual drinking-water dose over 1,000,000 years indicate that radionuclides released from a Yucca Mountain repository could experience little dilution, and extremely low release rates from the repository—either from a highly engineered waste container or a system for reducing water contact with containers—might be needed to achieve low individual dose rates. Two possible impacts of repository design on long-term performance are also identified: (1) larger containers could be more readily contacted by weeps and drilling; (2) hotter repositories could cause a greater perturbation in the flow field, resulting in more containers being contacted by weeps. Results from the composite-porosity model

indicate that normalized cumulative releases and doses are relatively insensitive to thermal loading and container size and emplacement. The YMIM corrosion models used by both the composite-porosity model and the weeps model predict that most container failures significant to performance occur during decay of the repository thermal pulse—within the first few thousand years. A 10-cm corrosion-allowance overpack for in-drift containers is predicted to be oxidized away within a few hundred years, with no contribution to performance. (The overpack could be more important than indicated because of processes not included in the models currently being used.) Indirect releases from volcanic activity are not found to be significant contributors to overall releases.

Recommendations regarding site-data needs derive primarily from nominal-condition results because human-intrusion results are largely site-independent and volcanism results are comparatively insignificant. The following recommendations are made acknowledging limitations and assumptions in the present models, as well as uncertainties in our knowledge of physical conditions within Yucca Mountain and future events. It should also be mentioned that data are being collected in a number of these areas and an effort is being made to ascertain that the data are useful to determining long-term performance.

- Because of the substantial difference between the results of the two groundwater flow models, the first priority should be the determination of the dominant flow mechanisms (in both time and space) operating in the unsaturated zone at Yucca Mountain.
- Concerning gaseous releases, more data are needed on the spatial distribution of bulk permeability throughout Yucca Mountain and on adsorption of CO<sub>2</sub> to tuff.
- Concerning aqueous releases, characterization at the repository horizon of percolation-flux magnitude and distribution (in both time and space) is a high priority.
- Concerning individual doses, a high priority is characterization of the amount of horizontal and vertical dispersion (factors in dilution) in the saturated zone.
- Additional hydrogeologic data from new drillholes are also needed, as is research on scaling of properties and hydraulic characterization of unsaturated fractures in the rock matrix.
- Additional information is needed on heterogeneity and spatial correlations for geostatistical modeling and on cross-correlations among parameters.
- Thermal and hydraulic properties of proposed backfill materials should be determined, and fault-zone hydrogeologic properties should be characterized.
- To develop reliable models of near-field interactions, integrated testing is needed in the areas of waste-container/groundwater contact, radionuclide transport from degraded

containers, coupled thermal-mechanical-hydrologic-chemical processes, and the interactions between natural and man-made system components.

- Further work is also recommended on waste-form alteration and container corrosion under realistic conditions.

Repository design must meet a number of requirements, with long-term performance being but one. Recommendations concerning long-term performance typically come from models that contain a number of limitations. Acknowledging this situation, the following design-related recommendations are made based on the TSPA-93 results.

- Calculated waste-container temperatures are very high for the in-drift cases, well above the thermal goals defined in the SCP. To approach the thermal goals, any backfill used with in-drift emplacement needs to be designed to allow for heat transfer.
- The biggest difference in the performance measures for the four repository configurations that are considered is a result of the difference in container "target size." Reduction in target size or engineered measures to reduce contact between containers and weeps or drilling paths is recommended.
- Container emplacement should be designed to reduce moisture contact with containers (both weeps and uniformly percolating water). Borehole emplacement attempts to achieve this reduction by specifying an air gap surrounding the container. For in-drift emplacement, backfill or a system within the backfill could possibly be engineered to control water contact.

Regulatory change could affect performance assessment for radioactive-waste disposal. If the radioactive-release standard changes to a measure based on individual dose rates over a time period much longer than 10,000 years, significant changes in site-characterization program priorities might be needed, with more emphasis on determining radionuclide release rates. If the standard is changed to an individual-dose standard but the regulated time period remains at 10,000 years, impact on the site-characterization needs would be lessened. Dose calculations require more information than cumulative-release calculations and would require additional characterization of the biosphere in the vicinity of Yucca Mountain. Information extrapolated into the distant future will introduce additional uncertainty into the calculations.

**YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT  
DISTRIBUTION LIST**

1	D.A. Dreyfus (RW-1) Director OCRWM US Department of Energy 1000 Independence Avenue SW Washington, DC 20585	1	S. J. Brocoum (RW-22) Analysis and Verification Division OCRWM US Department of Energy 1000 Independence Avenue SW Washington, DC 2585
1	L.H. Barrett (RW-2) Acting Deputy Director OCRWM US Department of Energy 1000 Independence Avenue SW Washington, DC 20585	1	D. Shelor (RW-30) Office of Systems and Compliance OCRWM US Department of Energy 1000 Independence Avenue, SW Washington, DC 20585
1	J.D. Saltzman (RW-4) Office of Strategic Planning and International Programs OCRWM US Department of Energy 1000 Independence Avenue SW Washington, DC 20585	1	J. Roberts (RW-33) Director, Regulatory Compliance Division OCRWM US Department of Energy 1000 Independence Avenue, SW Washington, DC 20585
1	J.D. Saltzman (RW-5) Office of External Relations OCRWM US Department of Energy 1000 Independence Avenue SW Washington, DC 20585	1	G. J. Parker (RW-332) Reg. Policy/Requirements Branch OCRWM US Department of Energy 1000 Independence Avenue, SW Washington, DC 20585
1	Samuel Rousso (RW-10) Office of Program and Resource Mgt. OCRWM US Department of Energy 1000 Independence Avenue SW Washington, DC 20585	1	R. A. Milner (RW-40) Office of Storage and Transporation OCRWM US Department of Energy 1000 Independence Avenue, SW Washington, DC 20585
1	J. C. Bresee (RW-10) OCRWM US Department of Energy 1000 Independence Avenue SW Washington, DC 20585	1	S. Rousso (RW-50) Office of Contract Business Management OCRWM US Department of Energy 1000 Independence Avenue, SW Washington, DC 20585
1	R.M. Nelson (RW-20) Office of Geologic Disposal OCRWM US Department of Energy 1000 Independence Avenue, SW Washington, DC 20585	1	T. Wood (RW-52) Director, M&O Management Division OCRWM US Department of Energy 1000 Independence Avenue, SW Washington, DC 20585

