1 of 1

**Modeling of Hydrologic Conditions and Solute
Movement in Processed Oil Shale Waste Embankments
Under Simulated Climatic Conditions**

**Annual Report
October 1991 - September 1992**

**John P. Turner
Tim L. Reeves
Quentin D. Skinner
Victor Hasfurther**

November 1992

Work Performed Under Contract No.: DE-FC21-86LC11084

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
University of Wyoming
Environmental Simulation Laboratory
Laramie, Wyoming

MASTER

DISCLAIMER

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

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available at (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161; phone orders accepted at (703) 487-4650.

**Modeling of Hydrologic Conditions and Solute
Movement in Processed Oil Shale Waste Embankments
Under Simulated Climatic Conditions**

**Annual Report
October 1991 - September 1992**

**John P. Turner
Tim L. Reeves
Quentin D. Skinner
Victor Hasfurther**

Work Performed Under Contract No.: DE-FC21-86LC11084

**For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

**By
University of Wyoming
Environmental Simulation Laboratory
P.O. Box 3354
Laramie, Wyoming 82071**

November 1992

Table of Contents

1.0	Introduction	1
2.0	Objectives	3
2.1	Milestone Schedule/Progress Summary	5
3.0	Technical Progress/Results	7
3.1	Effects of Weathering on Hydrologic and Geotechnical Properties	7
3.2	In Situ Hydrologic Analyses	15
3.3	In Situ Hydraulic Conductivity Tests	32
3.4	Preliminary Infiltration Measurements	33
3.5	Simulated Climatic Models	35
3.5.1	Time/Activity Schedule for Project Completion	37
3.6	Lysimeter Infiltration Measurements	38
3.7	Lysimeter Leaching Measurements	39
3.8	Hydrologic Modeling	50
4.0	Literature Cited	52

List of Tables

Table 3.1.1	10
Table 3.1.2	11
Table 3.2.1	18
Table 3.2.2	21
Table 3.2.3	22
Table 3.2.4	23
Table 3.2.5	23
Table 3.2.6	24
Table 3.2.7	25
Table 3.2.8	26
Table 3.2.9	27
Table 3.3.1	34

List of Figures

Figure 3.1.1	.....	12
Figure 3.1.2	.....	13
Figure 3.1.3	.....	14
Figure 3.2.1	.....	16
Figure 3.2.2	.....	17
Figure 3.2.3	.....	28
Figure 3.2.4	.....	29
Figure 3.2.5	.....	30
Figure 3.2.6	.....	31
Figure 3.6.1	.....	40
Figure 3.6.2	.....	41
Figure 3.7.1	.....	42
Figure 3.7.2	.....	43
Figure 3.7.3	.....	44
Figure 3.7.4	.....	45
Figure 3.7.5	.....	46
Figure 3.7.6	.....	47
Figure 3.7.7	.....	49
Figure 3.8.1	.....	51

1.0 INTRODUCTION

This research program was initiated in 1986 under a Cooperative Agreement between the U.S. Department of Energy, Laramie Projects Office and the University of Wyoming (UW), Contract Number DE-FC21-86LC11084. Cooperative agreements were also established between the University of Wyoming and Rio Blanco Oil Shale Co., Inc. (RBOSC) in 1987 and between the University of Wyoming and Exxon USA, Colony Shale Oil Project, in 1988.

A continuation application and proposal which outlined and described further research to be conducted was submitted to the LPO in January 1991. This addended proposed research program would be conducted over a two year period. Budgets were developed for the first and second years for this research and submitted as part of the proposal. The proposal was accepted by LPO and the Morgantown Energy Technology Center (METC) in April 1990. Work was initiated on the proposed research May 1, 1991 upon notification that the first year budget had been finalized by METC and UW.

The scope of the original research program and of its continuation is to study interacting hydrologic, geotechnical, and chemical factors affecting the behavior and disposal of combusted processed oil shale. The research combines bench-scale testing with large-scale testing sufficient to describe commercial-scale embankment behavior. The large-scale testing was accomplished by constructing five lysimeters, each 7.3 x 3.0 x 3.0 m deep, filled with processed oil shale that has been retorted and combusted by the Lurgi-Ruhrgas (Lurgi) process (Schmalfield 1975). Approximately 400 tons of Lurgi processed oil shale waste was provided by RBOSC to carry out this study.

Three of the lysimeters were established at the RBOSC Tract C-a in the Piceance Basin near Rifle, Colorado. Two lysimeters were established in the Environmental Simulation Laboratory (ESL) at UW. The ESL was specifically designed and constructed so that a large

range of climatic conditions could be physically applied to the processed oil shale which was placed in the lysimeter cells.

This report discusses and summarizes results from scientific efforts conducted between October 1991 and September 1992 for Fiscal Year 1992.

2.0 OBJECTIVES

Research objectives were designed to evaluate hydrologic, geotechnical, and chemical properties and conditions which would affect the design and performance of large-scale embankments. The objectives of the originally proposed research are:

- Assess the unsaturated movement and redistribution of water and the development of potential saturated zones and drainage in disposed processed oil shale under natural and simulated climatic conditions.
- Assess the unsaturated movement of solubles and major chemical constituents in disposed processed oil shale under natural and simulated climatic conditions.
- Assess the physical and constitutive properties of the processed oil shale and determine potential changes in these properties caused by disposal and weathering by natural and simulated climatic conditions.
- Assess the use of previously developed computer model(s) to describe the infiltration, unsaturated movement, redistribution, and drainage of water in disposed processed oil shale.
- Evaluate the stability of field scale processed oil shale solid waste embankments using computer models.

The objectives of the continuation research are:

- Determine and assess effects on the hydrologic and geotechnical properties of the disposed processed oil shale waste material caused by extreme precipitation input sufficient to achieve steady state drainage of water through the oil shale waste material.
- Determine and assess effects on the hydrologic and geotechnical properties of the disposed processed oil shale caused by multiple freeze-thaw cycles and extreme storm events.

Some tasks associated with the original project objectives require the destructive sampling of the processed oil shale that had been placed in the lysimeters. These tasks were postponed until completion of the climatic simulation experiments proposed for the

continuation research. The postponement of these tasks were described in the continuation application and research proposal and accepted by DOE.

2.1 Milestone Schedule/Progress Summary

Five milestones were outlined and discussed in the continuation research plan and the previous reports for this project. The time/activity schedule and a brief discussion of progress completed in FY 1992 is presented below for these milestones:

- 1. Prepare an interim report presenting data and discussing conclusions accomplished for Cooperative Agreement DE-FC21-86LC11084 from October 1986 to May 1991.**

Discussion: A draft of this report was completed for both internal review and review by the COTR in December 1991. The final draft for this report was completed in April 1992.

Status: Completed 4/92.

- 2. Design (model) a series of simulated climatic conditions and rainfall events which will provide extreme hydrologic and geotechnical conditions to the processed oil shale in the Environmental Simulation Laboratory (ESL).**

Discussion: Two climatic models were developed to accomplish the research objectives. The first climatic model and sampling program was designed to accommodate objectives for infiltration behavior, and to develop and analyze saturated conditions in the processed oil shale. The second climatic model was run after saturated conditions have been developed within the profile. This model was designed to produce a series of freeze thaw conditions and analyze the effects on the processed oil shale. A detailed discussion of the climatic models are presented in section 3.5

Status: Completed 12/91.

