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Preliminary Results of a Coupled Fracture-Flow Test at the 0.5m Scale

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February 28, 1997

Lawrence Livermore National Laboratory

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Interim Report

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Introduction

Understanding the hydrologic response of fluids present in the proposed repository horizon to the construction of a repository and the subsequent storage of high-level radioactive waste is crucial to the evaluation of Yucca Mountain as a suitable repository location. Moreover, recent analysis of site measurements imply that the rate of infiltration of water into Yucca Mountain is higher than previously thought, and an in-depth review of all data and analyses has so far confirmed the new estimates (Taylor, 1997). It is also known that the potential repository horizon at Yucca Mountain contains a significant number of fractures. This fact, coupled with higher estimates of the infiltration rate, has resulted in a revision of the general hydrologic model for Yucca Mountain; and it is now thought that the significant flow regime at this site is episodic fast flow in fractures. This implies that surface water can travel deep into Yucca Mountain through fractures (Taylor, 1997).

Given these recent developments, understanding flow in the fractured rock mass at Yucca Mountain is a critical requirement for viability assessment. Further, it is well known that the stress field in the rock surrounding the drifts will be altered by both the excavation of drifts and the heating of the rock associated with waste emplacement and storage. It also is generally accepted that flow in fractured rock is highly dependent on the stress field and temperature in the rock. This implies that the hydrologic behavior of rock surrounding emplacement drifts in the potential repository is dependent on the mechanical response of the fractured rock mass to excavation and waste emplacement.

The current understanding of coupled thermal-mechanical-hydrologic (TMH) behavior of fractured rock can be summarized as follows. Several investigators have shown that increasing stress across fractures causes a reduction in fracture aperture and, to the first order, flow in a fracture can be related to the cube of the fracture aperture (Raven and Gale, 1985). Generally, as compressive stress across a fracture is increased, the aperture is reduced, which reduces the fluid flow. More recent work indicates increases in shear stress across a fracture also may reduce the fracture permeability (Barton, *et. al.*, 1995). Heating the rock generally increases stress and reduces the fracture aperture. Finally, while a preliminary understanding of flow in single fractures is now available, it also is widely accepted that the hydrologic behavior of a fractured rock mass is controlled by a few, well connected fractures in the rock mass.

Clearly, more work is required to characterize adequately the TMH behavior of fractured rock. The purpose of this task is to perform laboratory experiments on 0.5m scale blocks of fractured rock from the repository horizon that will provide insight into the important processes controlling fluid flow in fractured rocks at the appropriate temperature and stress conditions, and to contribute to the database used in simulations of the potential repository. Tests at this scale have the benefit that known boundary and environmental conditions can be imposed on a rock sample that contains multiple fractures, while field data are often poorly constrained due to inherent limitations on boundary conditions, sampling intervals, and material characterization.

This report is documentation of progress on laboratory testing of small block samples of Topopah Spring tuff. The purpose of these tests is to investigate the thermal-mechanical, thermal-hydrological, and thermal-chemical response of the rock to conditions similar to the near-field environment (NFE) of a potential nuclear waste repository. This report contains preliminary results for flow measurements on a 0.5m scale block of Topopah Spring tuff containing an artificial fracture.

The fracture flow experiment described here represents the second phase of testing small block samples. The initial phase of testing the small block samples was reported in September 1996 (Blair and Berge, 1997). That report documented the first of a series of tests designed to study coupled processes in the near-field environment of a nuclear waste repository and provided new deformation and elastic wave velocity data which permit approximation of total rock mass properties and behavior for welded tuff units that contain fractures and vugs. It also provided guidance for input values used in equivalent continuum models of a repository.

We now are undertaking a series of flow experiments on small block samples. We expect that results of these experiments will provide constraints on how the flow and transport properties of the rock in the very near-field region of a repository may change as the temperature and stress fields change over time. A major objective is to provide a phenomenological understanding of coupled TMH properties of the tuff for use in computer modeling of the near-field environment. The experiments also are designed to provide information on behavior of waste package materials at conditions expected in the NFE. Laboratory experiments on 0.5m scale samples of

Topopah Spring tuff containing multiple natural fractures will provide data on changes in fracture permeability, mechanical properties, and geochemical reactions as a function of temperature, uniaxial stress, and time. These data also will permit development of scaling relations between properties measured in laboratory and field environments. This interim report is a description of progress on an experiment having the objective of measuring the flow of water through a horizontal, plane fracture as a function of normal stress to about 10 MPa and temperature to about 90°C.

