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Pre-Waste-Emplacement Ground-Water Travel Time Sensitivity and Uncertainty Analyses For Yucca Mountain, Nevada

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Abstract

Yucca Mountain, Nevada is a potential site for a high-level radioactive- waste repository. Uncertainty and sensitivity analyses were performed to estimate critical factors in the performance of the site with respect to a criterion in terms of pre-waste-emplacement ground-water travel time. The degree of failure in the analytical model to meet the criterion is sensitive to the estimate of fracture porosity in the upper welded unit of the problem domain. Fracture porosity is derived from a number of more fundamental measurements including fracture frequency, fracture orientation, and the moisture-retention characteristic inferred for the fracture domain.

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Table of Contents

1.0 INTRODUCTION	1-1
2.0 GEOLOGIC MODEL	2-1
2.1 One-Dimensional Sections	2-1
3.0 PROCESS MODEL	3-1
3.1 LLUVIA	3-1
3.2 Data Set	3-1
4.0 PERFORMANCE PARAMETER	4-1
5.0 UNCERTAINTY ANALYSES	5-1
5.1 UE-25a#1	5-3
5.2 USW G-4	5-19
5.3 Fault Zone	5-36
5.4 USW H-5	5-59
5.5 Summary	5-69
6.0 SENSITIVITY ANALYSES	6-1
6.1 Failure Analyses	6-1
6.1.1 UE-25a#1	6-2
6.1.2 USW G-4	6-4
6.1.3 Fault Zone	6-7
6.1.4 Summary	6-9
6.2 Sensitivity To Flux	6-9
6.3 Sensitivity To Fractures	6-10
7.0 DATA RECOMMENDATIONS	7-1
8.0 CONCLUSIONS	8-1
9.0 REFERENCES	9-1

List of Tables

2.1	Hydrostratigraphic Units	2-1
2.1.1	Elevations of Hydrostratigraphic Contacts and Unit Thickness .	2-2
3.2.1	Input Data For Monte Carlo Simulations	3-2
5.1.1	Summary Statistics For UE-25a#1	5-3
5.2.1	Summary Statistics For USW G-4	5-19
5.3.1	Summary Statistics For The Fault Zone	5-36
5.4.1	Summary Statistics For USW H-5	5-59
5.5.1	Summary Of Simulations In Which Failure Occurred	5-69
6.1.1.1	Rank Correlations For GWTT Less Than 1,000 Years With Input Hydrogeologic Parameters At UE-25a#1 At 0.6 mm/yr Flux .	6-3
6.1.2.1	Rank Correlations For GWTT Less Than 1,000 Years With Input Hydrogeologic Parameters At USW G-4 At 0.6 mm/yr Flux .	6-4
6.1.4.1	Summary Of Rank Correlation Coefficients For Ground Water Travel Time With Fracture Porosity In Unit Tpt-TM	6-9

List of Figures

2.1.1	Schematic Diagram Of Column USW H-5	2-4
2.1.2	Schematic Diagram Of The Fault Zone	2-5
2.1.3	Schematic Diagram Of Column USW G-4	2-6
2.1.4	Schematic Diagram Of Column UE-25a#1	2-7
5.1	Uncertainty Analysis	5-1
5.1.1	Plot Of GWTT Versus Flux For Column UE-25a#1	5-4
5.1.2	Plot Of The Coefficient Of Variation Of GWTT Versus Flux For Column UE-25a#1	5-4
5.1.3	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.6 mm/yr Flux	5-5
5.1.4	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.6 mm/yr Flux	5-5
5.1.5	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.6 mm/yr Flux	5-6
5.1.6	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.5 mm/yr Flux	5-6
5.1.7	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.5 mm/yr Flux	5-7
5.1.8	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.5 mm/yr Flux	5-7
5.1.9	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.4 mm/yr Flux	5-8
5.1.10	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.4 mm/yr Flux	5-8
5.1.11	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.4 mm/yr Flux	5-9
5.1.12	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.35 mm/yr Flux	5-9

List of Figures (cont.)

5.1.13	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.35 mm/yr Flux	5-10
5.1.14	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.35 mm/yr Flux	5-10
5.1.15	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.3 mm/yr Flux	5-11
5.1.16	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.3 mm/yr Flux	5-11
5.1.17	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.3 mm/yr Flux	5-12
5.1.18	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.25 mm/yr Flux	5-12
5.1.19	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.25 mm/yr Flux	5-13
5.1.20	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.25 mm/yr Flux	5-13
5.1.21	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.2 mm/yr Flux	5-14
5.1.22	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.2 mm/yr Flux	5-14
5.1.23	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.2 mm/yr Flux	5-15
5.1.24	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.1 mm/yr Flux	5-15
5.1.25	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.1 mm/yr Flux	5-16
5.1.26	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.1 mm/yr Flux	5-16
5.1.27	Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.01 mm/yr Flux	5-17
5.1.28	Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.01 mm/yr Flux	5-17

List of Figures (cont.)

5.1.29	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.01 mm/yr Flux	5-18
5.2.1	Plot Of GWTT Versus Flux For Column USW G-4	5-20
5.2.2	Plot Of The Coefficient Of Variation Of GWTT Versus Flux For Column USW G-4	5-20
5.2.3	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.6 mm/yr Flux	5-21
5.2.4	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.6 mm/yr Flux	5-21
5.2.5	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.6 mm/yr Flux	5-22
5.2.6	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.5 mm/yr Flux	5-22
5.2.7	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.5 mm/yr Flux	5-23
5.2.8	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.5 mm/yr Flux	5-23
5.2.9	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.4 mm/yr Flux	5-24
5.2.10	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.4 mm/yr Flux	5-24
5.2.11	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.4 mm/yr Flux	5-25
5.2.12	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.35 mm/yr Flux	5-25
5.2.13	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.35 mm/yr Flux	5-26
5.2.14	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.35 mm/yr Flux	5-26
5.2.15	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.3 mm/yr Flux	5-27

List of Figures (cont.)

5.2.16	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.3 mm/yr Flux	5-27
5.2.17	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.3 mm/yr Flux	5-28
5.2.18	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.2 mm/yr Flux	5-28
5.2.19	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.2 mm/yr Flux	5-29
5.2.20	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.2 mm/yr Flux	5-29
5.2.21	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.15 mm/yr Flux	5-30
5.2.22	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.15 mm/yr Flux	5-30
5.2.23	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.15 mm/yr Flux	5-31
5.2.24	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.13 mm/yr Flux	5-31
5.2.25	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.13 mm/yr Flux	5-32
5.2.26	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.13 mm/yr Flux	5-32
5.2.27	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.1 mm/yr Flux	5-33
5.2.28	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.1 mm/yr Flux	5-33
5.2.29	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.1 mm/yr Flux	5-34
5.2.30	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.01 mm/yr Flux	5-34
5.2.31	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.01 mm/yr Flux	5-35

List of Figures (cont.)

5.2.32	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.01 mm/yr Flux	5-35
5.3.1	Plot Of GWTT Versus Flux For The Fault Zone	5-37
5.3.2	Plot Of The Coefficient Of Variation Of GWTT Versus Flux For The Fault Zone	5-37
5.3.3	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 10.0 mm/yr Flux	5-38
5.3.4	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 10.0 mm/yr Flux	5-38
5.3.5	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 10.0 mm/yr Flux	5-39
5.3.6	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 6.0 mm/yr Flux	5-39
5.3.7	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 6.0 mm/yr Flux	5-40
5.3.8	Histogram Of Pre-Waste Emplacement Ground Water Travel Times For The Fault Zone At 6.0 mm/yr Flux	5-40
5.3.9	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 5.0 mm/yr Flux	5-41
5.3.10	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 5.0 mm/yr Flux	5-41
5.3.11	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 5.0 mm/yr Flux	5-42
5.3.12	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 4.0 mm/yr Flux	5-42
5.3.13	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 4.0 mm/yr Flux	5-43
5.3.14	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 4.0 mm/yr Flux	5-43
5.3.15	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 3.0 mm/yr Flux	5-44

List of Figures (cont.)

5.3.16	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 3.0 mm/yr Flux	5-44
5.3.17	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 3.0 mm/yr Flux	5-45
5.3.18	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 2.5 mm/yr Flux	5-45
5.3.19	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 2.5 mm/yr Flux	5-46
5.3.20	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 2.5 mm/yr Flux	5-46
5.3.21	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 2.0 mm/yr Flux	5-47
5.3.22	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 2.0 mm/yr Flux	5-47
5.3.23	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 2.0 mm/yr Flux	5-48
5.3.24	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 1.5 mm/yr Flux	5-48
5.3.25	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 1.5 mm/yr Flux	5-49
5.3.26	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 1.5 mm/yr Flux	5-49
5.3.27	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 1.0 mm/yr Flux	5-50
5.3.28	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 1.0 mm/yr Flux	5-50
5.3.29	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 1.0 mm/yr Flux	5-51
5.3.30	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 0.75 mm/yr Flux	5-51
5.3.31	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.75 mm/yr Flux	5-52

List of Figures (cont.)

