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Testing the Concept of Drift Shadow Using X-Ray Absorption Imaging

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ABSTRACT*

This research experimentally tests the concept of fluid diversion around an excavated drift due to the formation of a capillary barrier and the concept of a drift shadow under the drift. The proposed High-Level Nuclear Waste (HLNW) Repository at Yucca Mountain, NV, is located within the unsaturated zone of the fractured volcanic tuff unit Topopah Springs welded tuff (TSw). Infiltrating water needs to seep into the constructed drifts in order for radionuclides to be transported away from the site. An analytical model proposed by Philip, et al. (1989) predicts flow diversion around drifts due to the presence of a capillary barrier resulting in a drift shadow (low flux) beneath the drift.

Two small (cm-scale) test cells with different, continuous fracture apertures were constructed from TSw to verify the presence of the capillary barrier and drift shadow and validate the model. Fractures were located through the middle of the rock sample, parallel to the rock face and normal to the drift axis. X-ray absorption imaging visualized the movement of the potassium iodide (KI) solution through the fracture. A KI solution was introduced into the test cell and outflow collected at different lateral locations at the base of the cells and inside the drift cavity.

Preliminary results from 14 tests show the presence of the drift shadow and flow diversion away from the drift. Preliminary results also show the difficulties in comparing flow behavior between heterogeneous media and the predicted behavior in the model that assumes a homogenous media.

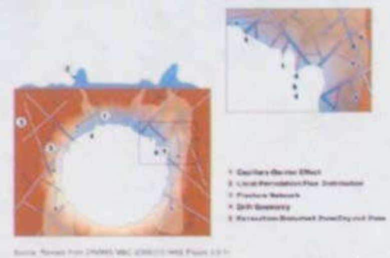
INTRODUCTION

The proposed HLNW storage repository at Yucca Mountain, NV is located in the unsaturated zone of a fractured volcanic tuff. In order to perform performance assessment calculations, it is necessary to quantify where fluid flows within the unit and how it may be affected by drift excavation. The analytical model of Philip et *al.* (1989) predicts that flow is diverted around the drift leading to an area of reduced flux beneath the drift, the drift shadow. The analytical model assumes a homogeneous, isotropic porous media, steady downward seepage through the media and spatially uniform flow velocity (Philip *et al.* 1989). The size of the drift shadow is dependant on drift diameter, capillary pressure and fracture aperture. The presence of a drift shadow, not accounted for in the current Yucca Mountain performance assessment, decreases the amount of fluid available to move radionuclides from the waste emplacement container to the water table.

Our research focuses on the movement of fluid through fractures relative to the excavated drift. In the test system, the fracture intersects the drift which allows us to predict whether or not we should expect seepage into the drift due to the intersection.

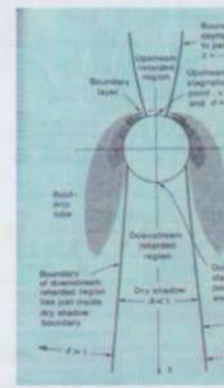
Preliminary results verify the existence of the drift shadow and flow diversion around the drift. Flow paths develop independent of flow rate and instead are controlled by geologic heterogeneities within the TSw.

CONCEPTUAL MODEL



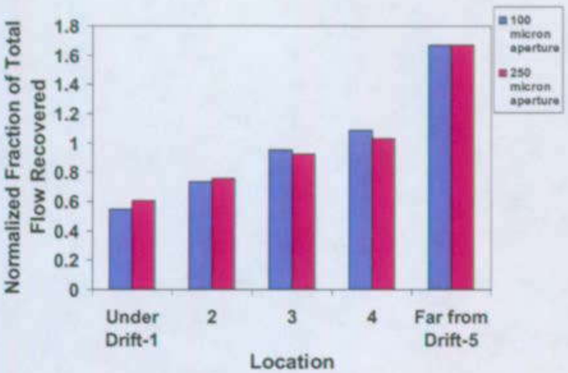
Conceptual Model of seepage into an excavated drift. Percolation into the drift is variable and seepage is predicted via both the matrix and fractures intersecting the drift. Arrows show some drift diversion and small drift shadow.