- 3. Apply the designed climatic conditions in the ESL and collect hydrologic and geotechnical data.**

Discussion: The environmental simulation laboratory has the capability of monitoring runoff and determining a runoff hydrograph via an automated weighing water collection system. Infiltration curves for each applied storm can be basically developed by subtracting the measured runoff hydrograph data from the applied rainfall hyetograph. Infiltration curves produced from different storm events will be evaluated as a function of the antecedent moisture content at several depths, and from the hydraulic gradients within the profile. Water contents will be measured before, during, and after all applied storm events. Hydraulic gradients will be calculated from water characteristic curves that were previously developed in this research program.

Schedule: 2/10/92 - 12/92 .

Status: Climatic simulations were initiated in February 1992. These analyses have been delayed and interrupted approximately one month because of equipment breakdown in the ESL. A detailed discussion of this progress is presented in section 3.5

4. Destructively sample and dispose of the processed waste material in the lysimeter beds of the ESL.

Discussion: Destructive sampling will be conducted to extract undisturbed specimens and cores of the processed oil shale at several different depths. These specimens will be used to evaluate hydrologic properties, soil mechanical properties, and leachate chemical properties. These data obtained and the properties measured from the "weathered" processed oil shale will be compared to the results from the testing program which was previously conducted.

Schedule: 3/93 - 5/93 (rescheduled)

Status: Because of delays caused by equipment breakdown and repair in the ESL, the application of this objective was suspended and postponed. The completion of this objective has been rescheduled to the above date (3/93 - 5/93). The destructive sampling program will be initiated after completion of all climatic simulations.

5. Analyze and evaluate all data sets and prepare final report.

Discussion: This report will be a comprehensive report, detailing all data and results, for this Cooperative Agreement.

Schedule: Data Analysis (7/93 - 9/93) Report (10/93 - 12/93)

3.0 TECHNICAL PROGRESS/RESULTS

3.1 Effects of Weathering on Hydrologic and Geotechnical Properties

To evaluate the potential effects of weathering on strength and hydraulic conductivity, samples of hydrated processed shale were subjected to wet-dry and freeze-thaw conditions in accordance with ASTM D 559-82, *"Standard Method for Wetting-Drying Tests of Compacted Soil-Cement Mixtures"* or ASTM D 560-82, *"Standard Method for Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures"* (ASTM 1985). Samples were compacted at either 15% or 27% water content (w/w) in special soil-cement molds (ASTM 1985) and were 7.1 cm in diameter and 14.2 cm high. Two samples were prepared for each test and then cured for 28 days at 20°C and 100% relative humidity.

In the wet-dry test, the 2 samples are submerged in a water bath for 5 hours. One of the specimens is weighed and measured to determine volume change. The second sample is given 2 firm strokes on all surface areas with a wire scratch brush and then is weighed and measured to determine cement loss as a percentage of initial sample weight. Both samples then are placed in an oven at 71°C for 42 hours. Twelve such cycles are applied, in accordance with ASTM (1985). In the freeze-thaw test, the 2 samples are maintained at -23°C for 24 hours. One sample is brushed and then both samples are weighed, measured, and placed in a moist room at 20°C and 100% relative humidity for 23 hours. Following the completion of twelve cycles of either wetting-drying or freezing-thawing, the hydraulic conductivity of each sample was measured using both the falling head and flow pump methods, followed by a consolidated undrained triaxial compression test.

A total of 30 pairs of samples were subjected to artificial weathering by wet-dry or freeze-thaw conditions. All samples withstood 12 cycles without failure. Tables 3.1.1 and

3.1.2 present the maximum volume change, maximum water content during testing, percent water retained following the final oven drying, and cement loss (as a percentage of total initial sample weight) for each pair of samples. As a comparison, for highway subgrade construction, cement-stabilized soils are required to withstand 12 cycles with a maximum cement loss of 14%. All cement losses for the processed shale were well below 14%. Note that the percent water retained is in the range of 3-5%, approximately the percentage of water believed to be bound up by cementation.

Effects on Strength. Following a 28 day curing period, 24 days of weathering, and two saturated hydraulic conductivity tests, one sample from each pair was subjected to a CU triaxial compression test. The resulting total stress Mohr's circles at failure are plotted in Figure 3.1.1. The weathered samples show considerably higher strengths than those measured for unweathered samples and the results fall into two groupings. The first group consists of the samples prepared at a water content of 15% (w/w) and exhibits lower strengths than the second group, prepared and cured at a water content of 27%. Apparently, the angle of friction does not change, but the cohesion changes significantly, probably because of cementation. The differences in strength between the weathered and unweathered samples and between the weathered samples at $\theta_w = 15\%$ versus $\theta_w = 27\%$ can be explained by the effects of sample preparation and curing on cementation. The unweathered samples were cured for 7 days and then tested in triaxial compression tests. The weathered samples were cured for 28 days, during which time they may have gained significantly higher strengths from cementation, with the samples at $\theta_w = 27\%$ developing considerably more cementitious bonding than those at $\theta_w = 15\%$. If it is assumed that the undrained friction angle does not change from 14.4 degrees, as was measured on unweathered samples, than

the increased cohesion resulting from longer curing times and different water contents of the weathered samples can be seen in Figure 3.1.1.

A third group of samples is being prepared to provide a control group for evaluating the effects of weathering. These samples will be cured for the same number of days as the weathered samples ($28 + 24 = 52$ days), tested for saturated hydraulic conductivity, and then tested in triaxial compression. This will provide a more consistent comparison with the weathered samples. These data will be discussed in the final report for this project.

Effects on Hydraulic Conductivity. Each of the 60 samples was subjected to falling head hydraulic conductivity tests following curing and wet-dry or freeze-thaw weathering. Eighteen samples were prepared at $\theta_w = 15\%$ and 12 were prepared at $\theta_w = 27\%$. The results are plotted with unweathered samples in Figures 3.1.2 and 3.1.3. Comparing results for unweathered samples with those presented in 3.1.3, there is no observable effect caused by weathering for samples prepared at $\theta_w = 15\%$. The weathered samples prepared at $\theta_w = 27\%$ show considerable scatter and no effect can be concluded. Four additional samples weathered for 7 days are also presented in Figure 3.1.3.

Table 3.1.1 Weathering results, soil-cement Samples at $\theta_w = 15\%$.

