MODELING ANALYSES OF THE NRC HLW NMSS/RES STAFF

FOR MODEL VALIDATION

PROGRESS REPORT NO. 1
(PREPARATION FOR INTRAVAL PARTICIPATION)

MODELING EXERCISE 11.001

MAY 1988 - OCTOBER 1988

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Tom Nicholson

1.0 Introduction

The NRC NMSS and RES staff under a Memorandum of Understanding have undertaken independent repository systems, groundwater flow and transport system and performance assessment modeling to improve licensing review competence. The first staff modeling activities utilized information from field investigations being conducted by the University of Arizona, (an NRC contractor) in unsaturated fractured rock at the Apache Leap Field Site near Superior, Arizona, (see Figure 1.0, 1.1). The rock type is partially welded fractured tuff. Researchers at the University of Arizona are conducting investigations to characterize and evaluate the physical, hydraulic, and pneumatic properties of a partially saturated fractured tuff in the context of radioactive waste disposal.

The initial purpose of the University of Arizona work is to understand site characterization needs and flow and transport phenomena in unsaturated fractured tuff (SOW; B-7291). Field and laboratory investigations from this work is also providing a data base that will be used by project teams of the international code validation project INTRAVAL. Participants in the INTRAVAL Project are attempting to validate hydrologic flow and transport models for use in evaluating waste disposal repository sites.

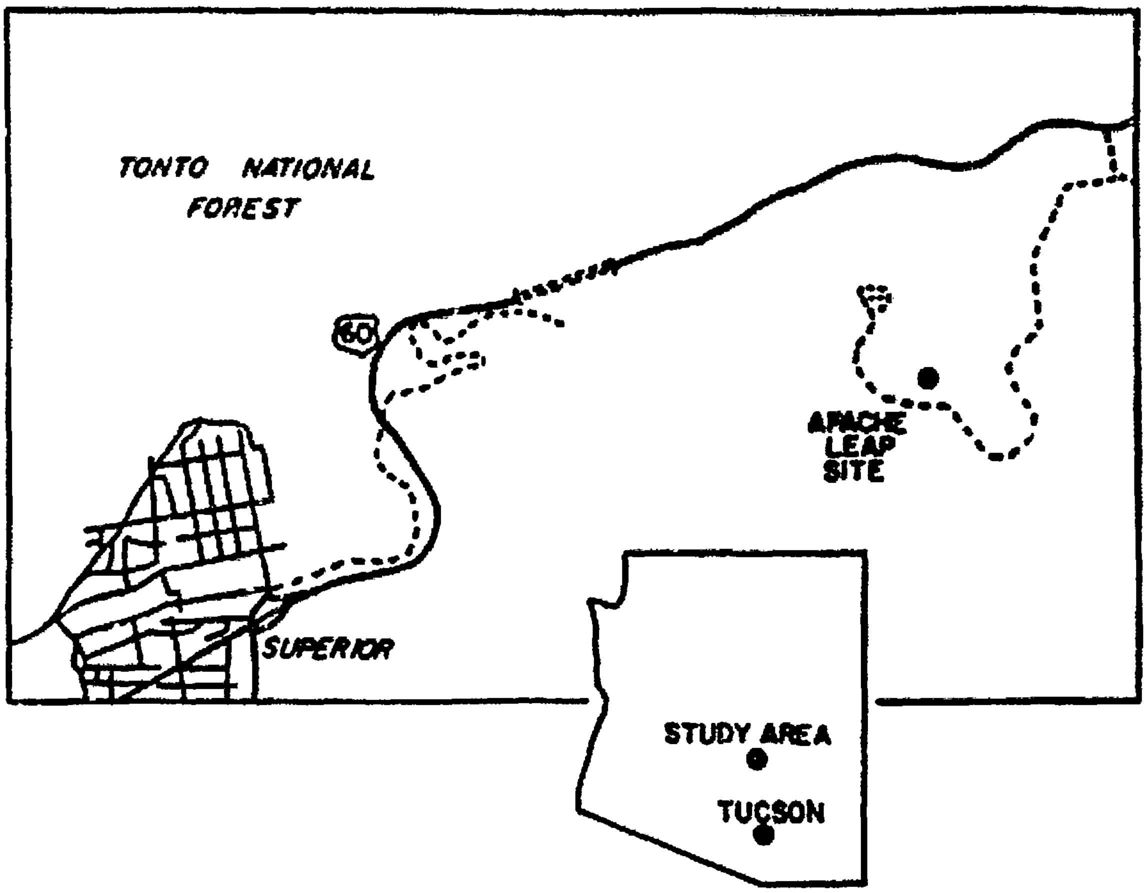

Figure 1.0. Site location map for the Apache Leap Tuff Site in central Arizona. (Draft University of Arizona Contract Report, "Unsaturated Fractured Rock Characterization Methods and Data Sets at Apache Leap Tuff Site" 12/88)

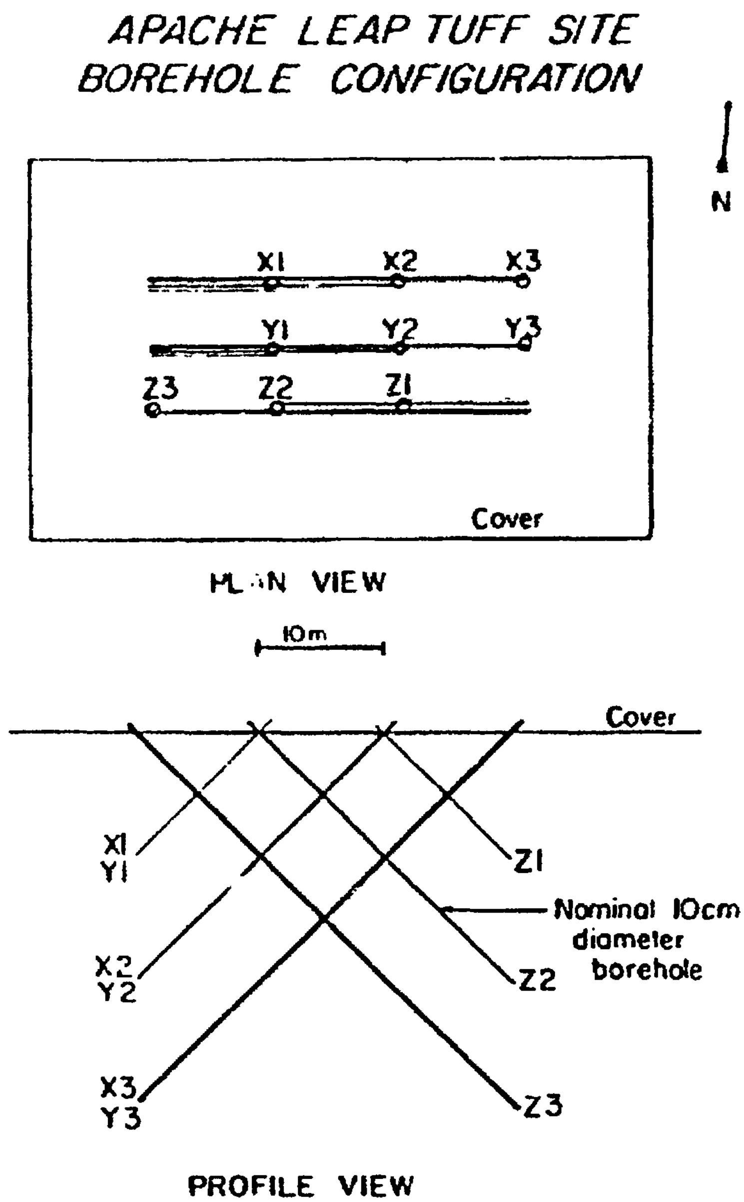

Figure 1.1 Borehole configuration at the Apache Leap Tuff Site showing inclined boreholes and 30 x 50 m plastic cover. (Yeh,1988)

This report is the first in a series reporting the results of NRC HLW NMSS/RES independent modeling endeavors for model validation and performance assessment.

1.1 UNIVERSITY OF ARIZONA EXPERIMENTS

Initial characterization of the Apache Leap Site began with the drilling of nine inclined boreholes (at 45 degrees) to a depth of 30 meters over an area of 20 meters by 30 meters (see Figure 1.2). Data collected from the boreholes include: 1) saturated hydraulic conductivities determined along 3 meter intervals in each of the nine boreholes; 2) in situ moisture content and pressure; and 3) laboratory analyses of core samples (see Figure 1.2) for characteristic curves (moisture content versus pressure, relative hydraulic conductivity versus pressure, and specific moisture capacity versus pressure) of the rock matrix. Details of the data and measurement methods have been previously discussed in the Draft INTRAVAL Test Case Description (see Appendix D) and (Yeh, 1988) and will not be discussed further here.

The first planned University of Arizona experiment was designed to examine the movement of a slug of water through the rock matrix. The experiment used the "Z" set of three boreholes (see Figure 1.2) in which the fracturing was minimal. Therefore, it was assumed that fluid flow in this experiment would be predominately in the rock matrix.

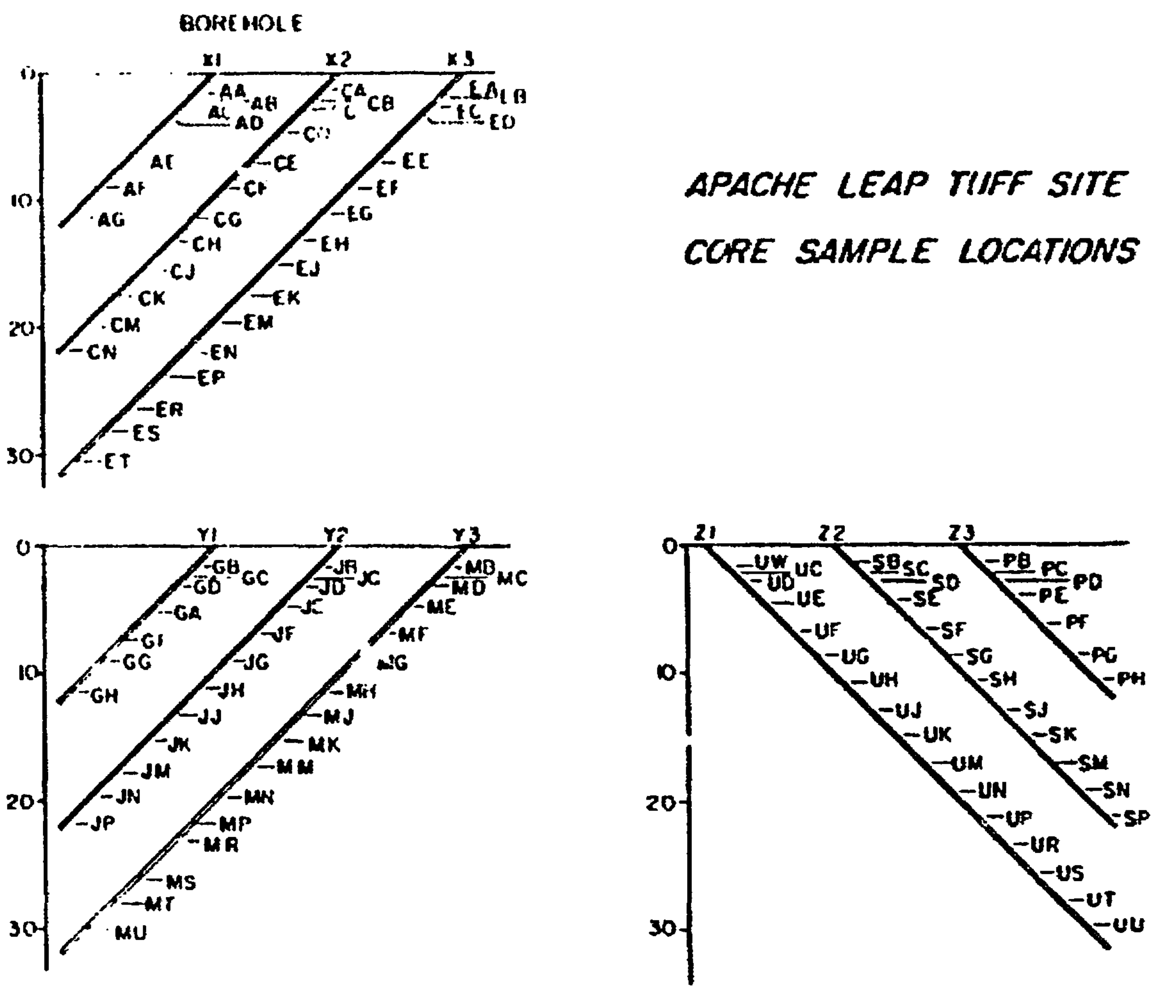

Figure 1.2 Core sample locations in inclined boreholes at the Apache Leap Tuff Site. (Yeh,1988)

This initial test identified as UA AL-001, was an injection test (the upper two Z boreholes filled with water for 30 days, see Figure 1.3) followed by a monitoring phase (the injection boreholes were drained of water and moisture contents in the set of three boreholes were monitored). The object of the test was to monitor the increase in moisture content in the lower borehole as the injected fluid moved downward.

1.2 NRC MODELING EXERCISE #001

The first modeling exercise was an approximate simulation of the initial field test. The data for the initial injection test were not available at the time of this modeling exercise. With data from the saturated conductivity tests and knowledge of the well field configuration, the following modeling exercise was developed. The primary objective of the exercise was to assist the NRC staff in formulating questions for the special INTRAVAL Workshop held on the unsaturated zone problems (July 19-21) and to better understand simulation and validation problems with respect to the Apache Leap Site (i.e., design of grids, simulation time and spatial scales, data needs and validation needs).

1.2.1 One-Dimensional Simulation

CHEMFLO

This modeling exercise was conducted to estimate the relative speed of water

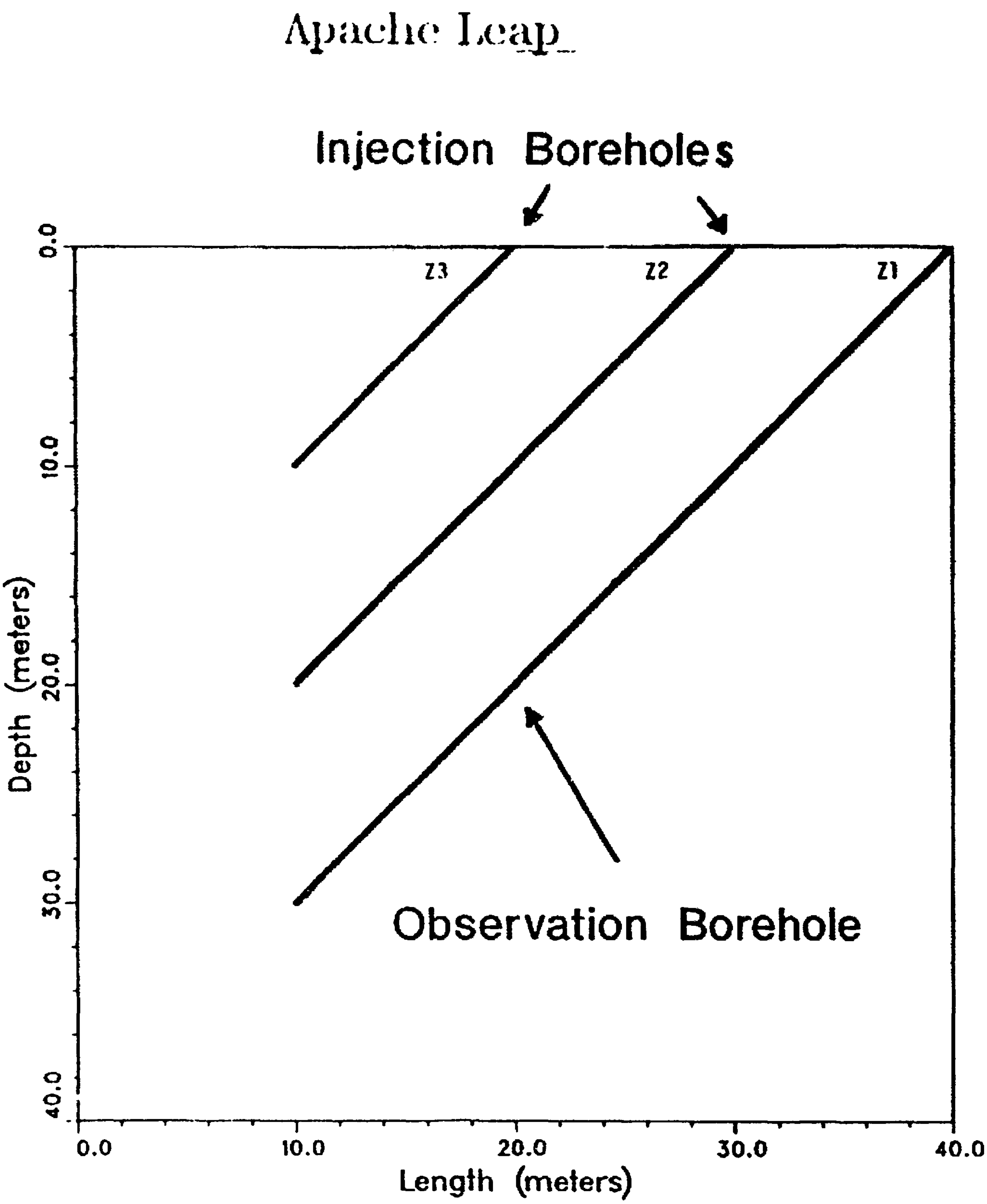

Figure 1.3 Experimental design of the water injection test at the Apache Leap site.

movement that might occur in the rock matrix for the borehole drainage experiment at the Apache Leap Field Test Site. No data were available to the staff on existing hydrologic conditions at the site when this preliminary modeling was done. However, it was known that the rock was a welded low permeability tuff that was very dry.