5.3.32	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.75 mm/yr Flux	5-52
5.3.33	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 0.5 mm/yr Flux	5-53
5.3.34	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.5 mm/yr Flux	5-53
5.3.35	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.5 mm/yr Flux	5-54
5.3.36	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 0.1 mm/yr Flu	5-54
5.3.37	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.1 mm/yr Flux	5-55
5.3.38	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.1 mm/yr Flux	5-55
5.3.39	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 0.05 mm/yr Flu	5-56
5.3.40	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.05 mm/yr Flux	5-56
5.3.41	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.05 mm/yr Flux	5-57
5.3.42	Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At 0.01 mm/yr Flu	5-57
5.3.43	Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.01 mm/yr Flux	5-58
5.3.44	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.01 mm/yr Flux	5-58
5.4.1	Plot Of GWTT Versus Flux For Column USW H-5	5-60
5.4.2	Plot Of The Coefficient Of Variation Of GWTT Versus Flux For Column USW H-5	5-60
5.4.3	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 4.0 mm/yr Flux	5-61

List of Figures (cont.)

5.4.4	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 4.0 mm/yr Flux	5-61
5.4.5	Histogram Of Pre-Waste-Emplacement Ground Water-Travel Times For Column USW H-5 At 4.0 mm/yr Flux	5-62
5.4.6	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 2.5 mm/yr Flux	5-62
5.4.7	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 2.5 mm/yr Flux	5-63
5.4.8	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW H-5 At 2.5 mm/yr Flux	5-63
5.4.9	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 1.0 mm/yr Flux	5-64
5.4.10	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 1.0 mm/yr Flux	5-64
5.4.11	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW H-5 At 1.0 mm/yr Flux	5-65
5.4.12	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 0.1 mm/yr Flux	5-65
5.4.13	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 0.1 mm/yr Flux	5-66
5.4.14	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW H-5 At 0.1 mm/yr Flux	5-66
5.4.15	Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 0.01 mm/yr Flux	5-67
5.4.16	Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 0.01 mm/yr Flux	5-67
5.4.17	Histogram Of Pre-Waste Emplacement Ground Water Travel Times For Column USW H-5 At 0.01 mm/yr Flux	5-68
6.1.1.1	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times Of 1,000 Years Or Less For Column UE-25a#1 At 0.6 mm/yr Flux	6-2

List of Figures (cont.)

6.1.1.2	Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Times Versus Fracture Porosity In Unit Tpt-TM For Column UE-25a#1 At 0.6 mm/yr Flux	6-3
6.1.1.3	Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Fracture Air-Entry Values In Unit Tpt-TV For Column UE-25a#1 At 0.6 mm/yr Flux	6-4
6.1.2.1	Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times Of 1,000 Years Or Less For Column USW G-4 At 0.6 mm/yr Flux	6-5
6.1.2.2	Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Times Versus Fracture Porosity In Unit Tpt-TM For Column USW G-4 At 0.6 mm/yr Flux	6-6
6.1.2.3	Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Fracture Air-Entry Values In Unit Tpt-TV For Column USW G-4 At 0.6 mm/y. Flux	6-6
6.1.2.4	Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Matrix Air-Entry Values In Unit Tcb-TN For Column USW G-4 At 0.6 mm/yr Flux	6-7
6.1.3.1	Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Times Versus Fracture Porosity In Unit Tpt-TM For The Fault Zone At 10.0 mm/yr Flux	6-8
6.1.3.2	Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Times Versus Fracture Porosity In Unit Tpt-TM For The Fault Zone At 3.0 mm/yr Flux	6-8
6.2.1	Mean Pre-Waste-Emplacement Ground-Water Travel Time Versus Steady-State Flux	6-10
7.1	Relationship Between The Model Coefficient Fracture Porosity And The Underlying Data	7-1
7.2	Coefficient Of Variation Versus Steady-State Flux	7-3

1.0 INTRODUCTION

Yucca Mountain, Nevada is the potential site of a repository for high-level radioactive waste. To be chosen for development as a repository, the site would be required to meet sets of legal, technical, and political criteria. Performance assessment is the probabilistic assessment of the likelihood that a system will meet the technical criteria governing its performance for a specified period of time (Harr, 1987). Performance assessment is used to determine the circumstances under which the site may fail to meet the compliance criteria, to prioritize information needs for further study and from site characterization, and, eventually, to provide an estimate of the degree of compliance with the criteria. Performance assessment is an iterative process that builds on existing technological capabilities and current understanding of the site and the processes at the site that may be of importance to compliance. With each iteration, needs for more information and better analytical capabilities may be identified. This iterative process continues until confidence in the performance of the system is achieved.

The analyses in this document have a specific purpose. That purpose is to provide an analytical basis for prioritizing certain kinds of information needs and data required from a program of site characterization within the framework of performance assessment. No claim is made that the assumptions in the models used for the analyses are valid. The claim is made, however, that the assumptions are reasonable given our current understanding of the site and the constraints of today's technology. The analyses suggest what information might be important, and they also suggest ways in which future analyses could be improved for the next iteration. The analyses in this document should not be interpreted as an attempt to estimate compliance with a legal criterion for ground-water travel time such as 10 CFR 60.113B(2) (Nuclear Regulatory Commission).

Sections 2, 3, and 4 discuss the elements of the conceptual model used in the analyses that follow. Section 2 describes the geologic model, primarily in terms of the geometric relationships among its components. Section 3 describes the process model, the computer program that is used to implement it, and the model input. Section 4 defines the criterion for pre-waste-emplacement ground-water travel time. The uncertainty analyses are described first, in Section 5. The sensitivity analyses are described in Section 6. Section 7 presents recommendations for data and information based on the results of Sections 5 and 6. Section 8 presents conclusions and suggestions for future analyses.

2.0 GEOLOGIC MODEL

The geologic model used in this exercise is a variation of the hydrostratigraphy defined in Barnard and Dockery (1991). The model assumes that the Yucca Mountain site is composed of layers, called hydrostratigraphic units, of hydraulically distinct materials. The model in this exercise was originally prepared for a total-system performance analysis and is discussed in detail in Barnard et al. (1992). The model domain extends vertically from the waste-emplacement horizon of the repository, or its projection, to the water table along an east-west cross section, defined on the west by drill hole USW H-5 and on the east by drill hole UE-25a#1. The hydrostratigraphic nomenclature followed in this exercise is given in Table 2.1.

Table 2.1
Hydrostratigraphic Units

symbol	lithology	significant characteristics
Tpt-TM	Ash-flow, moderately welded, non-lithophysal	jointed and fractured, non-zeolitic
Tpt-TV	Ash-flow, densely welded, vitrophyre	non-zeolitic, highly jointed and fractured
Tpt-TN	Ash-flow, non-welded	few fractures, zeolitic
Tcb-TN	Ash-flow, non-welded	few fractures, zeolitic
Tcpp-TP	Ash-flow, partially to moderately welded	slightly fractured, non-zeolitic

2.1 One-Dimensional Sections

The simulations in this exercise are all one-dimensional because of feasibility. Two- and three-dimensional simulations of Yucca Mountain require many hours of CPU time for each individual analysis. The uncertainty analyses, described in Section 5, consisted of 3,800 individual analyses. Four one-dimensional columns were modeled: three at the locations of the existing bore holes (USW H-5, USW G-4, UE-25a#1), and one at Ghost Dance Fault. At the location of the Ghost Dance Fault, fracture densities are arbitrarily assumed to be an order of magnitude greater than in the surrounding rock. The elevations of the hydrostratigraphic contacts and the thicknesses of the hydrostratigraphic units are given in Table 2.1.1 for each of the four locations. Figures 2.1.1 through 2.1.4 are schematic illustrations of the four columns showing the elevation of the contacts in meters above mean sea level, the thickness of the units, the lithology of the units, and the thickness of the column. The top of the column is taken to be the waste-emplacement horizon of the repository for the purpose of calculating ground-water travel time. The elevation of the waste-emplacement horizon is likely to change as site characterization proceeds and new information is incorporated in both design and performance assessment.

