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Scientific Notebooks # 301 & 302

301

LABORATORY NOTEBOOK

CNWRA/SwRI

NOTEBOOK NO.____________

ISSUED TO____________

ON____________ **19**____

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CNWRA
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COPY 301

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   - Avoid making notes on loose paper to be recopied.
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   - Give a complete account of your experiments and the results, both positive and negative, including your observations.
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   - Do not try to erase any incorrect entries; draw lines deleting them, note the corrections, sign and date the changes. This extra care is worthwhile because of the necessity of original data to prove priority of new discoveries.

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5. Since computer programs can be patented these instructions apply to the development of computer software. In this case a description of the structure and operation of the program should be recorded in the notebook, together with a basic flow diagram which illustrates the essential features of the program. In the course of developing the code, the number of lines of code written each day should be recorded in the notebook, together with a statement of the portion of the flow diagram to which the section of code is directed.

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Form 590

| | | | |

Project No. 20-1402-861

TITLE Fracture Flow lab work

Book No. 301

From Page No. ____

Initial Entry Also see CNWRA notebook 302

this notebook records laboratory experiments and modeling studies of capillary diversion – seepage exclusion from underground openings of unsaturated flow in fractures.

Principal Investigator is Debra L. Hughson
Laboratory Technician Troy

Additional guidance and technical direction provided by Ron Green

Basic idea is to construct an artificial fracture using two glass plates. An underground opening is simulated by creating a hole through the sheets of glass. Unsaturated flow can then be visualized by using dye treated water.

Modeling will be done using analytical expressions and the numerical code MultiFlo ver 1.2β.

Conceptual models will be tested and may be improved or modified as necessary.

The work completed here is expected to relate directly to the problem of seepage into drifts under both thermal and isothermal conditions at Yucca Mtn HLW Repository

To Page No. ____

Witnessed & Understood by me, | Date | Invented by Debra Hughson | Date Jan 7 1999
Recorded by DLH

Dec 30. Pick up two pieces of glass from Glass Service.

Dimensions 15" by 12" by 3/8"

These were taken to the SWRI fabrication shop to be sand blasted to roughen the surfaces

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		DH	Dec 30 1999

Troy builds frame

Profilemeter runs

Sand Blast Abrasive

Jebco Industrial Abrasives, Inc.
Hwy 71 South DH 8/28/00
Columbus TX ~~78334~~ 78394
409 732 8210

Grade 4 25ml sample collected

Spray distance 80"

Between 12/30/99 ~~And~~ 10/31/99 ~~and~~ ~~AND~~ 8/28/99 DH

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		DH	

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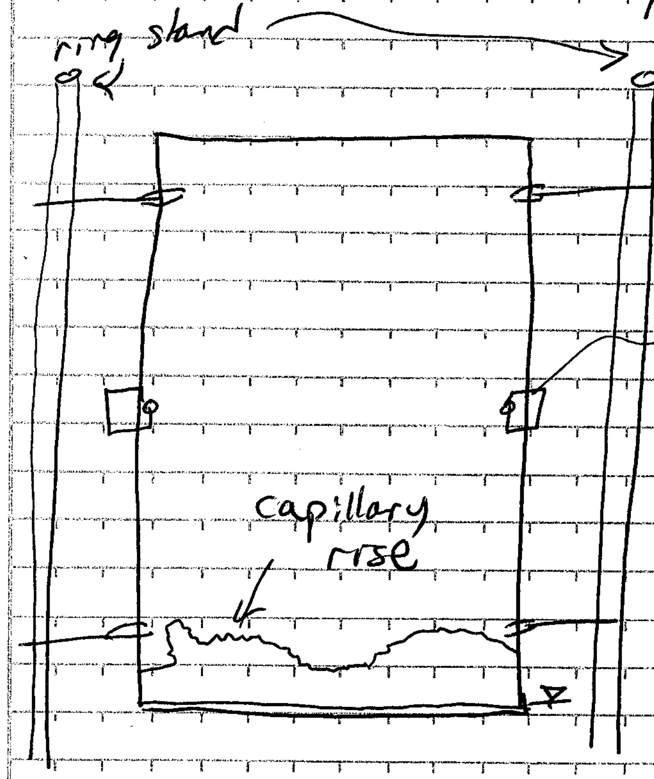
First attempt at measuring aperture.