This preliminary modeling exercise used the code CHEMFLO (Nofziger, 1987). CHEMFLO is a one dimensional finite difference unsaturated flow and transport code that makes use of the Richards equation. (Richards, 1931). To simulate the hydrologic properties of the low permeability tuff, a clay with a saturated hydraulic conductivity of 0.04 cm/hr. was used (Yolo Clay, Table A). To simulate the dry conditions of the tuff a matrix potential of -1000 cm was chosen. The model was constructed so that the soil was oriented vertically, the soil column was 100 cm long, the lower boundary was defined as a constant matrix potential boundary of -1000 cm, and the upper boundary was defined as a no flow (fluid) boundary. Initial conditions were defined so that saturated conditions existed in the upper 20 cm of the soil column. This was accomplished by assigning the upper 20 cm of the soil column a matrix potential of 1.0 cm. The remaining 80 cm of the soil column was assigned a matrix potential of -1000 cm. Initial conditions are displayed in Appendix A.

Table A   Properties used to calculate Yolo Clay characteristic curve.

Soil Name	:YOLO CLAY
Water Content Function (A, B, or C)	:B
Conductivity Function (A, B, C, D, E)	:A
Saturated Water Content, cc/cc	:0.495000
Residual Water Content, cc/cc	:0.124000
Water Content Parameter A	:739.000000
Water Content Parameter B	:4.000000
Saturated Conductivity, cm/hr	:4.428000E-2
Conductivity Parameter A	:124.599998
Conductivity Parameter B	:1.770000
Suggested Minimun Potential, cm	:-10000.000000
Suggested Maximum Potential, cm	:100.000000
Suggested Minimum Flux, cm/hr	:0.000000
Suggested Maximum Flux, cm/hr	:1.000000
Suggested Minimum Rainfall Rate,cm/hr	:0.000000
Suggested Maximum Rainfall Rate,cm/hr	:1.000000

The model was then allowed to run for a simulated time of 30 days (720 hrs.) to calculate how fast the water in the upper 20 cm would flow into the lower 80 cm. At the end of 30 days there was little or no movement of water (Appendix B).

The modeling exercise was quite preliminary, but suggested that water movement in the matrix at the field site would be very slow.

1.2.2 SELECTED UNSATURATED FLOW MODEL

The finite element model SUTRA was selected for simulating the Apache Leap injection test because of its ease of use, well documented users manual, and the ability of the model to simulate fluid flow and transport of either heat or solute in one or two dimensions. The solute transport feature of SUTRA will be of use when tracer experiments are conducted at the site. Additionally, the finite element grid used for SUTRA simulations is similar to the input required for the integrated finite difference grid employed in the TOUGH model. SUTRA input data can therefore be adapted for input with the TOUGH code.

Computer Model Description

SUTRA (Saturated - Unsaturated Transport) (Voss, 1984) is a computer program that simulates two dimensional fluid movement and the transport of either energy or dissolved substances in geologic media. The model employs a two-dimensional hybrid finite-element and integrated-finite-difference method to approximate the governing equations that describe the two interdependent processes that are simulated:

1) fluid density-dependent saturated or unsaturated ground-water flow; and either

2) transport of a solute in the ground water, in which the solute may be subject to equilibrium adsorption on the porous matrix, and both first-order and zero-order production or decay; or,

3) transport of thermal energy in the ground water and solid matrix of the aquifer.

SUTRA provides, as the primary calculated result, fluid pressures and either solute concentrations or temperatures as they vary with time, everywhere in the simulated (2-dimensional) subsurface system. SUTRA may also be used to simulate simpler subsets of the above processes.

1.2.3 SIMULATION RESULTS

1.2.3.1 Two-Dimensional Simulation

Initial simulation of the injection test used a two-dimensional regular grid (see Figure 1.4) with a nodal spacing of three meters. Although this spacing

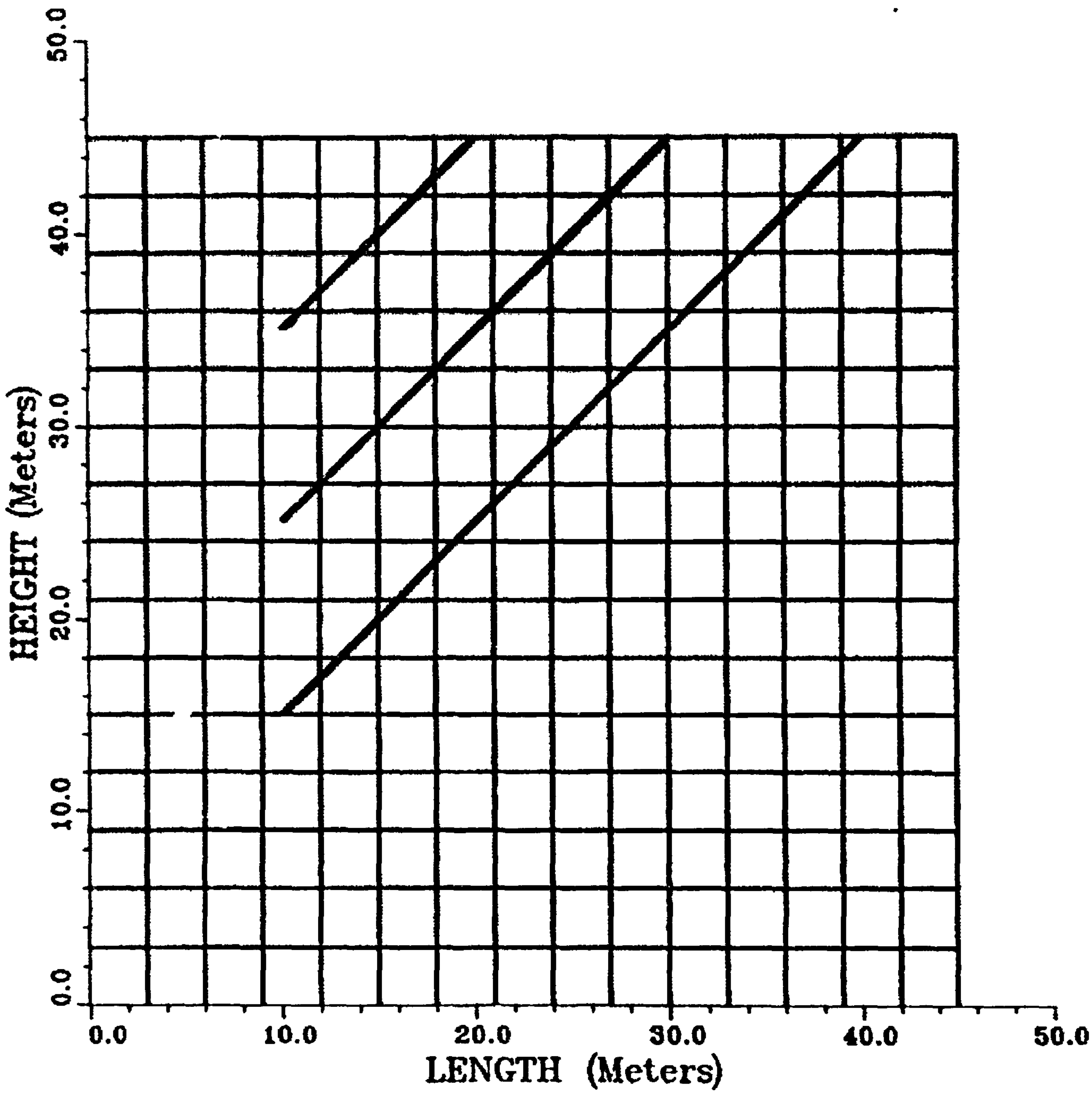

Figure ?.? Finite element grid used for the two-dimensional SUTRA simulation of a field test at the Apache Leap site.

is rather coarse to accurately represent the borehole diameter (10 cm) and resolve the wetting front, the mesh is considered adequate at this initial stage of the test case analyses. The simulated area was assumed to be a homogeneous isotropic porous medium. Hydrologic parameters were assigned the average values obtained from laboratory analyses of the rock matrix (see Figures 1.5-1.7) (Rasmussen, 1988). Fluid movement after the injection phase was simulated by setting the appropriate initial and boundary conditions. No-flow boundary conditions were maintained on all four sides while the pressure was set to an initial value of -4.0 meters everywhere except surrounding the injection borehole where the pressure was set to 0.0 to simulate the fully saturated conditions of the injected pulse (see Figure 1.8). The no-flow boundary conditions on the bottom boundary (25 meters below the bottom of the injection borehole), while somewhat unrealistic, was assumed to be placed well below the zone of saturation so that this boundary would have little or no effect on the movement of water until the moisture front moved well past the lower or observation borehole. The initial conditions, due to the grid size, certainly introduced more fluid into the system than is estimated to have been injected during the actual 30 day injection period, however, given the purpose of this initial simulation exercise, the initial conditions were deemed reasonable and conservative. A complete listing of the SUTRA input is presented in Appendix C.

The results of the two-dimensional simulations are presented in Figures 1.9 - 1.11. The results indicate that the movement of water through the matrix is extremely slow. In fact, the movement of water is so slow that the usefulness

Saturation vs Suction

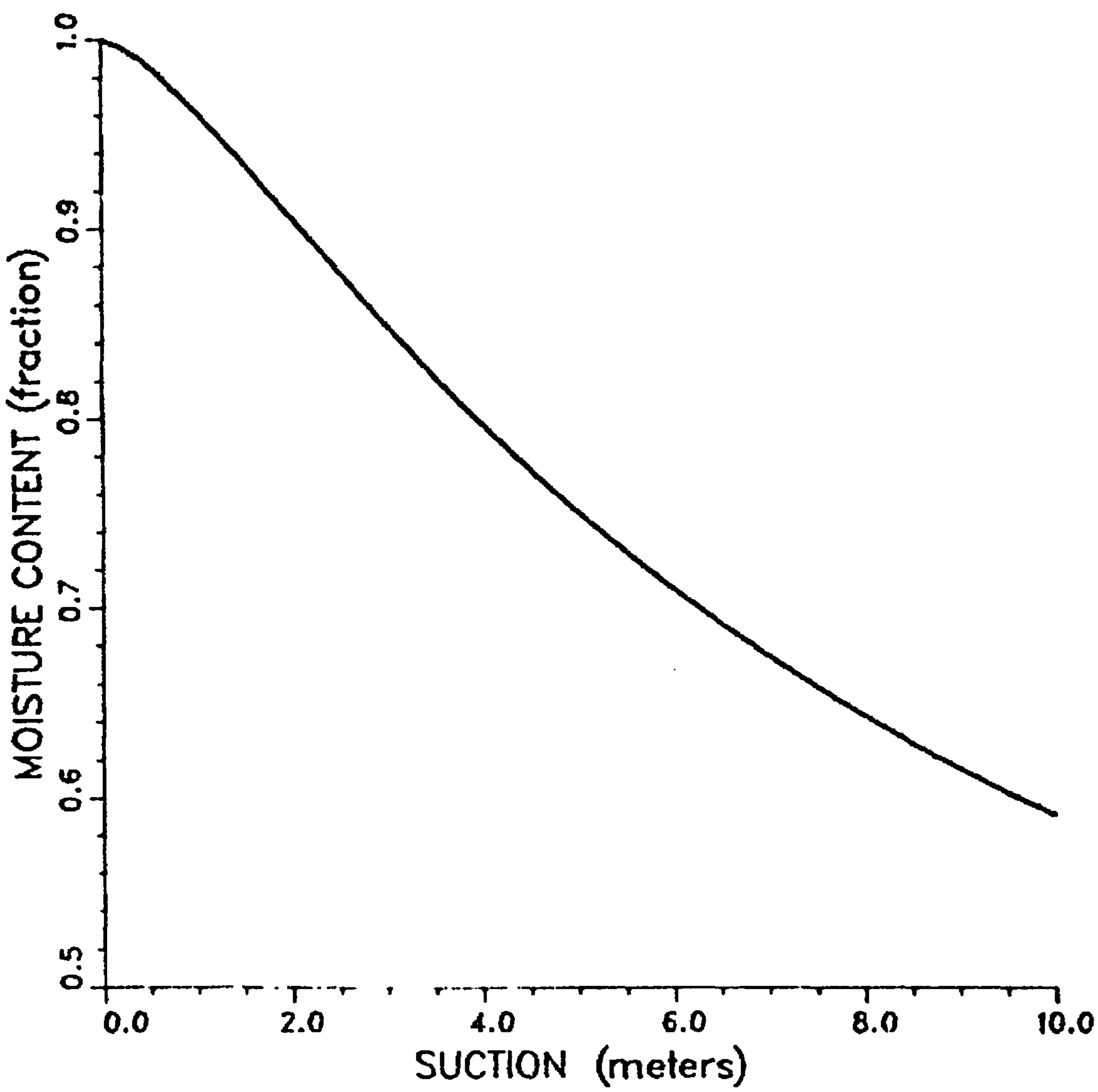

Figure 1.5 Variation of saturation with pressure used for Apache Leap Tuff (assuming a van Genuchten curve and fitting parameters; alpha=.025 1/kPa and n=1.5). (Rasmussen,1988)

Relative K vs Suction

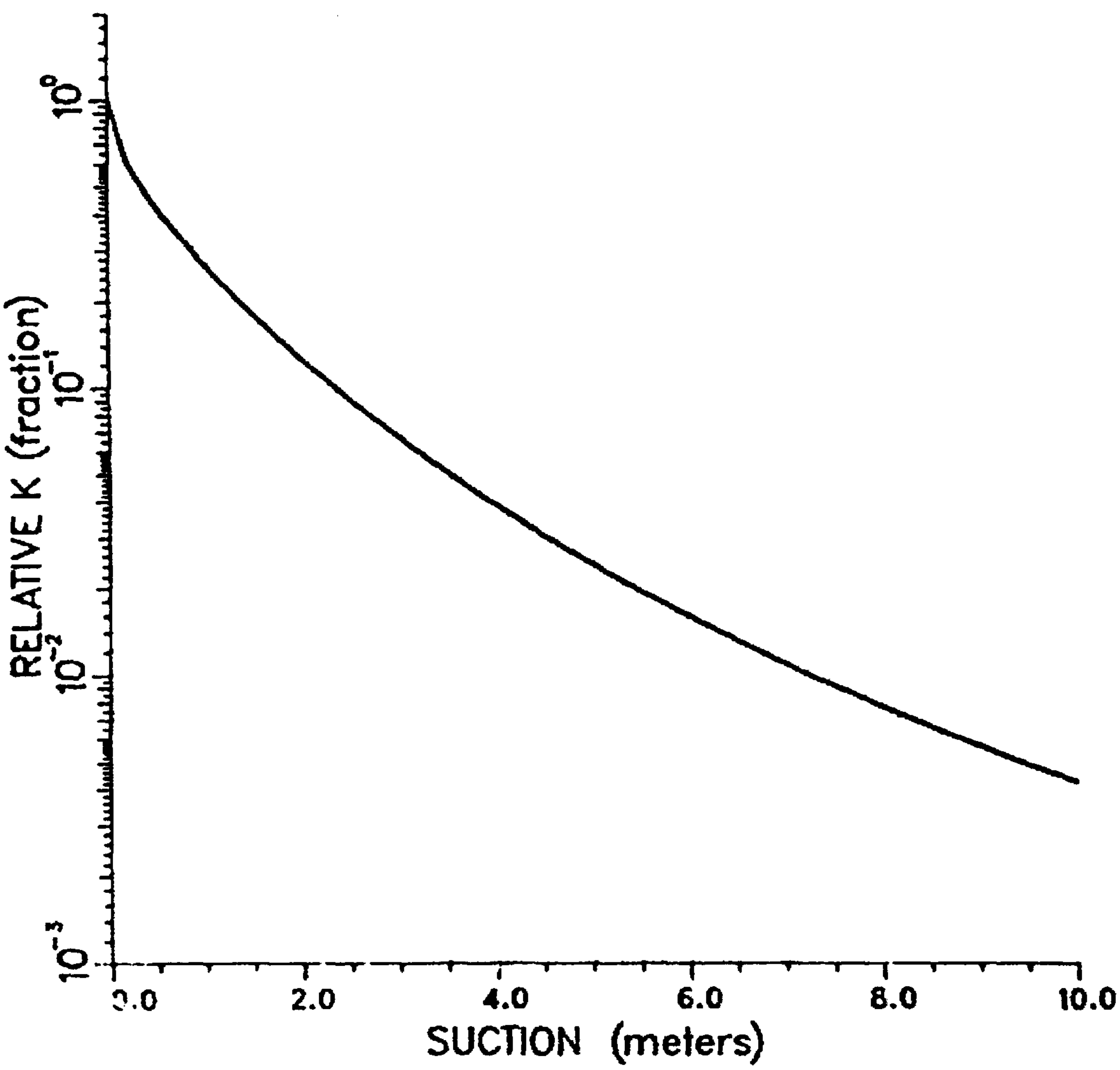

Figure 1.6 Variation of relative hydraulic conductivity with pressure used for Apache Leap Tuff (assuming a van Genuchten curve and fitting parameters; alpha=.025 1/kPa and n=1.5, and saturated hydraulic conductivity of 1.0 E-9 m/s). (Rasmussen,1989)