	A	B	C	D	E	F	G	H	I	J
1	WEATHERING RESULTS									
2										
3	SA #	w	DD	CURE	W-D vs.		Max. Vol.	Max. w	WATER	S C
4		(%)	(pcf)	TIME	F-TH		Change	w	RETAINED	LOSS
5				(wk)			(%)	(%)	(%)	(%)
6	M90-29	15	87.8	4	W-D		-0.4	37.1	4.6	-----
7	M90-30	15	87.7	4	W-D		-----	-----	-----	0.7
8	J90-13	15	88	4	W-D		-1	37.1	3.9	-----
9	J90-14	15	88.1	4	W-D		-----	-----	-----	3.8
10	JU90-14	15	87.9	4	W-D		0.55	35.4	3.9	-----
11	JU90-15	15	88.1	4	W-D		-----	-----	-----	4
12	M90-27	15	87.7	4	F-TH		4.4	39.4	4.2	-----
13	M90-28	15	87.9	4	F-TH		-----	-----	-----	4
14	J90-15	15	88.1	4	F-TH		3.9	38.7	3.9	-----
15	J90-16	15	88	4	F-TH		-----	-----	-----	2.4
16	JU90-16	15	88	4	F-TH		2.5	38.7	3.9	-----
17	JU90-17	15	88.1	4	F-TH		-----	-----	-----	0.8
18	JU90-27	15	88.1	4	W-D		0.64	36.9	4	-----
19	JU90-28	15	87.9	4	W-D		-----	-----	-----	3.4
20	J90-17	15	87.9	4	W-D		-0.6	36.9	3.9	-----
21	J90-18	15	88.1	4	W-D		-----	-----	-----	4.5
22	JU90-3	15	88	4	W-D		0.46	35.8	3.9	-----
23	JU90-4	15	87.9	4	W-D		-----	-----	-----	4.5
24	JU90-1	15	88	4	F-TH		0.57	38.5	2.7	-----
25	JU90-2	15	88	4	F-TH		-----	-----	-----	3.9
26	JU90-29	15	87.9	4	F-TH		4.6	36.8	2.8	-----
27	JU90-30	15	88.2	4	F-TH		-----	-----	-----	3.2
28	J90-19	15	88	4	F-TH		2.5	38.5	4.6	-----
29	J90-20	15	88.1	4	F-TH		-----	-----	-----	3.7
30	JU90-10	15	87.9	4	W-D		0.44	35.4	3.9	-----
31	JU90-11	15	87.8	4	W-D		-----	-----	-----	3.8
32	J90-5	15	88.1	4	W-D		0.57	36.7	3.9	-----
33	J90-6	15	88	4	W-D		-----	-----	-----	3.8
34	AU90-1	15	88	4	W-D		-0.44	36.7	4.7	-----
35	AU90-2	15	88.1	4	W-D		-----	-----	-----	4.7
36	JU90-12	15	88.3	4	F-TH		2	37.9	4.2	-----
37	JU90-13	15	88.1	4	F-TH		-----	-----	-----	4.7
38	J90-7	15	88.1	4	F-TH		2.6	37.4	4.3	-----
39	J90-8	15	88	4	F-TH		-----	-----	-----	3.8
40	AU90-3	15	88	4	F-TH		1.6	38.3	4.6	-----
41	AU90-4	15	88	4	F-TH		-----	-----	-----	4.1

Table 3.1.2 Weathering results, soil-cement samples at $\theta_w = 27\%$.

	A	B	C	D	E	F	G	H	I	J
1										
2										
3	SA #	w	DD	CURE	W-D or		Max. Vol.	Max.	WATER	S-C
4		(%)	(pcf)	TIME	F-TH		Change	w	RETAINED	LOSS
5				(wk)			(%)	(%)	(%)	(%)
6	M90-14	27	93	4	W-D		-0.88	31.6	4.1	-----
7	M90-15	27	93.1	4	W-D		-----	-----	-----	4.2
8	JU90-23	27	93.5	4	W-D		-0.85	31.3	4	-----
9	JU90-24	27	93	4	W-D		-----	-----	-----	4.3
10	JU90-25	27	93.1	4	F-TH		-0.35	31.7	4.1	-----
11	JU90-26	27	93.4	4	F-TH		-----	-----	-----	4.3
12	M90-12	27	93	4	F-TH		1.2	31.6	4.1	-----
13	M90-13	27	93	4	F-TH		-----	-----	-----	4.2
14	M90-35	27	93.2	4	W-D		-0.85	30.3	4.1	-----
15	M90-36	27	93.3	4	W-D		-----	-----	-----	3.8
16	JU90-35	27	93.3	4	W-D		0.42	31.3	4.1	-----
17	JU90-36	27	93.4	4	W-D		-----	-----	-----	3.8
18	M90-33	27	93.1	4	F-TH		0.5	31.5	4.1	-----
19	M90-34	27	93	4	F-TH		-----	-----	-----	3.8
20	JU90-33	27	93.5	4	F-TH		-0.28	32.5	3.7	-----
21	JU90-34	27	93.7	4	F-TH		-----	-----	-----	4.4
22	JU90-6	27	93.1	4	W-D		-1.2	31.2	4.1	-----
23	JU90-7	27	93.3	4	W-D		-----	-----	-----	3.7
24	J90-9	27	93.4	4	W-D		-0.75	30.9	4.1	-----
25	J90-10	27	93	4	W-D		-----	-----	-----	3.8
26	JU90-8	27	93.3	4	F-TH		-0.36	32.1	4	-----
27	JU90-9	27	93	4	F-TH		-----	-----	-----	3.9
28	J90-11	27	93.4	4	F-TH		-0.46	32.2	4.1	-----
29	J90-12	27	93.2	4	F-TH		-----	-----	-----	3.8
30	JA90-2	27	95.1	1	W-D		3.3	27.9	3.5	-----
31	JA90-3	26	93.7	1	W-D		-----	-----	-----	3.9
32	JA90-5	27	92.6	1	F-TH		4.7	33.4	3.7	-----
33	JA90-4	27	92.8	1	F-TH		-----	-----	-----	3.8

Figure 3.1.1 Results of consolidated undrained triaxial tests on weathered processed oil shale.

Figure 3.1.2 Hydraulic conductivity versus curing time for weathered and unweathered samples at $\theta_w = 15\%$.

Figure 3.1.3 Hydraulic conductivity versus curing time for weathered and unweathered samples at $\theta_w = 27\%$.

3.2 In Situ Hydrologic Analyses

Measurements of volumetric water content (θ_v) were taken from TDR probes placed in situ for each sampling date. For each replicative set of instrumentation in each of the 5 lysimeters (3 field lysimeters at RBOSC and 2 lysimeters in at UW), plots have been generated of θ_v versus depth below the ground surface for each sampling date. As an example, Figure 3.2.1 is a soil moisture profile for one set of TDR instrumentation in cell 1 at the RBOSC field site taken May 11, 1988. A complete set of raw data and soil moisture profiles for each sampling date is on file and can be obtained by contacting the project manager.

Soil moisture profiles were used to estimate two hydrologic parameters of the spent shale embankments: 1) volumetric flux of water, and 2) hydraulic gradient. These data were used to estimate the hydraulic conductivity, as follows:

According to Darcy's Law, which governs the flow of water through porous media,

$$q = k \times i$$

where q = volumetric flow rate or flux ($\text{cm}^3/\text{cm}^2/\text{sec}$), k = hydraulic conductivity (cm/sec), and i = the hydraulic gradient. To illustrate the numerical analysis, Table 3.2.1 presents the calculation of q , i , and k for one set of data in cell 1 at RBOSC, for the depth interval between 76 cm and 168 cm and for the time period between July 23 and August 12 of 1988. Figure 3.2.2 shows the moisture profiles for the two sampling dates. The shaded area between the curves represents the change in water content (change in storage) for the time period between the two readings. The area was determined by planimetry to be $1.03 \text{ cm}^3/\text{cm}^2$. The change in volumetric water content (ΔV) is divided by the time interval ($\Delta t = 20$ days) to yield the average volumetric flux (q) between these depths:

$$q = \Delta V / \Delta t$$

$$q = 1.03 \text{ cm} + 20 \text{ days} = 5.2 \times 10^{-2} \text{ cm/day.}$$

Figure 3.2.1 Moisture profile for cell 1 at the RBOSC field site on May 11, 1988.