Plates held together by tightened C-clamps & held vertical in a pan of water



capillary rise

max = 2 1/4 inches left
min = 5/8 inches center
max = 2 inches right

Laplace Formula

$P_c = \frac{2\sigma_{aw}}{r^*}$ $P_c = P_a - P_w$

$h_c = \frac{2\sigma_{aw}\cos\theta}{R\rho_w g}$ $\frac{R}{\cos\theta} = r^*$

Romm 1966
Cubic Law

$Q = \frac{\rho g b^2}{12\mu}(bw)\frac{dh}{dL}$

Snow (1968)
Equivalent hydraulic conductivity for set of planar fractures

$K = \frac{\rho g N b^3}{12}$ $k = \frac{N b^3}{12}$

N = # of fractures/unit length

Between 10/31/99 and 10/30/99 ECP 8/29/00

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From Corey pg 18

$P_c = \frac{2\sigma\cos\theta}{b}$ $\sigma = 72.75$ dynes/cm @ 20 C

$(5/8\ in)(2.54\ cm/in) = 1.59\ cm$

$(1.59\ cm)(.998\ g/cm^3)\ 980\ cm/s^2 = 1.553 \times 10^3\ dynes/cm^2$

$b = \frac{2(72.75\ g\,cm/s^2\,cm)}{1.553 \times 10^3\ g/cm\,s^2} = 9.37 \times 10^{-2}\ cm$

For 2 1/4 inches $b = 2.6 \times 10^{-2}$ cm

Aperture between 0.26 and 0.94 mm
260 to 940 μm

Vol of water $(15\ in)(2.54\ cm/in)(12\ in)(2.54\ cm/in)$ ~~(3/8 in)(2.54 in)~~ [initials] 8/28/00

~~Vol water =~~ [initials] 8/29/00
$(30.45\ cm^2)(2.6 \times 10^{-2}\ cm) = 0.79\ cm^3$
$(30.45\ cm^2)(9.37 \times 10^{-2}\ cm) = 2.86\ cm^3$

Wt of water .79 to 2.85 grams

$Q = KA\frac{dh}{dL}$ $K = \frac{\rho g b^2}{12\mu}$ $k = \frac{b^2}{12}$

Intrinsic permeability = $5.6 \times 10^{-5}\ cm^2$ to $7.3 \times 10^{-4}\ cm^2$ +

10/31/99
Between 12/30/99
ECP 8/29/00

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try to measure aperture with picnometer ~~picno~~

Ideal Gas law

seems measured b too large

Between 12/30/98 & 10/31/88

PCL 8/28/00

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$V_r = 781.87 + 3.468\ cm^3$

extra vol for correction

$P_r =$ ~~6 ft 1b~~ DH 8/28/00 ~~1.05 psi~~ DH 8/28/00

~~14.275~~ psi DH 8/28/00
~~15.0~~ DH 8/28/00

~~14.277~~ DH 8/28/00 14.278 1 psi
14.996

15"
12"
161.29 cm^2

14.2767 (14.2817) 1.1 psi
15.0127

Between 12/30/99 & 10/31/88

PCL 8/28/00

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From Page No.___ New Glass Plates

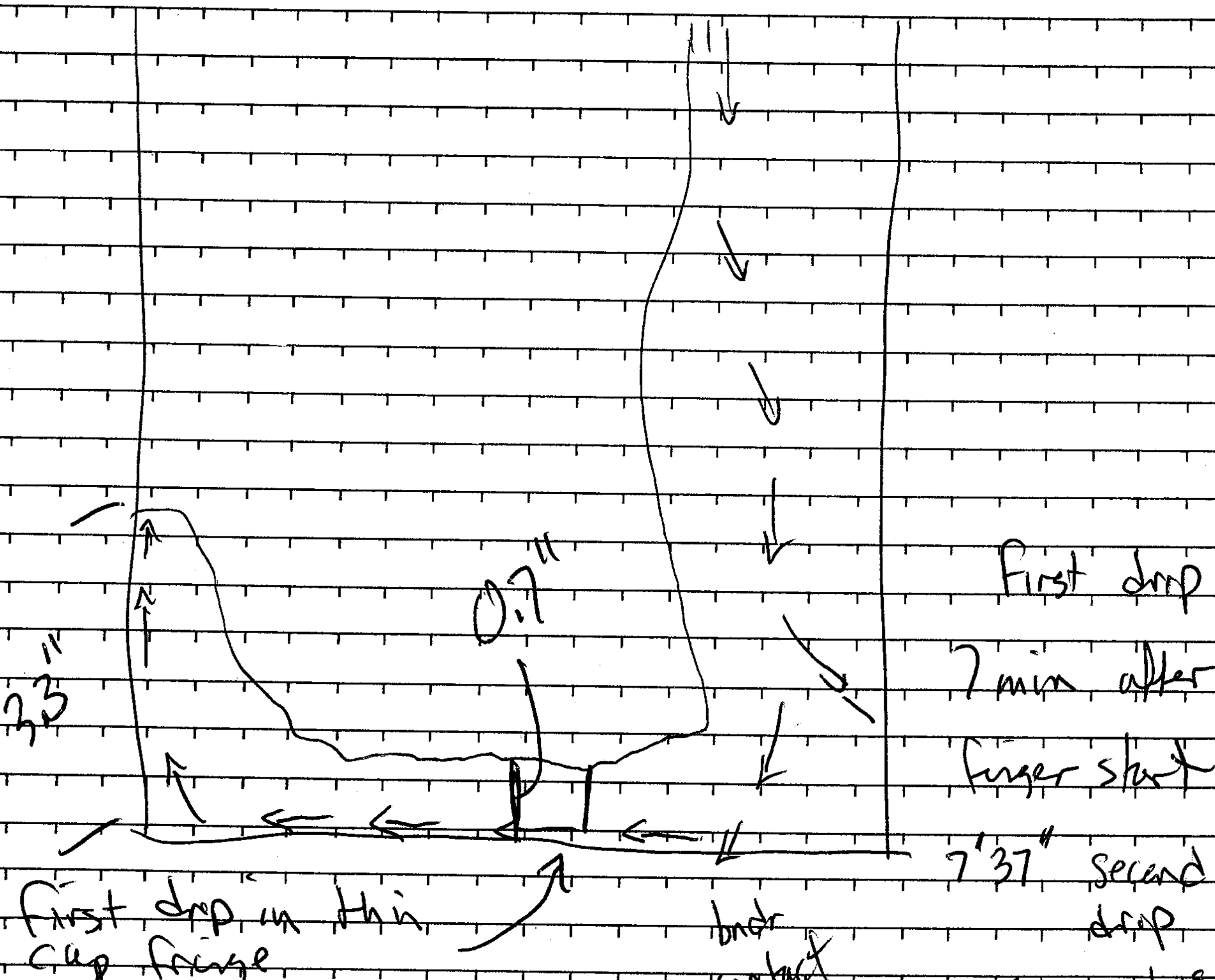
Sandblast Grit Extra fine (Close to Grade 5)