4	Victoria F. Reich, Librarian Nuclear Waste Technical Review Board 1100 Wilson Blvd, Suite 910 Arlington, VA 22209	1	NRC Document Control Desk Division of Waste Management US NRC Washington, DC 20555
5	R.M. Nelson Jr, Acting Project Manager Yucca Mountain Site Characterization Office US Department of Energy P.O. Box 98608--MS 523 Las Vegas, NV 89193-8608	1	Philip S. Justus NRC Site Representative 301 E Stewart Avenue, Room 203 Las Vegas, NV 89101
1	C. L. West, Director Office of External Affairs DOE Nevada Field Office US Department of Energy P.O. Box 98518 Las Vegas, NV 89193-8518	1	E. P. Binnall Field Systems Group Leader Building 50B/4235 Lawrence Berkeley Laboratory Berkeley, CA 94720
8	Technical Information Officer DOE Nevada Field Office US Department of Energy P.O. Box 98518 Las Vegas, NV 89193-8518	1	Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road Drawer 28510 San Antonio, TX 78284
1	P. K. Fitzsimmons, Technical Advisor Office of Assistant Manager for Environmental Safety and Health DOE Nevada Field Office US Department of Energy P.O. Box 98518 Las Vegas, NV 89193-8518	3	W. L. Clarke Technical Project Officer - YMP Attn: YMP/LRC Lawrence Livermore National Laboratory P.O. Box 5514 Livermore, CA 94551
1	D. R. Elle, Director Environmental Protection and Division DOE Nevada Field Office US Department of Energy P.O. Box 98518 Las Vegas, NV 89193-8518	1	J. A. Blink Deputy Project Leader Lawrence Livermore National Laboratory 101 Convention Center Drive Suite 820, MS 527 Las Vegas, NV 89109
1	Repository Licensing & Quality Assurance Project Directorate Division of Waste Management US NRC Washington, DC 20555	4	J. A. Canepa Technical Project Officer - YMP N-5, Mail Stop J521 Los Alamos National Laboratory P.O. Box 1663 Los Alamos, NM 87545
1	Senior Project Manager for Yucca Mountain Repository Project Branch Division of Waste Management US NRC Washington, DC 20555	1	H. N. Kalia Exploratory Shaft Test Manager Los Alamos National Laboratory Mail Stop 527 101 Convention Center Dr., #820 Las Vegas, NV 89101
1	Senior Project Manager for Yucca Mountain Repository Project Branch Division of Waste Management US NRC Washington, DC 20555	1	N. Z. Elkins Deputy Technical Project Officer Los Alamos National Laboratory Mail Stop 527 101 Convention Center Dr., #820 Las Vegas, NV 89101

5	L. E. Shephard Technical Project Officer - YMP Sandia National Laboratories Organization 6302, M/S 1333 P.O. Box 5800 Albuquerque, NM 87185	1	R. W. Craig, Chief Nevada Operations Office US Geological Survey 101 Convention Center Drive Suite 860, MS 509 Las Vegas, NV 89109
1	J. F. Devine Asst Director of Engineering Geology US Geological Survey 106 National Center 12201 Sunrise Valley Drive Reston, VA 22092	1	D. Zesiger US Geological Survey 101 Conventional Center Drive Suite 860, MS 509 Las Vegas, NV 89109
1	L. R. Hayes Technical Project Officer Yucca Mountain Project Branch MS 425 US Geological Survey P.O. Box 25046 Denver, CO 80225	1	G. L. Ducret, Associate Chief Yucca Mountain Project Division US Geological Survey P.O. Box 25046 421 Federal Center Denver, CO 80225
1	V. R. Schneider Asst. Chief Hydrologist--MS 414 Office of Program Coordination and Technical Support US Geological Survey 12201 Sunrise Valley Drive Reston, VA 22092	1	A. L. Flint US Geological Survey MS 721 P.O. Box 327 Mercury, NV 89023
1	J. S. Stuckless Geologic Division Coordinator MS 913 Yucca Mountain Project US Geological Survey P.O. Box 25046 Denver, CO 80225	1	D. A. Beck Water Resources Division, USGS 6770 S Paradise Road Las Vegas, NV 89119
1	D. H. Appel, Chief Hydrologic Investigations Program MS 421 US Geological Survey P.O. Box 25046 Denver, CO 80225	1	P. A. Glancy US Geological Survey Federal Building, Room 224 Carson City, NV 89701
1	E. J. Helley Branch of Western Regional Geology MS 427 US Geological Survey 345 Middlefield Road Menlo Park, CA 94025	1	Sherman S.C. Wu US Geological Survey 2255 N. Gemini Drive Flagstaff, AZ 86001
		1	J. H. Sass - USGS Branch of Tectonophysics 2255 N Gemini Drive Flagstaff, AZ 86001
		1	DeWayne Campbell Technical Project Officer - YMP US Bureau of Reclamation Code D-3790 P.O. Box 25007 Denver, CO 80225