Table 2.1.1
Elevations of Hydrostratigraphic Contacts and Unit Thickness

USW H-5

unit	elevation at base (meters amsl)	elevation above water table (m)	thickness (m)
repository	1030	260	
Tpt-TM	996	226	34
Tpt-TV	974	204	22
Tpt-TN	905	135	69
Tcb-TN	885	115	20
Tcpp-TP	770	0	115

FAULT ZONE

unit	elevation at base (meters amsl)	elevation above water table (m)	thickness (m)
repository	966	235	
Tpt-TM	875	144	91
Tpt-TV	863	132	12
Tpt-TN	832	101	31
Tcb-TN	734	3	98
Tcpp-TP	731	0	3

USW G-4

unit	elevation at base (meters amsl)	elevation above water table (m)	thickness (m)
repository	956	225	
Tpt-TM	869	138	87
Tpt-TV	860	129	9
Tpt-TN	836	105	24
Tcb-TN	731	0	105

Table 2.1.1 (continued)

UE-25a#1

unit	elevation at base (meters amsl)	elevation above water table (m)	thickness (m)
<u>repository</u>	870	141	
Tpt-TM	811	82	59
Tpt-TV	798	69	13
Tpt-TN	784	55	14
Tcb-TN	729	0	55

Figure 2.1.1 Schematic Diagram Of Column USW H-5

Figure 2.1.2 Schematic Diagram Of The Fault Zone

Figure 2.1.3 Schematic Diagram Of Column USW G-4

Figure 2.1.4 Schematic Diagram Of Column UE-25a#1

3.0 PROCESS MODEL

The process modeled in this exercise is the liquid phase flow of water. The model used is described by Peters and Klavetter (1988). It is assumed in the model that both the fractures and the matrix contribute to the flow of fluid through the domain, that flow is predominantly unsaturated, and that pressure heads in the matrix and the fractures at any given location are in equilibrium. An assumption specific to this exercise is that the flow in the domain of interest is steady-state.

3.1 LLUVIA

The computer code that implements the conceptual model under one-dimensional, steady-state conditions is called LLUVIA (Hopkins and Eaton, 1990). It was written to meet the demands required by Monte Carlo simulation: speed and efficiency. All the simulations in this exercise were conducted using LLUVIA.

3.2 DATA SET

The steady-state form of the conceptual model requires specification of ten hydrologic parameters in each hydrologic unit for a solution. Five of the parameters describe the hydrologic properties of the matrix. The other five describe the hydrologic properties of the fractures. A simulation also requires specification of the steady-state flux. The purpose of the Monte Carlo simulations in this exercise is to identify the consequences with respect to a ground-water-travel-time criterion of uncertainties in the values of the ten hydrologic parameters. Therefore, as input to the simulation, the probability density function of each of the ten parameters in each of the units is required. The simulation, as executed here, assumes that each of the parameters can be described by a four-parameter probability density function called a beta distribution. The four parameters of the beta distribution for the hydrologic parameter are defined in terms of the minimum value of the parameter, its maximum value, its expected value, and the coefficient of variation (CV). The available data describing these quantities are not extensive, and the values used in this study have been obtained with the aid of a paradigm for generating probability distributions of sparse data sets discussed in Kaplan (1991). This paradigm uses expert judgment, parameter specific data, natural analog data, and theoretical or functional constraints to estimate the form of the probability distribution. Like the geologic model, the input data set used in this exercise was originally constructed for the total-system performance assessment. The assumptions used to generate the data set are discussed in Barnard et al. (1992). The data set, given in Table 3.2.1, consists of an expected value, a minimum value, a maximum value, and a CV for each parameter in each unit. The fault zone is distinguished by a higher fracture porosity. Preparation of this data set for Latin hypercube sampling is discussed in Barnard et al. (1992).

Table 3.2.1
Input Data For Monte Carlo Simulations

matrix porosity

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	0.24	0.41	0.21	0.04	0.11
minimum	0.0	0.0	0.0	0.016	0.044
maximum	1.0	1.0	1.0	0.072	0.197
CV	0.2	0.2	0.2	0.2	0.2

matrix saturated conductivity (m/s)

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	1.4e-8	3.01e-12	7.99e-11	3.01e-12	2e-11
minimum	0.0	0.0	0.0	0.0	0.0
maximum	5.4e-7	1.3e-10	3.1e-9	1.3e-10	7.9e-10
CV	1.0	1.0	1.0	1.0	1.0

matrix residual saturation

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	0.066	0.01	0.164	0.052	0.08
minimum	0.027	0.004	0.065	0.021	0.032
maximum	0.118	0.018	0.293	0.093	0.143
CV	0.2	0.2	0.2	0.2	0.2

matrix air-entry parameter (1/m)
(van Genuchten alpha parameter)

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	0.014	0.022	0.0265	0.0017	0.0057
minimum	2.3e-3	3.5e-3	4.1e-3	4.8e-4	1.1e-3
maximum	3.5e-2	5.4e-2	6.5e-2	4.2e-3	1.4e-2
CV	0.37	0.37	0.37	0.37	0.37

Table 3.2.1 (continued)

**matrix desaturation parameter
(van Genuchten beta parameter)**

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	2.64	1.236	2.223	1.708	1.798
minimum	1.05	1.05	1.05	1.05	1.05
maximum	10.0	10.0	10.0	10.0	10.0
CV	0.2	0.2	0.2	0.2	0.2

fracture porosity

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	9.24e-4	3.36e-4	4.2e-4	7.48e-3	5.94e-3
minimum	0.0	0.0	0.0	0.0	0.0
maximum	0.0653	0.0241	0.0298	0.5281	0.4199
CV	1.02	1.02	1.02	1.02	1.02

fracture porosity (fault zone)

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	9.24e-3	3.36e-3	4.2e-3	7.48e-2	5.94e-2
minimum	0.0	0.0	0.0	0.0	0.0
maximum	0.6525	0.2376	0.2968	1.0	1.0
CV	1.02	1.02	1.02	1.02	1.02

fracture saturated conductivity (m/s)

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	8.25e-5	8.25e-5	8.25e-5	8.25e-5	8.25e-5
minimum	9.3e-6	9.3e-6	9.3e-6	9.3e-6	9.3e-6
maximum	2.4e-4	2.4e-4	2.4e-4	2.4e-4	2.4e-4
CV	0.524	0.524	0.524	0.524	0.524

Table 3.2.1 (continued)

fracture residual saturation

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	0.105	0.105	0.105	0.105	0.105
minimum	0.028	0.028	0.028	0.028	0.028
maximum	0.217	0.217	0.217	0.217	0.217
CV	0.269	0.269	0.269	0.269	0.269

**fracture air-entry parameter (1/m)
(van Genuchten alpha parameter)**

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	14.5	14.5	14.5	14.5	14.5
minimum	5.75	5.75	5.75	5.75	5.75
maximum	26.08	26.08	26.08	26.08	26.08
CV	0.203	0.203	0.203	0.203	0.203

**fracture desaturation parameter
(van Genuchten beta parameter)**

beta distribution parameters	unit Tcpp-Tp	unit Tcb-TN	unit Tpt-TN	unit Tpt-TV	unit Tpt-TM
expected value	2.68	2.68	2.68	2.68	2.68
minimum	1.05	1.05	1.05	1.05	10.5
maximum	10.0	10.0	10.0	10.0	10.0
CV	0.203	0.203	0.203	0.203	0.203

4.0 PERFORMANCE PARAMETER

The analyses in this document were designed to answer two questions. First, does the unsaturated zone model fail to meet a specified criterion for performance? Second, if the model fails, why did it fail? In other words, which combinations of parameter values in the process model produced a calculated estimate of failure? As a criterion for performance, the pre-waste-emplacement ground-water travel time (GWTT) is defined as the cumulative travel time from the top of the computer model to the base through either the matrix or the fractures in the unsaturated zone, whichever is faster. The algorithm for this calculation is discussed in Hopkins and Eaton (1990). The travel time, defined this way, has proven to be a useful sensitivity measure (Prindle and Hopkins, 1990). Ground-water travel times from the base of the unsaturated through the saturated zone to the accessible environment, a boundary 5 kilometers from the edge of the potential repository, are not considered or calculated as part of this analysis.

A "failure" is defined as a ground-water travel time less than or equal to 1,000 years from the top of the column to the base. Conceptually, this spatial domain can be thought of as from the base of the potential repository to the water table. This definition of failure is derived from the regulatory criterion in 10 CFR 60.113B(2) (Nuclear Regulatory Commission) that specifies ground-water travel time to the accessible environment shall be greater than 1,000 years and is commonly referred to as the criterion for pre-waste-emplacement ground-water travel time. Unfortunately, the regulation itself provides little guidance as to how the actual calculation should be defined. Simple differences in the conceptualization of ground-water travel time can lead to large differences in the calculated value (Kaplan et al., 1989).

This document is based on the assumption, which is not addressed in 10CFR60, that a stochastic approach is a viable way of addressing a question of performance. As a consequence, the performance parameter, ground-water travel time, is taken to be a random variable. This approach presents a number of alternatives for expressing compliance. Because the distribution of ground-water travel times can be computed from data like those described in Section 3.2, compliance can be expressed by comparing the criterion to the mean or median of the ground-water travel-time distribution. It can also be expressed as a probability of failure or success by determining what fraction of the ground-water travel-time distribution lies below or above the 1,000 year criterion. In Section 5, Uncertainty Analyses, mean, median, and probability of failure are all calculated. By way of reminder, it is not the purpose or intent of this document to calculate a ground-water travel time for comparison with the regulatory criterion in 10 CFR 60.113B(2). It is the purpose of this document to try and identify what information, if obtained from a program of site characterization, would be most likely to change a prediction of performance made with the model assumptions and the definition of the performance criterion used in this exercise.