Experiment

Overview

The laboratory sample (see Figure 1) containing an artificial, horizontal fracture was prepared using two right prism blocks of Topopah Spring tuff having typical edge dimensions of 25 cm. Uniaxial load is applied normal to the fracture plane using a 300 ton press. The sample assembly is heated using point source heaters on copper plates at the top and bottom of the assembly. Fluid flow is generated by a point source in the plane of the fracture at its center, connected to a pressurized fluid reservoir using a small diameter tubing. This creates a radial flow field to probe the effect of anisotropy of the rock fabric on the flow in the fracture. Diagnostics are average axial stress across the fracture plane, temperature at 12 points inside the sample, surface displacements along 16 baselines on the vertical surfaces of the sample, and fluid flow monitored at 38 locations at intervals of about 2.5 cm along the perimeter of the fracture.

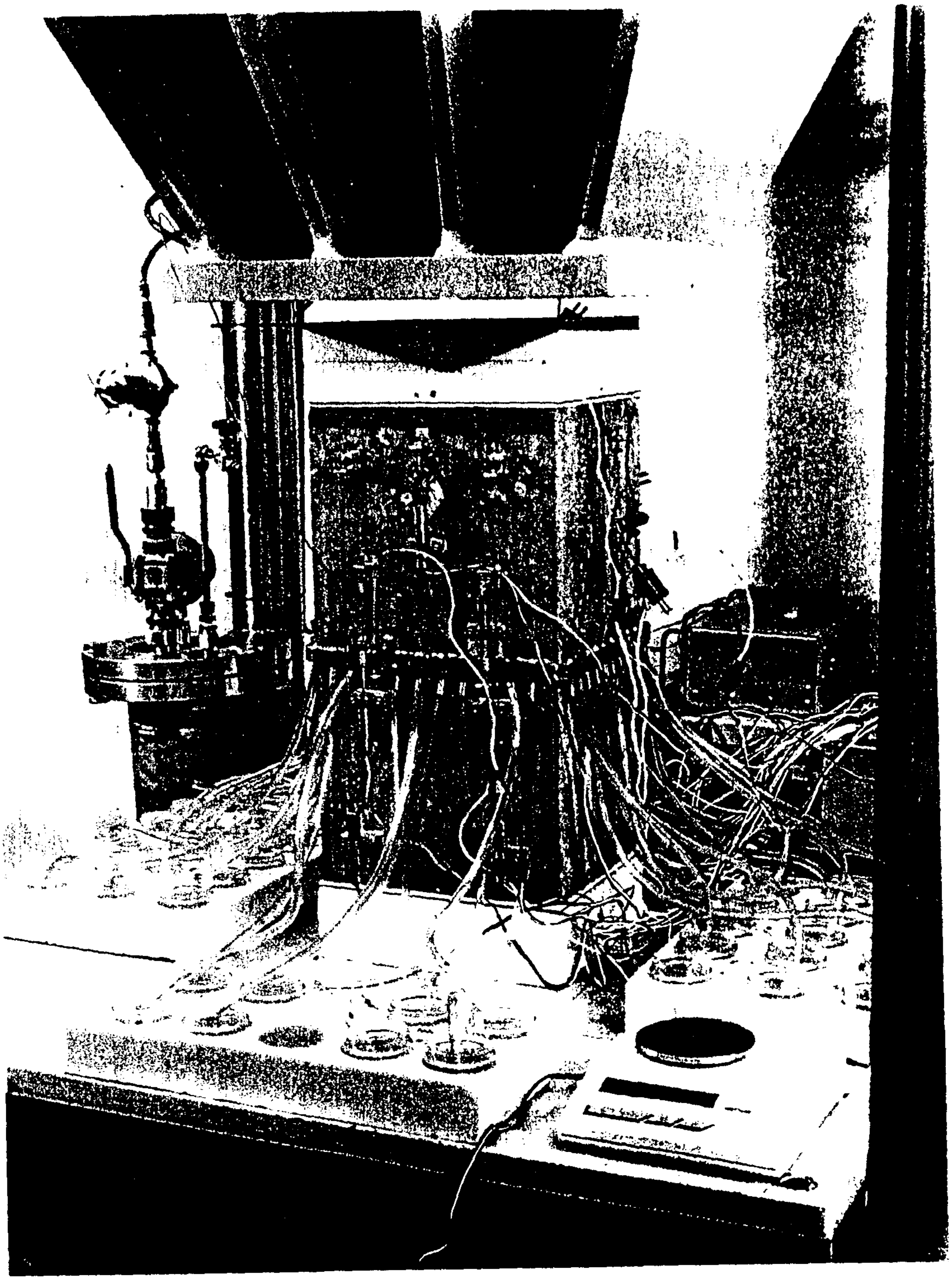

Figure 1. Overview of the Small Block Test SB3 Experiment 7051

The experiment plan is to:

1. Measure fluid flow through the virgin artificial fracture at room temperature and observe the effect of rock fabric anisotropy
2. Measure fluid flow and axial and Poisson strains as a function of axial stress to about 10 MPa at room temperature to provide data for the deformation modulus of the fractured material and changes in hydrologic behavior
3. Measure fluid flow and axial and Poisson strains as a function of axial stress and temperatures to about 90°C
4. Analyze coupons for corrosion performance.

Block Preparation

Owing to the difficulty in obtaining a 0.5 m scale sample with a suitable natural fracture, we made a sample with an artificial fracture. The sample, labeled "SB3," is made of a 26.2x24.5x49.0 cm^3 block cut from a boulder of Topopah Spring tuff excavated at the Large Block Test site at Fran Ridge, near Yucca Mountain, Nevada. The sample exhibits the typical Topopah Spring tuff fabric of subparallel