1	J. M. LaMonaca Records Specialist US Geological Survey 421 Federal Center P.O. Box 25046 Denver, CO 80225	1	B. W. Colston, President and General Manager Las Vegas Branch Raytheon Services Nevada MS 416 P.O. Box 95487 Las Vegas, NV 89193-5487
1	W. R. Keefer - USGS 913 Federal Center P.O. Box 25046 Denver, CO 80225	1	R. L. Bullock Technical Project Officer - YMP Raytheon Services Nevada Suite P-250, MS 403 101 Convention Center Drive Las Vegas, NV 89109
1	M. D. Voegele Technical Project Officer - YMP SAIC 101 Convention Center Drive Suite 407 Las Vegas, NV 89109	1	Paul Eslinger, Manager PASS Program Pacific Northwest Laboratory P.O. Box 999 Richland, WA 99352
2	L. D. Foust Nevada Site Manager TRW Environmental Safety Systems 101 Convention Center Drive Suite 540, MS 423 Las Vegas, NV 89109	1	A. T. Tamura Science and Technology Division OSTI US Department of Energy P.O. Box 62 Oak Ridge, TN 37831
1	C. E. Ezra YMP Support Office Manager EG&G Energy Measurements Inc MS V-02 P.O. Box 1912 Las Vegas, NV 89125	1	Carlos G. Bell Jr Professor of Civil Engineering Civil and Mechanical Engineering Dept. University of Nevada, Las Vegas 4505 S Maryland Parkway Las Vegas, NV 89154
1	E. L. Snow, Program Manager Roy F. Weston Inc 955 L'Enfant Plaza SW Washington, DC 20024	1	P. J. Weeden, Acting Director Nuclear Radiation Assessment Div. US EPA Environmental Monitoring Systems Lab P.O. Box 93478 Las Vegas, NV 89193-3478
1	Technical Information Center Roy F. Weston Inc 955 L'Enfant Plaza SW Washington, DC 20024		
1	D. Hedges, Vice President, QA Roy F. Weston Inc 4425 Spring Mountain Road Suite 300 Las Vegas, NV 89102	1	ONWI Library Battelle Columbus Laboratory Office of Nuclear Waste Isolation 505 King Avenue Columbus, OH 43201
1	D. L. Fraser, General Manager Reynolds Electrical & Engineering Co, Inc MS 555 P.O. Box 98521 Las Vegas, NV 89193-8521	1	T. Hay, Executive Assistant Office of the Governor State of Nevada Capitol Complex Carson City, NV 89710

3	<p><b>R. R. Loux</b>  <b>Executive Director</b>  <b>Agency for Nuclear Projects</b>  <b>State of Nevada</b>  <b>Evergreen Center, Suite 252</b>  <b>1802 N. Carson Street</b>  <b>Carson City, NV 89710</b></p>	1	<p><b>Eureka County Board of Commissioners</b>  <b>Yucca Mountain Information Office</b>  <b>P.O. Box 714</b>  <b>Eureka, NV 89316</b></p>
1	<p><b>C.H. Johnson</b>  <b>Technical Program Manager</b>  <b>Agency for Nuclear Projects</b>  <b>State of Nevada</b>  <b>Evergreen Center, Suite 252</b>  <b>1802 N. Carson Street</b>  <b>Carson City, NV 89710</b></p>	1	<p><b>Brad Mettam</b>  <b>Inyo County Yucca Mountain Repository Assessment Office</b>  <b>Drawer L</b>  <b>Independence, CA 93526</b></p>
1	<p><b>John Fordham</b>  <b>Water Resources Center</b>  <b>Desert Research Institute</b>  <b>P.O. Box 60220</b>  <b>Reno, NV 89506</b></p>	1	<p><b>Lander County Board of Commissioners</b>  <b>315 South Humbolt</b>  <b>Battle Mountain, NV 89820</b></p>
1	<p><b>David Rhode</b>  <b>Desert Research Institute</b>  <b>P.O. Box 60220</b>  <b>Reno, NV 89506</b></p>	1	<p><b>Vernon E. Poe</b>  <b>Office of Nuclear Projects</b>  <b>Mineral County</b>  <b>P.O. Box 1026</b>  <b>Hawthorne, NV 89415</b></p>
1	<p><b>Eric Anderson</b>  <b>Mountain West Research-Southwest Inc</b>  <b>2901 N Central Avenue #1000</b>  <b>Phoenix, AZ 85012-2730</b></p>	1	<p><b>Les W. Bradshaw</b>  <b>Program Manager</b>  <b>Nye County Nuclear Waste Repository Program</b>  <b>P.O. Box 153</b>  <b>Tonopah, NV 89049</b></p>
1	<p><b>The Honorable Cyril Schank</b>  <b>Chairman</b>  <b>Churchill County Board of Commissioners</b>  <b>190 W First Street</b>  <b>Fallon, NV 89406</b></p>	1	<p><b>Florindo Mariani</b>  <b>White Pine County Nuclear Waste Project Office</b>  <b>457 Fifth Street</b>  <b>Ely, NV 89301</b></p>
1	<p><b>Dennis Bechtel, Coordinator</b>  <b>Nuclear Waste Division</b>  <b>Clark County Department of Comprehensive Planning</b>  <b>301 E Clark Avenue, Suite 570</b>  <b>Las Vegas, NV 89101</b></p>	1	<p><b>Judy Foremaster</b>  <b>City of Caliente Nuclear Waste Project Office</b>  <b>P.O. Box 158</b>  <b>Caliente, NV 89008</b></p>
1	<p><b>Juanita D. Hoffman</b>  <b>Nuclear Waste Repository Oversight Program</b>  <b>Esmeralda County</b>  <b>P.O. Box 490</b>  <b>Goldfield, NV 89013</b></p>	1	<p><b>Phillip A. Niedzielski-Eichner</b>  <b>Nye County Nuclear Waste Repository Project Office</b>  <b>P.O. Box 221274</b>  <b>Chantilly, VA 22022-1274</b></p>
		1	<p><b>Jason Pitts</b>  <b>Lincoln County Nuclear Waste Project Office</b>  <b>Lincoln County Courthouse</b>  <b>Pioche, NV 89043</b></p>