5.0 UNCERTAINTY ANALYSES

The purpose of the uncertainty analysis is to identify consequence as a function of lack of knowledge. In other words, we are determining the consequences of our ignorance. Specifically, in regard to the problem defined in this document, "consequence" is taken to mean a failure to meet the ground-water travel-time criterion, and "lack of knowledge" is the inability to accurately define the model domain, the essential flow processes, and the values of the parameters of the performance-assessment model. In this exercise the parameters are treated as random variables. The model domain was defined in Section 2 as four one-dimensional columns of variably layered volcanic tuff. The process model was defined in Section 3. Uncertainty in the values of the hydrologic parameters is incorporated in the probability density function for each of the parameters. At a given flux, 100 samples of each of the hydrologic parameters are taken by Latin hypercube sampling (Iman and Shortencarrier, 1984) of each individual parameter's probability distribution. Each sample is taken to be an equally likely realization of the value the individual hydrologic parameter could take. This process generates 100 equally likely data sets or realizations of the hydrologic parameters. A ground-water travel time is calculated for each of the data sets. This generates a distribution of 100 ground water-travel times for each column at each individual flux. Each set of 100 ground-water travel times at a fixed flux is a simulation. Uncertainty in the steady-state flux is addressed by incrementally increasing the value of the flux in each successive simulation of 100 ground-water travel times starting at a value of 0.01 millimeter per year until one of two constraints discussed below is met. Figure 5.1 is a schematic illustration of the process just described. The purpose of this analytical

Figure 5.1. Uncertainty Analysis

process is to determine whether a failure can occur. The purpose of Section 6.0, Sensitivity Analyses, is to identify the set of parameter values that produced any failures identified during the uncertainty analyses.

The steady-state flux parameter deserves some discussion. The maximum amount of flux that can be applied to a given column is unknown prior to the start of the simulations but is constrained by the following argument. Three of the columns used in the simulation represent locations of existing bore holes and there is no evidence of perched water at these locations. The assumption is made, that the observed absence of perched water is a valid constraint on the simulation. Because fluid potentials in excess of 0.0 define saturated or perched conditions, flux cannot be applied to any one column that results in potentials in excess of 0.0 at any location within the column. Therefore, the amount of water that can be introduced is constrained. In the case of the Monte Carlo simulations that constitute the uncertainty analysis, the following rule was obeyed: if any individual realization out of the one hundred at a given flux generated potentials in excess of 0.0, then the maximum flux for the column was taken to be the immediately preceding increment. In the case where each of the 100 ground-water travel times in a simulation is faster than the 1,000 year criterion once a certain value of flux is applied and no potentials in excess of 0.0 have been calculated, no additional simulations are conducted at higher fluxes. This particular set of circumstances occurs in the analysis of the fault zone (Section 5.3).

The minimum amount of flux is also unknown. It is quite likely that the net infiltration flux at Yucca Mountain may be less than or equal to zero. Given the purpose of this particular analysis, an attempt to identify failure, it was assumed that only fluxes greater than zero are relevant. The value of 0.01 mm/yr was chosen as the minimum starting point because it represents what could be the best current estimate of the magnitude of flux consistent with the model, the available data, and the observed in-situ saturations currently available (Barnard and Dockery, 1991; Rush et al, 1984; Weeks and Wilson, 1984). Although failure at a flux of 0.01 mm/yr is unlikely, a very real question in performance assessment is whether it is possible to fail to meet a criterion under expected conditions, conditions that represent what is often the basis for design. In the simulations that follow, flux is increased substantially, by several orders of magnitude, above the 0.01 mm/yr value until the constraints discussed above are met.

The rest of this section is divided into five sub-sections. There is a sub-section for each of the four columns containing a plot of both the mean and median of the distribution of the 100 pre-waste-emplacement ground-water travel times versus flux; a plot of the coefficient of variation, the ratio of the standard deviation to the mean, versus flux; a scatter diagram of the calculated potentials at each flux; a scatter diagram of the calculated saturations at each flux; and a histogram of the ground-water travel times calculated at each flux. The fifth sub-section summarizes the uncertainty analysis.

The scatter diagrams and the histogram were felt to be the best way to summarize the results of any one Monte Carlo simulation. The scatter diagrams of potential are plots of potential calculated as a function of elevation for all 100 calculations of ground-water travel time in the simulation. The plot provides a visual check that water potentials are all less than or equal to zero. The scatter diagrams of saturation are plots of saturation as a function of elevation for all 100 calculations of ground-water travel time in the simulation. These diagrams are discussed in Section 7, Data Recommendations.

5.1 UE-25a#1

Nine Monte Carlo simulations of 100 realizations each were conducted at incremental fluxes ranging from a minimum of 0.01 mm/yr to a maximum of 0.6 mm/yr. Summary statistics and the probability of failure for each simulation are tabulated in Table 5.1.1. As was the case in all the columns, the majority of simulations were conducted over a narrow range of flux once failure starts to occur. This narrow range appears to be where the rate of change of the coefficient of variation with respect to flux is the greatest and also the least predictable. The probability of failure, the dependent variable in the analysis, is simply the ratio of the number of failures to the number of trials.

Table 5.1.1
Summary Statistics For UE-25a#1

flux (mm/yr)	mean (years)	median (years)	coefficient of variation	probability of failure
0.60	6,209	4,613	0.770	0.16
0.50	8,364	6,021	0.700	0.12
0.40	11,830	8,795	0.660	0.11
0.35	14,719	16,871	0.604	0.08
0.30	18,738	22,559	0.562	0.05
0.25	24,814	28,507	0.530	0.05
0.20	33,319	36,508	0.499	0.01
0.10	84,465	80,448	0.590	0.00
0.01	1,572,933	1,029,038	0.629	0.00

From Table 5.1.1 it can be observed that no failures occur at fluxes below 0.20 mm/yr. A simulation conducted at 0.75 mm/yr generated high positive fluid potentials. For the purpose of this exercise, 0.60 mm/yr was taken as the maximum flux consistent with the constraints given in Section 5.0.

Figure 5.1.1 is a plot of the ground-water travel time (GWTT) versus the steady-state flux for all nine simulations. Both the mean travel time and the median travel time are plotted on log-log scale. Figure 5.1.2 is a plot of the coefficient of variation of ground-water travel time versus the steady-state flux for all nine simulations with flux plotted in log scale. Figures 5.1.3 through 5.1.29 are the scatter diagrams of potential, the scatter diagrams of saturation, and the histograms of ground-water travel time for each of the nine simulations.

Figure 5.1.1 Plot Of GWTT Versus Flux For Column UE-25a#1

Figure 5.1.2 Plot Of The Coefficient Of Variation Versus Flux For Column UE-25a#1

Figure 5.1.3 Scatter Diagram of Water Potential As A Function of Elevation For Column UE-25a#1 At 0.6 mm/yr Flux

Figure 5.1.4 Scatter Diagram of Saturation As A function of Elevation For Column UE-25a#1 At 0.6 mm/yr Flux

Figure 5.1.5 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.6 mm/yr Flux

Figure 5.1.6 Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.5 mm/yr Flux

Figure 5.1.7 Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.5 mm/yr Flux

Figure 5.1.8 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.5 mm/yr Flux

Figure 5.1.9 Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.4 mm/yr Flux

Figure 5.1.10 Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.4 mm/yr Flux

Figure 5.1.11 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.4 mm/yr Flux

Figure 5.1.12 Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.35 mm/yr Flux

Figure 5.1.13 Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.35 mm/yr Flux

Figure 5.1.14 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.35 mm/yr Flux

Figure 5.1.15 Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.3 mm/yr Flux

Figure 5.1.16 Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.3 mm/yr Flux

Figure 5.1.17 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.3 mm/yr Flux

Figure 5.1.18 Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.25 mm/yr Flux

Figure 5.1.19 Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.25 mm/yr Flux

Figure 5.1.20 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.25 mm/yr Flux

Figure 5.1.21 Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.25 mm/yr Flux

Figure 5.1.22 Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.2 mm/yr Flux

Figure 5.1.23 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.2 mm/yr Flux

Figure 5.1.24 Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.1 mm/yr Flux

Figure 5.1.25 Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.1 mm/yr Flux

Figure 5.1.26 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.1 mm/yr Flux

Figure 5.1.27 Scatter Diagram Of Water Potential As A Function Of Elevation For Column UE-25a#1 At 0.01 mm/yr Flux

Figure 5.1.28 Scatter Diagram Of Saturation As A Function Of Elevation For Column UE-25a#1 At 0.01 mm/yr Flux

Figure 5.1.29 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column UE-25a#1 At 0.01 mm/yr Flux

5.2 USW G-4

Ten Monte Carlo simulations of 100 realizations each were conducted at incremental fluxes ranging from a minimum of 0.01 mm/yr to a maximum of 0.6 mm/yr. Summary statistics and the probability of failure for each simulation are tabulated in Table 5.2.1.