sprayed from 80" Torse 10A-16

Initial Flow Rate .3 ml/min

35s for finger from top to bottom 15"

advancing finger width ~2" – after nonwetting
reinvasion ~ thin finger ~ .1 to .2 ~ in



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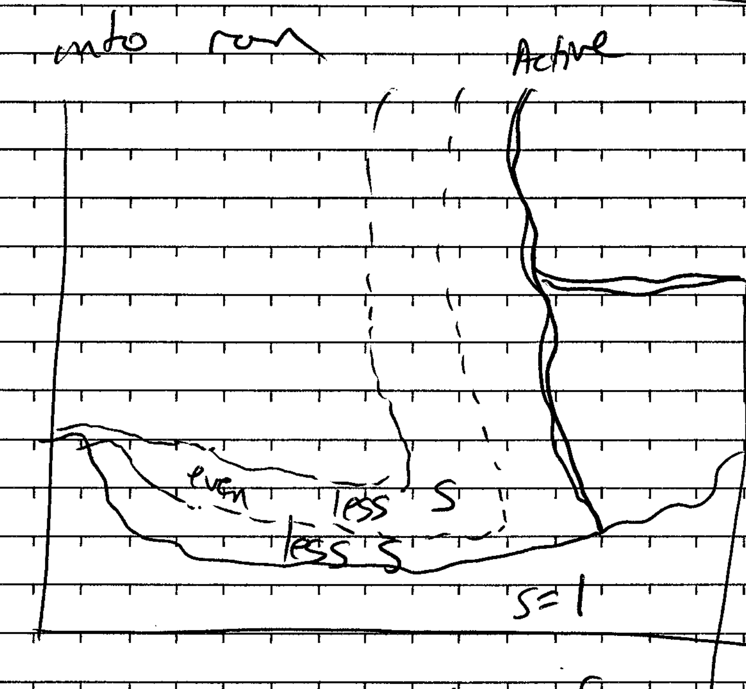
advancing fingertip ~ 1"

drop	time	drop	time
0	0	0	0
1	27s	1	30s
0	0	2	30s
1	27s	3	29s
2	26s	4	30s
3	26s	5	31s
4	31		

at 45 min into run

drop	time
1	32s
2	30s
3	30s



water flows in pulses down active finger with occassional lateral migration to right edge.

1hr lateral migration stole flow from main finger. Now all flow going to right side & along edge

1hr 10 min ~ lateral flow stopped & flow returned to main active finger — continued lateral spreading of "even less S" zone

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1hr 20min

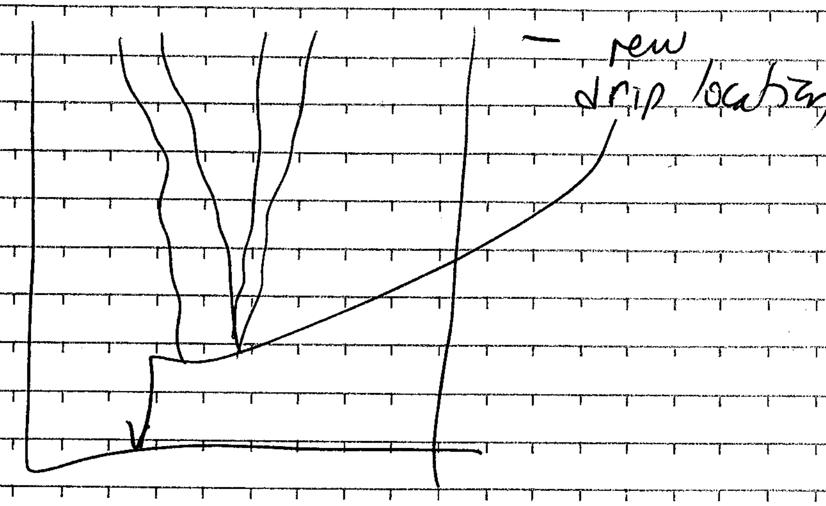
drip	time
0	39s
1	38s
2	40
3	38s

dhh 8/28/00

Bump flow rate to 7 ml/min

at 1hr 35min

almost immediately 2 new fingers — drip from same place



capillary rise rose ~ .2-.3" approx.