vugs in pink and gray densely welded tuff. The cuts were oriented so that the dominant fracture and vug major axes are parallel to a block face. The original block was cut into two pieces at the midplane of the long direction to form the artificial fracture. The surfaces forming the fracture were ground parallel to within 0.001," then roughened using a bead blaster and 100 μm silicon dioxide beads. A total of about 0.6 cm of material was removed from the internal surfaces during the cutting and grinding operations. After preparation of the surfaces, the blocks were exposed to the ambient laboratory environment with no special temperature/humidity controls. For ease of reference, the faces of the blocks are labeled "North (N)," "West (W)," "East (E)," "South (S)," "Top (T)," and "Bottom (B)." The N, W, S, and E faces form the vertical sides of the sample assembly. The B face of the upper block and the T face of the lower block form the fracture. Load is applied to the T face of the top block and the B face of the bottom block.

A slit about 3 mm wide, 150 mm long and 25 mm deep at its deepest point was cut into the top surface of the bottom block at its centerline. The slit was intended to hold metal coupons for corrosion measurements, but subsequently was filled with grout to permit introduction of fluid at a point, rather than a line, source. A small opening (see below) was left ungrouted to form the point source.

Surface Mapping

Features intersecting the surfaces of the blocks were mapped by overlaying millimeter-grid tracing paper, then transferring the measurements to a 3-D computer graphics application for display and analysis. Figures 2a-l show that the crack/fracture/vug distribution is not homogeneous. There is a clear anisotropy of the rock fabric from east to west, with the major axis of the oblate cracks parallel to the axial stress direction. The fabric in the fracture surface shows the cracks/vugs running generally E-W, so that we would expect higher flow in channel along the E and W faces.