Table 5.2.1
Summary Statistics For USW G-4

flux (mm/yr)	mean (years)	median (years)	coefficient of variation	probability of failure
0.60	10,002	7,921	0.732	0.16
0.50	13,405	10,315	0.665	0.12
0.40	18,949	15,481	0.629	0.11
0.35	23,362	25,615	0.578	0.07
0.30	29,409	35,426	0.538	0.05
0.20	52,038	56,425	0.530	0.01
0.15	72,916	77,978	0.487	0.00
0.13	85,728	90,435	0.468	0.00
0.10	133,913	119,872	0.721	0.00
0.01	2,672,959	1,486,990	0.719	0.00

From Table 5.2.1 it can be observed that no failures occur at fluxes below 0.20 mm/yr. A simulation conducted at 0.70 mm/yr generated high positive fluid potentials. For the purpose of this exercise, 0.60 mm/yr was taken as the maximum flux consistent with the constraints given in Section 5.0.

Figure 5.2.1 is a plot of the ground-water travel time (GWTT) versus the steady-state flux for all ten simulations. Both the mean travel time and the median travel time are plotted on log-log scale. Figure 5.2.2 is a plot of the coefficient of variation of ground-water travel time versus flux for all ten simulations with flux plotted on log scale. Figures 5.2.3 through 5.2.32 are the scatter diagrams of potential, the scatter diagrams of saturation, and the histograms of ground-water travel time for each of the ten simulations.

Figure 5.2.1 Plot Of GWTT Versus Flux For Column USW G-4

Figure 5.2.2 Plot Of The Coefficient Of Variation Versus Flux For Column USW G-4

Figure 5.2.3 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.6 mm/yr Flux

Figure 5.2.4 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.6 mm/yr Flux

Figure 5.2.5 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.6 mm/yr Flux

Figure 5.2.6 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.5 mm/yr Flux

Figure 5.2.7 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.5 mm/yr Flux

Figure 5.2.8 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.5 mm/yr Flux

Figure 5.2.9 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.4 mm/yr Flux

Figure 5.2.10 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.4 mm/yr Flux

Figure 5.2.11 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.4 mm/yr Flux

Figure 5.2.12 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.35 mm/yr Flux

Figure 5.2.13 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.35 mm/yr Flux

Figure 5.2.14 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.35 mm/yr Flux

Figure 5.2.15 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.3 mm/yr Flux

Figure 5.2.16 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.3 mm/yr Flux

Figure 5.2.17 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.3 mm/yr Flux

Figure 5.2.18 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.2 mm/yr Flux

Figure 5.2.19 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.2 mm/yr Flux

Figure 5.2.20 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.2 mm/yr Flux

Figure 5.2.21 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.15 mm/yr Flux

Figure 5.2.22 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.15 mm/yr Flux

Figure 5.2.23 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.15 mm/yr Flux

Figure 5.2.24 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.13 mm/yr Flux

Figure 5.2.25 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.13 mm/yr Flux

Figure 5.2.26 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.13 mm/yr Flux

Figure 5.2.27 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.1 mm/yr Flux

Figure 5.2.28 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.1 mm/yr Flux

Figure 5.2.29 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.1 mm/yr Flux

Figure 5.2.30 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW G-4 At 0.01 mm/yr Flux

Figure 5.2.31 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW G-4 At 0.01 mm/yr Flux

Figure 5.2.32 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW G-4 At 0.01 mm/yr Flux

5.3 FAULT ZONE

Fourteen Monte Carlo simulations of 100 realizations each were conducted at incremental fluxes ranging from a minimum of 0.01 mm/yr to a maximum of 10.0 mm/yr. Summary statistics and the probability of failure for each simulation are tabulated in Table 5.3.1. Of the four columns, the fault zone was the only column where it was possible to generate a probability of failure of 1.0.

Table 5.3.1
Summary Statistics For The Fault Zone

flux (mm/yr)	mean (years)	median (years)	coefficient of variation	probability of failure
10.0	137	109	0.638	1.00
6.00	284	187	0.953	0.94
5.00	379	233	0.987	0.89
4.00	529	314	0.957	0.82
3.00	868	473	0.897	0.72
2.50	1,162	634	0.847	0.65
2.00	1,711	997	0.776	0.52
1.50	2,945	3,337	0.776	0.32
1.00	5,839	5,992	0.675	0.11
0.75	9,447	8,366	0.666	0.04
0.50	17,106	14,024	0.597	0.00
0.10	146,188	142,762	0.501	0.00
0.05	355,327	296,253	0.607	0.00
0.01	2,847,325	1,695,476	0.641	0.00

From Table 5.3.1 it can be observed that no failures occur at fluxes below 0.75 mm/yr. No simulations were conducted at fluxes in excess of 10.0 mm/yr because 100 percent failure has occurred. The high potentials in the scatter diagram of potential versus elevation for the 10.0 mm/yr simulation (Figure 5.3.3) suggest that 10.0 mm/yr is just about the limit the column can pass without developing zones of perched water.

Figure 5.3.1 is a plot of the ground-water travel time (GWTT) versus the steady-state flux for all fourteen simulations. Both the mean travel time and the median travel time are plotted on log-log scale. Figure 5.3.2 is a plot of the ground-water travel time (GWTT) versus the steady-state flux for all fourteen simulations. Both the mean travel time and the median travel time are plotted on log-log scale. Figure 5.3.2 is a plot of the coefficient of variation of ground-water travel time versus flux for all fourteen simulations with flux plotted on log scale. Figure 5.3.3 through 5.3.44 are the scatter diagrams of potential, the scatter diagrams of saturation, and the histograms of ground-water travel time for each of the fourteen simulations.

Figure 5.3.1 Plot Of GWTT Versus Flux For The Fault Zone

Figure 5.3.2 Plot Of The Coefficient Of Variation Versus Flux For The Fault Zone

Figure 5.3.3 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 10.0 mm/yr Flux

Figure 5.3.4 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 10.0 mm/yr Flux

Figure 5.3.5 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 10.0 mm/yr Flux

Figure 5.3.6 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 6.0 mm/yr Flux

Figure 5.3.7 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 6.0 mm/yr Flux

Figure 5.3.8 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 6.0 mm/yr Flux

Figure 5.3.9 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 5.0 mm/yr Flux

Figure 5.3.10 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 5.0 mm/yr Flux

Figure 5.3.11 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 5.0 mm/yr Flux

Figure 5.3.12 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 4.0 mm/yr Flux

Figure 5.3.13 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 4.0 mm/yr Flux

Figure 5.3.14 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 4.0 mm/yr Flux

Figure 5.3.15 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 3.0 mm/yr Flux

Figure 5.3.16 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 3.0 mm/yr Flux

Figure 5.3.17 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 3.0 mm/yr Flux

Figure 5.3.18 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 2.5 mm/yr Flux

Figure 5.3.19 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 2.5 mm/yr Flux

Figure 5.3.20 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 2.5 mm/yr Flux

Figure 5.3.21 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 2.0 mm/yr Flux

Figure 5.3.22 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 2.0 mm/yr Flux

Figure 5.3.23 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 2.0 mm/yr Flux

Figure 5.3.24 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 1.5 mm/yr Flux

Figure 5.3.25 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 1.5 mm/yr Flux

Figure 5.3.26 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 1.5 mm/yr Flux

Figure 5.3.27 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 1.0 mm/yr Flux

Figure 5.3.28 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 1.0 mm/yr Flux

Figure 5.3.29 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 1.0 mm/yr Flux

Figure 5.3.30 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 0.75 mm/yr Flux

Figure 5.3.31 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.75 mm/yr Flux

Figure 5.3.32 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.75 mm/yr Flux

Figure 5.3.33 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 0.5 mm/yr Flux

Figure 5.3.34 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.5 mm/yr Flux

Figure 5.3.35 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.5 mm/yr Flux

Figure 5.3.36 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 0.1 mm/yr Flux

Figure 5.3.37 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.1 mm/yr Flux

Figure 5.3.38 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.1 mm/yr Flux

Figure 5.3.39 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 0.05 mm/yr Flux

Figure 5.3.40 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.05 mm/yr Flux

Figure 5.3.41 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.05 mm/yr Flux

Figure 5.3.42 Scatter Diagram Of Water Potential As A Function Of Elevation For The Fault Zone At A 0.01 mm/yr Flux

Figure 5.3.43 Scatter Diagram Of Saturation As A Function Of Elevation For The Fault Zone At 0.01 mm/yr Flux

Figure 5.3.44 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For The Fault Zone At 0.01 mm/yr Flux

5.4 USW H-5

Five Monte Carlo simulations of 100 realizations each were conducted at incremental fluxes ranging from a minimum of 0.01 mm/yr to a maximum of 4.0 mm/yr. Summary statistics and the probability of failure for each simulation are tabulated in Table 5.4.1.