Shut down 1hr 45min

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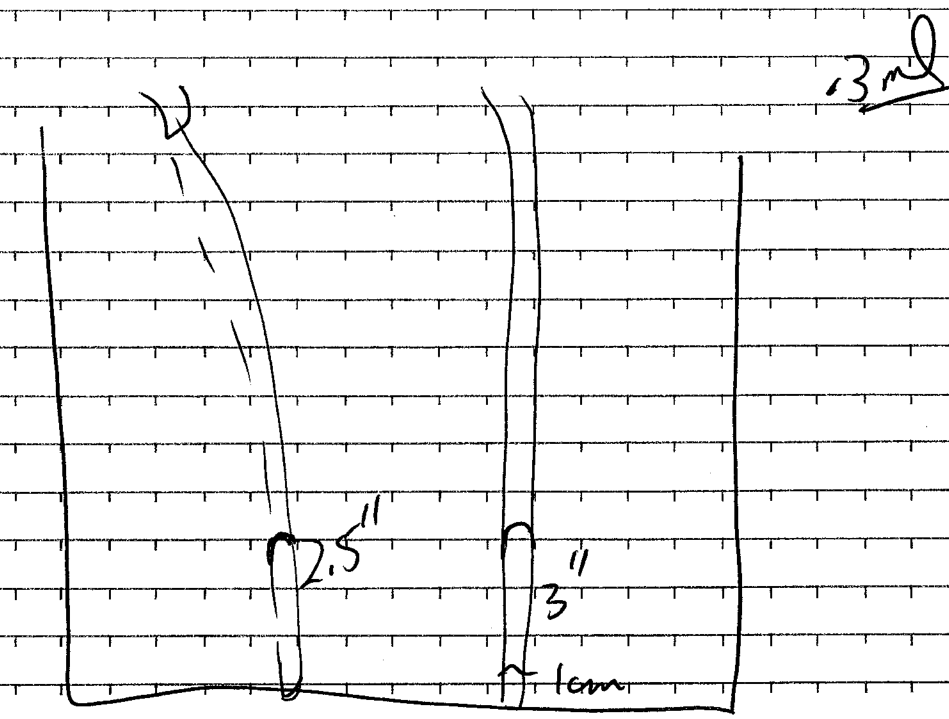

wetted finger ~2.5"-3" length

dripped immediately

flow comes in intermittent pulses — each saturated tip ~ 2" long or so

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From CRC handbook

Water @ 20C $\rho = .99821\ g/cm^3$ $\sigma = 72.75\ mN/m$

72.5 dyne/cm

dyne = $g\,cm/s^2$

Newton = $kg\,m/s^2$

$P_c\ \cancel{K} = \frac{2\sigma\cos\alpha}{b}$

alcohol @ 20C $\rho = .79\ g/cm^3$ $\sigma = 24$ dyne/cm

$h = \frac{P_c}{\rho g} = \frac{2\sigma\cos\alpha}{\rho g b}$

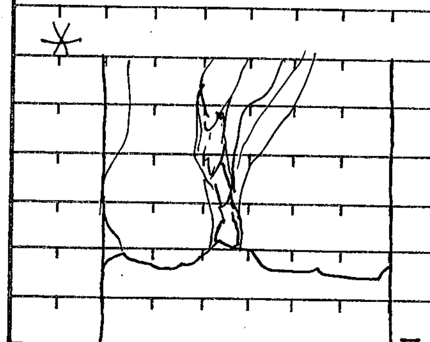
For water $h_w = \frac{2(72.5\ g/s^2)}{.998\ g/cm^3\ 981\ cm/s^2}\frac{\cos\alpha}{b} = 0.148\ cm^2\ \frac{\cos\alpha}{b}$

DH 8/28/00

For alcohol $h_a = \frac{2(24\ g/s^2)}{.79\ g/cm^3\ 981\ cm/s^2}\frac{\cos\alpha}{b} = 0.062\ cm^2\ \frac{\cos\alpha}{b}$

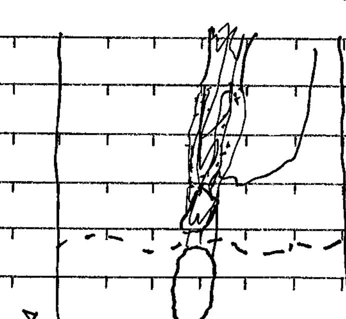
Troy observed theoretical (our hypothesis) behavior while using alcohol to clean the plates.