ANALYTICAL MODEL



Analytical Model of seepage into an excavated drift, after Philip, *et al.* (1989). Model assumes constant downward seepage velocity which is diverted around the drift. Predictions include areas of increased saturation due to diversion, termed "roof-drip lobes," and a region downstream of the drift where flow is severely retarded, termed the drift shadow.

*Abstract has changed slightly from that which was published.



Analytical model predictions indicated the location along the drift where we expect to see inflow recovered. Cumulative percent of inflow has been normalized assuming outflow at each port would be 0.20 without the drift shadow. Therefore, values less than 1 assume discharge less than if there was no drift shadow.

METHODOLOGY

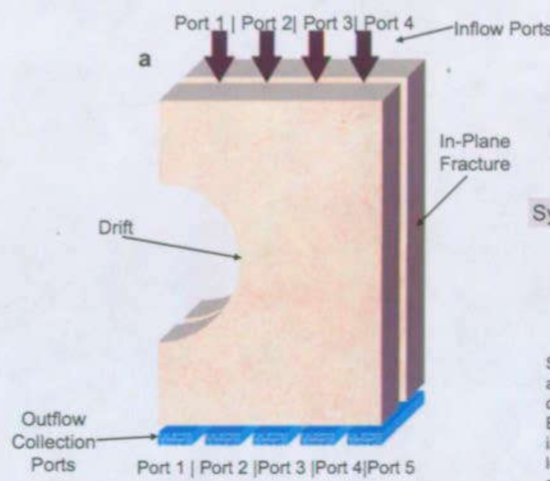
Test Cells

Test cell dimensions of 10 cm x 1 5cm x 1.25 cm

- Two slabs pressed together aperture controlled by aluminum wire between 2 slabs
  - 100-μm aperture fracture
  - 250-μm aperture fracture
- Natural fracture present beneath drift of 250-μm aperture fracture
- Fractures oriented normal to drift axis
- Aluminum bars put around the cell to decrease X-ray scatter
- Assembled cell encased in epoxy to decrease evaporative loss

Experimental

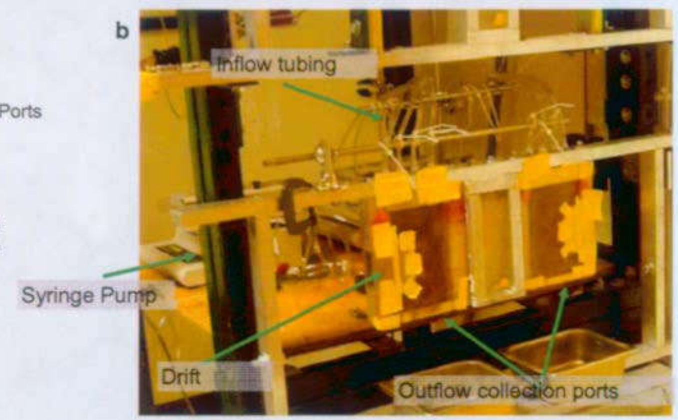
- Initially saturate sample with deionized water
- X-ray sample prior to start of experiment
- Initiate dripping of KI solution in ports at top of sample
- Outflow collected using sponges
- X-ray sample through out the experiment
- X-rays allow for visualization of I^- flowing through the sample



Statistical Analysis

- H_0: The analytical model predicts test system
- Chi Square Goodness of Fit test to compare the outflow results predicted in the model and those we observed.
- Discharge into the drift not accounted for because it is not figured into model
- Used total cumulative percent of outflow at each port
- (observed-expected)^2/expected into chi squared equation, 4 degrees of freedom

b



Schematic of test cell (a) and experimental set-up (b). Fracture is continuous throughout the test cell and is oriented perpendicular to the drift axis. Blue boxes beneath the cell (a) indicate the location of outflow collection ports. Black arrows along the top of the schematic show inflow location points. Experimental set-up (b) includes 2 syringe pumps to control inflow rate, administered by needles inserted into the fracture. Test cells are visible through epoxy coating, used to minimize evaporative losses to the system. Gold foil is taped to the epoxy to cover the Al frame surrounding the test cell and over the drift area. This is done to minimize scatter of x-rays which may compromise the resulting x-ray image.