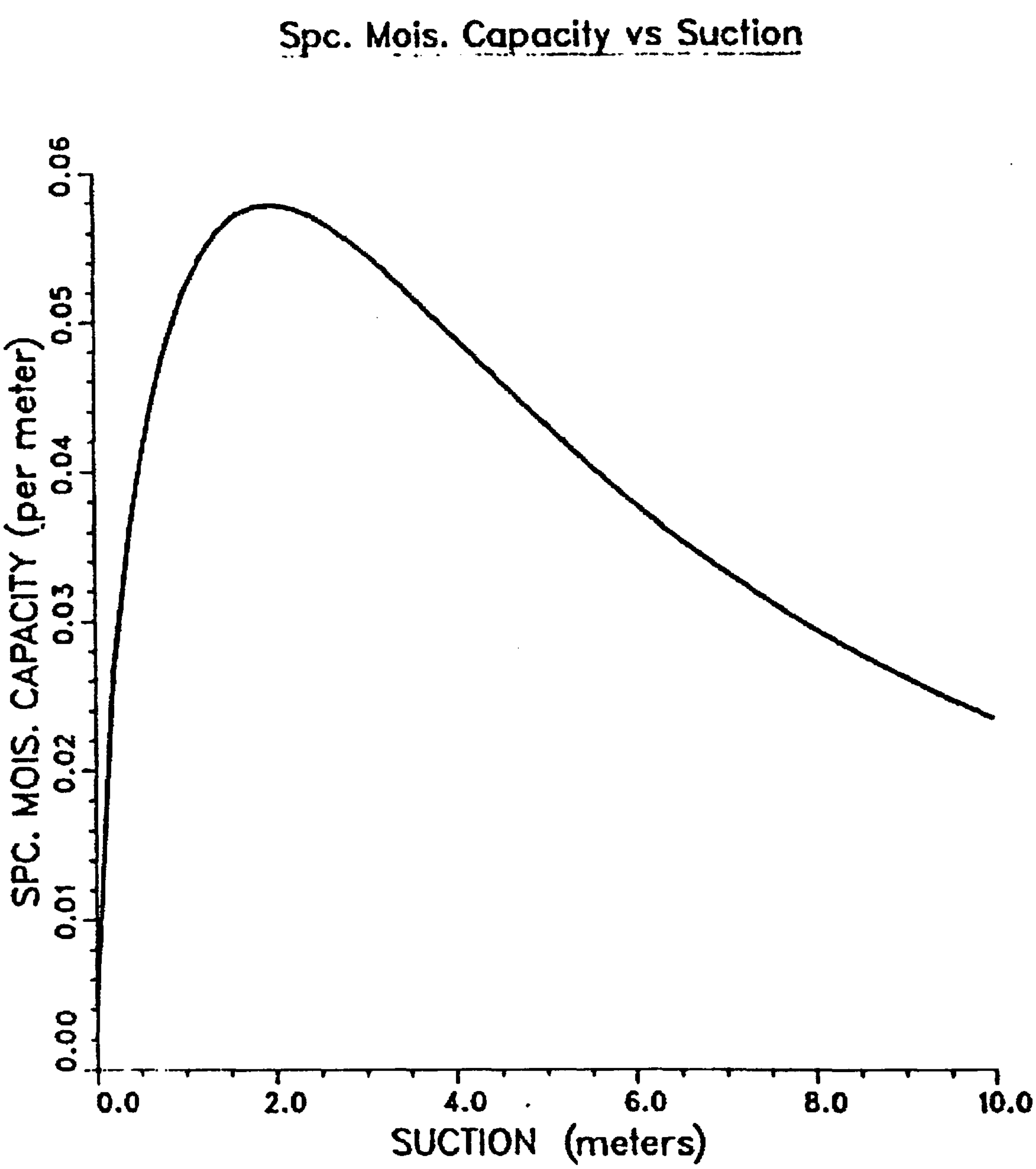

Figure 1.7 Variation of specific moisture capacity with pressure used for Apache Leap Tuff (assuming a van Genuchten curve and fitting parameters; alpha=.025 1/kPa and n=1.5). (Rasmussen,1988)

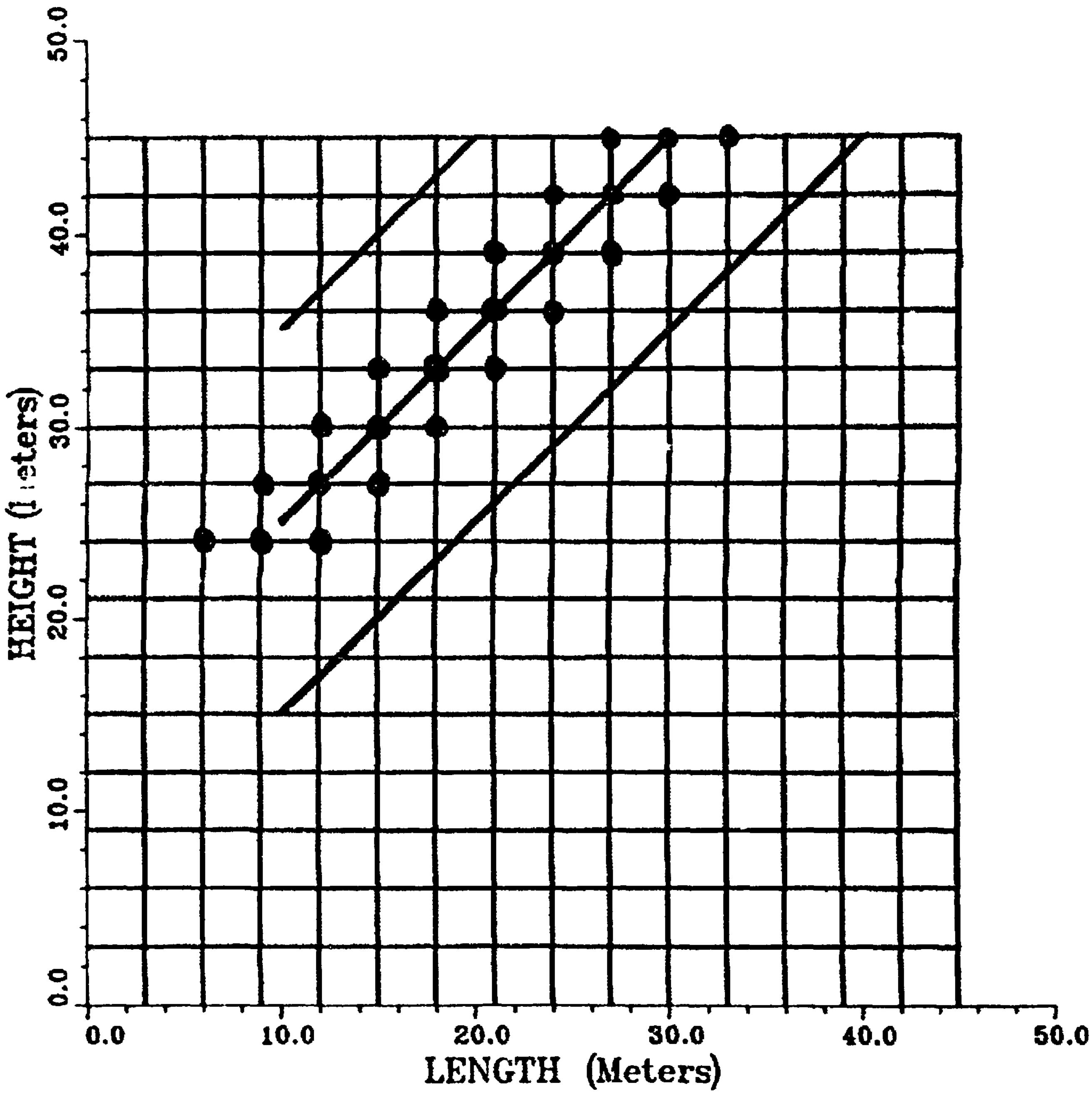

Figure 1.9 Initial conditions used in the SUTRA simulation of moisture redistribution following water injection at the Apache Leap site (solid circles indicate finite element nodes set to an initial saturation of 1.0).

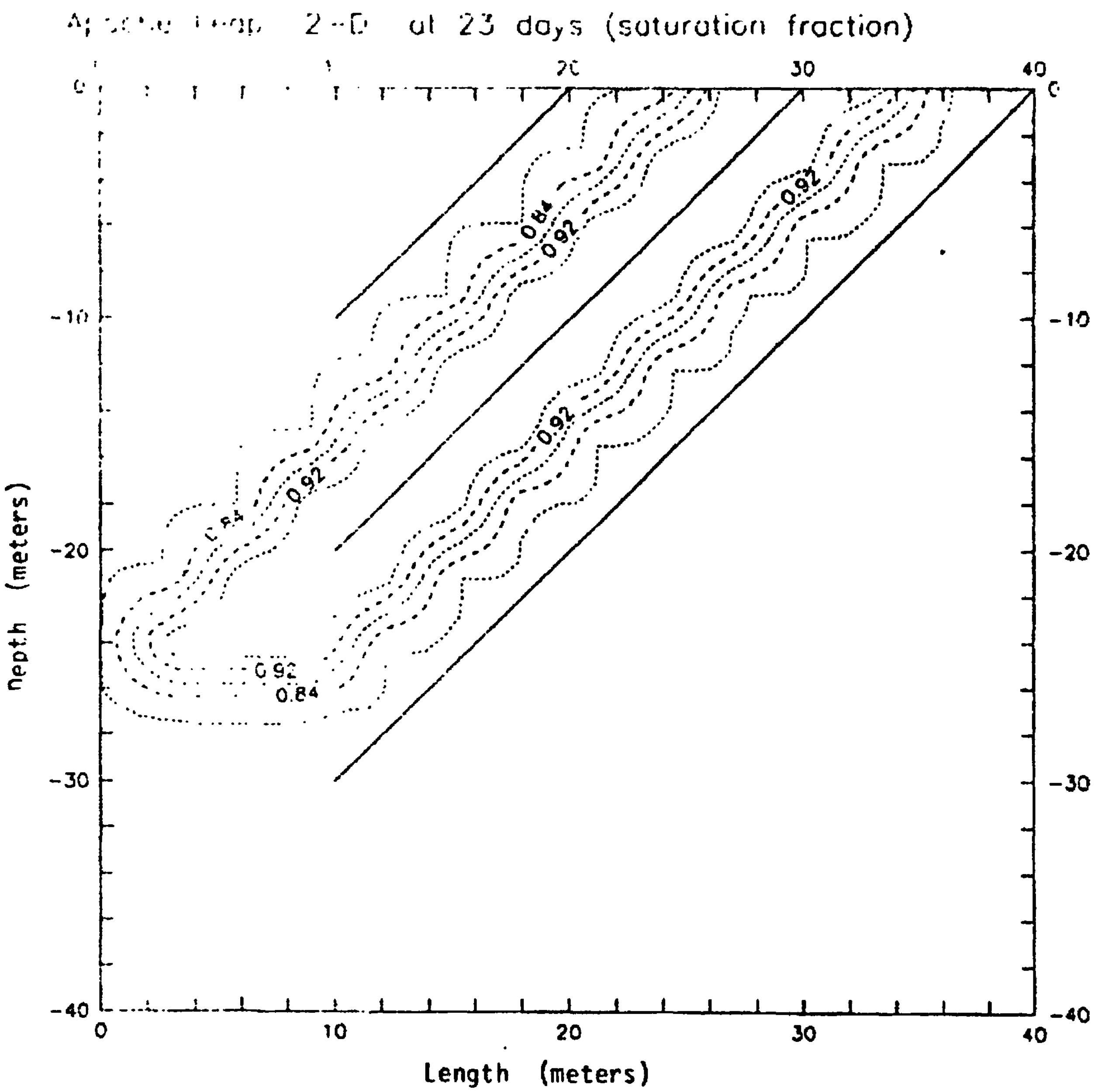

Figure 1.9 Two-dimensional SUTRA simulation of moisture redistribution following water injection at the Apache Leap site.

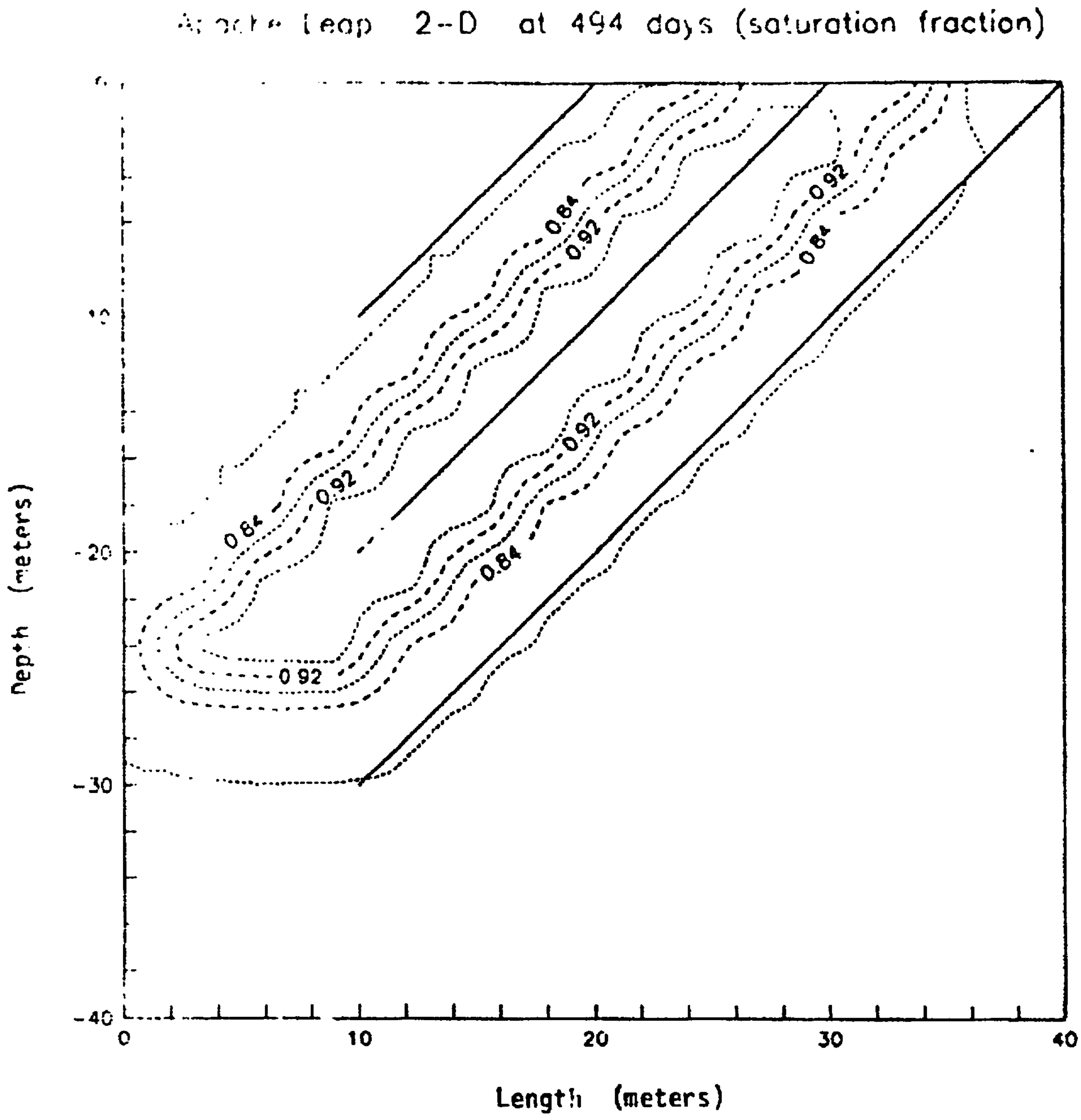

Figure 1.10 Two-dimensional SUTRA simulation of moisture redistribution following water injection at the Apache Leap site.