Table 5.4.1
Summary Statistics For USW H-5

flux (mm/yr)	mean (years)	median (years)	coefficient of variation	probability of failure
4.00	5,636	5,434	0.317	0.01
2.50	9,646	9,331	0.306	0.00
1.00	27,783	28,014	0.253	0.00
0.10	333,745	328,619	0.189	0.00
0.01	34,978,742	34,773,852	0.188	0.00

From Table 5.4.1 it can be observed that a probability of failure of only 0.01 was realized at the maximum flux. The inability to generate significant failures at this column is the reason for the small number of simulations. A simulation conducted at 5.0 mm/yr generated positive fluid potentials. For the purpose of this exercise, 4.0 mm/yr was taken as the maximum flux consistent with the constraints given in the first part of this section.

Figure 5.4.1 is a plot of the ground-water travel time (GWTT) versus the steady-state flux for all five simulations. Both the mean travel time and the median travel time are plotted on log-log scale. Figure 5.4.2 is a plot of the coefficient of variation of ground-water travel time versus flux for all five simulations with flux plotted on log scale. Figures 5.4.3 throughout 5.4.17 are the scatter diagrams of potential, the scatter diagrams of saturation, and the histograms of ground-water travel time for each of the five simulations.

Figure 5.4.1 Plot Of GWTT Versus Flux For Column USW H-5

Figure 5.4.2 Plot Of The Coefficient Of Variation Of GWTT Versus Flux For Column USW H-5

Figure 5.4.3 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 4.0 mm/yr Flux

Figure 5.4.4 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 4.0 mm/yr Flux

Figure 5.4.5 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW H-5 At 4.0 mm/yr Flux

Figure 5.4.6 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 2.5 mm/yr Flux

Figure 5.4.7 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 2.5 mm/yr Flux

Figure 5.4.8 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW H-5 At 2.5 mm/yr Flux

Figure 5.4.9 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 1.0 mm/yr Flux

Figure 5.4.10 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 1.0 mm/yr Flux

Figure 5.4.11 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW H-5 At 1.0 mm/yr Flux

Figure 5.4.12 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 0.1 mm/yr Flux

Figure 5.4.13 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 0.1 mm/yr Flux

Figure 5.4.14 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW H-5 At 0.1 mm/yr Flux

Figure 5.4.15 Scatter Diagram Of Water Potential As A Function Of Elevation For Column USW H-5 At 0.01 mm/yr Flux

Figure 5.4.16 Scatter Diagram Of Saturation As A Function Of Elevation For Column USW H-5 At 0.01 mm/yr Flux

Figure 5.4.17 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times For Column USW H-5 At 0.01 mm/yr Flux

5.5 SUMMARY

The purpose of the uncertainty analyses was to determine whether it was possible to generate a failure to meet the ground-water travel time criterion given uncertainty in the value of the input flux, the appropriate choice of hydrogeologic parameter values, and the geometry of the problem. The first, and most obvious, conclusion that can be drawn from the analyses is that the assumptions and information used in the analyses do not preclude a failure to meet the performance criterion. Table 5.5.1 summarizes the individual Monte Carlo simulations that generated probabilities of failure greater than zero.

Table 5.5.1
Summary Of Simulations In Which Failure Occurred

hole	flux (mm/yr)	mean (years)	probability of failure
UE-25a#1	0.60	6,209	0.16
UE-25a#1	0.50	8,364	0.12
UE-25a#1	0.40	11,830	0.11
UE-25a#1	0.35	14,719	0.08
UE-25a#1	0.30	18,738	0.05
UE-25a#1	0.25	24,814	0.05
UE-25a#1	0.20	36,508	0.01
USW G-4	0.60	10,002	0.16
USW G-4	0.50	13,405	0.12
USW G-4	0.40	18,949	0.11
USW G-4	0.35	25,615	0.07
USW G-4	0.30	35,426	0.05
USW G-4	0.20	52,425	0.01
Fault Zone	10.0	137	1.00
Fault Zone	6.00	284	0.94
Fault Zone	5.00	379	0.89
Fault Zone	4.00	529	0.82
Fault Zone	3.00	868	0.72
Fault Zone	2.50	1,162	0.65
Fault Zone	2.00	1,711	0.52
Fault Zone	1.50	2,945	0.32
Fault Zone	1.00	5,839	0.11
Fault Zone	0.75	9,447	0.04
USW H-5	4.00	5,434	0.01

One important point becomes clear by looking at Table 5.5.1. Long mean travel times do not exclude the probability of failing to meet the performance criterion. A review of the histograms of ground-water travel time for many of the simulations shows

them to be multimodal. For example, the histogram of ground-water travel times for UE-25a#1 at 0.25 mm/yr flux, figure 5.1.20, shows two very distinct modes. One mode peaks in excess of 30,000 years, the other mode peaks at a value less than 10,000 years. The mean, being an equilibrant of all the outcomes, does not provide information relevant to this particular performance problem. An earlier exercise (Kaplan, 1992) gave reason to believe that the median might be a more robust predictor of performance. The median in the case just discussed, column UE-25a#1 at 0.25 mm/yr flux, is 28,507 years. The median, in this case, would also be a poor indicator of performance. Except for column USW H-5, complex multi-modal responses are common. The histograms offer clear visual evidence as to why simple measures of central tendency, such as the mean or median, may not provide the information necessary to estimate the tails of the distribution.

In Section 6, the relationship between the failures and the input assumptions is investigated. No further attempt is made in this document to understand or decompose any response other than the failures.

6.0 SENSITIVITY ANALYSES

The purpose of a sensitivity analysis is to relate a consequence to a set of assumptions. Consequence, in the context of this exercise, is defined as a failure to meet the pre-waste-emplacement ground-water travel time criterion defined in Section 4.0. A sensitive assumption will be defined as a decision made by the analyst in setting up the uncertainty analyses that, in the end, contributed directly to the failure. Three of the decisions made in this document that contributed to the failures will be discussed in this section - the distributions of the input hydrogeologic parameters, the choice of an input flux, and the decision to assume that the domain includes both matrix and fractures. Each of these will be discussed in the following three subsections.

Two additional decisions may affect the consequences but are not discussed here. The geometry of the system, in the case of one-dimensional analysis the thickness and number of hydrostratigraphic units, is believed to profoundly affect the response and the estimate of ground-water travel time. The sensitivity to geometric assumptions will be tested in the future. The choice of a one-dimensional, steady-state, composite continuum model obviously affects the results. The full consequences of this choice will need further investigation.

6.1 Failure Analysis

In this section the relationship between the estimate of the values of the hydrogeologic parameters and the failures is investigated. Columns UE-25a#1, USW G-4, and the fault zone are analyzed. Column USW H-5 did not, for all practical purposes, fail. Each column will be analyzed independently. Common factors will be discussed in the summary, Section 6.1.5.

To determine if there is a relationship between the values of the hydrologic parameters chosen for input in a simulation and the values of the ground-water travel time calculated in the simulation, samples of each hydrologic parameter were rank correlated with the calculated ground-water travel times. The rank correlation coefficient describes the degree to which high or low values of one random variable are correlated with high or low values of a second random variable. Unlike the correlation coefficient, which describes the degree in which two random variables are linearly related, the rank correlation coefficient describes the degree to which two random variables exhibit a monotonic relationship.

The analyses that follow will determine only if there is a monotonic relationship between the ground-water travel times in the mode of the histogram where failure occurred and the values of the hydrogeologic parameters used as input to the simulation. Rank correlation coefficients with absolute values less than 0.40 are not tabulated in the analyses in this sections. Absolute values less than 0.40 are assumed to have little, if any, significance. The scatter diagrams of the individual hydrogeologic parameter values versus the calculated ground-water travel times are not plotted for rank correlation coefficients with absolute values less than 0.50, because the visual relationship between the variables is not clearly distinguishable.

No attempt was made to determine whether the shapes of the distributions of the hydrogeologic parameters are important and affect the outcome of a simulation. All the parameters in the uncertainty analyses were treated as independent random variables both with respect to cross correlation and with respect to auto-correlation. The sensitivity of the results to correlation structure is suggested as an area for future study.

6.1.1 UE-25a#1

The Monte Carlo simulation conducted at a flux of 0.6 mm/yr, because it generated the greatest number of failures, was used as the basis of the failure analysis. In the first mode of the histogram (Fig. 5.1.5), the mode containing the fastest ground-water travel times, all sixteen of the individual trials failed to meet the criterion for ground-water travel time. A histogram of the sixteen travel times is illustrated in Figure 6.1.1.1. These sixteen travel times correlate to the one large spike of very rapid travel times in the equal interval histogram of all 100 trials shown in Figure 5.1.5. The forty hydrogeologic parameters used as input in each of the sixteen trials were rank correlated with the sixteen ground-water travel times. Table 6.1.1.1 tabulates the results of the rank correlation.