1	Economic Development Dept. City of Las Vegas 400 E. Stewart Avenue Las Vegas, NV 89101	1	Nye County District Attorney P.O. Box 593 Tonopah, NV 89049
1	Community Planning and Development City of North Las Vegas P.O. Box 4086 North Las Vegas, NV 89030	1	William Offutt Nye County Manager Tonopah, NV 89049
1	Community Development and Planning City of Boulder City P.O. Box 61350 Boulder City, NV 89006	1	Charles Thistlethwaite, AICP Inyo County Planning Department Drawer L Independence, CA 93526
1	Commission of the European Communities 200 Rue de la Loi B-1049 Brussels BELGIUM	1	R. F. Pritchett Technical Project Officer - YMP Reynolds Electrical & Engineering Company Inc MS 408 P.O. Box 98521 Las Vegas, NV 89193-8521
2	M. J. Dorsey, Librarian YMP Research and Study Center Reynolds Electrical & Engineering Co Inc MS 407 P.O. Box 98521 Las Vegas, NV 89193-8521	1	Dr. Moses Karakouzian 1751 E Reno #125 Las Vegas, NV 89119
1	Amy Anderson Argonne National Laboratory Building 362 9700 S Cass Avenue Argonne, IL 60439	3	Brenda Bailey White CCS 5301 Central NE Suite 1520 Albuquerque, NM 87108
1	Steve Bradhurst P.O. Box 1510 Reno, NV 89505	1	Clarence R. Allen NWTRB 1000 E. California Blvd. Pasadena, CA 91106
1	Michael L. Baughman 35 Clark Road Fiskdale, MA 01518	1	Johan Andersson SKI Division of Nuclear Waste Sehlstedtgatan II Box 27106 S-102 52 Stockholm SWEDEN
1	Glenn Van Roekel Director of Community Development City of Caliente P.O. Box 158 Caliente, NV 89008	1	Michael J. Apted Intera Sciences 3609 S. Wadsworth Blvd Denver, CO 80235
1	Ray Williams, Jr P.O. Box 10 Austin, NV 89310	1	Dwayne Chesnut Lawrence Livermore National Laboratory P.O. Box 808 M/S L202 Livermore, CA 94551

1	Richard Codell US Nuclear Regulatory Commission M/S 4-H-3 Washinton, DC 20555	1	A.B. Gureghian CNWRA 6220 Culebra Road San Antonio, TX 78228-0510
1	Seth M. Coplan US Nuclear Regulatory Commission M/S 4-H-3 Washington, DC 20555	5	William G. Halsey Lawrence Livermore National Laboratory P.O. Box 808 M/S L-204 Livermore, CA 94551
1	Kevin Coppersmith Geomatrix Consultants 100 Pine Street, 10th Floor San Francisco, CA 94111	1	M.E. Harr School of Civil Engineering Purdue University 1284 Civil Engineering Building West Lafayette, IN 47907-1284
1	C.F. Costa Nuclear Radiation Assessment Division US EPA Environmental Monitoring Systems Laboratory P.O. Box 93478 Las Vegas, NV 89193-3478	1	Dwight Hoxie US Geological Survey 101 Convention Center Drive Suite 860 Las Vegas, NV 89109
1	Allen G. Croff Chemical Technology Division Oak Ridge National Laboratory 4500N, MS-6235 P.O. Box 2008 Oak Ridge, TN 37831-6235	1	Edwin E. Kinter Bradley Hill Road P.O. Box 682 Nortwich, VT 05055
1	Bruce M. Crowe Los Alamos National Laboratory 101 Convention Center Drive Suite 820 Las Vegas, NV 89109	1	Donald Langmuir Nuclear Waste Technical Review Board 109 So. Lookout Mountain Cr. Golden, CO 80401
1	Department of Comprehensive Planning Clark County 225 Bridger Avenue, 7th Floor Las Vegas, NV 89155	1	Lincoln County Commission Lincoln County P.O. Box 90 Pioche, NV 89043
1	D.W. Engel Pacific Northwest Laboratory P.O. Box 999 M/S K7-34 Richland, WA 99352	1	Ian Miller Golder Associates Inc 4104 148 Avenue NE Redmond, WA 98052
1	Leonard J. Fiorenzi P.O. Box 257 Eureka, NV 89316	1	R.W. Nelson INTERA-M&O 101 Convention Center Drive Suite P110 Las Vegas, NV 89109
		1	Claudia Newbury Yucca Mountain Project Office US Department of Energy P.O. Box 98608 M/S 523 Las Vegas, NV 89193-8518