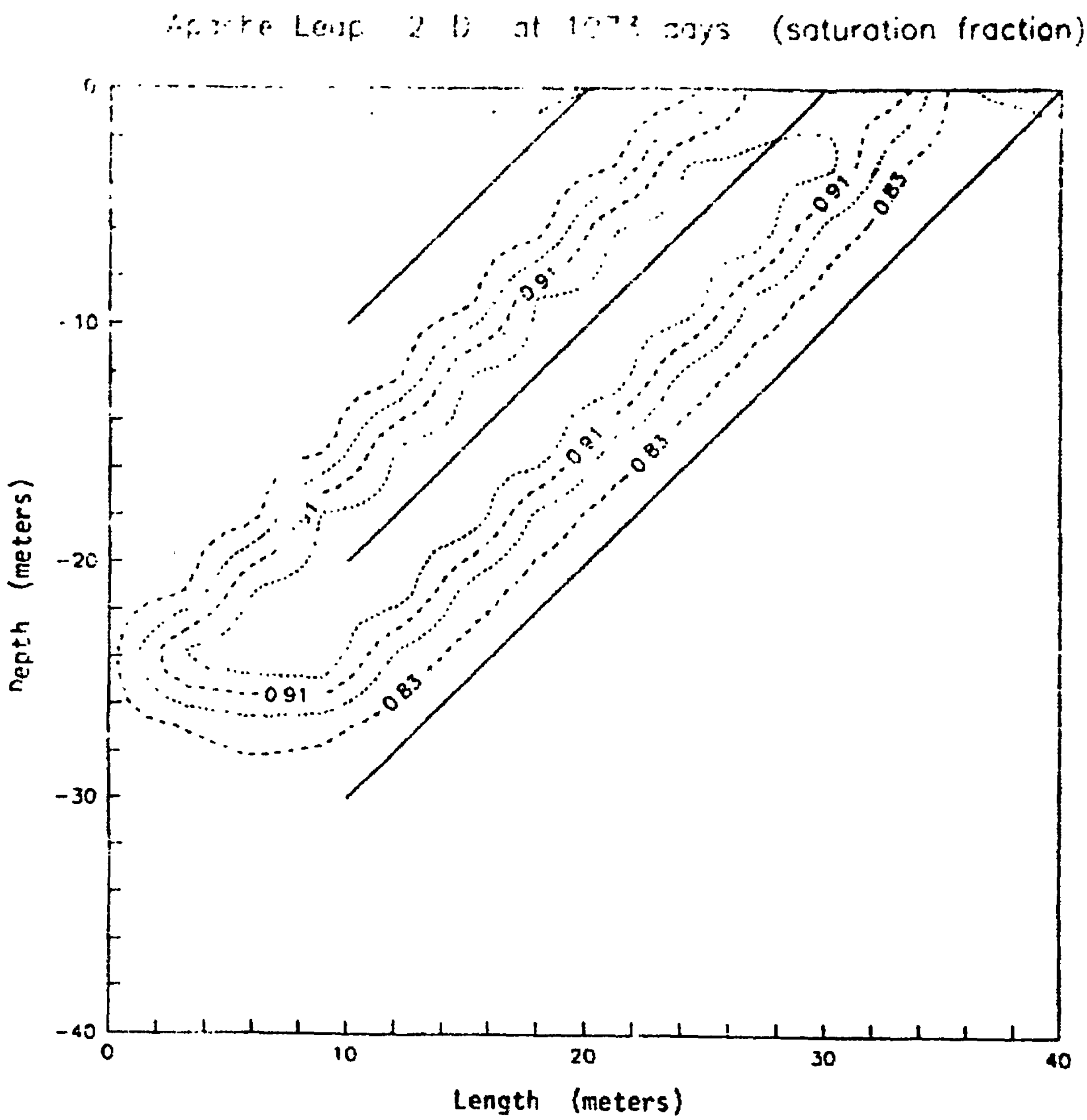

Figure 1.11 Two-dimensional SUTRA simulation of moisture redistribution following water injection at the Apache Leap site..

of this type of experiment for validation of fluid flow in the rock matrix is highly questionable (no significant moisture change is seen in the lower borehole after 1000 days). There is additional data from this experiment, not originally considered for use in the INTRAVAL evaluations, that might be useful. Specifically, additional data from the field experiment that would be extremely valuable for the simulation are: 1) the total amount of fluid injected in the borehole, and 2) the variation with time of moisture content in the rock matrix around the injection borehole.

1.2.3.2. One-Dimensional Modeling

SUTRA

One-dimensional simulations were carried out to evaluate the effect the grid size had on the two-dimensional simulation results (the coarseness of the 3 meter grid may have a smearing effect on the fluid front). Two one-dimensional grids were employed to examine this effect (one with a grid spacing of 3 meters and the other with a spacing of .25 meters). The results of the two different spacings are presented in Figures 1.12 and 1.13. These results indicate that the coarse grid does introduce a small amount of smearing into the fluid front but does not result in a dramatic alteration in the front shape. Need for finer grids is dictated more by the need for a more accurate representation of the volumetric extent of the initial saturated pulse than concern for the smearing of the moisture front.

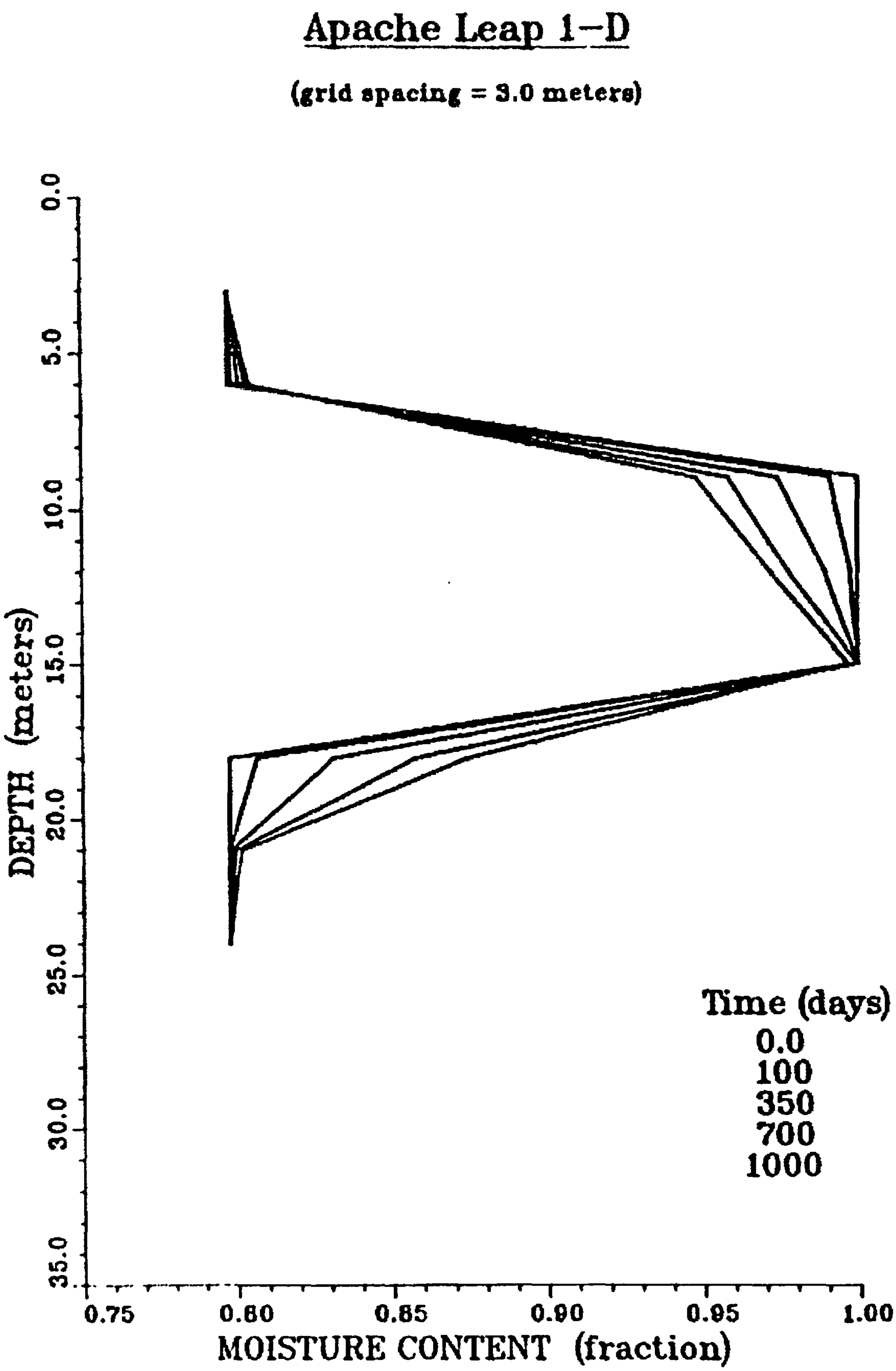

Figure 1.12 One-dimensional SUTRA simulation, using a 3 meter grid spacing, of moisture redistribution following water injection (reported as moisture contents at various times after the cessation of water injection).

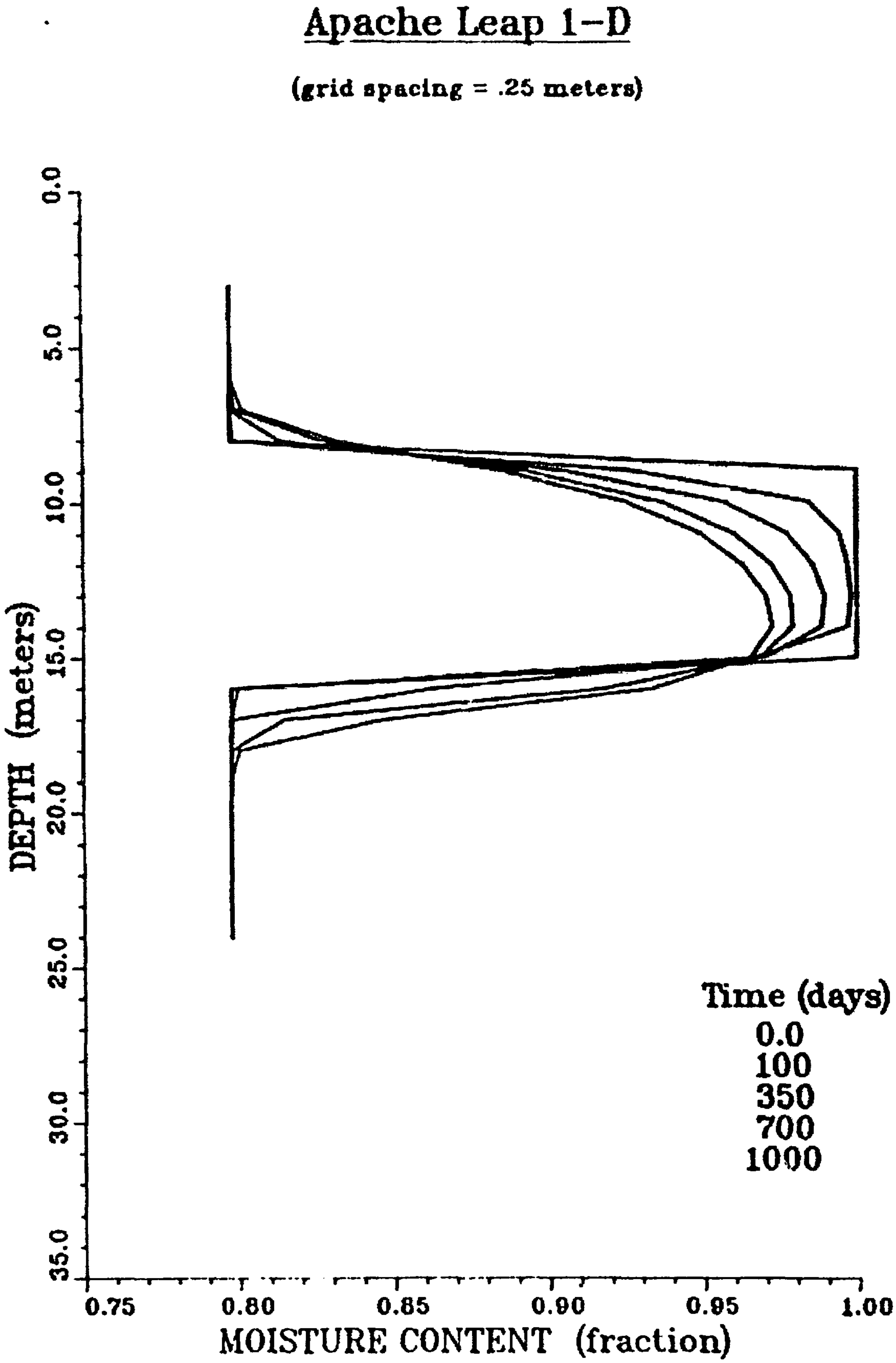

Figure 1.13 One-dimensional SUTRA simulation, using a .25 meter grid spacing, of moisture redistribution following water injection (reported as moisture contents at various times after the cessation of water injection).

REFERENCES

1. INTRAVAL Project Status Report, "Apache Leap Tuff Site," INTRAVAL(88)5, Appendix 4:1.

2. Rasmussen, T.C., 1987, "Computer Simulation of Steady Fluid Flow and Solutc Transport Through Three-Dimensional Networks of Variability Saturated, Discrete Fractures," in Flow and Transport Through Unsaturated Fractured Rock, AGU Geophysical Monograph 42, pp. 107-114.

3. Rasmussen, T.C., and Evans, D.D., 1987, "Unsaturated Flow and Transport Through Fractured Rock - Related to High- Level Waste Repositories," NUREG/CR-4655, U.S. Nuclear Regulatory Commission, Washington, D.C., p. 474.

4. Yeh, T.C., Rasmussen, T.C. and D.D. Evans, "Simulation of Liquid and Vapor Movement in Unsaturated Fractured Rock at the Apache Leap Tuff Site: Models and Strategies," NUREG/CR-5087, INTRAVAL(88)5, Appendix 4:2

5. Nofziger, D.L. and Hornsby, A.G., 1987, Chemical Movement in Layered Soils: User's Manual, Department of Agronomy Oklahoma State University and Soil Science Department, University, Computer Software Series CSS-30

6. Richards, L.A., 1931, Capillary Conduction of Liquids Through Porous Mediums, Physics 1:318-333

7. Yeh, T.C., et al, 1988, Simulation of Liquid and Vapor Movement in Unsaturated Fractured Rock at the Apache Leap Tuff Site, NUREG/CR-5097

8. Ballard, R.L., and Silberberg, M., 1988, Implementation of Memorandum of Understanding on HLW Performance Assessment Modeling Activities conducted by NRC Staff, Memorandum to Robert E. Browning & Guy A. Arlotto, dated 12/09/88.

9. Voss, C., 1984, "SUTRA - A Finite-Element Simulation Model for Saturated-Unsaturated, Fluid-Density-Dependent Ground-Water Flow with Energy Transport or Chemically-Reactive Single Species Solute Transport," USGS Water Resources Investigations Report 84-4369.

10. Rasmussen, T.C., 1988, Personal Communication.

APPENDIX A

INITIAL CONDITIONS

Date of Run.