*



Hypothesis

Wetting liquid invasion gravity unstable finger contacts $P_c = 0$ boundary will flow laterally and fill up fracture to level of capillary rise prior to first drip



← time ←

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Whereas with water he has been unsuccessful in producing this behavior. At low flow rates ~ .05 to .075 ml/min drops often form ~~prior~~ (DH 8/28/00) before lateral diversion has reached 1/3 to 1/2 ~~the~~ bottom edge length.

Can use this in our presentation

$Q = KA\frac{dh}{dl} = \frac{\rho g b^2}{12\mu}(bw)\frac{dh}{dl}$ $K = \frac{\rho g b^2}{12\mu} = \frac{k\rho g}{\mu}$

so intrinsic permeability $k = \frac{b^2}{12}$

$h_c = \frac{P_c}{\rho g} = \frac{2\sigma\cos\alpha}{\rho g b} = \alpha^{-1}$ pore size distribution parameter

diversion increases with $\frac{\rho g b^2}{12\mu}$ $\frac{2\sigma\cos\alpha}{\rho g b}$

~~decreases with $\frac{\rho g b}{2\sigma\cos\alpha}$~~ DH 8/28/00

$\frac{b}{12\mu}$ $\frac{2\sigma\cos\alpha}{\rho g}$

10/31/99
+ 12/30/99

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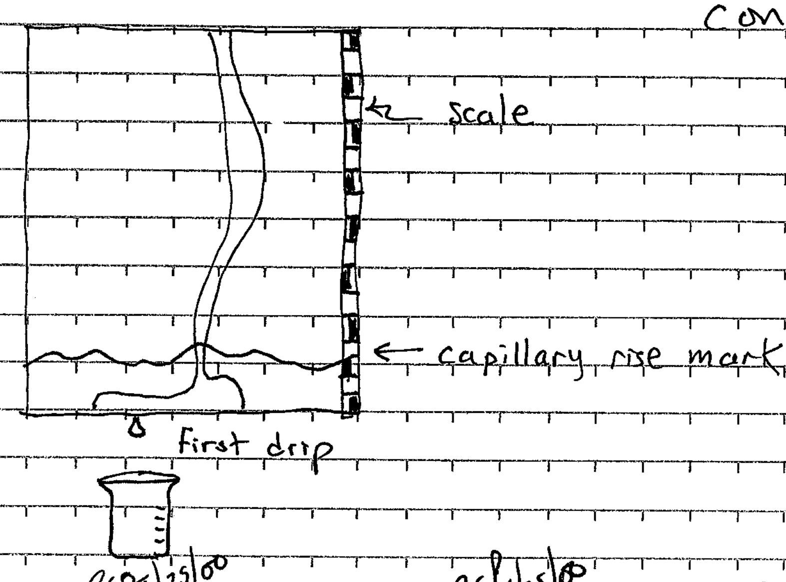
Experiment 1 Glass Initially dry

1) Clean glass with solvent and dry *
2) as a check, drop water on plate edge. It should imbibe immediately.
3) Run low flow rate 0.01 - 0.05 mL/min
4) advancing finger should creep slowly downward
5) Record progress of finger lateral diversion

6) Photograph First drip

8) Photograph final steady flow condition.



Results

2- photographs
2- lines on trace paper w/ edge reference
1- quantity of drips
1- elapsed time

9cf 8/21/00 9cf 8/21/00

7) ~~Record~~ / measure / ~~amount~~ / volume of water dripped from first drip to steady flow conditions. Also record time elapsed

* Find the capillary rise of alcohol
Transfer line to trace paper w/ ref to glass edge

* Mark clearly on the glass the correct location of capillary rise of water. Transfer to trace paper
Also include scale

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Experiment 2 Initially damp

1) Drain water from final state result in Experiment 1
2) Re-establish same flow rate.
3) Record progress of lateral diversion.
4) Photograph first drip
5) Measure volume dripped and time elapsed to reach steady condition
6) Re Photograph final condition

Results: 2 photographs 1 vol dripped & time elapsed

Experiment 3 Alcohol as wetting phase

1) Establish low flow rate of alcohol
2) Repeat exercise of 1 and 2 by Recording progress of lateral diversion Initiation of dripping & Final steady state condition. Photographs as appropriate to illustrate different behavior.

Repeat, as time permits, to assess repeatability, consistency, and variability of water finger lateral diversion. Measure drip volume and time elapsed from initial drip to steady state condition.

Photograph entire experimental apparatus including pump.