1	D. Warner North NWTRB Decision Focus Inc 4984 El Camino Real Los Altos, CA 94062	1	Joseph Wang Lawrence Berkeley Laboratory Earth Sciences Division 1 Cyclotron Road Berkeley, CA 94720
2	William J. O'Connell Lawrence Livermore National Laboratory P.O. Box 808, M/S L-195 Livermore, CA 94551	1	R.V. Watkins, Chief Project Planning and Management USGS P.O. Box 25046 421 Federal Center Denver, CO 80225
1	Michael Revelli Lawrence Livermore National Laboratory P.O. Box 808 M/S L-206 Livermore, CA 94551	1	Ed Weeks -USGS P.O. Box 25046 Federal Center M/S 413 Lakewood, CO 80225
1	Benjamin Ross Disposal Safety Inc 1660 L Street NW, Suite 314 Washington, DC 20036	1	C.L. West, Director Office of External Affairs DOE Field Office, Nevada US DOE P.O. Box 98518 Las Vegas, NV 89193-8518
2	SAIC-T & MSS Library 101 Convention Center Drive Suite 407 Las Vegas, NV 89109	1	Robert F. Williams EPRI Nuclear Power Division P.O. Box 10412 Palo Alto, CA 94303
1	Frank W. Schwartz 195 Thornbury Lane Powell, OH 43065	1	George Zivoloski Geoanalysis Group Los Alamos National Lab M/S F665 Los Alamos, NM 87545
1	Bjorn Selinder 190 W. First Street Fallon, NV 89406	1	Jean Younker TRW 101 Convention Center Drive Suite P110 Las Vegas, NV 89109
1	Ardyth Simmons Yucca Mountain Project US DOE P.O. Box 98608 M/S 523 Las Vegas, NV 89193-8518	1	Dr. June Fabryka-Martin Los Alamos National Lab MS J-514 Los Alamos, NM 87545
1	Scott Sinnock TRW 101 Convention Center Drive Suite P110 Las Vegas, NV 89109	1	Dr. F. Owen Hoffman Oak Ridge National Lab P.O. Box 2008 Oak Ridge, TN 37831-6036
1	Ellis D. Verink Nuclear Waste Technical Review Board 4401 NW 18th Place Gainesville, FL 32605	1	Dr. Arjun Makhijani Institute for Energy and Environmental Research 6935 Laurel Avenue Takoma Park, MD 20912

- |   |   |   |   |
|---|---|---|---|
| 1 | Dr. James E. Martin<br>Assistant Professor of<br>Radiological Health<br>University of Michigan<br>School of Public Health<br>Ann Arbor, MI 48109            | 1 | Dr. Wilfried Albert<br>NAGRA<br>Hardstrasse 73<br>CH-5430 Wettingen<br>Switzerland  |
| 1 | Dr. H. Robert Meyer<br>C.N.S.I.<br>750 East Park Drive<br>Suite 200<br>Harrisburg, PA 17111   | 1 | Runo Barrdahl<br>Swedish Radiation Protection<br>Institute<br>P.O. Box 60204<br>S-104 01 Stockholm<br>Sweden                                    |
| 1 | Jess Riley<br>Heinman Research Labs<br>P.O. Box 35457<br>Charlotte, NC 28207  | 1 | Dr. John E. Gale<br>Fracflow Consultants Inc<br>36 Pearson Street<br>St. John's, Newfoundland<br>Canada A1A 3R1                                 |
| 1 | James E. Watson Jr<br>Environ. Science and Engineering<br>Campus Box 7400<br>University of North Carolina<br>Chapel Hill, NC 27599-7400                     | 1 | Dr. Furruccio Gera<br>ISMES S.P.S.<br>Via dei Crociferi 44<br>00187 Rome, Italy   |
| 1 | Dr. William M. Murphy<br>Center for Nuclear Waste<br>Regulatory Analyses<br>Southwest Research Institute<br>6220 Culebra Road<br>San Antonio, TX 78238-5166 | 1 | Dr. Gunnar Gustafson<br>Department of Geology<br>Chalmers University of Technology<br>and University of Goteborg<br>S-412 96 Goteborg<br>Sweden |
| 1 | Miroslav Kucerka, Consultant<br>Radioactive Waste Management<br>Botevova 3104<br>143 00 Praha 4<br>Czech Republic   | 1 | Dr. Alan W. Herbert<br>AEA Technology<br>Theoretical Studies Department<br>Harwell Laboratory B424.4<br>Oxfordshire OX11 0RA<br>United Kingdom  |
| 1 | Dr. John Kessler<br>Nuclear Power Division<br>EPRI<br>P.O. Box 10412<br>Palo Alto, CA 94303-0813  | 1 | David Hodgkinson<br>INTERA<br>Chiltern House<br>45 Station Road<br>Henley-on-Thames, Oxon<br>RG9 1AT<br>United Kingdom                          |
| 1 | Per-Eric Ahlstrom<br>Research Director<br>Swedish Nuclear Fuel and<br>Waste Management Co<br>Box 5864 S-102 48<br>Stockholm, Sweden                         | 1 | Dr. Yong Soo Hwang<br>Korea Atomic Energy<br>Research Institute<br>P.O. Box 7<br>Daeduk-Danji<br>Taejeon, Korea                                 |
| 1 | W.A. Seddon<br>AECL Technologies<br>9210 Corporate Boulevard<br>Suite 410<br>Rockville, MD 20850  | 1 | Dr. Katsumi Kamemura<br>Shinozuka Research Institute<br>5F Maguna Kogyo Building 1-31-13<br>Yoyogi, Shibuya-ku<br>Tokyo, 151, Japan             |