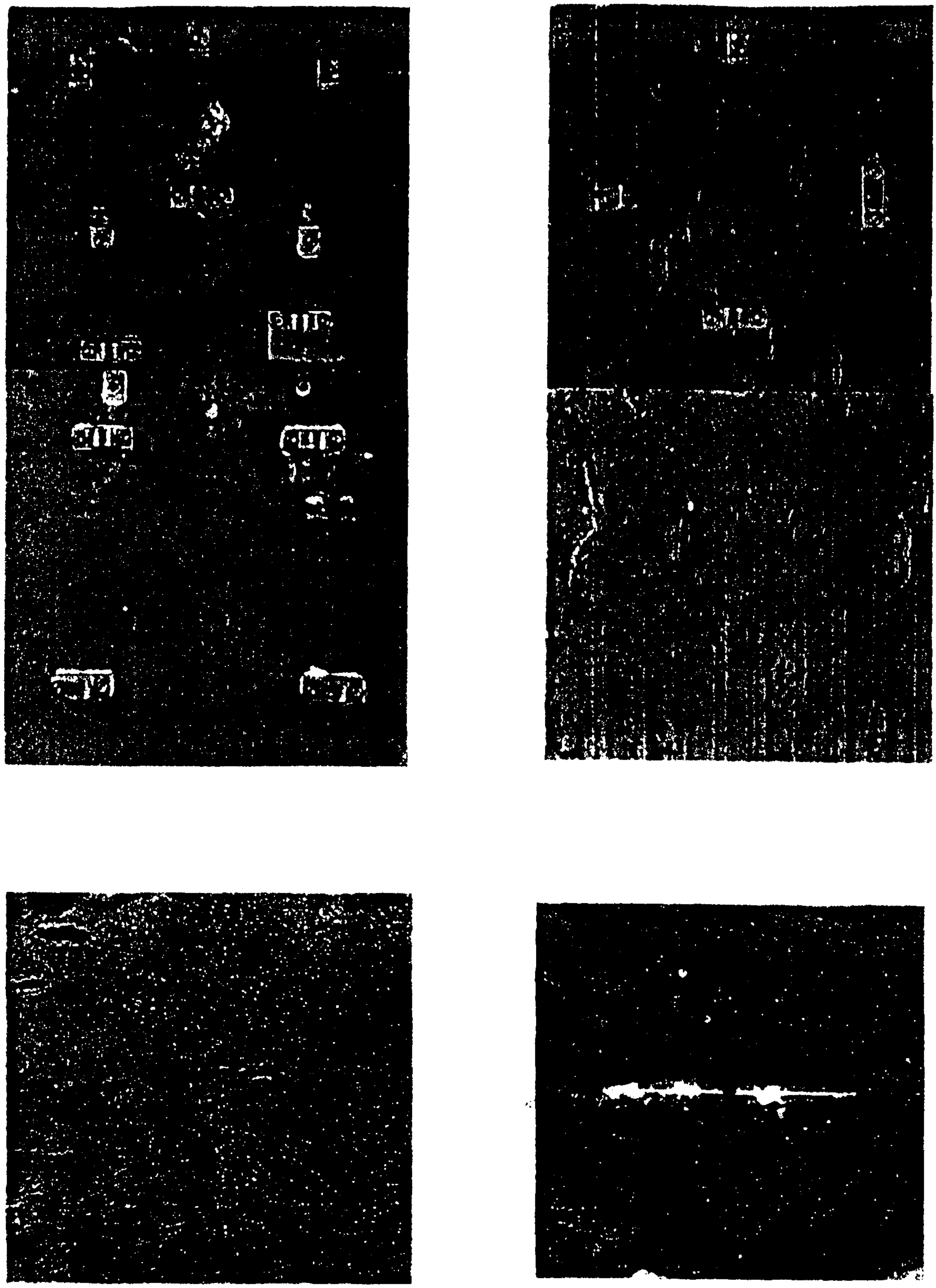

Figure 2. Clockwise from the top left: a) North face; b) West face; c) Top of the bottom block (fracture surface); d) Bottom of the top block (fracture surface);