Figure 3.2.2 Moisture profiles for two sampling dates July 23, and August 12, 1988. The shaded area between the curves represents the change in water content for the time period.

Table 3.2.1 Sample calculations for hydraulic flux, gradient, and conductivity.

Pt. A: $z = 76 \text{ cm}$ $\Delta V = 1.03 \text{ cm}$ (by planimetry)
 Pt. B: $z = 168 \text{ cm}$ $q = 1.03 \text{ cm} \div 20 \text{ days} = 5.2 \times 10^{-2} \text{ cm/day}$
 $\Delta z = 92 \text{ cm}$

	7/23/88		8/12/88	
	Pt. A	Pt. B	Pt. A	Pt. B
θ_v (%)	30.0	28.7	28.5	28.0
Soil Suction (kPa)	-37.0	-43.9	-45.0	-47.2
Pressure Head (cm)	-370.0	-439.0	-450.0	-472.0
Total Head	-279.0	-439.0	-359.0	-472.0

Gradient₁ = $(-279 - -439)/92 = 1.73$ $i_2 = (-359 - -472)/92 = 1.23$
 Average Gradient = 1.48

Hydraulic Conductivity: $k = 5.2 \times 10^{-2} / 1.48 = 3.5 \times 10^{-2} \text{ cm/day} = 4.1 \times 10^{-7} \text{ cm/sec}$

The hydraulic gradient (i) was estimated for the soil moisture profile using the soil moisture characteristic curves generated previously in this study. For each sampling date, the water contents at depths A and B were used to estimate soil suctions from the soil moisture characteristic curve. For example, θ_v at depth A ($z = 76$ cm) on July 28 was 30%. From the soil moisture characteristic curve, the corresponding soil suction is approximately 0.37 bar (37.0 kPa or 0.37 kg/cm²). Soil suction is then converted to pressure head (H_p) by

$$H_p = u + \gamma_w$$

$$H_p = -0.37 \text{ kg/cm}^2 + 1 \text{ g/cm}^3 = -370 \text{ cm}$$

where u = soil suction, and γ_w = unit weight of water. The negative sign indicates negative pore water pressure or soil suction. Pressure head at depth B ($z = 76$ cm) for the same date is found to be -439 cm. The total head (H_t) at each point is the sum of the pressure head and elevation head. If depth B is taken as an elevational reference datum, the elevation head at depth A is 91 cm and the elevation head at depth B is 0 cm. H_t for each depth A and B are then given by:

$$H_t = H_e + H_p$$

$$H_{t,A} = 91 - 370 = -279 \text{ cm}$$

$$H_{t,B} = 0 - 439 = -439 \text{ cm}$$

where H_e is the elevational head. The hydraulic gradient (i) over this depth interval then is computed as:

$$i = \Delta H / L$$

$$i = (-279 - -439) / (168 - 76) = 1.73$$

where ΔH represents the difference in total head between depths A and B and L = vertical distance between A and B. The pressure heads and resulting gradient for the August 12 sampling date are computed similarly and the gradient is found to be 1.23. The average

gradient over the 20 day time interval is estimated as the average of the beginning and ending gradients.

$$i_{avg} = (1.73 + 1.23) / 2 = 1.48$$

From Darcy's Law, the hydraulic conductivity is then computed as:

$$k = q/i$$

$$k = 5.2 \times 10^{-2} \text{ cm/day} / 1.48 = 3.5 \times 10^{-2} \text{ cm/day}$$

$$k = 4.1 \times 10^{-7} \text{ cm/sec}$$

The method of back calculating unsaturated hydraulic conductivity from in situ water content data was described by Everett et al. (1984). Further investigations and development of this method may need to be conducted, such as the identification of potential sources of error, establishment of specific boundary conditions for application of the method, and the development of a more refined and reliable soil moisture characteristic curve to convert measured water content (θ_v) to negative pore water pressures. The back calculated values of k will also be compared with in situ methods, including a Guelph permeameter as well as k measured using bench-scale samples prepared in the laboratory.

Tables 3.2.2 through 3.2.9 summarize the results of hydrologic analyses for each instrument replication at both the RBOSC field site and in the ESL. Figures 3.2.3 through 3.2.6 are plots of hydraulic conductivity versus water content for cells 1 and 2 at the field site and cells 1 and 2 of the ESL. There appears to be a general trend of increasing conductivity with increasing water content, but there is too much scatter in the data to make definitive conclusions regarding the relationship between k and water content (θ_v).

Table 3.2.2 Hydrologic data analyses by date for cell 1 replication 1 at RBOSC.

Time Period	Depth Interval (cm)		Mean Hydraulic Gradient	Mean Water Content (%)	Mean Hydraulic Conductivity (cm/sec)
14-Apr-88 11-May-88	30	46	1.3	30.2	2.1E-06
	46	61	-3.5	30.2	8.2E-07
23-Jul-88 12-Aug-88	46	61	-7.7	28.0	6.3E-07
	61	76	7.7	28.4	4.5E-07
08-Sep-88 22-Nov-88	30	61	-4.2	26.7	7.1E-07
	61	76	5.6	26.8	3.1E-07
	76	168	-10.9	22.8	5.7E-07
22-Nov-88 10-Jan-89	15	30	-12.3	24.7	4.2E-07
	30	46	5.7	24.0	7.4E-07
18-May-89 29-Jun-89	15	30	9.5	27.3	3.1E-07
	61	76	3.3	26.8	7.6E-07
	76	168	-12.0	22.4	9.6E-07
19-Jul-89 30-Nov-89	15	30	-12.0	25.1	6.2E-08
	30	46	1.7	24.2	6.3E-07
	46	61	-9.4	23.8	1.4E-07
	61	76	10.3	24.1	1.2E-07
	76	168	-12.8	20.7	4.0E-07
30-Nov-89 03-Apr-90	76	168	-12.9	21.2	5.9E-07
03-Apr-90 16-May-90	76	168	-8.3	24.2	7.1E-07
15-Jul-90 29-Jul-90	15	30	-4.7	25.3	2.0E-06

Table 3.2.3 Hydrologic data analyses by date for cell 1 replication 2 at RBOSC.