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2- Propanol or Isopropyl alcohol $.7855\ g/cm^3 = \rho$

dyne = $g\,cm/s^2$ $\qquad \sigma = 21.7$ dyne/cm

$$h = \frac{2\sigma\cos\alpha}{\rho g b} \qquad b = \frac{2\sigma\cos\alpha}{\rho g h} \qquad \text{assume } \alpha = 0$$

$$b = \frac{(2)\,21.7\ g/s^2}{.7855\ g/cm^3 \cdot 981\ cm/s^2 \cdot h} \qquad \frac{g/s^2}{g/cm^3 \cdot cm/s^2 \cdot cm} \rightarrow cm$$

DH 8/28/00

For Water $\rho = .987\ g/cm^3$ $\quad \sigma = ?$ $\quad \alpha = ?$
not pure

Meas. h, assume b is same as for alcohol

Find $\sigma\cos\alpha$ for the water.

$$\sigma\cos\alpha = \frac{h_w \rho_w g b}{2} \qquad \sim \text{about } 13 \text{ dyne/cm} \quad std = 1.4$$

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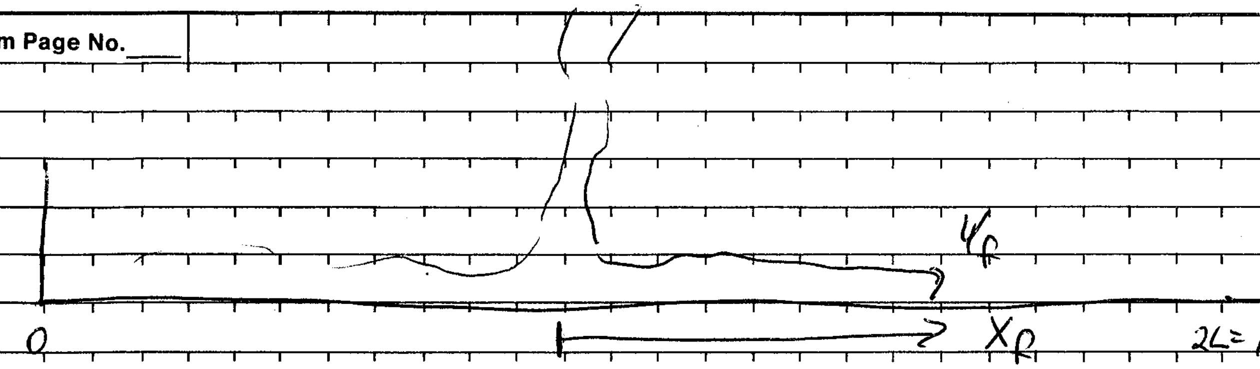

$$q = +K\frac{\psi_f}{x_f} = \theta_s \frac{dx_f}{dt} \qquad \theta_s \sim 1$$

$$\frac{dx_f}{dt} = +K\frac{\psi_f}{x_f} \qquad K = \frac{b^2 \rho g}{12\mu}$$

$$\psi_f = \frac{2\sigma\cos\alpha}{b\rho g}$$

$$Lq = \frac{b^2\rho g}{12\mu}\,\frac{2\sigma\cos\alpha}{b\rho g} = \frac{b\,2\sigma\cos\alpha}{12\mu}$$

$$A = \frac{b\,2\sigma\cos\alpha}{b\rho g} = \frac{2\sigma\cos\alpha}{\rho g}$$

$$qA = Q = \frac{b\,2\sigma\cos\alpha}{12\mu}\,\frac{2\sigma\cos\alpha}{\rho g}\,\frac{1}{L}$$

$$Q = \frac{b(2\sigma\cos\alpha)^2}{12\mu\rho g L} \qquad \mu\ \left[\frac{N s}{m^2}\right]$$

$$\frac{(m)(N/m)^2}{\left(\frac{Ns}{m^2}\right)\left(\frac{kg}{m^3}\right)\left(\frac{m}{s^2}\right)(m)} = \frac{N}{s\,\frac{kg}{m^3}\,\frac{m}{s^2}} = \frac{\left(\frac{kg\,m}{s^2}\right)}{\frac{kg}{m^2 s}} = \frac{m^3}{s} \qquad \sigma\ [N/m]$$

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From CRC (mathCad Reference Tables)
1 atm & 300 K

	water	propanol - 2
ρ	997.1 kg/m³	800 kg/m³
μ	0.00089 Ns/m²	0.00192 Ns/m²
σ	0.07197 N/m	0.0235 N/m

Plate 1

Alcohol 1 mL/min - 4.2 mL/min

10/31/99

& 2/11/2000

8/29/2000

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H52C-10 Dripping Threshold from a Glass Plate Hele-Shaw Fracture Analog

Hughson, D L, Maxwell, T Green, R; Center for Nuclear Waste Regulatory Analyses, 6220 Culebra Road, San Antonio, TX 78238-5166

Abstract

Lateral diversion of unsaturated flow in fractures due to the boundary condition created by open drifts has significant implications for performance assessment of the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. Previous experimental observations, using a glass plate Hele-Shaw model as an analog for a natural fracture, have shown a transition from gravity destabilized to gravity stabilized wetting phase invasion of liquid water fingers at a bottom boundary open to the atmosphere (Nicholl et al., 1993). Lateral flow in the saturated fringe along the bottom edge of Hele-Shaw models suggests a similar process may occur in unsaturated fractured rock at the boundary with underground openings. We postulate the existence of a dripping threshold, as a function of fracture aperture, above which dripping occurs along with gravity stable, capillary driven lateral flow. A simplified model of this threshold is presented that may be sufficient for performance assessment.