Figure 6.1.1.1 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times Of 1,000 Years Or Less For Column UE-25a#1 At 0.6 mm/yr Flux

Table 6.1.1.1
Rank Correlations For GWTT Less Than 1,000 Years With Input Hydrogeologic
Parameters At UE-25a#1 At 0.6 mm/yr Flux

parameter	unit	rank correlation coefficient
matrix air-entry	Tcb-TN	0.45
fracture porosity	Tpt-TV	0.46
fracture porosity	Tpt-TM	0.98
fracture air-entry	Tpt-TV	-0.62
fracture pore-size index	Tpt-TV	-0.47
fracture saturated conductivity	Tpt-TN	-0.48

Figure 6.1.1.2 is a scatter diagram of the ground-water travel time versus the fracture porosity in unit Tpt-TM plotted on log-log scale. A strong positive relationship between increasing values of fracture porosity and longer travel times is clearly visible in the diagram. Figure 6.1.1.3 is a scatter diagram of the ground-water travel time versus the fracture air-entry values for unit Tpt-TV. A negative relationship, increasing values of the air-entry parameter associated with decreasing ground-water travel times, is visible in the diagram. As suggested by the lower absolute value of the rank correlation coefficient, there is more scatter in Figure 6.1.1.3 than in Figure 6.1.1.2.

Figure 6.1.1.2 Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel
Time Versus Fracture Porosity In Unit Tpt-TM For Column UE-25a#1 At
0.6 mm/yr Flux

Figure 6.1.1.3 Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Fracture Air-Entry Values In Unit Tpt-TV For Column UE-25a#1 At 0.6 mm/yr Flux

6.1.2 USW G-4

The Monte Carlo simulation conducted at a flux of 0.6 mm/yr, because it generated the greatest number of failures, was used as the basis of the failure analysis. In the first mode of the histogram (Fig. 5.2.5), the mode containing the fastest ground-water travel times, all sixteen of the individual trials failed to meet the criterion for ground-water travel time. A histogram of the sixteen travel times is illustrated in Figure 6.1.2.1. These sixteen travel times correlate to the one large spike of very rapid travel times in the equal-interval histogram of all 100 trials shown in Figure 5.2.5. The forty hydrologic parameters used as input in each of the sixteen trials were rank correlated with the sixteen ground-water travel times. Table 6.1.2.1 tabulates the results of the rank correlation. Only correlations whose absolute value is greater than 0.4 are given in this table.

**Table 6.1.2.1
Rank Correlations For GWTT Less Than 1,000 Years With Input Hydrogeologic Parameters At USW G-4 At 0.6 mm/yr Flux**

parameter	unit	rank correlation coefficient
matrix air-entry	Tcb-TN	0.54
fracture porosity	Tpt-TM	0.94
fracture air-entry	Tpt-TV	-0.59

Figure 6.1.2.1 Histogram Of Pre-Waste-Emplacement Ground-Water Travel Times Of 1,000 Years Or Less For Column USW G-4 At 0.6 mm/yr Flux

Figure 6.1.2.2 is a scatter diagram of the ground-water travel time versus the fracture porosity in unit Tpt-TM plotted on log-log scale. A strong positive relationship between increasing values values of fracture porosity and ground-water travel time is clearly visible in the diagram. Figure 6.1.2.3 is a scatter diagram of the ground-water travel time versus the fracture-air-entry values for unit Tpt-TV plotted on log-linear scale. A negative relationship, increasing values of the air-entry parameter associated with decreasing ground-water travel times, is visible in the diagram. As suggested by the lower absolute value of the rank correlation coefficient, there is more scatter in Figure 6.1.2.3 than in Figure 6.1.2.2. Figure 6.1.2.4 is a scatter diagram of the ground-water travel time versus the matrix air-entry parameter for unit Tcb-TN plotted on log-log scale. A positive relationship, increasing values of the air-entry parameter associated with increasing ground-water travel times, is visible in the daigram. As suggested by the lower absolute value of the rank correlation coefficient, there is more scatter in Figure 6.1.2.4 than in Figure 6.1.2.2.

Figure 6.1.2.2 Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Fracture Porosity In Unit Tpt-TM For Column USW G-4 At 0.6 mm/yr Flux

Figure 6.1.2.3 Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Fracture Air-Entry Values In Unit Tpt-TV For Column USW G-4 At 0.6 mm/yr Flux

Figure 6.1.2.4 Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Matrix Air-Entry Values In Unit Tcb-TN For Column USW G-4 At 0.6 mm/yr Flux

6.1.3 Fault Zone

Two Monte Carlo simulations were chosen for analysis. The first is the simulation conducted at 10.0 mm/yr flux. Under this boundary condition, all of the trials in the simulation failed to meet the ground-water travel time criterion. The second analysis is the Monte Carlo simulation conducted at 3.0 mm/yr flux. Under this boundary condition 72 out of 100 trials failed to meet the criterion. The ground-water travel time histograms of the two simulations exhibit different behavior. Figure 5.3.5, the histogram for the 10.0 mm/yr simulation, has a single mode. Figure 5.3.17, the histogram for the 3.0 mm/yr simulation is, quite clearly, bimodal. It is not clear, prior to some analysis, whether or not the failures in the 10.0 mm/yr case are sensitive to the same input data as the failures in the 3.0 mm/yr case.

For the 10.0 mm/yr case the 50 hydrologic parameters (5 hydrostratigraphic units times 10 parameters per unit) used as input in each of the 100 trials were rank correlated with the 100 ground-water travel times. Only the value of fracture porosity in unit Tpt-Tm, with correlation coefficient of 0.77, exhibited a correlation with ground-water travel time. Figure 6.1.3.1 is a scatter diagram of the ground-water travel time versus the fracture porosity in unit Tpt-TM plotted on log-log scale. A positive relationship between increasing values of fracture porosity and longer ground-water travel times is visible in the diagram.

Figure 6.1.3.1 Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Fracture Porosity In Unit Tpt-TM For The Fault Zone At 10.0 mm/yr Flux

For the 3.0 mm/yr case the first mode of the histogram (Fig. 5.3.17), the mode containing the fastest ground-water travel times, was analyzed. The 50 hydrologic parameters used as input in each of the 72 trials that failed to meet the performance

Figure 6.1.3.2 Scatter Diagram Of Pre-Waste-Emplacement Ground-Water Travel Time Versus Fracture Porosity In Unit Tpt-TM For The Fault Zone At 3.0 mm/yr Flux

criterion were rank correlated with the corresponding ground-water travel times. Only the value of fracture porosity in unit Tpt-TM, with correlation coefficient of 0.76, exhibited a correlation with ground-water travel time. Figure 6.1.3.2 is a scatter diagram of the ground-water travel time versus the fracture porosity in unit Tpt-TM plotted on log-log scale. A positive relationship between increasing values of fracture porosity and longer ground-water travel times is visible in the diagram.

6.1.4 Summary

The occurrence of fast ground-water travel times in this exercise appears predominantly sensitive to the estimate of the value of fracture porosity in the upper hydrostratigraphic unit, Tpt-TM, of the problem domain. Rank correlation coefficients describing the degree to which ground-water travel time and fracture porosity in the one unit are monotonically related for the four cases analyzed are summarized in Table 6.1.4.1.

Table 6.1.4.1
Summary Of Rank Correlation Coefficients For Ground Water Travel Time With
Fracture Porosity In Unit Tpt-TM

column	flux (mm/yr)	rank correlation coefficient
UE-25a#1	0.60	0.98
USW-G4	0.60	0.94
Fault Zone	10.0	0.77
Fault Zone	3.0	0.76

6.2 Sensitivity To Flux

In the uncertainty analyses, a steady-state flux of water was specified as the upper boundary condition of a one-dimensional problem. Figure 6.2.1 is a log-log plot of the mean ground-water travel time calculated in each of the Monte Carlo simulations versus the steady-state flux for each of the four columns. This figure summarizes the information in figures 5.1.1, 5.2.1, 5.3.1, and 5.4.1. Despite the differences between individual curves, in each case mean ground-water travel time is a monotonically decreasing function of flux. This should be interpreted as a function of the one-dimensional constraint on the model. In a multi-dimensional system, very low fluxes entering the system can converge to create locally high fluxes. Conversely, high local infiltration rates can be dissipated. Two-dimensional sensitivity analyses (Prindle and Hopkins, 1990) have demonstrated that, under some circumstances, the estimate of ground-water travel time in a one-dimensional model can be much longer than the estimate from a two-dimensional model at the same infiltration rate. There should be no general conclusions drawn about the relationship between flux and the ground-water travel time performance criterion from any of the studies conducted so far.

Figure 6.2.1 Mean Pre-Waste-Emplacement Ground-Water Travel Time Versus Steady-State Flux

6.3 Sensitivity to Fractures

In each of the hydrostratigraphic units in each of the columns, fractures are included. This one assumption, more than any other in the uncertainty analyses, is the root cause of the failures. The fractures provide a high-permeability pathway through a system composed of alternating layers of low-permeability tuff. In the absence of the fracture pathways it is unlikely that ground-water travel times that are faster than the 1,000 year criterion could be calculated. Project data should be reviewed to determine how likely some of the units are to have interconnected fracture pathways. Fracture densities, particularly in the non-welded and bedded tuffs are so low in some of the core holes (Spengler and Chornack, 1984) that the likelihood of connected fracture pathways could be very small. Sensitivity studies should be conducted to determine what effect the lack of fractures, in at least part of the domain, would have on estimates of compliance with the regulatory criteria.