1	Dr. Bill Lanyon Geo-Science Limited Falmouth Business Park Bickland Water Road Falmouth, Cornwall TR11 4SZ, United Kingdom	1	David Leaver Polestar Four Main Street Los Altos, CA 94022
1	Dr. Jussi Palmu Imatran Voima Oy Rajatorpantie 8 P.O. Box 112 SF-01601 Vantaa, Finland	1	James Gansemer Lawrence Livermore National Laboratory P.O. Box 808 Livermore, CA 94551
1	Dr. Carmen Bajos Parada ENRESA Emilio Vargas 7 28043 Madrid, Spain	1	Lynn C. Lewis Lawrence Livermore National Laboratory P.O. Box 808 Livermore, CA 94551
1	Dr. Gunnar Ramqvist ELTEKNO AB Gruvvagen 1 S-714 00 Kopparberg Sweden	1	Alan D. Lamont Lawrence Livermore National Laboratory P.O. Box 808 Livermore, CA 94551
1	Dr. Robert Rundberg Los Alamos National Lab Mail Stop J-514 Los Alamos, NM 87545	1	Ines Triay Los Alamos National Laboratory P.O. Box 1663 Los Alamos, NM 87545
1	James A. Steadman Building Research Establishment Structural Performance Division Garston, Watford WD2 7JR United Kingdom	1	David Morris Los Alamos National Laboratory P.O. Box 1663 Los Alamos, NM 87545
1	Dr. Ove Stephansson Department of Engineering Geology Royal Institute of Technology S-100 44 Stockholm, Sweden	1	Ning Lu USGS P.O. Box 25046, MS 421 Denver Federal Center Lakewood, CO 80225
1	Dr. Juhani Vira Teollisuuden Voiman Oy Annankatu 42 C SF-00100 Helsinki Finland	1	Gary LeCain USGS P.O. Box 25046 Denver Federal Center Lakewood, CO 80225
1	Peter Wallman Golder Associates 4104 148 Avenue NE Redmond WA 98052	1	Edward Kwicklis USGS P.O. Box 25046 Denver Federal Center Lakewood, CO 80225
1	Minoru Yamakuma Geoscience Research Project PNC Tokyo, Japan	1	Jerry McNeish INTERA M/S 423 101 Convention Center Drive Las Vegas, NV 89109

1	April V. Gil Yucca Mountain Project M/S 523 101 Convention Center Drive Las Vegas, NV 89109	1	Tom Bjerstedt Yucca Mountain Project US DOE P.O. Box 98608 M/S 523 Las Vegas, NV 89193-8518
1	Joseph J. Dlugosz Yucca Mountain Project M/S 523 101 Convention Center Drive Las Vegas, NV 89109	1	Maxwell Blanchard Yucca Mountain Project P.O. Box 98608 M/S 523 Las Vegas, NV 89193-8518
1	Wendy R. Dixon Yucca Mountain Project M/S 523 101 Convention Center Drive Las Vegas, NV 89109	2	Jeremy Boak Yucca Mountain Project US DOE P.O. Box 98608 M/S 523 Las Vegas, NV 89193-8518
1	Jeanne C. Nesbit Yucca Mountain Project M/S 523 101 Convention Center Drive Las Vegas, NV 89109	1	Garry D. Brewer Nuclear Waste Technical Review Board University of Michigan Dana Bldg, Room 3516 Ann Arbor, MI 48109-1115
1	Susan B. Jones Yucca Mountain Project M/S 523 101 Convention Center Drive Las Vegas, NV 89109	1	Daniel B. Bullen Iowa State University P.O. Box 1768 Ames, IA 50010
1	William B. Simecka Yucca Mountain Project M/S 523 101 Convention Center Drive Las Vegas, NV 89109	1	Thomas A. Buscheck Lawrence Livermore National Laboratory P.O. Box 808 M/S L206 Livermore, CA 94550
1	Dennis R. Williams Yucca Mountain Project M/S 523 101 Convention Center Drive Las Vegas, NV 89109	1	John E. Cantlon, Chairman Nuclear Waste Technical Review Board 1795 Bramble Drive East Lansing, MI 48823
1	C. Thomas Statton Yucca Mountain Project M&O/WCFS M/S 423 101 Convention Center Drive Las Vegas, NV 89109	1	K.W. Causseaux NHP Reports Chief U.S. Geological Survey 421 Federal Center P.O. Box 25046 Denver, CO 80225
1	Yvonne Tsang Lawrence Berkeley Laboratory Earth Sciences Division 1 Cyclotron Road Berkeley, CA 94720	1	Pat Domenico NWTRB 1100 Wilson Boulevard, Suite 910 Arlington, VA 22209

2	A.L. Dudley SPECTRA Research Institute 1603 University NE Albuquerque, NM 87102	1	Russell McFarland NWTRB 100 Wilson Blvd, Suite 910 Arlington, VA 22209
1	William Dudley US Geological Survey P.O. Box 25046 M/S 425 Denver, CO 80225	1	Robin McGuire Risk Engineering Inc 5255 Pine Ridge Road Golden, CO 80403
1	J. Russell Dyer Yucca Mountain Project Office US DOE P.O. Box 98608 M/S 425 Las Vegas, NV 89193-8518	1	John J. McKetta NWTRB Department of Chemical Engineering CRE Building 1450 Austin, TX 78712-1062
1	Norman A. Eisenberg US Nuclear Regulatory Commission M/S 4-H-3 Washington, DC 20555	1	Ian McKinley NAGRA Hardstrasse 73 Wettingen, CH-5430 SWITZERLAND
1	W.W.-L. Lee Environmental Evaluation Group 7007 Wyoming NE Suite F-2 Albuquerque, NM 87109	1	Fred W. McLafferty Department of Chemistry Cornell University 2600 Baker Laboratory Ithaca, NY 14853-1301
1	R.E. Lowder MAC Tec 101 Conventional Center Drive Suite 1100 Las Vegas, NV 89109	1	Arend Meijer GCX Inc P.O. Box 87198-2427 Albuquerque, NM 87198
1	R.R. Luckey USGS Building 53 Denver Federal Center Room H2314/MS 5421 Denver, CO 80225	1	Dr. Martin Mifflin Water Resources Center Desert Research Center 2505 Chandler Avenue, Suite 1 Las Vegas, NV 89120
1	Annette MacIntyre Lawrence Livermore National Laboratory P.O. Box 808 M/S L-194 Livermore, CA 94551	1	Suresh Pahwa INTERA 6850 Austin Center Blvd Suite 300 Austin, TX 78731
1	Edward A. Mason Amoco Resource Center P.O. Box 451 46 Admirals Lane Osterville, MA 02655-0451	1	Planning Department Nye County P.O. Box 153 Tonopah, NV 89049
		1	F. Joseph Pearson Jr 1304 Walnut Hill Lane Suite 210 Irving, TX 75038