Time Period	Depth Interval (cm)		Mean Hydraulic Gradient	Mean Water Content (%)	Mean Hydraulic Conductivity (cm/sec)
23-Jul-88 12-Aug-88	76	168	-1.4	28.8	1.0E-05
	168	259	-3.3	26.5	1.3E-06
12-Aug-88 05-Sep-88	76	168	-0.8	28.0	7.5E-06
05-Sep-88 22-Nov-88	46	76	-9.3	30.1	3.8E-07
	76	168	-0.2	27.2	1.9E-05
31-Mar-89 25-Apr-89	76	168	-1.4	29.3	6.9E-06
	168	259	-2.8	27.2	3.1E-06
25-Apr-89 18-May-89	76	168	-1.3	29.0	4.2E-06
	168	259	-2.9	27.6	1.5E-06
18-May-89 29-Jun-89	15	30	3.6	24.0	3.8E-07
	30	46	21.1	28.2	8.3E-08
	46	76	-6.1	29.8	8.7E-07
	76	168	-0.8	27.9	2.1E-05
	168	259	-3.4	26.2	2.4E-06
29-Jun-89 30-Nov-89	15	30	-2.4	21.9	3.2E-07
	30	46	30.4	25.6	3.4E-08
	46	76	-10.0	26.8	2.0E-07
	76	168	0.5	25.2	8.6E-06
03-Apr-90 16-May-90	15	30	23.7	20.6	7.9E-08
	46	76	-7.1	25.5	5.6E-07
	76	168	-0.6	26.5	7.1E-06
16-May-90 29-Jun-90	46	61	-5.2	30.3	6.8E-07
	61	73	-15.0	27.6	1.3E-07
29-Jun-90 18-Jul-90	15	30	-0.3	21.0	1.7E-05
	46	61	-3.2	31.7	2.5E-06
	76	168	0.2	26.3	1.9E-04
18-Jul-90 29-Jul-90	15	30	48.9	20.0	3.4E-07
	168	259	-0.4	29.1	9.9E-05

Table 3.2.4 Hydrologic data analyses by date for cell 2 replication 1 at RBOSC.

Time Period	Depth Interval (cm)		Mean Hydraulic Gradient	Mean Water Content (%)	Mean Hydraulic Conductivity (cm/sec)
14-Apr-88 11-May-88	168	259	-2.3	21.2	3.5E-06
	259	290	-12.8	19.3	2.9E-07
05-Sep-88 22-Nov-88	91	107	-14.9	19.7	6.9E-08
	107	168	7.0	21.1	6.2E-07
	168	259	-4.0	21.8	6.6E-07
	259	290	-9.5	19.4	1.5E-07
10-Jan-89 31-Mar-89	91	107	-2.4	18.6	2.2E-07
	107	168	5.8	20.2	3.9E-07
25-Apr-89 18-May-89	91	107	-4.9	19.1	6.4E-07
	107	168	4.8	20.3	2.1E-06
18-May-89 29-Jun-89	91	107	-5.4	19.2	2.8E-07
	107	168	3.1	20.0	2.6E-06
	168	259	-3.0	20.2	2.7E-06
	259	290	-7.3	18.8	4.5E-07
29-Jun-90 18-Jul-90	76	91	75.2	15.2	7.7E-08

Table 3.2.5 Hydrologic data analyses by date for cell 2 replication 2 at RBOSC.

Time Period	Depth Interval (cm)		Mean Hydraulic Gradient	Mean Water Content (%)	Mean Hydraulic Conductivity (cm/sec)
29-JUN-90 18-JUL-90	107	168	-1.9	16.9	9.2E-06

Table 3.2.6 Hydrologic data analyses by date for cell 1 replication 1 in the ESL.

Time Period		Depth Interval (cm)		Mean Hydraulic Gradient	Mean Water Content (%)	Mean Hydraulic Conductivity (cm/sec)
25-Jun-89 05-Sep-89		15	61	9.8	21.4	4.4E-07
		61	76	-25.4	21.9	4.5E-08
		76	152	0.7	20.5	7.1E-06
		152	213	-12.9	18.7	3.1E-07
05-Sep-89 15-Sep-89		15	61	-1.0	24.2	9.2E-05
21-Sep-89 02-Oct-89		15	30	0.3	31.0	1.2E-04
		30	52	-13.3	28.4	2.3E-06
		52	61	-24.0	23.9	3.1E-07
		61	76	-18.0	21.2	5.5E-07
05-Oct-89 11-Oct-89		15	30	-5.9	28.3	3.7E-06
		30	61	-8.9	25.5	3.4E-06
13-Oct-89 23-Oct-89		15	21	-3.0	27.4	5.4E-07
		21	30	-5.5	27.0	1.1E-06
		30	61	-3.5	26.0	9.2E-06
		61	76	-30.3	22.7	1.8E-07
23-Oct-89 25-Oct-89		15	30	5.2	32.4	3.9E-05
		30	61	-7.4	30.7	3.4E-05
25-Oct-89 01-Nov-89		15	30	5.0	33.3	9.7E-06
		30	61	-8.3	31.3	6.8E-06
01-Nov-89 15-Nov-89		15	30	4.0	27.8	2.3E-06
		30	49	-0.4	28.7	1.8E-05
		49	61	-1.5	28.6	2.7E-05
10-Jan-90 16-Jan-90		15	61	-2.0	30.8	2.9E-05
25-Jun-90 05-Sep-90		15	30	2.7	22.4	3.3E-07
		30	61	9.4	26.1	3.4E-07
05-Sep-90 13-Sep-90		15	21	-1.0	22.6	2.4E-06
		21	30	-6.0	22.5	1.6E-06
		30	61	13.6	25.8	2.6E-06
13-Sep-90 25-Sep-90		15	30	-10.0	25.3	1.9E-08
		30	61	8.9	26.8	3.5E-06
24-Oct-90 25-Oct-90		15	61	2.4	27.5	1.6E-04

Table 3.2.7 Hydrologic data analyses by date for cell 1 replication 2 in the ESL.

Time Period	Depth Interval (cm)		Mean Hydraulic Gradient	Mean Water Content (%)	Mean Hydraulic Conductivity (cm/sec)
28-Jun-89 05-Sep-89	15	30	24.8	19.7	2.8E-08
	30	46	-32.5	19.4	1.8E-08
05-Sep-89 15-Sep-89	9	15	-33.0	22.2	3.7E-07
	15	30	23.2	24.5	2.0E-06
	30	46	-53.9	22.8	6.1E-07
15-Sep-89 21-Sep-89	9	15	-65.4	26.5	5.6E-08
	46	76	3.2	18.9	7.1E-06
23-Oct-89 25-Oct-89	9	15	-53.3	26.0	6.5E-07
25-Oct-89 01-Nov-89	9	15	-67.5	25.5	1.8E-07
08-Dec-89 10-Jan-90	9	15	-11.4	26.5	2.6E-07
10-Jan-90 16-Jan-90	9	15	-46.4	27.2	2.7E-07
20-Jan-90 29-Jan-90	9	15	-59.5	23.3	4.5E-08
	15	30	34.0	25.7	2.2E-07
08-Feb-90 15-Feb-90	76	152	-18.9	17.1	5.2E-06
	152	213	18.4	16.4	2.2E-06
15-Feb-90 06-Mar-90	9	15	-48.5	23.7	4.7E-08
	15	30	30.8	26.3	2.5E-07
	30	43	-38.4	26.7	1.1E-07
	46	76	2.9	20.1	1.8E-06
06-Mar-90 15-Mar-90	9	15	-57.0	24.1	5.6E-08
	15	30	31.8	26.6	4.4E-07
	30	40	-36.7	27.5	1.7E-07
	40	46	-75.0	21.9	2.1E-08
	46	76	2.5	20.1	5.2E-06
06-Mar-90 15-Mar-90	88	152	-22.6	16.2	1.8E-06
	152	213	21.0	15.9	1.8E-06
25-Jun-90 05-Sep-90	30	46	-74.5	20.8	2.1E-08
	46	76	25.2	18.9	1.4E-07
05-Sep-90 13-Sep-90	9	15	-53.0	22.5	1.5E-07
	15	30	36.1	25.4	7.0E-07
	30	46	-118.2	21.9	2.1E-07
28-Sep-90 24-Oct-90	9	15	-62.3	23.1	2.1E-08
	15	30	35.4	25.5	1.4E-07
24-Oct-90 25-Oct-90	15	30	33.9	26.0	5.3E-06
	30	46	-35.1	26.1	3.6E-06

Table 3.2.8 Hydrologic data analyses by date for cell 1 replication 3 in the ESL.