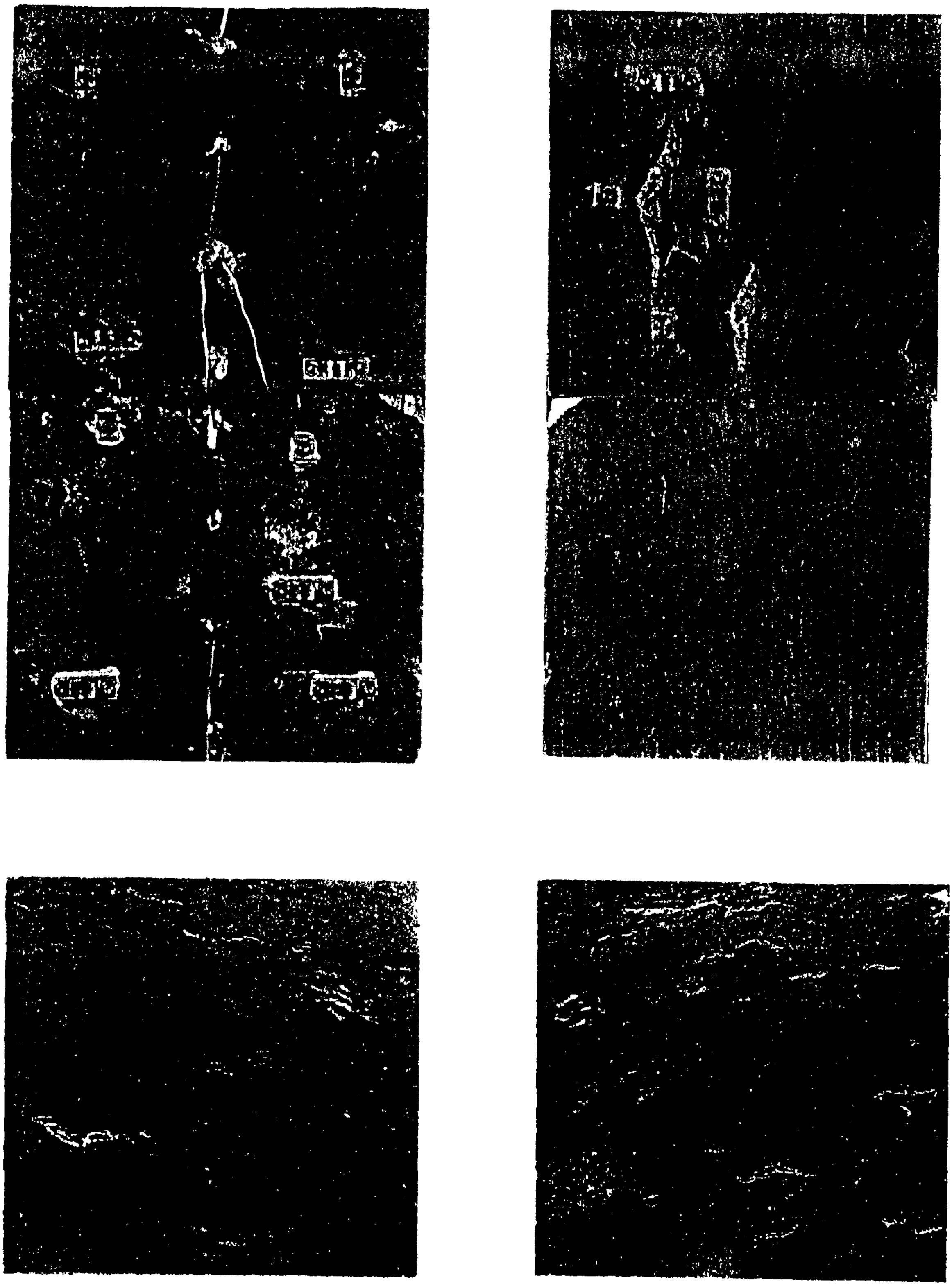

Figure 2 (cont) e) South face; f) East face; g) Bottom of the bottom block; and h) Top of the top block

Transducer Placement

Sixteen linear voltage displacement transducers (LVDTs) were mounted using aluminum brackets screwed into threaded inserts grouted into the block. The LVDTs were positioned, as shown in Figure 3, to measure axial displacement along a baseline the entire length of the two blocks, axial displacement along a short baseline across the fracture, lateral displacement along a baseline having no surface imperfections, and along perpendicular baselines spanning the intersection of a large vug with the surface. Extensions of 0.125″ diameter quartz rod were affixed using high temperature grout to LVDTs with baselines larger than the length of the transducers. Care was taken to ensure the LVDTs were mounted parallel and normal, as appropriate, to the principal stress direction.