Regulatory Background

Tasked by Congress to determine the suitability of Yucca Mountain, Nevada, for geological disposal of high-level radioactive waste, the Department of Energy (DOE) has conducted unique underground field-scale experiments in unsaturated fractured rock. Water dripping into waste emplacement drifts would promote waste package corrosion and radionuclide release. The DOE assumes that unsaturated flow through the Topopah Springs Tuff and into drifts can be modeled by a dual-permeability (DKM) formulation of interacting porous media continua representing fractures and matrix. Reports on studies in niches and alcoves of the Exploratory Studies Facility (ESF) suggest a threshold flux for initiation of seepage into drifts.

The Nuclear Waste Policy Act of 1982 (NWPA), the Nuclear Waste Policy Amendments Act (NWPAA) of 1987, and the Energy Policy Act of 1992 charge the Nuclear Regulatory Commission (NRC) with responsibility for determining if the proposed repository at Yucca Mountain meets standards set by the Environmental Protection Agency (EPA).

Our objective with this poster is to support development of review methods for the NRC Yucca Mountain Review Plan (YMRP).

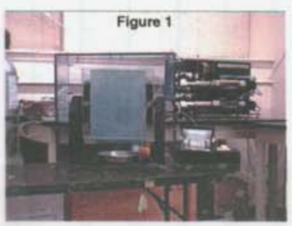


Figure 1

Experiment Description

Two Hele-Shaw models, labeled ***A*** and ***B***, were constructed by sandblasting 0.3 × 0.38 × 0.01 m plates of glass with extra fine grit then pressing the roughened surfaces together with bolts tightened to a torque of 10.8 N-m and held vertically in a frame. Prior to assembly the glass surfaces were cleaned with an Alconox® solution, rinsed with tap water then rinsed with deionized water. ***Figure 1*** shows the assembled apparatus and the pneumatic pump used to supply a constant flow rate. The pexiglass hood and pan of fluid are to reduce evaporation.

Observations of capillary flow at the bottom boundary open to the atmosphere were made with three liquids in the sequence: nanopure water, tap water, and isopropyl alcohol (2-Propanol). Capillary rise of the liquid was first marked on the glass then a constant flow rate was applied at a point near the center of the top boundary of the initially dry model.

As the advancing liquid finger arrived at the bottom boundary one of two things could happen:

1. The liquid could migrate laterally along the bottom boundary, reaching the edges before dripping.
2. Dripping could occur before lateral flow reached the edges of the model.

In second case we said the ***DRIPPING THRESHOLD*** was exceeded.

Results

Capillary rises of the three liquids are shown in ***Figure 2*** for models ***A*** and ***B***. Properties of surface tension, density, and viscosity used for 2-Propanol and nanopure water are given in Table 1.

Table 1. Properties of fluids from the CRC Handbook.

Liquid	σ [Nm^{-1}]	ρ [kgm^{-3}]	μ [Nsm^{-2}]
Nanopure water	0.072	997	0.00089
2-Propanol	0.0235	800	0.00192

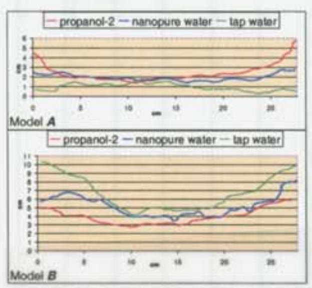


Figure 2. Capillary rise of three fluids at the bottom boundary.

With the properties in Table 1, assuming a zero contact angle, nanopure water should have a greater capillary rise than 2-Propanol by a factor of about 2.5. Apparently the glass, particularly model ***A***, developed some kind of thin film or coating which decreased its wettability by water. Our cleaning technique did not remove this film.

Flow rates, in mL/minute, bracketing the dripping threshold, Q^*, for models ***A*** and ***B*** are presented in Table 2.

Table 2. Experiment results of flow rates in mL/minute bracketing the dripping threshold Q^*.

Liquid	Model *A*	Model *B*
Nanopure water	$Q^* < 0.025$	$Q^* \approx 7$
Tap water	$Q^* < 0.025$	$20 < Q^* < 40$
2-Propanol	$3 < Q^* < 10$	$1 < Q^* < 5$

An Estimate of Maximum Lateral Flow

Darcy's Law

$$Q = KAJ \tag{1}$$

Assuming (Green and Ampt approximation)

$$J = \frac{\psi_f}{x_f} \tag{2}$$

Area

$$A = bh_s \tag{3}$$

From the cubic law

$$K = \frac{b^2 \rho g}{12\mu} \tag{4}$$

The Laplace-Young formula for capillary rise

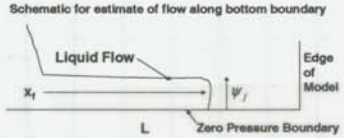
$$\psi_f = \frac{2\sigma\cos(\alpha)}{\rho g b} = h_s \tag{5}$$