Time Period	Depth Interval (cm)		Mean Hydraulic Gradient	Mean Water Content (%)	Mean Hydraulic Conductivity (cm/sec)
28-Jun-89 05-Sep-89	76	152	4.1	20.4	2.3E-06
	152	213	-12.8	19.4	5.6E-07
05-Sep-89 15-Sep-89	76	152	3.9	20.2	1.5E-05
	152	213	-13.4	19.1	2.9E-06
21-Sep-89 02-Oct-89	15	46	-23.1	20.3	3.6E-07
	46	76	5.7	18.2	2.4E-06
	46	152	4.3	19.7	4.8E-06
13-Oct-89 23-Oct-89	46	76	7.7	20.1	1.8E-06
	76	152	0.3	21.7	1.1E-04
23-Oct-89 25-Oct-89	46	76	12.3	21.9	7.3E-06
	76	152	-2.2	23.4	8.8E-05
15-Nov-89 08-Dec-89	9	15	-10.0	22.7	1.2E-07
08-Dec-89 10-Jan-90	15	46	-15.1	22.6	1.2E-07
10-Jan-90 16-Jan-90	15	46	-13.3	22.6	2.4E-06
20-Jan-90 29-Jan-90	76	152	-1.8	26.5	1.4E-05
	152	186	-12.6	23.5	9.5E-07
06-Mar-90 15-Mar-90	9	15	-14.1	23.2	4.1E-07
	15	46	-9.1	21.6	1.4E-06
	9	46	-9.9	21.9	1.6E-06
15-Mar-90 26-Mar-90	9	15	-4.5	22.7	3.8E-07
	15	46	-9.5	21.4	8.1E-07
05-Sep-90 13-Sep-90	9	15	7.5	22.6	5.7E-07
	15	46	-10.1	21.4	1.4E-06

Table 3.2.9 Hydrologic data analyses by date for cell 2 replication 1 in the ESL.

Time Period	Depth Interval (cm)		Mean Hydraulic Gradient	Mean Water Content (%)	Mean Hydraulic Conductivity (cm/sec)
25-Oct-89 01-Nov-89	30	46	14.3	29.4	1.8E-06
04-Dec-89 05-Dec-89	46	61	14.1	30.3	1.6E-06
08-Dec-89 10-Jan-90	46	61	12.8	30.1	1.8E-07
10-Jan-90 16-Jan-90	46	61	4.4	32.4	4.4E-06
	61	76	-2.2	33.7	1.0E-05
	76	213	-4.3	28.2	3.1E-05
	61	213	-4.1	28.7	3.8E-05
05-Feb-90 08-Feb-90	46	61	20.1	30.7	1.7E-06
08-Feb-90 15-Feb-90	46	61	19.6	31.3	1.1E-06
28-Sep-90 24-Oct-90	9	30	17.1	19.7	2.9E-07
	30	46	21.9	24.0	4.7E-07
	46	61	24.6	32.1	3.4E-07
20-Jan-90 29-Jan-90	76	152	-5.2	26.8	8.3E-06
29-Jan-90 05-Feb-90	30	76	-5.6	28.8	9.0E-06
	76	152	-2.9	25.2	2.0E-05
05-Feb-90 08-Feb-90	30	76	-4.8	29.8	4.1E-05
	76	152	-3.6	25.9	6.3E-05
06-Mar-90 15-Mar-90	30	76	-2.5	29.2	4.1E-05
	76	152	-4.5	25.9	1.8E-05
15-Mar-90 26-Mar-90	30	76	-2.5	26.7	9.9E-06
	76	152	-3.4	24.7	6.6E-06

Figure 3.2.3 Unsaturated hydraulic conductivity versus water content (θ_v) for cell 1 at RBOSC.

Figure 3.2.4 Unsaturated hydraulic conductivity versus water content (θ_v) for cell 2 at RBOSC.

Figure 3.2.5 Unsaturated hydraulic conductivity versus water content (θ_v) for cell 1 in the ESL.

Figure 3.2.6 Unsaturated hydraulic conductivity versus water content (θ_v) for cell 2 in the ESL.

3.3 In Situ Hydraulic Conductivity Tests

In situ hydraulic conductivity tests were conducted on the processed oil shale in cell 1 at the UW ESL using a Guelph Permeameter. The Guelph Permeameter is an in-hole (in situ) constant-head permeameter. The method involves measuring the steady-state rate of water recharge into unsaturated soil from a well hole bored into the profile. The measurement is conducted under a constant head condition (i.e. influent water maintained at a constant level).

The method consisted of drilling a bore-hole to the required depth using a hand auger. Bore-holes were drilled from 15.2 cm to 228.6 cm deep at intervals of 15.2 cm. The Guelph Permeameter was placed into the bore-hole. A constant head water level in the well hole was established and maintained by regulating the level of the bottom of an air tube which was located in the center of the permeameter (i.e. mariotte principal). A constant head level of 5 cm was established by slowly raising the air tube. The rate of fall of water in the reservoir was observed and recorded at regular intervals. The rate of fall of water in the reservoir was monitored continuously until the rate of fall did not change significantly in three consecutive intervals. As the level of water in the reservoir falls, a vacuum is created in the air space above the water. The vacuum can only be relieved when air, which enters at the top of the air tube, bubbles out of the air inlet tip and rises to the top of the reservoir. Whenever the water level in the well begins to drop below the air inlet tip, air bubbles emerge from the tip and rise into the reservoir air space. The vacuum is partially relieved and water from the reservoir replenishes water in the well. When the permeameter is operating, an equilibrium is established. The reduced pressure in the air above the water in the reservoir together with the pressure of the water column extending from the surface of the well to the surface of the water in the reservoir always equals the atmospheric pressure. This is the mariotte principal and is how a constant pressure head is maintained during the measurement. The size of

opening and geometry of the air inlet tip is designed to control the size of the air bubbles in order to prevent the well water level from fluctuating. Preliminary data are presented in Table 3.3.1. These data are being evaluated and will be compared to hydraulic conductivity values obtained by bench scale tests conducted previously in this research program. Preliminary analyses of these data indicated that hydraulic conductivity may be higher the interface between lifts of the placed processed oil shale than within a lift. Analysis of these data are continuing.