1	Chris Pflum SAIC 101 Conventional Center Drive Las Vegas, NV 89109	1	Aaron Thode Los Alamos National Lab M/S F607 P.O. Box 1663 Los Alamos, NM 87545
1	T.H. Pigford University of California Department of Nuclear Engineering Berkeley, CA 94720	1	K.T. Thomas National Academy of Sciences 2001 Wisconsin Ave NW Harris Bldg, Room 456 Washington, DC 20007
1	P.T. Prestholt NRC Site Representative 301 E. Stewart Avenue, Room 203 Las Vegas, NV 89101	1	C.F. Tsang Lawrence Berkeley Laboratory Earth Sciences Division 1 Cyclotron Road Berkeley, CA 94720
1	Dennis L. Price NWTRB 1011 Evergreen Way Blackburg, VA 24060	1	Greg Valentine Los Alamos National Lab P.O. Box 1663 M/S F665 Los Alamos, NM 87545
1	Karsten Pruess Lawrence Berkeley Laboratory Earth Sciences Division 1 Cyclotron Road Berkeley, CA 94720	1	Richard Van Konynenburg Lawrence Livermore National Lab P.O. Box 808 Livermore, CA 94551
1	Norman C. Rasmussen MIT Department of Nuclear Engineering Bldg 24-205 Cambridge, MA 02139	1	Abraham Van Luik Intera-M&O 101 Convention Center Drive Suite #P110 Las Vegas, NV 89109
1	Leon Reiter NWTRB 1100 Wilson Blvd, Suite 910 Arlington, VA 22209-2297	1	C. John Mann Department of Geology 245 Natural History Building 1301 West Green Street Urbana, Illinois 61801
1	Everett Springer Los Alamos National Laboratory P.O. Box 1663 M/S J495 Los Alamos, NM 87545	1	Henry Loo Westinghouse Idaho Nuclear Co. P.O. Box 4000 M/S 5219 Idaho Falls, ID 83415
1	Roger Staehle University of Minnesota Department of Chemical Engineering and Materials Science 22 Red Fox Road North Oaks, MN 55127	1	Kjell Andersson Karinta-Konsult P.O. Box 6048 S-183 06 Taby, Sweden
1	Jane Summerson US DOE Forrestal RW-22, 7F-091/FORS Washington, DC 20555	1	Dr. G. Ross Heath College - Ocean/Fishery Sciences 583 Henderson Hall University of Washington Seattle, WA 98195

1	Carl Anderson National Academy of Sciences 2101 Constitution Ave NW Harris Building, Room 456 Washington, DC 20418	1	Margaret Federline Nuclear Regulatory Commission Washington, DC 20555-0001
1	Dorothy M. Clark Secretary, Science Advisory Board US EPA 401 M Street SW, A-101F Washington, DC 20460	1	Dr. Alan Hooper United Kingdom Nirex Limited Curie Avenue, Harwell Didcot, Oxfordshire OX11 0RH United Kingdom
1	Kathleen W. Conway Science Advisory Board - EPA 401 M Street SW, A-101F Washington, DC 20460	1	Dr. Michael J. Bell IAEA Wagramerstrasse 5 P.O. Box 100 A-1400 Vienna Austria
1	Dr. Chris Whipple Clement International 160 Spear Street Suite 1380 San Francisco, CA 94105-1535	1	Dr. Neil Chapman INTERA Park View House 14B Burton Street Melton Mowbray, Leicestershire United Kingdom LE13 1AE
13	Priscilla Bunton US DOE, OCRWM (RW-331) 1000 Independence Ave SW Washington, DC 20585	1	Dr. James G.T. Chyr Taiwan Power Company AF 2 Alley 15 Lane 196 Sec 4 Roosevelt Road Taipei, Taiwan Republic of China
1	Linda Desell US DOE, OCRWM (RW-331) Suite 200 1000 Independence Ave SE Washington, DC 20585	1	Dr. Nestor R. Correa NAGRA Hardstrasse 73 CH-5430 Wettingen Switzerland
1	Robert J. Budnitz, President Future Resources Associates Inc 2000 Center Street, Suite 418 Berkeley, CA 94704	1	Kenneth W. Dormuth, AECL Whiteshell Laboratories Pinawa, Manitoba Canada ROE 1L0
1	Thomas A. Cotton JK Research Associates Inc 4429 Butterworth Place, NW Washington, DC 20016	1	Dr. Esko Eloranta Finnish Centre for Radiation P.O. Box 268 SF-00101 Helsinki Finland
1	Srikanta Mishra M&O/ INTERA M/S 423 101 Convention Center Drive Las Vegas, NV 89109	1	Dr. Helmut D. Fuchs Gesellschaft für Nuklear- Service mbH Lange Laube 7 D-3000 Hannover 1 Germany
200	Eric Smistad Yucca Mountain Project M/S 523 101 Convention Center Drive Las Vegas, NV 89109		