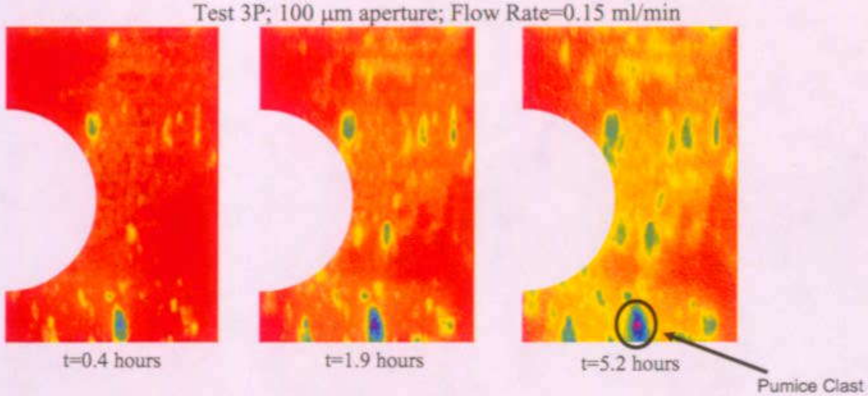
RESULTS

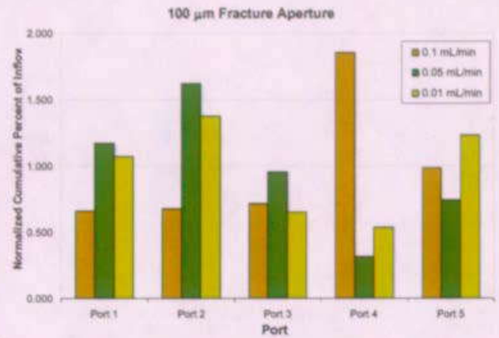
100 µm-Aperture Fracture

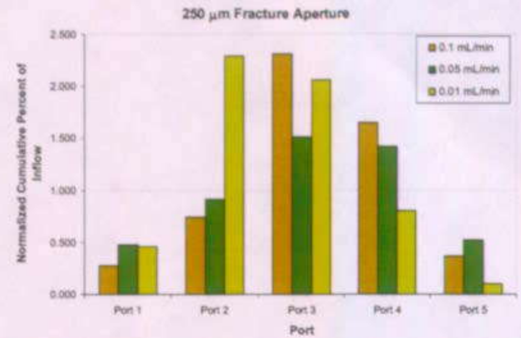
Table 1. Summary of four experiments performed on the 100 µm-fracture test cell. Listed flow rate is that which was programmed into syringe pumps and not necessarily that which actually flowed into the system. Mass balance was calculated using actual inflow rate.

Flow Rate (ml/min)	Test Nomenclature	Experiment Length (min)	Density of KI Solution (g/ml)	Mass Balance Error (%)	Cumulative Discharge into Drift (%)	p-value (Chi Squared)
0.01	5P	485	1.09	10.1	0.80	1.71×10^{-5}
0.05	2P	320	1.09	11.2	0.62	1.51×10^{-11}
0.1	1P	126	1.09	7.9	0.21	1.15×10^{-3}
0.15	3P	132	1.09	9.9	0.88	1.10×10^{-19}

Test 3P; 100 µm aperture; Flow Rate=0.15 ml/min







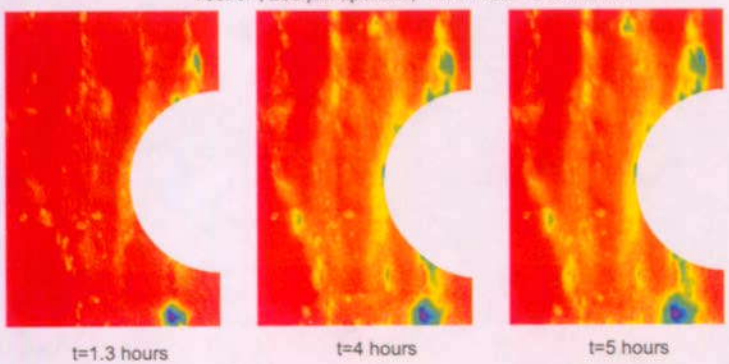
Comparison of observed outflow from three separate tests broken down by location along the base of the fracture. Cumulative percentage of inflow has been normalized assuming outflow at each port would be 0.20 without the drift-shadow effect. Therefore, values less than 1 assume discharge less than if there was no drift shadow effect.