3.4 Preliminary Infiltration Measurements

Preliminary infiltration tests were conducted on the processed oil shale in cell 1 at the UW ESL using a standard double ring infiltrometer. This method consisted of driving two open cylinders, one inside the other, into the ground. The outer ring was 61.0 cm diameter and the inner ring was 30.4 cm diameter. Both the rings were approximately 50.8 cm high. The purpose of the outer ring is to promote one-dimensional, vertical flow beneath the inner ring.

A constant head within the inner and annular space between the rings was maintained using a Mariotte tube similar to that of the Guelph Permeameter. Depth gages were installed to maintain a constant head. The constant head in both the inner and annular space between the rings is maintained as closely as possible throughout the test. The volume of water required to maintain a constant head in the inner and annular space during each time interval was recorded by measuring the change in elevation of water level in the appropriate Mariotte tube. From the volume of water used during each measured time interval, incremental infiltration velocity for both the inner ring and annular space was determined. These data were not analyzed at the time of this report.

Table 3.3.1 Mean Hydraulic Conductivity by Depth for Cell 1 at UW-ESL

Depth of Well (cm)	Hydraulic Conductivity (cm/s)
15.2	0.0006703
30.5	0.003461
45.7	0.00051
61.0	0.00754
76.2	0.000662
91.4	0.005834
106.7	0.0003146
121.9	0.00511
137.2	0.00332
152.4	0.001142
167.6	0.00206
182.9	0.00195
198.1	0.000467
213.4	0.0015
228.6	0.00109

3.5 Simulated Climatic Models

Two climatic models were developed to accomplish the research objectives. The first climatic model was designed to accommodate objectives for infiltration behavior, and to develop and analyze saturated conditions or conditions of steady state drainage within the processed oil shale. Hydrologic analysis from the RBOSC, Tract C-a field lysimeters taken from 1988 - 1992, indicated that the greatest flux of water infiltration was during this period. These data have been discussed in previous quarterly reports, the FY 1990 annual report, and the Comprehensive Interim Technical Progress Report for 1986 - 1991. Ambient temperature and relative humidity conditions were modeled (designed) based on the Normal mean-monthly temperature and relative humidity measured for Rifle, Colorado, near the Piceance Basin. The Normals for May were used because it was assumed that the primary input of water to an embankment or a disposal facility would occur during the April/May period. The climatic model was designed to provide a constant ambient temperature of 17.1°C and 48% relative humidity. A constant solar flux of 30 W/m^2 was designed for input by the light source for 12.5 hours per day. The constant climatic conditions were designed to help insure constant evaporation from the processed oil shale.

The second climatic model was designed to run after saturated conditions had developed within the profile to produce a series of freeze thaw events. Based on earlier freeze tests, it was determined that the freezing front within the processed oil shale would progress at an adequate rate at temperatures between less than -12°C . The climatic model, therefore, was designed to produce temperatures between -18° and -12°C . Relative humidity was designed to be between 30% and 90% in psychrometric ranges common for the desired ambient temperatures requested. Solar flux of 95 W/m^2 was designed for input by the light source for 8.5 hours per day. Two objectives of this series of climatic experiments are to document

potential changes in infiltration rate and infiltration behavior caused by the freeze-thaw cycles, and to determine potential mechanical/geotechnical changes in the processed oil shale caused the freeze-thaw cycles. Infiltration tests will again be conducted after freeze-thaw conditons and compared to those previously measured.

The first climatic model and sampling program consisted of the application of storm events which were designed to saturate the oil shale and produce conditons of steady state drainage. Each storm consisted of a rainfall rate of 76 mm/hr for approximately 1.5 hours with storms being applied every other day. A total of 24 storm events were applied to the processed oil shale deposits in the ESL between February 17 and April 15, 1992.

The application of the second climatic model to produce a series of freeze thaw events was initiated in May 1992, however, the application of this model was suspended and postponed because of breakdown of equipment necessary to run the ESL. Specifically, a compressor seal on the freezing system of the ESL broke during normal operation after 5 days of the freezing model scenario. The freezer/compressor component of the ESL is not a redundant system. Repair of the freezer compressor took three weeks. The replacement equipment had been installed and was being tested at the conclusion of this quarter.

The application of the second climatic model was resumed in August 1992. The model application was continuing at the time of this report and scheduled to run through December 1992. The destructive sampling program will be initiated after completion of all climatic simulations. A time/activity/milestone schedule has been designed for the remainder of this project, based on the scheduled completion of this objective. This schedule is presented in section 3.5.1 below.

3.5.1 Time/Activity Schedule for Project Completion

- Continue application of freeze/thaw climatic model.
Schedule: August - December 1992.
- Conduct post freeze/thaw infiltration and in situ hydraulic conductivity measurements.
Schedule: January - February 1993.
- Process necessary data, information, and reports in order to meet state and federal regulatory requirements for permanent disposal of the processed oil shale.
Schedule: February - June 1993.
- Develop and finalize the destructive sampling plan for the processed oil shale in the lysimeters.
Schedule: February 1993
- Develop and finalize processed shale removal and disposal plan.
Schedule: March 1993
- Conduct destructive sampling of processed oil shale to obtain cores for the measurement of hydraulic conductivity, leachate chemistry, and soil mechanical properties.
Schedule: April - May 1993
- Remove processed shale from lysimeters and implement disposal according to developed plan according to all regulatory requirements.
Schedule: May - July 1993
- Complete data analysis for project.
Schedule: July - September 1993
- Complete final report and close out contract.
Schedule October - December 1993

3.6 Lysimeter Infiltration Measurements

The ESL has the capability of monitoring runoff and determining a runoff hydrograph from the plots via an automated weighing water collection system. In order to measure infiltration using this system rainfall must exceed the infiltration rate of the material and runoff must be generated. Based on previous experience, and the in situ infiltration measurements reported in the previous quarter, it was determined that a rainfall rate of 76 mm/hr would liberally, exceed the infiltration rate of processed oil shale waste in the lysimeters. Runoff would be generated and passed over a weir system where it would be collected and measured by a pressure transducer system. The processed oil shale was placed into the lysimeter cells at a 1% slope to the weir. Placement of the material into the ESL lysimeter cells was previously described in the FY 1989 Annual Report.

Storm events were designed to be input by the rainfall simulation system of the ESL at a rate of 76 mm/hr. Storm events were applied for approximately 1.5 hours three times per week. Infiltration curves for each applied storm were developed by subtracting the measured runoff hydrograph data from the applied rainfall hyetograph. Accumulated runoff was automatically measured every thirty seconds by the pressure transducer/data logging system. Infiltration curves were developed by smoothing the runoff measurements to eliminate noise, and subtracting them from the applied rainfall amounts for each storm. Soil moisture measurements were taken using TDR and Neutron Moderation before and after storm events. Future data analysis will consist of comparing and correlating infiltration measurements with in situ water contents and existing hydraulic conditions. Hydraulic gradients will be calculated from water characteristic curves that were previously developed in this research program. The development of water-characteristic curves were discussed in the Comprehensive Interim

Technical Progress Report. multiple regression techniques will aid in analyzing effects of existing hydraulic gradients and antecedent moisture contents by different depths.