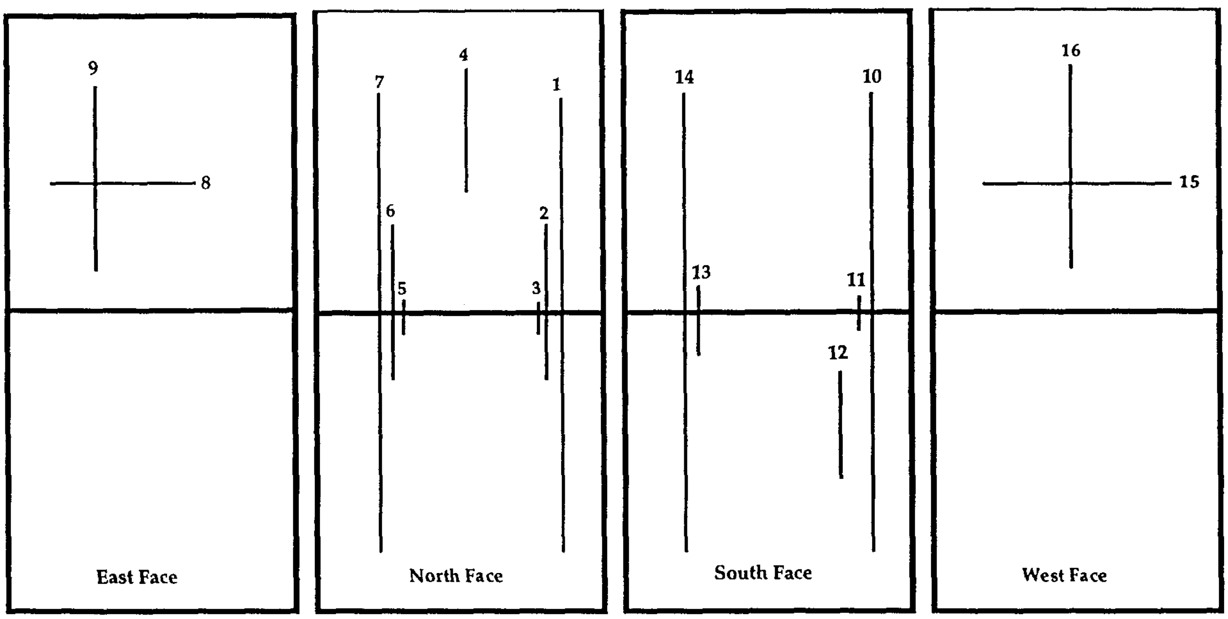

Figure 3. SB3 LVDT Layout

Thermocouple Placement

Twelve, 0.062" diameter Type J thermocouples were mounted in 0.125" diameter holes on a grid, as shown in Figure 4. The junctions of the thermocouples lie in a vertical plane parallel to the south face and at the center of the sample. The thermocouples were secured by grout or by epoxy, both for mechanical stability and to prevent fluid flow along a hole.