7.0 DATA RECOMMENDATIONS

As explained in Section 6, failure to meet the ground-water travel time criterion was sensitive to the estimate of fracture porosity in hydrostratigraphic unit Tpt-TM. Travel times decrease as fracture porosity decreases. Fracture porosity is a coefficient in the particular model used in this analysis and is defined as the product of the fracture aperture times fracture density times unit area. By this definition, as the aperture or the fracture density or both become smaller, the travel times become faster. The faster travel times result because, as the area available for flow decreases, flow velocity must increase in order to sustain the same areal flux at a given saturation. Just as fracture porosity is defined as the product of more fundamental parameters, fracture density and aperture, those two parameters are defined from a more basic data set. Fracture aperture, in this particular model, is related to the air-entry parameter of the soil-moisture characteristic curve for the porous-media equivalent of the fracture. Fracture density, as used in this model, is a function of the number of fractures per linear measure of drill hole and their orientation. These relationships are illustrated in Figure 7.1. It should be noted that even more fundamental test and measurement data underlie the moisture characteristic.

Figure 7.1 Relationship Between The Model Coefficient Fracture Porosity And The Underlying Data

The recommendation for data is not for fracture porosity, a derived coefficient specific to the model, but for the information along the bottom row of Figure 7.1 - the moisture characteristic, fracture frequency, and fracture orientation. This information is likely to be of value in a number of alternative conceptual models for both liquid-phase and vapor-phase flow of water at the Yucca Mountain site. It is also likely that the degree to which the fractures are interconnected may prove to be a function of fracture frequency and orientation. The presence or absence of interconnected fracture pathways is a key issue in performance-assessment calculations.

It is also recommended that geostatistical techniques be used to estimate the values of these parameters throughout the domain of interest. Because the model domain

used in this exercise is highly schematic, it is not recommended that the data on moisture characteristic, fracture frequency, and fracture orientation be limited to the welded tuffs of the Topopah Spring, the unit corresponding to the model unit Tpt-TM. Limiting the investigation to this one unit would assume an unwarranted degree of confidence in the models used for the analyses.

Also, as a result of the uncertainty analyses, recommendations are made as to the value of obtaining measurements of saturation and water potential. As a constraint on estimating the ambient conditions at the site, these data would be invaluable. For an example, review the scatter diagram of calculated saturations as a function of elevation for column UE-25a#1 for the 0.6-mm/yr simulation (Figure 5.1.4). The large spike of saturations that range from about 0.9 to 1 represents our uncertainty as to what values of saturation we would be likely to see at a flux of 0.6 mm/yr given our uncertainty in the parameter values of the hydrostratigraphic unit Tpt-Tn, a vitric, non-welded tuff. Assume that after the actual measurement of saturations within that unit, we could say, with some confidence, that saturations in excess of 0.85 would be unlikely under ambient or pre-emplacement conditions. If this information is used as a constraint in a similar exercise, it is clear from the scatter diagrams of saturation generated for each of the fluxes imposed on column UE-25a#1 that all saturations generated at fluxes in excess of 0.10 mm/yr exceed the constraint (Fig. 5.1.22). That is, any flux in excess of 0.10 is inconsistent with both the data from the site and the assumptions in the model. For estimates of flux of 0.10 or less, saturations both above and below the value of 0.85 are predicted on the basis of the uncertainty as to the appropriate values of hydrologic parameters (Fig. 5.1.25). This suggests that the actual measured saturation value can be used to constrain the uncertainty in the values of the hydrogeologic parameters by restricting the values to estimates that provide predictions within the measured constraints. The table of summary statistics for UE-25a#1, Table 5.1.1, quite clearly illustrates the effect of this constraint, a maximum estimate of 0.85 saturation, on the estimate of the probability of failure with respect to the ground-water travel-time criterion at this location. For a flux of 0.10 mm/yr, the estimate of the probability of failure is zero. This is in contrast with the estimate of a 0.16 probability of failure under the maximum flux allowed in this current exercise, which is constrained only by the requirement that the system remain under unsaturated conditions. The same arguments hold for water potential.

The scatter diagrams of saturation and potential illustrate another important point in regard to data collection. Some lithologies are likely to be much better predictors of the state of the system than others. Using the same scatter diagrams as discussed above, it can be observed that saturations in unit Tpt-TV and unit Tcb-TN do not respond differently to the two different boundary conditions. In each case it is predicted that they remain almost completely saturated. Potentials are slightly lower under the lower flux condition, but the predicted differences are small and there is a wide overlap in the predicted values. The simulations predict that saturations and potentials in the higher-porosity, higher-conductivity materials are more sensitive indicators of the state of the system than the low-porosity, low-conductivity materials. It is recommended that measurements of both saturation and potential be taken, preferably at the location at which hydrologic parameters are measured. The measurements should not be restricted to any one unit or any one lithology, as this would assume an unwarranted degree of confidence in the model used in this exercise.

There are two more implications with respect to data collection suggested by the analyses in this document. The first has to do with the worth or value of data. The second has to do with the precision of the data.

If data have worth because their collection and inclusion in a model change a prediction of performance with respect to a specified criterion, then the collection of more data about most of the parameters used in these analyses would be worthless with respect to the prediction of compliance with the ground-water travel time criterion. Unfortunately, the prediction of compliance is highly specific to the model. Critical factors to performance could be very different under a different set of model assumptions. However, the analyses suggest that in a model with many parameters, not all data have equal value. Performance-assessment exercises should continue to offer all guidance possible as to the value of information despite the uncertainties.

Figure 7.2 Coefficient Of Variation Versus Steady-State Flux

It is commonly believed that if the variance in the model input could be reduced, the variance in the model output would also be reduced. The results of the uncertainty analyses suggest there are at least three other factors, other than the variance of the input, that contribute to the variance of the output - process, geometry, and boundary conditions. Figure 7.2 summarizes the information from Figures 5.1.2, 5.2.2, 5.3.2, and 5.4.2, the plots of coefficient of variation versus flux for each of the simulations at each of the four columns. Each of the Monte Carlo simulations was run using the same input data chosen from the same distributions of the input parameters. Clearly, for any

individual column, the coefficient of variation fluctuates in a complex manner as the flux is increased. There is also an obvious difference in the behavior of the fluctuation from one column to the next. The complex behavior is assumed to be a consequence of the non linearity embedded in the process model. Although no analysis of this response has been attempted, the consequence of the response is to suggest that very precise data may contribute little to reducing the dispersion of the output. Another way to express this is to say that because a number of factors may degrade the information going into the model money spent in improving the precision and accuracy of the input may not always increase the value of the output.

The recommendations and comments made in this section apply to the analyses in this document. That is, a numerical experiment was conducted in which a specific model, constrained by a number of specific assumptions, was used to address the question of compliance with an arbitrary criterion.

8.0 CONCLUSIONS

The results of these analyses emphasize an important point that others have remarked upon (Summerling and Thompson, 1992). That is, critical performance factors are very hard to estimate prior to the analysis. The sensitivity of performance in regard to ground-water travel time to only one parameter, the fracture porosity, in only one of several hydrostratigraphic units, came as something of a surprise. Unfortunately, too little is known to say with any confidence that this is the one and only piece of information that is required in order to predict a degree of compliance with the performance criterion. The analyses clearly illustrate, though, that not all data have equal worth and that analysis is a powerful tool in the effort to prioritize information needs and data requirements.

As logical next steps, the model should be tested for sensitivity to both auto and cross correlation. Sensitivity of the output to the number of Latin hypercube samples taken should also be tested. The circumstances under which a one-dimensional model is a valid approximation need more study, as are the circumstances under which the assumption of only a single liquid phase is valid.

The most obvious conclusion from the study is also the most intuitive. We do not know enough to preclude circumstances under which the site might violate a criterion of performance. This conclusion is consistent with the plans to conduct a multibillion dollar program of site characterization and analysis in the coming years. The failures that appeared in this exercise were a consequence of our lack of knowledge as to the appropriate data, geometry, and models to use as the basis for performance of the Yucca Mountain Site itself. Uncertainty prevents us from distinguishing which of the failures are potentially real. Indeed, it was the express purpose of this exercise to try and generate the failures. If we can come to understand the mechanisms and circumstances under which a failure could occur and if, through a program of site characterization and performance assessment, we can conclude that the circumstances under which failure occurs are either likely or unlikely at the Yucca Mountain site, then a much higher degree of confidence in the ability of the site to serve its intended function will be realized.

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APPENDIX A

Information from the Reference Information Base Used in this Report

This report contains no information from the Reference Information Base.

Candidate Information for the Reference Information Base

This report contains no candidate information for the Reference Information Base.

Candidate Information for the Site & Engineering Properties Data Base

**This report contains contains no candidate information for the Site and
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**The work described in this report was conducted under WBS Element
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