Infiltration curves were plotted for individual storms along with cumulative infiltration, precipitation and runoff. Results from a particular storm will be use as an example to show how the data was plotted and used to determine rainfall-infiltration relationships. Storm six was ran on March 2, 1992 with a requested rainfall rate of three inches per hour with an actual duration of 1.183 hours (approximately 71 minutes). Figure 3.6.1 shows the plots of rainfall requested by the computer, rainfall measured by the tipping bucket rain gage in the ESL, and infiltration rate. The rainfall data points measured by the tipping bucket raingage are used to verify the rainfall input by the rainfall simulators.

Figure 3.6.2 is a plot of cumulative precipitation against cumulative infiltration for the same storm event. This graph demonstrates the total precipitation the plot received against the total amount of water infiltrated into the substrate.

3.7 Lysimeter Leaching Measurements

As was discussed in section 3.5, the first climatic model was designed to accommodate measurements for infiltration, and to develop and analyze saturated conditions or conditions of steady state drainage within the processed oil shale. The processed waste was placed in the ESL lysimeters above a 15 cm coarse gravel layer to allow drainage of leachate through perforated well pipe to the outside. The analysis of the conditions leading to steady state drainage through the processed oil shale and the subsequent generation of leachate was being analyzed at the time of this report.

Preliminary data is presented in Figures 3.7.1-3.7.6. Each graph shows the original in situ water content profile before application of the first climatic model and rainstorm events

and profiles before and after specific rainstorm events. Data are presented for each cell at dates in the beginning, middle, and near the end of the application of heavy rainfall events. As was previously indicated, these data will be analyzed in detail to determine flux, changes in hydraulic gradients, and changes in unsaturated hydraulic conductivity during drainage conditions.

Figure 3.6.1 Infiltration and rainfall rate measured for cell 1. Storm was produced on March 22, 1992 in the ESL.

Figure 3.6.2 Cumulative infiltration and cumulative rainfall for cell 1. Storm was produced on March 22, 1992 in the ESL.

Figure 3.7.1 Water content profiles for cell 1 showing the initial baseline condition, before a rainstorm produced in the ESL on February 20 1992, and 24 hours after conclusion of the storm.

Figure 3.7.2 Water content profiles for cell 2 showing the initial baseline condition, before a rainstorm produced in the ESL on February 20 1992, and 24 hours after conclusion of the storm.

Figure 3.7.3 Water content profiles for cell 1 showing the initial baseline condition, before a rainstorm produced in the ESL on March 9, 1992, and 24 hours after conclusion of the storm.

Figure 3.7.4 Water content profiles for cell 2 showing the initial baseline condition, before a rainstorm produced in the ESL on March 9, 1992, and 24 hours after conclusion of the storm.

Figure 3.7.5 Water content profiles for cell 1 showing the initial baseline condition, before a rainstorm produced in the ESL on April 15, 1992, and 24 hours after conclusion of the storm.

Figure 3.7.6 Water content profiles for cell 2 showing the initial baseline condition, before a rainstorm produced in the ESL on April 15, 1992, and 24 hours after conclusion of the storm. previously indicated, these data will be analyzed in detail to determine flux, changes in hydraulic gradients, and changes in unsaturated hydraulic conductivity during drainage conditions.

It is apparent from these data, however, that saturated conditions and steady state drainage of leachate developed in cell 2 before cell 1. Two conditions may have contributed to this difference. The processed oil shale in cell 2 of the ESL was placed with 40% w/w, 15 cm nominal, overburden. The oil shale in this cell may have a slightly higher hydraulic conductivity than the material in cell 1 because of the overburden mixture. A factor which may be more important, however, is that the overburden material caused the surface roughness of cell 2 to be much higher than that of cell 1. This factor was easily noticeable when observing rainfall events within the ESL. The coarse material lying on the surface of cell 2 significantly slowed surface runoff toward the weir system. This causes increased water retention time, and therefore, the amount of water which infiltrated into the plot. These conditions would increase gravitational heads within cell 2 also promoting faster drainage.

Leachate water has been sampled for cell 1 and cell 2 on a daily basis from the time leachate first appeared from each cell. This sampling was continuing at the time of this report. Water samples will be analyzed for the following chemical constituents: Sodium (Na), Calcium (Ca), Magnesium (Mg), Copper (Cu), Boron (B), Molybdenum (Mo), Iron (Fe), Lead (Pb), Selenium (Se), Arsenic (As), Sulfate (SO_4), Chloride (Cl), Fluorine (F), total organic carbon (TOC), total alkalinity, and pH.

For the last several storms of the climatic model, measurements were made of the volume of water draining (i.e. leaching) from the bottom of each cell in the ESL. Figure 3.7.7 shows curves of rate of drainage versus time during and following the last two storms. As can be observed, the rate of drainage is significantly higher in cell 2 (spent shale/overburden mix) than in cell 1 (spent shale only). Also, there is a time lag between the peak drainage rate

in cell 1 and cell 2. This behavior is consistent with a higher hydraulic conductivity in spent shale mixed with overburden rock.

Figure 3.7.7 Leachate drainage versus time for lysimeter cells 1 and 2 in the ESL.

3.8 Hydrologic Modeling

The computer program UNSAT2D is being used to model the flow of water through the test embankments in the ESL. This program uses the finite element method to obtain an approximate solution to the governing differential equations for 2-dimensional flow through a porous medium. Efforts to date have focused on setting up the finite element mesh, specifying the appropriate initial and boundary conditions, and determining the appropriate material properties for the spent shale. To simulate the higher horizontal hydraulic conductivity at lift boundaries, as observed from in-situ conductivity tests using the Guelph permeameter, thin elements with anisotropic conductivities were input at lift boundaries. Rainstorms are simulated as a flux boundary condition at the surface.

An initial trial run was executed to simulate a storm lasting 1.25 hours with a total rainfall of 75 mm. The initial moisture profile was specified to simulate the measured profile that existed during February, 1992, immediately before the first storms were applied to create "extreme" climatic conditions in the ESL. Results of the program were used to create a plot showing contours of equal pressure head (soil suction) versus spatial position in cell 1 of the ESL (Figure 3.8.1).

Further simulations are being used to model the test embankments during the entire series of storms applied between February and May, 1992. The program will be used to predict moisture content profiles, runoff and infiltration amounts, and drainage at the bottom of the cells. These will be compared to the measured soil moisture profiles, runoff vs. infiltration curves, and drainage.

Figure 3.8.1 Results of UNSAT2D model run applied to the processed oil shale in cell #1 of the ESL after application of a 75mm storm for 1.25 hours. Figure shows contour lines of equal pressure head in the embankment.

Literature Cited

Annual Book of ASTM Standards. 1985. Vol. 04.08, American Society for Testing and Materials, Philadelphia, PA.

Everett, L.G., L.G. Wilson, and E.W. Hoylman. 1984. Vadose zone monitoring for hazardous waste sites. Noyes Data Corporation, Park Ridge, New Jersey, USA, 358 p.

Schmalfield, I.P., The use of the Lurgi-Ruhrgas process for the distillation of oil shale, *Quart. Colorado School of Mines*, 70, 129-145, 1975.

**DATE
FILMED**

10/25/93

END