Soil: YOLO CLAY Orientation: 0.0 Degrees From Vertical Downward Initial Condition for Water:
Non-Uniform initial condition

Water Boundary Condition at upper Soil Surface:
Flux Density = 0.000 cm/hr Water Boundary Condition at Distance of 100.00 cm:
Matric Potential = -1000.0 cm

Boundary Condition imposed at time 0.000 hr

Time: 0.0000 hr Net Inflow: 0.0000 cm
Cumulative Inflow by Integration of Water Content : 0.0000 cm
Cumulative Inflow by Integration of Surface Fluxes : 0.0000 cm

Inflow Rate at upper Surface : 0.000000 cm/hr Outflow Rate at lower Surface : 0.000000 cm/hr Mesh size in depth =1.000000e+000; Mesh size in time =1.000000e-002

Distance cm	Potential cm	Water_Content cc/cc	Flux_Water cm/hr
0.000	1.000	0.495	0.000
1.000	1.000	0.495	0.000
2.000	1.000	0.495	0.000
3.000	1.000	0.495	0.000
4.000	1.000	0.495	0.000
5.000	1.000	0.495	0.000
6.000	1.000	0.495	0.000
7.000	1.000	0.495	0.000
8.000	1.000	0.495	0.000
9.000	1.000	0.495	0.000
10.000	1.000	0.495	0.000
11.000	1.000	0.495	0.000
12.000	1.000	0.495	0.000
13.000	1.000	0.495	0.000
14.000	1.000	0.495	0.000
15.000	1.000	0.495	0.000
16.000	1.000	0.495	0.000
17.000	1.000	0.495	0.000
18.000	1.000	0.495	0.000
19.000	1.000	0.495	0.000
20.000	1.000	0.495	0.000
21.000	-1000.000	0.215	0.000
22.000	-1000.000	0.215	0.000
23.000	-1000.000	0.215	0.000
24.000	-1000.000	0.215	0.000
25.000	-1000.000	0.215	0.000
26.000	-1000.000	0.215	0.000
27.000	-1000.000	0.215	0.000
28.000	-1000.000	0.215	0.000
29.000	-1000.000	0.215	0.000
30.000	-1000.000	0.215	0.000
31.000	-1000.000	0.215	0.000

32.000	-1000.000	0.215	0.000
33.000	-1000.000	0.215	0.000
34.000	-1000.000	0.215	0.000
35.000	-1000.000	0.215	0.000
36.000	-1000.000	0.215	0.000
37.000	-1000.000	0.215	0.000
38.000	-1000.000	0.215	0.000
39.000	-1000.000	0.215	0.000
40.000	-1000.000	0.215	0.000
41.000	-1000.000	0.215	0.000
42.000	-1000.000	0.215	0.000
43.000	-1000.000	0.215	0.000
44.000	-1000.000	0.215	0.000
45.000	-1000.000	0.215	0.000
46.000	-1000.000	0.215	0.000
47.000	-1000.000	0.215	0.000
48.000	-1000.000	0.215	0.000
49.000	-1000.000	0.215	0.000
50.000	-1000.000	0.215	0.000
51.000	-1000.000	0.215	0.000
52.000	-1000.000	0.215	0.000
53.000	-1000.000	0.215	0.000
54.000	-1000.000	0.215	0.000
55.000	1000.000	0.215	0.000
56.000	-1000.000	0.215	0.000
57.000	-1000.000	0.215	0.000
58.000	-1000.000	0.215	0.000
59.000	-1000.000	0.215	0.000
60.000	-1000.000	0.215	0.000
61.000	-1000.000	0.215	0.000
62.000	-1000.000	0.215	0.000
63.000	-1000.000	0.215	0.000
64.000	-1000.000	0.215	0.000
65.000	-1000.000	0.215	0.000
66.000	-1000.000	0.215	0.000
67.000	-1000.000	0.215	0.000
68.000	-1000.000	0.215	0.000
69.000	-1000.000	0.215	0.000
70.000	-1000.000	0.215	0.000
71.000	-1000.000	0.215	0.000
72.000	-1000.000	0.215	0.000
73.000	-1000.000	0.215	0.000
74.000	-1000.000	0.215	0.000
75.000	-1000.000	0.215	0.000
76.000	-1000.000	0.215	0.000
77.000	-1000.000	0.215	0.000
78.000	-1000.000	0.215	0.000
79.000	-1000.000	0.215	0.000
80.000	-1000.000	0.215	0.000
81.000	-1000.000	0.215	0.000
82.000	-1000.000	0.215	0.000
83.000	-1000.000	0.215	0.000
84.000	-1000.000	0.215	0.000
85.000	-1000.000	0.215	0.000

86.000	-1000.000	0.215	0.000
87.000	-1000.000	0.215	0.000
88.000	-1000.000	0.215	0.000
89.000	-1000.000	0.215	0.000
90.000	-1000.000	0.215	0.000
91.000	-1000.000	0.215	0.000
92.000	-1000.000	0.215	0.000
93.000	-1000.000	0.215	0.000
94.000	-1000.000	0.215	0.000
95.000	-1000.000	0.215	0.000
96.000	-1000.000	0.215	0.000
97.000	-1000.000	0.215	0.000
98.000	-1000.000	0.215	0.000
99.000	-1000.000	0.215	0.000
100.000	-1000.000	0.215	0.000

Time: 20.0000 hr Net Inflow: -2.8758 cm
Cumulative Inflow by Integration of Water Content : -5.7511 cm
Cumulative Inflow by Integration of Surface Fluxes : -0.0005 cm

Inflow Rate at upper Surface : 0.000000 cm/hr Outflow Rate at lower Surface :
0.000027 cm/hr Mesh size in depth =1.000000e+000; Mesh size in time =1.000000e-002

Distance cm	Potential cm	Water_Content cc/cc	Flux_Water cm/hr
0.000	-1021.007	0.214	0.000
1.000	-1020.007	0.214	0.000
2.000	-1019.007	0.214	0.000
3.000	-1018.007	0.214	0.000
4.000	-1017.008	0.214	0.000
5.000	-1016.008	0.214	0.000
6.000	-1015.010	0.214	0.000
7.000	-1014.013	0.214	0.000
8.000	-1013.018	0.214	0.000
9.000	-1012.026	0.214	0.000
10.000	-1011.040	0.214	0.000
11.000	-1010.062	0.215	0.000
12.000	-1009.096	0.215	0.000
13.000	-1008.147	0.215	0.000
14.000	-1007.222	0.215	0.000
15.000	-1006.327	0.215	0.000
16.000	-1005.472	0.215	0.000
17.000	-1004.663	0.215	0.000
18.000	-1003.915	0.215	0.000
19.000	-1003.229	0.215	0.000
20.000	-1002.615	0.215	0.000
21.000	-1002.076	0.215	0.000
22.000	-1001.614	0.215	0.000
23.000	-1001.228	0.215	0.000
24.000	-1000.912	0.215	0.000
25.000	-1000.662	0.215	0.000
26.000	-1000.468	0.215	0.000

APPENDIX B

FINAL CONDITIONS AFTER 720 HOURS (30 DAYS)

Time: 720.0000 hr Net Inflow: -2.8947 cm
Cumulative Inflow by Integration of Water Content : -5.7700 cm
Cumulative Inflow by Integration of Surface Fluxes : -0.0194 cm

Inflow Rate at upper Surface : 0.000000 cm/hr Outflow Rate at lower Surface : 0.000027 cm/hr Mesh size in depth =1.000000e+000; Mesh size in time =1.000000e-001

Distance cm	Potential cm	Water_Content cc/cc	Flux_Water cm/hr
0.000	-1030.456	0.214	0.000
1.000	-1029.467	0.214	0.000
2.000	-1028.498	0.214	0.000
3.000	-1027.550	0.214	0.000
4.000	-1026.622	0.214	0.000
5.000	-1025.715	0.214	0.000
6.000	-1024.828	0.214	0.000
7.000	-1023.961	0.214	0.000
8.000	-1023.115	0.214	0.000
9.000	-1022.289	0.214	0.000
10.000	-1021.482	0.214	0.000
11.000	-1020.696	0.214	0.000
12.000	-1019.929	0.214	0.000
13.000	-1019.182	0.214	0.000
14.000	-1018.454	0.214	0.000
15.000	-1017.745	0.214	0.000
16.000	-1017.056	0.214	0.000
17.000	-1016.385	0.214	0.000
18.000	-1015.733	0.214	0.000
19.000	-1015.099	0.214	0.000
20.000	-1014.484	0.214	0.000
21.000	-1013.886	0.214	0.000
22.000	-1013.306	0.214	0.000
23.000	-1012.744	0.214	0.000
24.000	-1012.200	0.214	0.000
25.000	-1011.672	0.214	0.000
26.000	-1011.161	0.214	0.000
27.000	-1010.666	0.214	0.000
28.000	-1010.188	0.215	0.000
29.000	-1009.726	0.215	0.000
30.000	-1009.280	0.215	0.000
31.000	-1008.849	0.215	0.000
32.000	-1008.433	0.215	0.000
33.000	-1008.032	0.215	0.000
34.000	-1007.646	0.215	0.000
35.000	-1007.274	0.215	0.000
36.000	-1006.916	0.215	0.000
37.000	-1006.572	0.215	0.000
38.000	-1006.240	0.215	0.000
39.000	-1005.922	0.215	0.000
40.000	-1005.617	0.215	0.000
41.000	-1005.324	0.215	0.000
42.000	-1005.043	0.215	0.000
43.000	-1004.774	0.215	0.000

44.000	-1004.516	0.215	0.000
45.000	-1004.270	0.215	0.000
46.000	-1004.034	0.215	0.000
47.000	-1003.809	0.215	0.000
48.000	-1003.594	0.215	0.000
49.000	-1003.389	0.215	0.000
50.000	-1003.193	0.215	0.000
51.000	-1003.007	0.215	0.000
52.000	-1002.829	0.215	0.000
53.000	-1002.661	0.215	0.000
54.000	-1002.500	0.215	0.000
55.000	-1002.348	0.215	0.000
56.000	-1002.203	0.215	0.000
57.000	-1002.065	0.215	0.000
58.000	-1001.935	0.215	0.000
59.000	-1001.812	0.215	0.000
60.000	-1001.695	0.215	0.000
61.000	-1001.585	0.215	0.000
62.000	-1001.481	0.215	0.000
63.000	-1001.382	0.215	0.000
64.000	-1001.289	0.215	0.000
65.000	-1001.202	0.215	0.000
66.000	-1001.119	0.215	0.000
67.000	-1001.042	0.215	0.000
68.000	-1000.968	0.215	0.000
69.000	-1000.900	0.215	0.000
70.000	-1000.835	0.215	0.000
71.000	-1000.775	0.215	0.000
72.000	-1000.718	0.215	0.000
73.000	-1000.665	0.215	0.000
74.000	-1000.615	0.215	0.000
75.000	-1000.568	0.215	0.000
76.000	-1000.524	0.215	0.000
77.000	-1000.483	0.215	0.000
78.000	-1000.445	0.215	0.000
79.000	-1000.409	0.215	0.000
80.000	-1000.376	0.215	0.000
81.000	-1000.344	0.215	0.000
82.000	-1000.315	0.215	0.000
83.000	-1000.288	0.215	0.000
84.000	-1000.262	0.215	0.000
85.000	-1000.239	0.215	0.000
86.000	-1000.216	0.215	0.000
87.000	-1000.195	0.215	0.000
88.000	-1000.175	0.215	0.000
89.000	-1000.157	0.215	0.000
90.000	-1000.139	0.215	0.000
91.000	-1000.123	0.215	0.000
92.000	-1000.107	0.215	0.000
93.000	-1000.092	0.215	0.000
94.000	-1000.078	0.215	0.000
95.000	-1000.064	0.215	0.000
96.000	-1000.051	0.215	0.000
97.000	-1000.038	0.215	0.000

98.000	-1000.025	0.215	0.000
99.000	-1000.013	0.215	0.000
100.000	-1000.000	0.215	0.000

APPENDIX C

SUTRA INPUT LISTING FOR THE TWO-DIMENSIONAL SIMULATION

Appendix: SUTRA Input Listing for the Two-Dimensional Simulation

```
[illegible] DE [illegible]
[illegible] FSTIN,NAME=[illegible] TWO',DISP=[illegible]
[illegible]
[illegible] ILE[illegible]
[illegible] T[illegible]
[illegible] SIMULATION FOR [illegible]
**** FLUID REDISTRIBUTION FROM A SATURATED BOREHOLE ****
 [illegible]  [illegible]  [illegible]  0  14  0  0  0  [illegible]  50
 11     [illegible]          +1    +1
        [illegible]          [illegible]
  100           [illegible]        [illegible]              [illegible]        1.2          5[illegible].
    5    [illegible]   [illegible]   0    +1     0    +1    +1
        30        1.0       1.0
   4.4E-10                1.0E-07      1000.         [illegible].0         0.0        1124.
  1.02E-07                             2100.
NONE
        0.[illegible]        [illegible].0        0.0        0.0
        0.0        -9.8
NODE        1.[illegible]        1.0        1.0        1.0
     1    0.0000     0.0000     1.0    0.1700
     2    3.0000     0.0000     1.0    0.1700
     3    6.0000     0.0000     1.0    0.1700
     4    9.0000     0.0000     1.0    0.1700
     5   12.0000     0.0000     1.0    0.1700
     6   15.0000     0.0000     1.0    0.1700
     7   18.0000     0.0000     1.0    0.1700
     8   21.0000     0.0000     1.0    0.1700
     9   24.0000     0.0000     1.0    0.1700
    10   27.0000     0.0000     1.0    0.1700
    11   30.0000     0.0000     1.0    0.1700
    12   33.0000     0.0000     1.0    0.1700
    13   36.0000     0.0000     1.0    0.1700
    14   39.0000     0.0000     1.0    0.1700
    15   42.0000     0.0000     1.0    0.1700
    16   45.0000     0.0000     1.0    0.1700
    17    0.0000     3.0000     1.0    0.1700
    18    3.0000     3.0000     1.0    0.1700
    19    6.0000     3.0000     1.0    0.1700
    20    9.0000     3.0000     1.0    0.1700
    21   12.0000     3.0000     1.0    0.1700
    22   15.0000     3.0000     1.0    0.1700
    23   18.0000     3.0000     1.0    0.1700
    24   21.0000     3.0000     1.0    0.1700
    25   24.0000     3.0000     1.0    0.1700
    26   27.0000     3.0000     1.0    0.1700
    27   30.0000     3.0000     1.0    0.1700
    28   33.0000     3.0000     1.0    0.1700
    29   36.0000     3.0000     1.0    0.1700
    30   39.0000     3.0000     1.0    0.1700
    31   42.0000     3.0000     1.0    0.1700
```

32	45.0000	3.0000	1.0	0.1700
33	[illegible]	6.0000	1.0	0.1700
34	[illegible]	[illegible]	1.0	0.1700
35	[illegible]	[illegible]	1.0	0.1700
36	[illegible]	[illegible]	1.0	0.1700
37	[illegible]	[illegible]	1.0	0.1700
38	15.0000	[illegible]	1.0	0.1700
39	18.0000	6.0000	1.0	0.1700
40	21.0000	6.0000	1.0	0.1700
41	24.0000	6.0000	1.0	0.1700
42	27.0000	6.0000	1.0	0.1700
43	30.0000	6.0000	1.0	0.1700
44	33.0000	6.0000	1.0	0.1700
45	36.0000	6.0000	1.0	0.1700
46	39.0000	6.0000	1.0	0.1700
47	42.0000	6.0000	1.0	0.1700
48	45.0000	6.0000	1.0	0.1700
49	0.0000	9.0000	1.0	0.1700
50	3.0000	9.0000	1.0	0.1700
51	6.0000	9.0000	1.0	0.1700
52	9.0000	9.0000	1.0	0.1700
53	12.0000	9.0000	1.0	0.1700
54	15.0000	9.0000	1.0	0.1700
55	18.0000	9.0000	1.0	0.1700
56	21.0000	9.0000	1.0	0.1700
57	24.0000	9.0000	1.0	0.1700
58	27.0000	9.0000	1.0	0.1700
59	30.0000	9.0000	1.0	0.1700
60	33.0000	9.0000	1.0	0.1700
61	36.0000	9.0000	1.0	0.1700
62	39.0000	9.0000	1.0	0.1700
63	42.0000	9.0000	1.0	0.1700
64	45.0000	9.0000	1.0	0.1700
65	0.0000	12.0000	1.0	0.1700
66	3.0000	12.0000	1.0	0.1700
67	6.0000	12.0000	1.0	0.1700
68	9.0000	12.0000	1.0	0.1700
69	12.0000	12.0000	1.0	0.1700
70	15.0000	12.0000	1.0	0.1700
71	18.0000	12.0000	1.0	0.1700
72	21.0000	12.0000	1.0	0.1700
73	24.0000	12.0000	1.0	0.1700
74	27.0000	12.0000	1.0	0.1700
75	30.0000	12.0000	1.0	0.1700
76	33.0000	12.0000	1.0	0.1700
77	36.0000	12.0000	1.0	0.1700
78	39.0000	12.0000	1.0	0.1700
79	42.0000	12.0000	1.0	0.1700
80	45.0000	12.0000	1.0	0.1700
81	0.0000	15.0000	1.0	0.1700