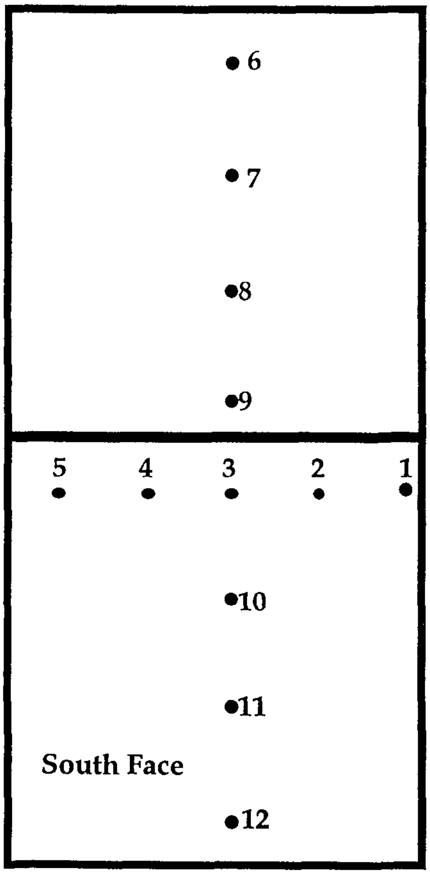

Figure 4. SB3 thermocouple layout

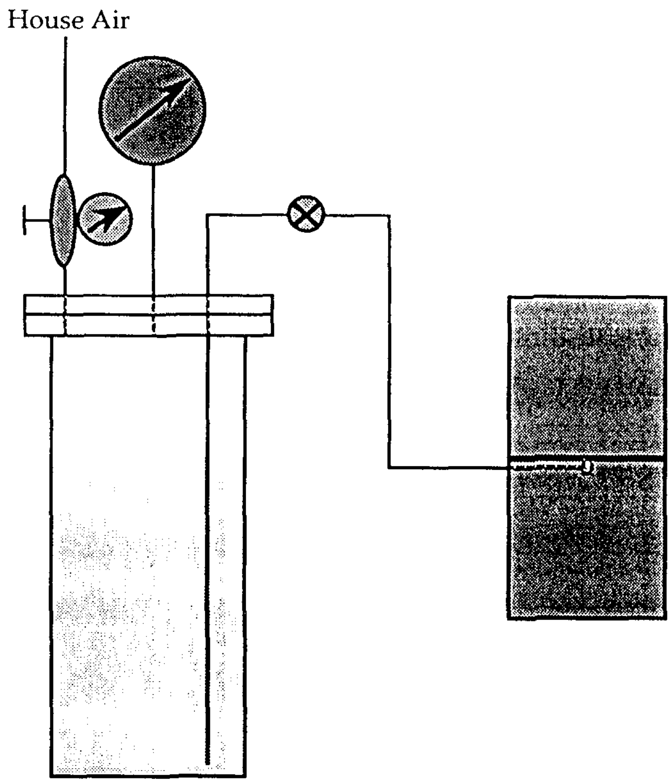

Figure 5. SB3 Fluid Flow System. The source cavity is about 2x6x10 mm^3, centered in the upper face of the bottom block.

Fluid Flow System

The fluid flow system, shown in Figure 5, is comprised of a pressurized reservoir, a point source at the center of the fracture, and a collection manifold along the fracture perimeter. Fluid pressure of up to 80 Psi is controlled to within ±0.1 Psi using a regulator and laboratory compressed air. The fluid is introduced into a 2x6x10 mm^3 "point source" by means of a .062" OD x .044" ID stainless steel tubing grouted into a 0.125" hole in the bottom block parallel to and about 1 cm below the fracture. The fluid used for Experiment 7051, described in this interim report, was tap water.

The fluid is collected along the perimeter of the crack using a simple manifold (see Figure 6) made of brass with copper and PVC tubing. Flow through the fracture at each face is collected into ten, equally spaced ports about 20 mm long, separated by about 4 mm. The manifold is mounted to the blocks using Dow Corning 739 RTV Sealant, which also ensures there is no fluid flow between the ports. A length of PVC tubing carries the fluid to a collection container for that port, which is weighed to determine the amount of fluid exiting the fracture at the port.

Data Acquisition

The data acquisition system is shown in Figure 7. The 12 thermocouples are connected to a National Instruments (NI) Mdl SCXI 1100 multiplexer using a NI Mdl SCXI 1303 Low Thermal terminal block with a precision reference temperature sensor. Temperature is accurate to ±1°C. The 16 LVDTs and the signal from the pressure transducer are connected similarly. The precision of the LVDT data, limited by the resolution of the A/D card, is about $5(10^{-4})$ inches. The accuracy of the Teledyne-Taber

Mdl 2403 pressure transducer is about 0.5%. We calculate average axial stress by measuring the pressure in the rams driving the load frame platen, converting the pressure to a force, then dividing by the cross section area of the block at 0.1 MPa. A NI NB MIO-16L ±10V, 12-bit A/D card in a MacIntosh MacIIfx computer reads, displays, and stores the data using NI LabView software. We measure fluid pressure to about ±1 Psi by observing a bourdon tube gauge. As noted above, we find the volume of fluid collected at each port by weighing and dividing by its density.

Corrosion Coupons

Ten coupons of 1020 carbon steel were placed in natural or machined cavities in the top surface of the bottom block. Comparison of unreacted and reacted weights and chemical analysis at the end of the experimental plan will permit an assessment of the corrosion resistance when exposed to the rock-fluid-pressure-temperature-time conditions. Intial weights and locations of the coupons are given in Table 1.

Table 1. Weights and locations of corrosion coupons for SB3. Locations are relative to the North-East corner of the top of the bottom block.