An approximation for maximum lateral capillary flow

$$Q^* = \frac{b(2\sigma\cos\alpha)^2}{12\mu\rho g L} \tag{6}$$

x_f	Distance of Lateral Flow [m]
L	Horizontal Length of Boundary [m]
$\psi_f = h_s$	Pressure Head (Suction) at Wetting Front [m]
b	Aperture [m]
σ	Surface Tension [Nm^{-1}]
μ	Viscosity [Nsm^{-2}]
ρ	Density [kgm^{-3}]
α	Contact angle

Schematic for estimate of flow along bottom boundary



Dripping threshold was estimated by first assuming a zero contact angle for 2-Propanol. Capillary rise was digitized at 85 uniformly spaced locations and the aperture calculated from (5) using properties in Table 1 and the capillary rise of 2-Propanol. An estimate of the contact angle for nanopure water, of between 60 and 78 degrees, was obtained from the calculated aperture and the capillary rise of nanopure water using properties from Table 1. For tap water, the product $\sigma\cos(\alpha)$ was estimated from the calculated aperture and the capillary rise of tap water. Since the capillary rise is variable along the bottom boundary, estimated maximum lateral capillary flow is given in Table 3 as minimum and maximum. The estimate from (6) is doubled in Table 3 because the downward flowing finger splits and flows in both directions at the bottom boundary.

Table 3. Estimated dripping threshold flow rates in mL/minute.

Liquid	Model *A*	Model *B*
Nanopure water	$1 < Q^* < 17$	$3 < Q^* < 15$
Tap water	$0.05 < Q^* < 14$	$6 < Q^* < 19$
2-Propanol	$1 < Q^* < 4$	$1 < Q^* < 2$

Discussion

The simple "back-of-the-envelope" estimate of dripping threshold gave a reasonably close approximation for 2-Propanol in both models. This suggests that (6) may be an adequate estimate for capillary diversion of a liquid finger flowing in a fracture above an open drift if the assumptions are satisfied. On the other hand, the estimate was poor for both nanopure and tap water, perhaps due to the unknown contact angles. The surprising hydrophobicity of model ***A*** underscores the importance of the wettability of fracture surfaces in understanding capillary diversion around, and dripping into, underground openings in fractured rock.

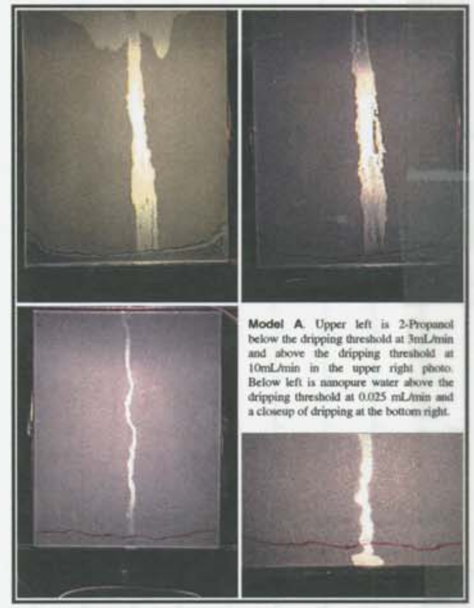
Future Work

The unknown contact angles are a weakness in the current work. Should funding be available to continue this project we will obtain the necessary instruments to characterize contact angles and wettability of various surfaces, including fracture surfaces of the lower lithophysal unit of the Topopah Springs tuff.

The experiments presented here are very preliminary and only roughly bracketed the dripping threshold flow rate. Further experiments are planned to more accurately bound the dripping threshold for both horizontal and dipping boundary edges and for irregularly shaped boundaries.

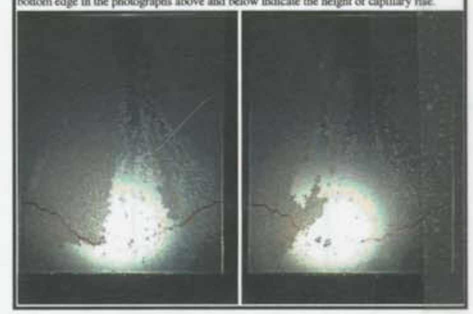
Reference

Nicholl, M.J., R.J. Glass, and H.A. Nguyen, Small-scale behavior of single gravity-driven fingers in an initially dry fracture, *High Level Radioactive Waste Management, Proceedings of the Fourth Annual International Conference*, American Nuclear Society, April 26-30, Las Vegas, NV, pp. 2023-2032, 1993.



Model A. Upper left is 2-Propanol below the dripping threshold at 3mL/min and above the dripping threshold at 10mL/min in the upper right photo. Below left is nanopure water above the dripping threshold at 0.025 mL/min and a closeup of dripping at the bottom right.

Model B. Tap water below the dripping threshold at 20 mL/min is shown in the bottom left and above the dripping threshold at 40 mL/min in the bottom right. Lines along the bottom edge in the photographs above and below indicate the height of capillary rise.



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