82	3.0000	15.0000	1.0	0.1700
83	[illegible]	15.0000	1.0	0.1700
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
85	12.0000	[illegible]	[illegible]	0.1700
86	15.0000	[illegible]	1.0	0.1700
87	18.0000	15.0000	1.0	0.1700
88	21.0000	15.0000	1.0	0.1700
89	24.0000	15.0000	1.0	0.1700
90	27.0000	15.0000	1.0	0.1700
91	30.0000	[illegible]	1.0	0.1700
92	33.0000	15.0000	1.0	0.1700
93	36.0000	15.0000	1.0	0.1700
94	39.0000	15.0000	1.0	0.1700
95	42.0000	15.0000	1.0	0.1700
96	45.0000	15.0000	1.0	0.1700
97	0.0000	18.0000	1.0	0.1700
98	3.0000	18.0000	1.0	0.1700
99	6.0000	18.0000	1.0	0.1700
100	9.0000	18.0000	1.0	0.1700
101	12.0000	18.0000	1.0	0.1700
102	15.0000	18.0000	1.0	0.1700
103	18.0000	18.0000	1.0	0.1700
104	21.0000	18.0000	1.0	0.1700
105	24.0000	18.0000	1.0	0.1700
106	27.0000	18.0000	1.0	0.1700
107	30.0000	18.0000	1.0	0.1700
108	33.0000	18.0000	1.0	0.1700
109	36.0000	18.0000	1.0	0.1700
110	39.0000	18.0000	1.0	0.1700
111	42.0000	18.0000	1.0	0.1700
112	45.0000	18.0000	1.0	0.1700
113	0.0000	21.0000	1.0	0.1700
114	3.0000	21.0000	1.0	0.1700
115	6.0000	21.0000	1.0	0.1700
116	9.0000	21.0000	1.0	0.1700
117	12.0000	21.0000	1.0	0.1700
118	15.0000	21.0000	1.0	0.1700
119	18.0000	21.0000	1.0	0.1700
120	21.0000	21.0000	1.0	0.1700
121	24.0000	21.0000	1.0	0.1700
122	27.0000	21.0000	1.0	0.1700
123	30.0000	21.0000	1.0	0.1700
124	33.0000	21.0000	1.0	0.1700
125	36.0000	21.0000	1.0	0.1700
126	39.0000	21.0000	1.0	0.1700
127	42.0000	21.0000	1.0	0.1700
128	45.0000	21.0000	1.0	0.1700
129	0.0000	24.0000	1.0	0.1700
130	3.0000	24.0000	1.0	0.1700
131	6.0000	24.0000	1.0	0.1700

132	[illegible]	24.0000	1.0	0.1700
133	12.0000	24.0000	1.0	0.1700
134	[illegible]	24.0000	1.0	0.1700
135	[illegible]	24.0000	1.0	0.1700
136	[illegible]	24.0000	1.0	0.1700
137	24.0000	24.0000	1.0	0.1700
138	[illegible]	24.0000	1.0	0.1700
139	30.0000	24.0000	1.0	0.1700
140	33.0000	24.0000	1.0	0.1700
141	[illegible]	24.0000	1.0	0.1700
142	[illegible]	24.0000	1.0	0.1700
143	42.0000	24.0000	1.0	0.1700
144	45.0000	24.0000	1.0	0.1700
145	0.0000	27.0000	1.0	0.1700
146	3.0000	27.0000	1.0	0.1700
147	6.0000	27.0000	1.0	0.1700
148	9.0000	27.0000	1.0	0.1700
149	12.0000	27.0000	1.0	0.1700
150	15.0000	27.0000	1.0	0.1700
151	18.0000	27.0000	1.0	0.1700
152	21.0000	27.0000	1.0	0.1700
153	24.0000	27.0000	1.0	0.1700
154	27.0000	27.0000	1.0	0.1700
155	30.0000	27.0000	1.0	0.1700
156	33.0000	27.0000	1.0	0.1700
157	36.0000	27.0000	1.0	0.1700
158	39.0000	27.0000	1.0	0.1700
159	42.0000	27.0000	1.0	0.1700
160	45.0000	27.0000	1.0	0.1700
161	0.0000	30.0000	1.0	0.1700
162	3.0000	30.0000	1.0	0.1700
163	6.0000	30.0000	1.0	0.1700
164	9.0000	30.0000	1.0	0.1700
165	12.0000	30.0000	1.0	0.1700
166	15.0000	30.0000	1.0	0.1700
167	18.0000	30.0000	1.0	0.1700
168	21.0000	30.0000	1.0	0.1700
169	24.0000	30.0000	1.0	0.1700
170	27.0000	30.0000	1.0	0.1700
171	30.0000	30.0000	1.0	0.1700
172	33.0000	30.0000	1.0	0.1700
173	36.0000	30.0000	1.0	0.1700
174	39.0000	30.0000	1.0	0.1700
175	42.0000	30.0000	1.0	0.1700
176	45.0000	30.0000	1.0	0.1700
177	0.0000	33.0000	1.0	0.1700
178	3.0000	33.0000	1.0	0.1700
179	6.0000	33.0000	1.0	0.1700
180	9.0000	33.0000	1.0	0.1700
181	12.0000	33.0000	1.0	0.1700

5.

[illegible]	[illegible]	[illegible]	1.0	0.1700
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	0.1700
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	1.0	0.1700
[illegible]	[illegible]	[illegible]	1.0	0.1700
[illegible]	[illegible]	[illegible]	1.0	0.1700
[illegible]	3.0000	[illegible]	1.0	0.1700
195	6.0000	36.0000	1.0	0.1700
196	9.0000	36.0000	1.0	0.1700
197	12.0000	36.0000	1.0	0.1700
198	15.0000	36.0000	1.0	0.1700
199	18.0000	36.0000	1.0	0.1700
200	21.0000	36.0000	1.0	0.1700
201	24.0000	36.0000	1.0	0.1700
202	27.0000	36.0000	1.0	0.1700
203	30.0000	36.0000	1.0	0.1700
204	33.0000	36.0000	1.0	0.1700
205	36.0000	36.0000	1.0	0.1700
206	39.0000	36.0000	1.0	0.1700
207	42.0000	36.0000	1.0	0.1700
208	45.0000	36.0000	1.0	0.1700
209	0.0000	39.0000	1.0	0.1700
210	3.0000	39.0000	1.0	0.1700
211	6.0000	39.0000	1.0	0.1700
212	9.0000	39.0000	1.0	0.1700
213	12.0000	39.0000	1.0	0.1700
214	15.0000	39.0000	1.0	0.1700
215	18.0000	39.0000	1.0	0.1700
216	21.0000	39.0000	1.0	0.1700
217	24.0000	39.0000	1.0	0.1700
218	27.0000	39.0000	1.0	0.1700
219	30.0000	39.0000	1.0	0.1700
220	33.0000	39.0000	1.0	0.1700
221	36.0000	39.0000	1.0	0.1700
222	39.0000	39.0000	1.0	0.1700
223	42.0000	39.0000	1.0	0.1700
224	45.0000	39.0000	1.0	0.1700
225	0.0000	42.0000	1.0	0.1700
226	3.0000	42.0000	1.0	0.1700
227	6.0000	42.0000	1.0	0.1700
228	9.0000	42.0000	1.0	0.1700
229	12.0000	42.0000	1.0	0.1700
230	15.0000	42.0000	1.0	0.1700
231	18.0000	42.0000	1.0	0.1700

232	21.0000	42.0000	1.0	0.1700
233	[illegible]	42.0000	1.0	0.1700
234	[illegible]	[illegible]	1.0	[illegible]
235	[illegible]	[illegible]	[illegible]	[illegible]
236	[illegible]	[illegible]	[illegible]	[illegible]
237	[illegible]	[illegible]	[illegible]	0.1700
238	39.0000	42.0000	1.0	0.1700
239	42.0000	42.0000	1.0	0.1700
240	45.0000	42.0000	1.0	0.1700
241	[illegible]	45.0000	1.0	0.1700
242	3.00	45.0000	1.0	0.1700
243	6.0000	45.0000	1.0	0.1700
244	9.0000	45.0000	1.0	0.1700
245	12.0000	45.0000	1.0	0.1700
246	15.0000	45.0000	1.0	0.1700
247	18.0000	45.0000	1.0	0.1700
248	21.0000	45.0000	1.0	0.1700
249	24.0000	45.0000	1.0	0.1700
250	27.0000	45.0000	1.0	0.1700
251	30.0000	45.0000	1.0	0.1700
252	33.0000	45.0000	1.0	0.1700
253	36.0000	45.0000	1.0	0.1700
254	39.0000	45.0000	1.0	0.1700
255	42.0000	45.0000	1.0	0.1700
256	45.0000	45.0000	1.0	0.1700

EMENT							
		.1147	.1147	1.0	1.0	1.0	0.1
	1	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	2	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	3	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	4	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	5	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	6	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	7	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	8	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	9	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	10	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	11	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	12	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	13	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	14	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	15	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	16	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	17	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	18	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	19	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	20	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	21	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	22	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	23	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
	24	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0

[illegible]	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
[illegible]	[illegible]	[illegible]	1.0	1.0	[illegible]	1.0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.0
[illegible]	[illegible]	[illegible]	[illegible]	1.0	[illegible]	[illegible]
30	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
31	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
32	0.10E-08	0.10E-08	1.	.0	1.0	1.0
33	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
34	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
35	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
36	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
37	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
38	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
39	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
40	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
41	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
42	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
43	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
44	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
45	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
46	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
47	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
48	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
49	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
50	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
51	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
52	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
53	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
54	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
55	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
56	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
57	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
58	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
59	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
60	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
61	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
62	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
63	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
64	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
65	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
66	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
67	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
68	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
69	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
70	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
71	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
72	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
73	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
74	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0

75	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
76	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
77	0.10E-08	0.10E-08	1.	1.0	1.0	1.0
78	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
79	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
80	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
81	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
82	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
83	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
84	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
85	0.10E-09	0.10E-08	1.0	1.0	1.0	1.0
86	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
87	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
88	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
89	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
90	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
91	0.10E-0E	0.10E-06	1.0	1.0	1.0	1.0
92	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
93	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
94	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
95	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
96	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
97	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
98	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
99	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
100	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
101	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
102	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
103	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
104	0.10E-08	0.10E-06	1.0	1.0	1.0	1.0
105	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
106	0.10E-08	0.10E-09	1.0	1.0	1.0	1.0
107	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
108	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
109	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
110	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
111	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
112	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
113	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
114	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
115	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
116	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
117	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
118	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
119	0.10E-0F	.10E-08	1.0	1.0	1.0	1.0
120	0.10E-0	.10E-06	1.0	1.0	1.0	1.0
121	0.10E-08	10E-08	1.0	1.0	1.0	1.0
122	0.10E-08	..10E-08	1.0	1.0	1.0	1.0
123	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
124	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0

125	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
126	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
[illegible]	[illegible]	[illegible]	[illegible]	1.0	[illegible]	[illegible]
128	0.10E-08	[illegible]	1.0	1.0	1.0	1.0
129	0.10E-08	[illegible]	1.0	1.0	1.0	1.0
130	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
131	0.10E-08	0.10E-08	1.	1.0	1.0	1.0
132	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
133	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
134	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
135	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
136	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
137	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
138	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
139	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
140	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
141	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
142	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
143	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
144	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
145	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
146	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
147	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
148	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
149	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
150	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
151	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
152	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
153	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
154	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
155	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
156	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
157	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
158	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
159	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
160	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
161	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
162	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
163	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
164	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
165	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
166	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
167	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
168	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
169	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
170	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
171	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
172	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
173	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
174	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0

175	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
176	[illegible]	[illegible]	1.0	1.0	1.0	1.0
[illegible]	[illegible]	[illegible]	1.0	1.0	1.0	1.0
[illegible]	[illegible]	[illegible]	1.0	1.0	1.0	1.0
[illegible]	[illegible]	[illegible]	1.0	[illegible]	1.0	1.0
180	[illegible]	[illegible]	[illegible]		1.0	1.0
181	[illegible]	0.10E-08	[illegible]		1.0	1.0
182	[illegible]	0.10E-08	1.0	[illegible]	1.0	1.0
183	0.10E-08	[illegible]	1.0		1.0	1.0
184	[illegible]	0.10E-08	1.0	[illegible]	1.0	1.0
185	[illegible]	0.10E-08	1.0	1.0	1.0	1.0
186	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
187	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
188	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
189	[illegible]	0.10E-08	1.0	1.0	1.0	1.0
190	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
191	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
192	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
193	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
194	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
195	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
196	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
197	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
198	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
199	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
200	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
201	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
202	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
203	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
204	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
205	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
206	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
207	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
208	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
209	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
210	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
211	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
212	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
213	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
214	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
215	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
216	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
217	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
218	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
219	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
220	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
221	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
222	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
223	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0
224	0.10E-08	0.10E-08	1.0	1.0	1.0	1.0

II.

[illegible]	[illegible]	[illegible]	1.[illegible]	1.0	1.[illegible]	1.0

[illegible]	-[illegible]	[illegible].0
3	-39[illegible].	[illegible].0
[illegible]	[illegible]92[illegible].	0.[illegible]
5	-39200.	0.0
[illegible]	-39200.	0.0
[illegible]	-39200.	0.0
8	-392[illegible]0.	0.0
[illegible]	[illegible]9200.	0.0
10	-39200.	0.0
11	-39200.	0.0
12	-39200.	0.0
13	-39200.	0.0
14	-39200.	0.0
15	-39200.	0.0

116	117	118	119	120	121	122	132	133	134	135	136	137	138	148
150	151	[illegible]	[illegible]	154	164	165	166	167	168	169	170	180	181	182
184	185	[illegible]	[illegible]	197	198	199	200	201	202	212	213	214	215	216
218	228	[illegible]	[illegible]	231	232	233	234	0	0	0	0	0	0	0

1	1	[illegible]	18	17
2	2		19	18
3	3		20	19
4	4	[illegible]	21	20
5	5	6	22	21
6	6	7	23	22
7	7	8	24	23
8	8	9	25	24
9	9	10	26	25
10	10	11	27	26
11	11	12	28	27
12	12	13	29	28
13	13	14	30	29
14	14	15	31	30
15	15	16	32	31
16	17	18	34	33
17	18	19	35	34
18	19	20	36	35
19	20	21	37	36
20	21	22	38	37
21	22	23	39	38
22	23	24	40	39
23	24	25	41	40
24	25	26	42	41
25	26	27	43	42
26	27	28	44	43
27	28	29	45	44

[illegible]	[illegible]	[illegible]	46	45
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	51	[illegible]
[illegible]	[illegible]	35	[illegible]	51
[illegible]	36	37	53	52
[illegible]	37	38	54	53
[illegible]	[illegible]	39	55	54
[illegible]	39	40	56	55
[illegible]	40	41	57	56
39	41	42	53	57
40	42	43	59	58
41	43	44	60	59
42	44	45	61	60
43	45	46	62	61
44	46	47	63	62
45	47	48	64	63
46	49	50	65	65
47	50	51	67	66
48	51	52	68	67
49	52	53	69	68
50	53	54	70	69
51	54	55	71	70
52	55	56	72	71
53	56	57	73	72
54	57	58	74	73
55	58	59	75	74
56	59	60	76	75
57	60	61	77	76
58	61	62	78	77
59	62	63	79	78
60	63	64	80	79
61	65	66	82	81
62	66	67	83	82
63	67	68	84	83
64	68	69	85	84
65	69	70	86	85
66	70	71	87	86
67	71	72	88	87
68	72	73	89	88
69	73	74	90	89
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APPENDIX D

INTRAVAL PROJECT

INTRAVAL Project

I. INTRODUCTION

A. Pilot Group Identification - U.S. Nuclear Regulatory Commission (NRC), Division of Engineering, Office of Nuclear Regulatory Research, Washington, D.C; NRC Contractor, University of Arizona, Tucson, AZ, USA

B. Experimental Location - Apache Leap Tuff Experimental Area in non-welded to welded tuff dated 19 m.y. B.P. near Superior, Arizona, approximately 160 km north of Tucson, AZ, USA.

C. Objective(s) - Obtain calibration data sets for fluid flow and solute transport models in unsaturated fractured rock. Data is collected for hydraulic, pneumatic, and thermal properties for fractures and the rock matrix. Calibration data sets will be used for model simulation studies as well as to compare model simulation results with field experimental data. Evaluation of alternative modeling strategies for their ability to accurately represent fluid flow and solute transport processes in unsaturated fractured rock. NUREG/CR-5097 by Yeh et al. (1988) discusses the various conceptual models being considered along with a review of possible numerical codes to simulate the site conditions.

D. Theories Tested - Equivalent porous media representation of fractured rock fluid flow as opposed to discrete fracture slow network representation. Use of moisture characteristic and unsaturated hydraulic conductivity curves for fractures. Soil science methods for determining hydraulic properties of rock core samples with field estimates. Laboratory methods for determining hydraulic, pneumatic and thermal properties of rock matrix cores. Verification of relevant processes within stratified tuff horizon.

E. Validation Aspects - Comparisons will be made between field experimental results with results obtained using analytic stochastic, equivalent porous medium and discrete fracture network flow models. Calibration data sets will be provided for generating simulated flow and transport. Comparison of simulated with observed flow behavior will help identify model abilities and failures.