250 µm-Aperture Fracture

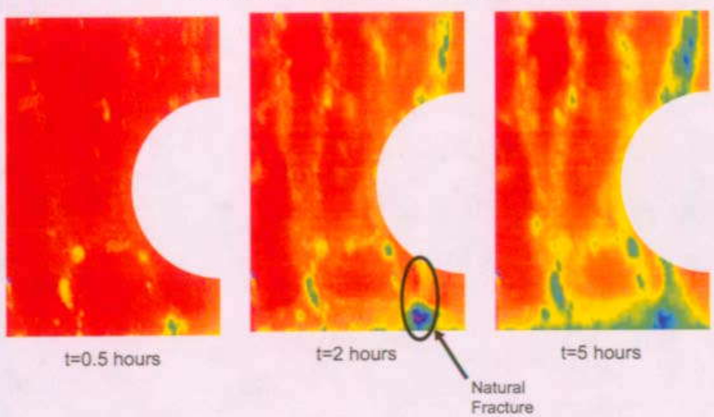
Table 2. Summary of the eight experiments performed on the 250 µm fracture-test cell. Listed flow rate is that which was programmed into syringe pumps and not necessarily that which actually flowed into the system. Mass balance was calculated using actual inflow rate.

Flow Rate (ml/min)	Test Nomenclature	Experiment Length (min)	Density of KI solution (g/ml)	Mass Balance Error (%)	Cumulative Discharge into Drift (%)	p-value (Chi squared)
0.01	5P	485	1.09	-4.5	0.0	5.96×10^{-19}
0.01	4P	484	1.22	-0.6	1.77	3.27×10^{-33}
0.01	1B	428	1.09	-15.4	1.72	3.24×10^{-22}
0.05	2P	320	1.09	10.1	1.27	1.71×10^{-5}
0.05	6P	419	1.09	-11.6	0.6	1.72×10^{-12}
0.1	1P	126	1.09	1.6	0.22	6.18×10^{-15}
0.1	2B	300	1.09	10.4	0.2	1.82×10^{-7}
0.15	3P	132	1.09	9.7	0.26	1.09×10^{-7}

Test 6P; 250 μm aperture; Flow Rate= 0.05 ml/min



Test 3P; 250 μm aperture; Flow Rate= 0.15 ml/min



DISCUSSION AND CONCLUSIONS

We are unable to validate the Philip *et al.* (1989) model with our current fracture apertures. Instead we see variation in the ports where outflow is collected. We believe the main reason for this observation is the heterogeneities within our sample, which are not accounted for in the analytical model. Heterogeneities include pumice clasts and natural fractures, which can influence the flow paths. Other potential explanations include experimental artifacts and film flow within the drift.

Despite not being able to validate the Philip *et al.* (1989) model, the experiments provide some evidence for a drift shadow. This is seen by discharge less than expected under the drift and discharge greater than expected just beyond the drift. X-ray absorption imaging also shows a tracer-solution flow path from above the drift being diverted around the drift and shedding off beyond the drift. However, we also observe high tracer concentrations in the natural fracture under the drift in the 250-μm fracture aperture. It is unclear whether these high concentrations are due to film flow on the interior of the drift, diversion around the drift and back under the drift due to heterogeneities, or experimental artifacts.

There is strong evidence of capillary diversion. The X-ray absorption imaging shows flow paths over the drift being diverted around the drift in the 250-μm aperture cell. In addition measured discharge into the drift was very small (2% maximum). Unfortunately, the fracture aperture in the 100-μm aperture cell is too small to contain enough tracer to clearly observe the flow paths.

FUTURE RESEARCH

- New test cell with 500-μm fracture aperture to test affects of aperture width on flow path development
- In depth statistical analysis of model results and observed results

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