1	Ito Fumio c/o Prof. Swoboda University of Innsbruck Technikerstr 13 A-6020 Innsbruck Austria	1	Maria Onofrei, AECL Whiteshell Laboratories Pinawa, Manitoba Canada ROE 1L0
1	Dr. Hilikka Leino-Forsman VTT, Technical Research Centre of Finland Otakaari 3 A P.O. Box 200 SF-02151 Espoo, Finland	1	Dr. Liu Wen-Chung Radwaste Administration Atomic Energy Council 6F 65 Lane 144 Keelung Road Section 4 Taipei Taiwan
1	Dr. Robert W. Lieb NAGRA Hardstrasse 73 CH-5430 Wettingen Switzerland	1	Dr. Sidney H. Whitaker AECL Whiteshell Laboratories Pinawa, Manitoba Canada ROE 1L0
1	Dr. J.W. Lloyd School of Earth Sciences Edgbaston, Birmingham B 15 2TT, United Kingdom	1	Dr. Roger Yearsley Inspectorate of Pollution Room A5.02 Romney House 43 Marsham Street London SW1P 3Py United Kingdom
1	D. Ganpat S. Lodha, AECL Whiteshell Laboratories Pinawa, Manitoba Canada ROE 1L0	1	Dr. Piet Zuidema NAGRA Hardstrasse 73 CH-5430 Wettingen Switzerland
1	Douglas E. Metcalfe Waste Management Division P.O. Box 1046, Station B 270 Albert Street Ottawa, Canada K1P 5S9	1	Dr. Arthur Motta Nuclear Engineering Department Pennsylvania State University 231 Sackett Building University Park, PA 16802
1	Dr. Ivars Neretnieks Department of Chemical Engineering Royal Institute of Technology Teknikringen 26 S-100 44 Stockholm Sweden	1	Dr. M.R. Chandratillake Capcis March Limited Bainbridge House, Granby Row Manchester M1 2PW United Kingdom
1	Dr. Jean-Pierre Olivier OECD/NEA 12 Boulevard des Iles 92130 Issy Les Molineaux France	1	Serge Runge Eurisys Consultants S.A. 14 rue du Printemps 74017 Paris, France
1	Dr. Olle Olsson Conterra AB P.O. Box 493 S-751 06 Uppsala, Sweden	1	Peter Suci Montana State University Bozeman, MT
		1	Dr. David Kreamer Geoscience Department - UNLV 4505 South Maryland Parkway Las Vegas, NV 89159

1 Richard Forester  
USGS  
P.O. Box 25046  
Denver Federal Center  
Lakewood, CO 80225

1 Zell Peterman  
USGS  
P.O. Box 25046  
Denver Federal Center  
Lakewood, CO 80225

1 Kevin McCoy  
B&W Fuel Company  
101 Convention Center Drive  
Suite P110  
Las Vegas, NV 89109

1 John Nitao  
Lawrence Livermore National  
Laboratory  
P.O. Box 808  
Livermore, CA 94551

1 Anne-Marie Meike  
Lawrence Livermore National  
Laboratory  
P.O. Box 808  
Livermore, CA 94551

1 G.S. Bodvarsson  
Lawrence Berkeley Laboratory  
1 Cyclotron Road  
Berkeley, CA 94720

1 Jiamin Wan  
Lawrence Berkeley Laboratory  
1 Cyclotron Road  
Berkeley, CA 94720

1 Robert Andrews  
INTERA  
M/S 423  
101 Convention Center Drive  
Las Vegas, NV 89109

1 Tim Dale  
INTERA  
M/S 423  
101 Convention Center Drive  
Las Vegas, NV 89109

1 Dan McCright  
Lawrence Livermore National  
Laboratory  
P.O. Box 808  
M/S L-204  
Livermore, CA 94551

1 Ray Stout  
Lawrence Livermore National  
Laboratory  
P.O. Box 808  
M/S L-204  
Livermore, CA 94551

## INTERNAL DISTRIBUTION

MS  
4 1330 G. M. Gerstner-Miller, 6352  
100/12541/SAND93-2675/QA  
20 1330 WMT Library, 6352  
1 0827 P. J. Hommert, 1502  
1 1375 D. A. Dahlgren, 4400  
5 0899 Technical Library, 7141  
1 0619 Technical Publications, 7151  
10 1119 Document Processing for  
DOE/OSTI, 7613-2  
1 9018 Central Technical Files, 8523-2  
  
1 0827 J. C. Cummings, 1502  
1 0827 J. S. Rottler, 1511  
1 0827 P. L. Hopkins, 1511  
1 0827 M. J. Martinez, 1511  
1 0835 R. R. Eaton, 1513  
1 0835 R. D. Skocypec, 1513  
1 1324 P. D. Davies, 6115  
1 1324 R. J. Glass, 6115  
1 1324 C. A. Rautman, 6115  
1 1324 V. C. Tidwell, 6115  
1 1324 C. Ho, 6115  
1 1320 M. D. Siegel, 6119  
1 1333 F. J. Schelling, 6302  
10 1326 H. A. Dockery, 6312  
10 1326 R. W. Barnard, 6312  
10 1326 G. E. Barr, 6312  
10 1326 J. H. Gauthier, 6312  
1 1326 P. G. Kaplan, 6312  
1 1326 T. H. Robey, 6312  
1 1326 L. H. Skinner, 6312  
1 1326 W. G. Perkins, 6312  
1 1326 A. R. Schenker, 6312  
1 1326 S. A. Shannon, 6312  
60 1326 M. L. Wilson, 6312  
  
1 1325 L. S. Costin, 6313  
1 1325 R. E. Finley, 6313  
1 1325 E. Dunn, 6313  
1 1325 J. F. Holland, 6313  
1 1325 J. Pott, 6313  
1 1325 C. S. Chocas, 6313  
1 1325 E. E. Ryder, 6313  
1 1325 S. R. Sobolik, 6313  
1 1330 M. C. Brady, 6314  
1 1345 T. J. Brown, 6331

1 1328 M. E. Fewell, 6342  
1 1328 C. T. Stockman, 6342  
1 1328 R. P. Rechard, 6342  
1 1328 M. G. Marietta, 6342  
1 0755 B. D. Zak, 6612  
1 1315 T. E. Blejwas, 7500  
1 9043 R. Nilson, 8745