F. Background Information - The Apache Leap Tuff Site is located near Superior, Arizona, in partially welded fractured tuff. Also located nearby is an abandoned road tunnel in welded tuff, and a haulage tunnel, also in welded tuff. The facilities allow access to different levels of a thich tuff sequence with variable degrees of welding and fracturing.

II. EXPERIMENTAL DESIGN

A. Parameters Measured - Key measurements include:

1. Hydraulic diffusivity $D(\theta)$ and moisture characteristic $\psi(\theta)$ curves for a wide range of rock suctions. Curves will be generated using laboratory data from 100 rock core segments taken at 3 m intervals.

2. Hydraulic conductivity $K(\psi)$ and specific water capacity $C(\psi)$ curves obtained from data in 1, above.

3. Soil property parameters using both the exponential and van Genuchten models.

4 Saturated hydraulic conductivity for three meter intervals within boreholes at the Apache Leap Tuff Site.

5. Physical properties, including effective porosity, bulk density, grain density, and pore size and pore area distributions obtained from cores sampled at three meter intervals.

6. Borehole temperatures as a function of depth and season to a depth of thirty meters sampled at a three meter interval.

7. Borehole water contents at three meter intervals sampled using a neutron moisture meter.

8. Borehole air flow rates sampled using a hot-wire anemometer. NUREG/CR-5097 in Yeh et al. (1988) discusses both the matrix and fracture characterization program including parameters being determined.

B. Spatial and Temporal Scales - Many of the borehole analyses (e.g., borehole temperature, water content, air flow rates) are repetively measured during different seasons. Also, all the moisture-dependent hydraulic parameters are measured at three meter intervals. The maximum distance is approximately thirty meters. The longest time series of measurements is approximately 18 months for borehole water contents and temperature profiles.

C. Experimental Setup - Nine inclined boreholes have been installed in three rows of three boreholes per row (see Figure 1). The boreholes within a row are echelon at 10 m intervals. The rows are 5 m apart. The surface of the site has been covered with a (30 x 50 m) plastic sheet to reduce natural infiltration and evaporation. Experimental conditions can be controlled more precisely by prescribing constant boundary conditions to the upper surface. Experiments in the boreholes include interval testing for temperature, water content, and saturated hydraulic conductivity. Also, pneumatic properties are also tested on intervals.

D. Sampling Strategy - To evaluate the spatial variability of moisture dependent hydraulic parameters, a sampling interval of three meters has been selected. Samples of oriented cores from the boreholes are extracted at the specified locations, and field tests are also conducted at those locations.

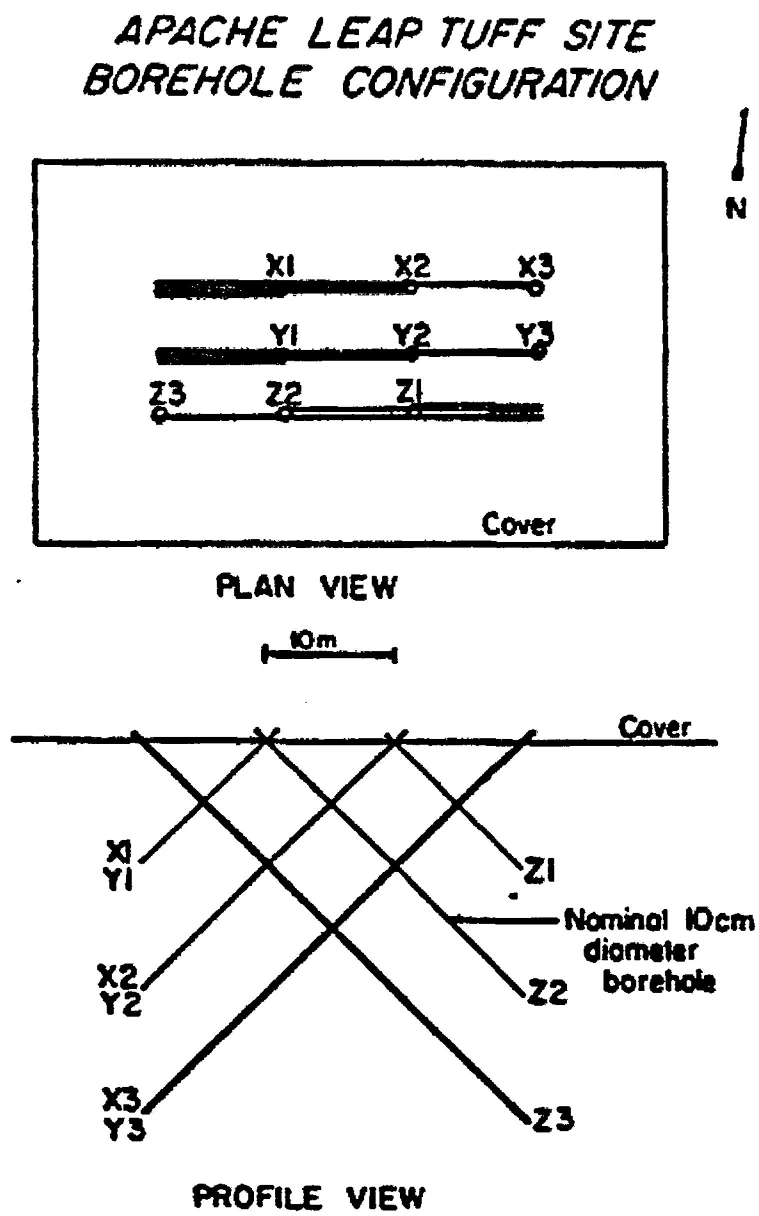

Figure 1: Borehole configuration at the Apache Leap Tuff Site showing inclined boreholes and 30 x 50 m plastic cover.

1. Rock matrix and rock fracture characterization parameters are determined using field and laboratory data. Matrix parameters are obtained from field data for 90 samples located at depths varying from 3 to 30 m (see Figure 2). The rock samples are collected from 5 cm diameter, oriented cores which were extracted at the time of borehole construction. The samples are removed from unfractured core sections at roughly three meter intervals along the core. By comparing field tests and comparing results from the field tests with laboratory tests, specific flow properties can be separated. For example, testing of unfractured cores for saturated hydraulic conductivity compares closely to field tests of saturated hydraulic conductivity. This indicates that, in most intervals, fractures do not contribute to fluid flow.

2. The saturated hydraulic conductivity is estimated using six centimeter diameter core segments cut to five centimeter length. The core segment is saturated under a vacuum and placed inside of a permeameter (see Figure 3). An inflatable packer within the permeameter is then pressurized to at least three bars to prevent bypassing of water between the core and the permeameter wall. A known pressure head of nitrogen gas, approximately one bar, is applied to the upper surface of a column of water which is in contact with the upper surface of the rock core. The outflow is measured by collecting water from the bottom of the permeameter.

3. The matric moisture characteristic curve relates the fluid content of a rock sample to the ambient fluid potential within the matrix. This relationship can be generated by applying capillary theory to the pore size distribution of by using a pressure plate extractor or a Tempe pressure cell. Both the pressure plate extractor and the Tempe pressure cell are us to apply a known positive pressure to the sample and to measure the resulting liquid displacement. The rock matrix moisture characteristic curve

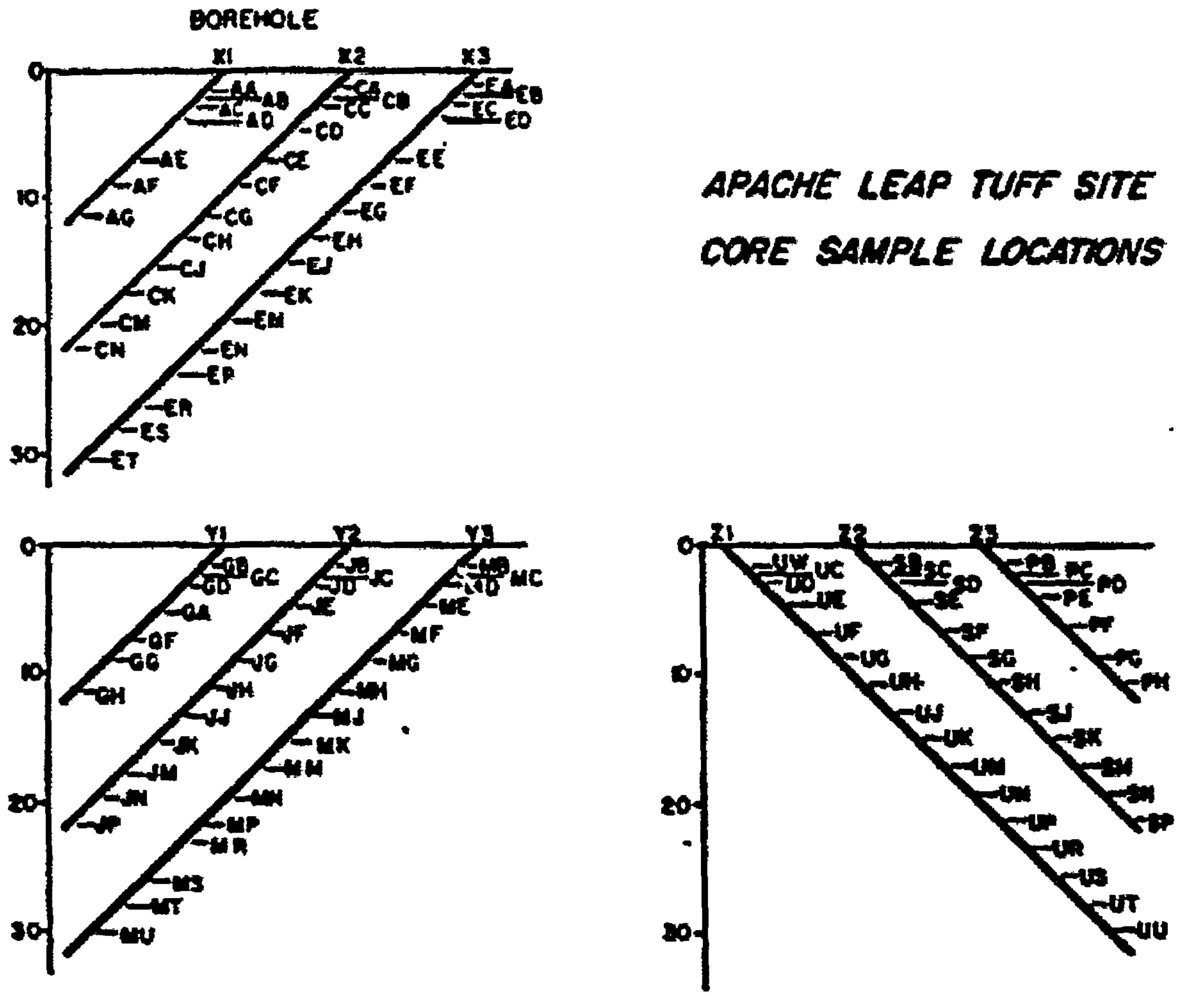

Figure 2: Core sample locations in inclined boreholes at the Apache Leap Tuff Site.

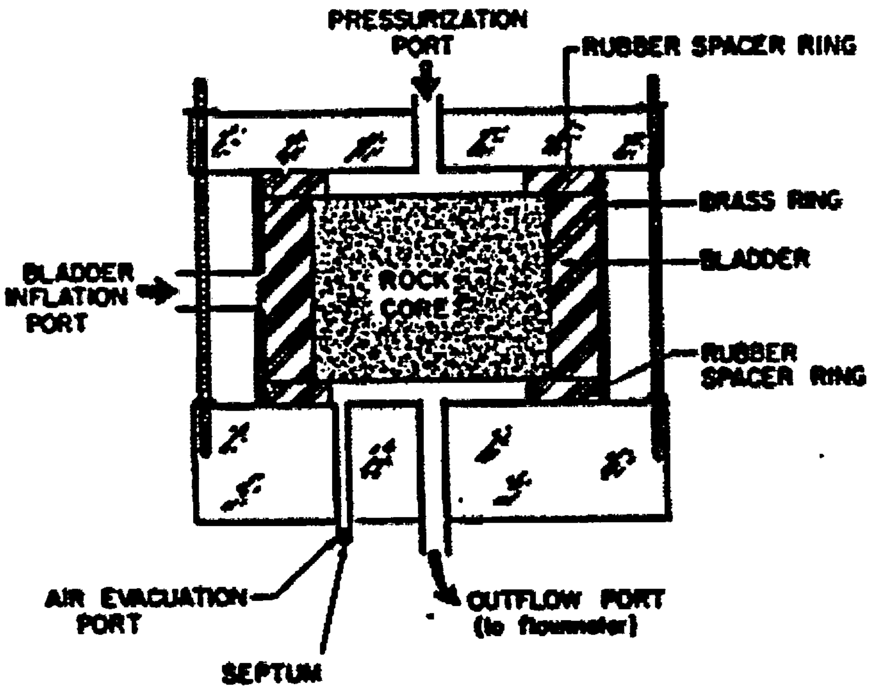

Figure 3: Permeameter used to obtain saturated hydraulic conductivity and unsaturated pneumatic permeabilities for rock core samples obtained from the Apache Leap Tuff Site.

between zero and one bar suction is obtained using the outflow method for the core segments. The outflow method uses a Tempe pressure cell with a one bar porous plate to provide an enclosed chamber within which an air pressure greater than atmospheric is applied (see Figure 4).

4. Both the moisture characteristic and unsaturated transmissivity curves for individual fractures have not been obtained due to the difficulty in monitoring both fracture water content and fracture potential. Experimental laboratory procedures are being developed (Haldeman, in preparation) to determine the moisture characteristic curve and the unsaturated hydraulic conductivity for an individual fracture within a 20 x 20 x 50 cm block of tuff. Porus plates will be affixed to the upper and lower surfaces with individual plates aligned along the fracture trace. The rock and plates will be contained within a pressure chamber which can be maintained at a pressure of up to one bar above atmospheric (see Figure 5). The water content of the fracture will be monitored using mass balance calculations. The fluid potential will be determined by the pressure maintained within the pressure chamber. The flow rate between the upper and lower plates (each maintained at a constant potential) will be used to calculate the unsaturated transmissivity.

E. Independence Between Data Sets - Substantial correlation should exist between data sets. Evaluation of the correlation is an integral part of data evaluation. By evaluating the difference between field and laboratory results, a better conceptual model can be obtained. Also, air and water permeabilities should be comparable, thus allowing the use of air permeability as a surrogate measure of the hydraulic conductivity.

F. Biases Inherent in the Design - Because the data is obtained only over a small area. larger variabilities will not be evaluated. Only local variations on the order of up to 20 m will be evaluated.

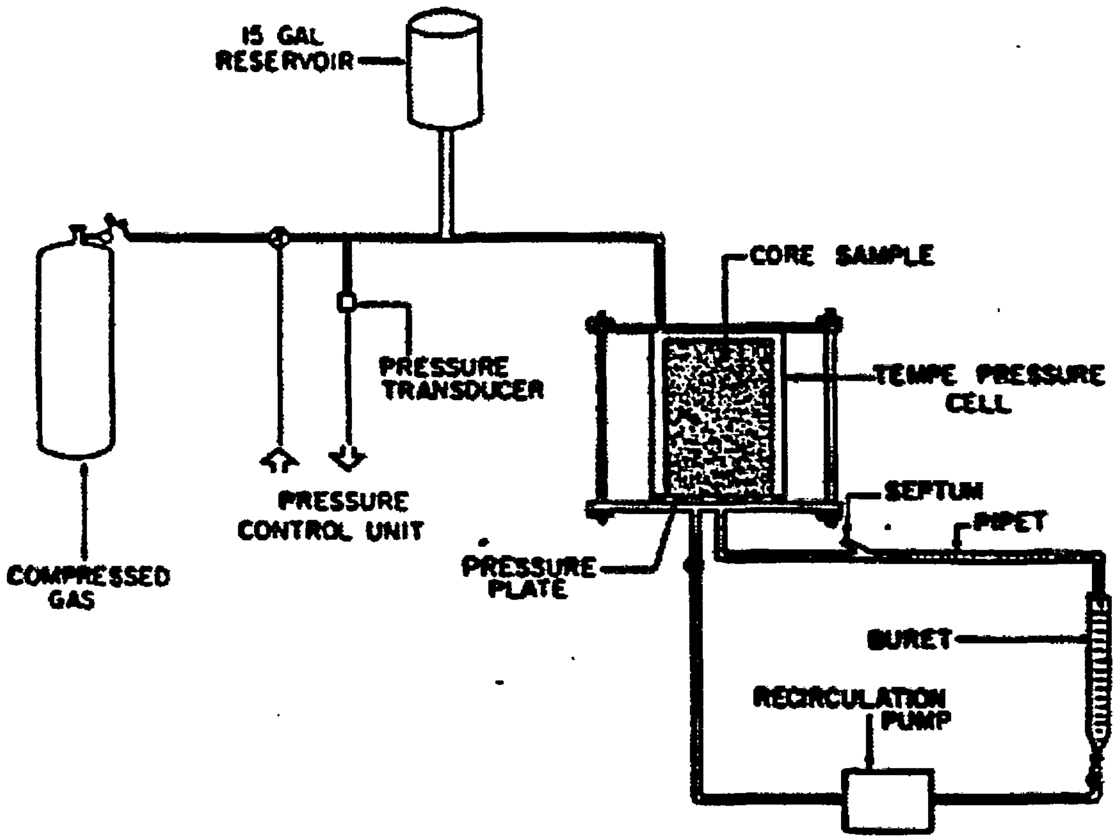

Figure 4: Outflow method experimental setup for determining unsaturated hydraulic conductivity and characteristic curves for rock core samples obtained from the Apache Leap Tuff Site.

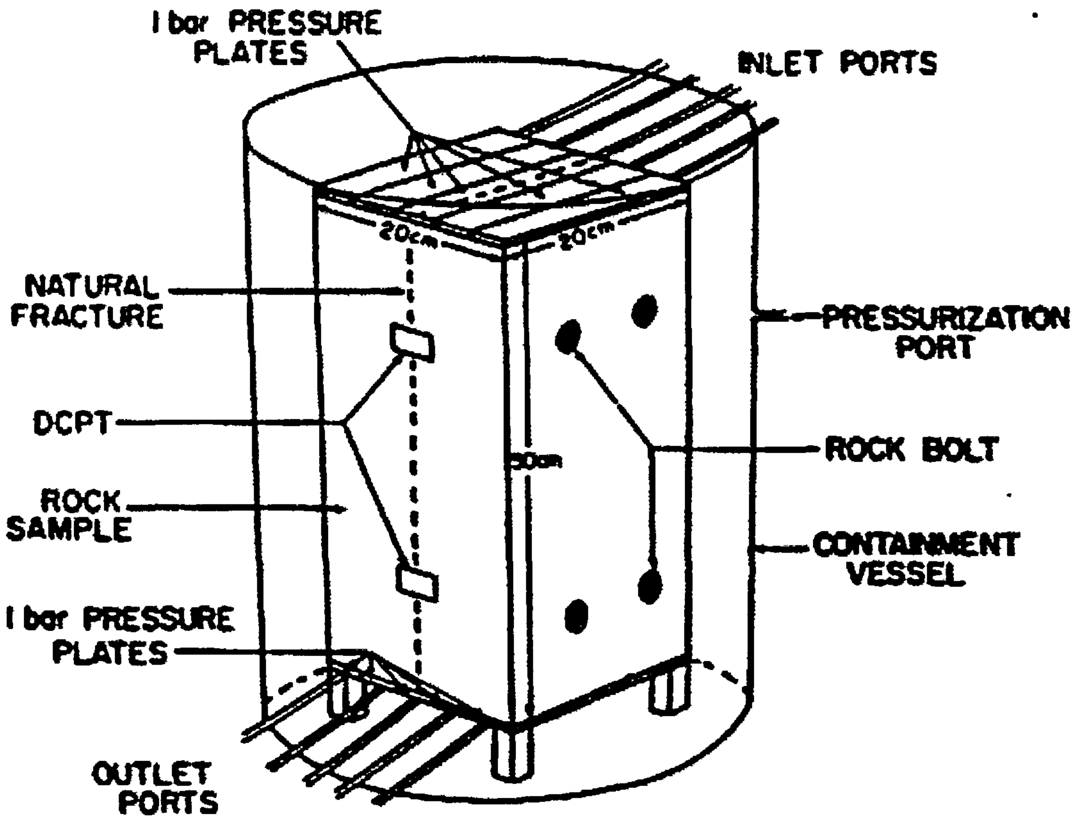

Figure 5: Experimental setup for unsaturated fracture-matrix flow studies.

Regional variations must be characterized by performing repetitions of the local sampling at other sites. Such variation, however, is beyond the scope of this study.

G. Complementary Experiments - Additional experiments in the abandoned road tunnel and the mine haulage tunnel will also provide important data in welded tuff. Comparison of parameters between sites should allow models developed at one site to be verified at another.

III. CURRENT STATUS AND EXPERIMENTAL SCHEDULE

Data from cores about moisture-dependent hydraulic properties are currently being collected and should be available by July 1988. Additional field data sets will also be available then. Pneumatic and thermal testing in the field will begin by July, 1988. Water balance data for rainfall, infiltration, deep percolation and recharge are limited by the paucity of storm events to date. Additional data will become available as weather permits.

IV. EXPERIMENTAL RESULTS

A. Raw Data - Existing processed data are available from Professor Daniel D. Evans, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ, 85721.

B. Processed Data - Exisiting processed data are available from Professor Daniel D. Evans, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ, 85721 and from Thomas J. Nicholson, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Engineering.

C. Data Storage - Raw data are currently stored in microcomputer data base files. Processed data are available as ASCII files.

V. PREVIOUS MODELING

Huang and Evans (1985) have published a discrete fracture network computer model. Extensions by Rasmussen et al. (1985), and Rasmussen (1986, 1987, 1988) have been performed using data obtained from other sites. No applications to the Apache Leap Tuff Site have been performed previous to this study.

VI. EXPECTATIONS FROM INTRAVAL PARTICIPATION

A. Experimentalists' View - Methods for obtaining data from unsaturated fractured rock will be provided. Extensions from soil science methods will be demonstrated. The ability to use existing techniques developed for soil and other porous media for consolidated geologic material needs to be evaluated. Parameters and governing equations used to interpret laboratory and field results need to be inspected to ensure that proper account is given to fundamental differences between flow through fractures and porous media. Also, methods to determine parameters for flow through fractures, such as the moisture characteristic and relative permeability curves, must be developed and confirmed. The spatial and temporal variability of media and flow properties is also addressed.

B. Modellers' View - Techniques for modeling flow through variably saturated fractured rock will be developed using calibration data sets. The uniqueness of the data set will allow the application of existing and new codes to a problem of direct relevance to issues of waste containment. The importance of flow through fractures is of major concern and can be directly assessed using simulation tools once appropriate input data sets are available. Forecasts and predictions of fluid flow through a fractured rock mass can then be used to guide additional field and laboratory experiments. Evaluation of sensitivity coefficients between field parameters and mass transport rates can be used to design testing strategies for containment capabilities. The use of local stochastic data sets for generating large scale transport characteristics is also of interest. The comparison of local with large scale behavior using observed data should allow confirmation of fluid flow models.

VII. INFORMATION EXCHANGE

<u>Addresses of Key Personnel</u>

Name	Address	Telephone No. 6
Daniel D. Evans Todd C. Rusmussen	Department of Hydrology and Water Resources University of Arizona Tucson, AZ 85721	(602) 621-7118
Thomas J. Nicholson	Division of Engineering Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Comm. Washington, DC 20005	(301) 492-3856

VIII. POSSIBILITIES FOR FUTURE EXPERIMENTS AND DATA COLLECTION

Future investigations at other field sites within the same tuff formation will allow the evaluation of small-scale variations from site to site to be compared, as well as to estimate-large scale variabilities.

The extension of the existing testing facilities to evaluate alternate transport scenarios (e.g., vapor vs liquid phase, thermal vs gravitational driving forces, etc.) will be evaluated and recommendations will be made for experimental design. Fundamental to the design will be the definition of relevant processes and their relative importance. The evaluation of the alternate processes can be made using simulation models with preliminary available from existing data sets.

IX. OUTPUT FORMAT

Raw and processed data will be provided for subsequent researchers, along with sampling and experimental procedures. Interpreted parameters will be qualified so that incorrect application of the parameters to other sites will not occur. A compendium of experimental methods and procedures will be provided, along with details of the quality assurance program used.

X. REFERENCES

Books

Evans, D.D. and T.J. Nicholson (eds.), 1987, Flow and Transport Through Unsaturated Fractured Rock, AGU Geophysical Monograph 42, 187 pp.

Peer Reviewed Articles

Schrauf, T.W. and D.D. Evans, 1986, "Laboratory Studies of Gas Flow Through a Single Natural Fracture", Water Resour. Res., 22(7):1038-1050

Kilbury, R.K., and T.C. Rasmussen, D.D. Evans, and A.W. Warrick, 1986, "Water and Air Intake Measurement Technique for Fractured Rock Surfaces", Water Resour. Res/, 22(10):1431-1443.

Evans, D.D. and T.J. Nicholson, 1987, "Flow and Transport Through Unsasturated Fractured Rock, AGU Geophysical Monograph 42, p. 1-10.

Rasmussen, T.C., 1987, "Computer Simulation of Steady Fluid Flow and Solute Transport Through Three-Dimensional Networks of Variably Saturated, Discrete Fractures", in Flow and Transport Through Unsaturated Fractured Rock, AGU Geophysical Monograph 42, p. 107-114.

NUREG Publications issued by The U.S. Nuclear Regulatory Commission

Evans, D.D., 1983, "Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories," NUREG/CR-3206, U.S. Nuclear Regulatory Commission, Washington, D.C., 231 pp.

Schrauf, T.W. and D.D. Evans, 1984, "Relationship Between the Gas Conductivity and Geometry of a Natural Fracture," NUREG/CR-3680, U.S. Nuclear Regularoty Commission, Washington, D.C., 131 pp.

Huang, C. and D.D. Evans, 1985, "A Dimensional Computer Model to Simulate Simulate Fluid Flow and Contaminant Transport Through a Rock Fracture System," NUREG/CR-CR-4654, U.S. Nuclear Regulatory Commission, Washington, D.C., 163 pp.

Green, R.T. and D.D. Evans, 1987, "Radionuclide Transport as Vapor Through Unsaturated Fractured Rock," NUREG-CR-4654, U.S. Nuclear Regulatory Commission, Washington, D.C., 163 pp.

Rasmussen, T.C. and D.D. Evans, 1987, "Unsaturated Flow and Transport Through Fractured Rock - Related to High-Level Waste Repositories," NUREG/CR-4655, U.S. Nuclear Regulatory Commission, Washington, D.C., 474 pp.

Yeh, T.C.J., T.C.Rasmussen and D.D. Evans, 1988, "Simulation of Liquid and Vapor Movement in Unsaturated Fractured Rock at the Apache Leap Tuff Site: Models and Strategies," NUREG/CR-5097, U.S. Nuclear Regulatory Commission, Washington, D.C., 73 pp.

Published Proceedings

Evans, D.D. and C. Huang., 1983, "Role of Desaturation on Transport Through Fractured Rock, in Role of the Unsaturated Zone in Radioactive and Hazardous Waste Disposal, Ann Arbor, p. 165-178.

Green, R.T. and D.D. Evans, 1985, "Radionuclide Transport as Vapor Through Unsaturated Fractured Rocks", in Memoirs of Congress on Hydrology of Rocks of Low Permeability, International Association of Hydrogeologists, Tucson, AZ., 17(1):254-266.

Rasmussen, T.C., C. Huang, and D.D. Evans, 1985, "Numerical Experiments on Artificially Generated, Three-Dimensional Fracture Networks: An Examination of Scale and Aggregation Effects", in Memoirs of Congress on Hydrology of Rocks of Low Permeability, International Association of Hydrogeologists, AZ., 17(2):676-682.

Rasmussen, T.C., 1986, "Improved Site Characterization Using Multiple Approaches", in Groundwater Flow and Transport Modeling for Performance Assessment of Deep Geologic Disposal of Radioactive Waste: A Critical Evaluation of the State of the Art, NUREG/CP-0079, pp. 101-113.

Green, R.T., and W.L. Filipone, and D.D. Evans, 1987, "Effect of Electric Fields on Vapor Transport Near a High-Level Waste Canister", in Coupled Processes Associated with Nuclear Waste Repositories, Academic Press, Inc., p. 421-432.

Rasmussen, T.C. 1987, "Meso-Scale Estimates of Unsaturated Fractured Rock Fluid Flow Parameters", in Rock Mechanics: Proceedings of the 28th US Symposium, A.A. Balkema, p. 525-532.

Evans, D.D., T.C. Rasmussen, and T.J. Nicholson, 1987, "Fracture System characterization for Unsaturated Rock", Waste Management '87, 2:209-212.

Presented Papers

Cullinan, S.R., C. Huang, and D.D. EVANS, 1982, "Non-Isothermal Vapor Transport in a Single Unsaturated Rock Fracture," EOS, 63(45):934.

Evans, D.D., R.C. Trautz, J.W. Andrews, and D.E. Earp, 1983, "Water Flow in an Unsaturated Fractured Rock: A Case Study," EOS, 64(18):228.

Earp, D.E., D.D. Evans, and C. Huang, 1983, "An Osmotic Tensiometer for Measuring Pressure Head in Unsaturated Fractured Rock," EOS, 64(18):228.

Huang, C. and D.D. Evans, 1983, "Modeling Flow in Unsaturated, Fractured Rock Formations with Application to Nuclear Waste Repositories," EOS, 64(18):229.

Schrauf, T.W. and D.D. Evans, 1983, "Laboratory Studies of Gas Flow Through a Single Natural Fracture," EOS, 64(45):704.

Green, R.T. and D.D. Evans, 1984, "Radionuclide Transport as Vapor Through Unsaturated Fractured Rock," EOS, 65(45):881.

Rasmussen, T.C., 1985, "Improved Site Characterization Using Multiple Approaches," at Symposium on Groundwater Flow and Transport Modeling for Performance Assessment of Deep Geologic Disposal of Radioactive Waste, Albuquerque, NM, May 20, 1985.

Kilbury, R.K., T.C. Rasmussen, and D.D. Evans, 1985, "Water Intake Across the Atmosphere-Earth Boundary into a Fractured Rock System," EOS, 66(18):226

Nicholson, T.J., and D.D. Evans, 1985, "High Level Radioactive Waste Repository Site Characterization: Unsaturated Zone," EOS, 66(18):269.

Rasmussen, T.C., and D.D. Evans, 1985, "Three-Dimensional Computer Modeling of Discrete Fracture Networks: Application to Unsaturated Media," EOS, 66(18):275.

Green, R.T., W.L. Filipone, and D.D. Evans, 1985, "Effect of Electric Fields on Vapor Transport near a High-Level Waste Canister," International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Lawrence Berkeley Laboratories, September 18-20.

Rasmussen, T.C., and D.D. Evans, 1985, "Three-Dimensional Computer Model of Discrete Fracture Networks Incorporating Matrix Diffusion, EOS, 66(46).

Rasmussen, T.C., 1986, "Modeling of Three-Dimensional Fracture Networks," presented at Unsaturated Rock/Conaminant Transport Workshop II, Tucson, AZ, January 8, 1986.

Theses and Dissertations

Andrews, Jon W., 1983, "Water Content of Unsaturated, Fractured, Crystalline Rocks from Electrical Resistivity and Neutron Logging," M.S. Thesis.

Cullinan, Steve R., 1983, "Non-Isothermal Vapor Transport in a Single Unsaturated Rock Fracture," M.S. Thesis.

Schrauf, Todd W., 1984, "Relationship Between the Gas Conductivity and Geometry of a Natural Fracture," M.S. Thesis.

Trautz, Robert C., 1984, "Rock Fracture Aperture and Gas Conductivity Measurements In Situ," M.S. Thesis.

Green, Ron T., 1985, "Transport of Radionuclides as Vapor in Unsaturated Fractured Rock," Ph.D. Dissertation.

Matthews, Daniel, 1986, "Thermally Induced Counter-Current Flow in Unsaturated Rock," M.S. Thesis.

Rahi, Khayyun, 1986, "Hydraulic Conductivity Assessment for a Variably-Saturated Rock Matrix," M.S. Thesis.

Amter, Steven, 1987, "Injection-Recovery Techniques for Vacuum Lysimeter Sampling in Highly Unsaturated Media," M.S. Thesis.

Amutis, Rikki, 1987, "The Application of Thermoelectric Cooling Techniques to Sampling and Detection of Solutes in Unsaturated Fractured Rock," M.S. Thesis.

Anderson, Ingrid, 1987, "Measurement of Unsaturated Rock-Water Potential In Situ," M.S. Thesis.

Davies, Bill, 1987, "Measurement of Thermal conductivity and Diffusivity in an Unsaturated, Welded Tuff," M.S. Thesis.

Weber, Dan, 1987, "Mineralogic, Isoltopic and Spatial Properties of Fractures in an Unsaturated, Partially-Welded Tuff near Superior, Arizona," M.S. Thesis.

Elder, Alexander N., In Progress, "Theoretical Calibration of Neutron Gauges," M.S. Thesis.

Rasmussen, Todd Christian, In Progress, "Fluid Flow and Solute Transport Through Three-Dimensional Networks of Variably-Saturated Discrete Fractures," Ph.D. Dissertation.

Goering, Tim, In Progress, "Use of Fluorescent Dyes as Tracers in Unsaturated, Fractured Rock," M.S. Thesis.