Coupon	Coupon ID	Initial Weight (Gms)	Location (in) x	y
B	0087	0.4313	7.7	4.3
C	0087	0.4985	2.1	8.2
D	0087	0.5846	2.1	1.0
E	0065	0.4323	8.3	5.8
F	0065	0.4294	6.2	2.9
G	0065	0.6085	7.7	9.2
H	0065	0.5755	8.8	2.9
J	0086	0.4304	2.1	5.8
K	0086	0.4310	6.7	1.9
L	0086	0.5119	4.1	5.3
M	0086	0.5287	8.3	8.2

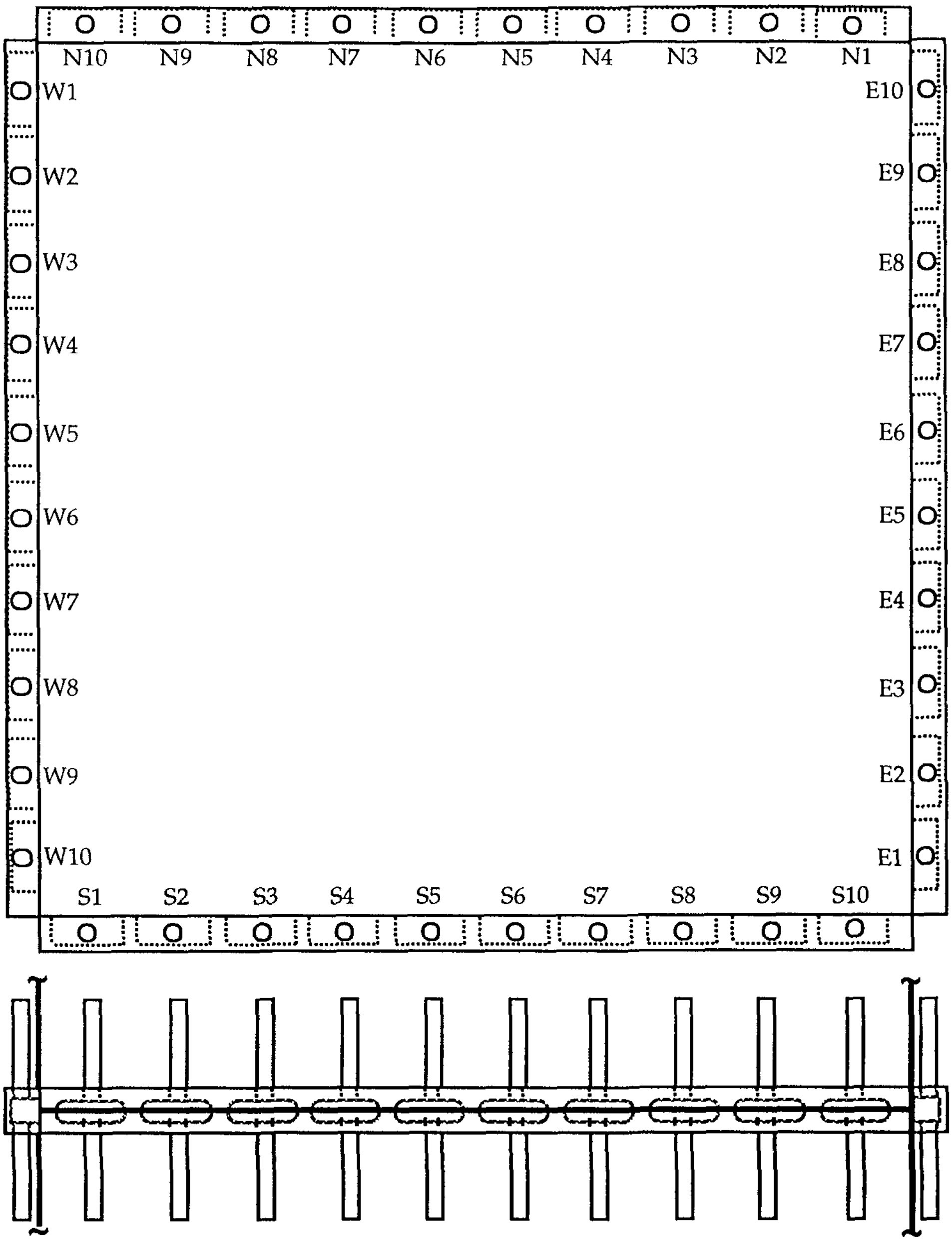

Figure 6. SB3 fluid collection manifold

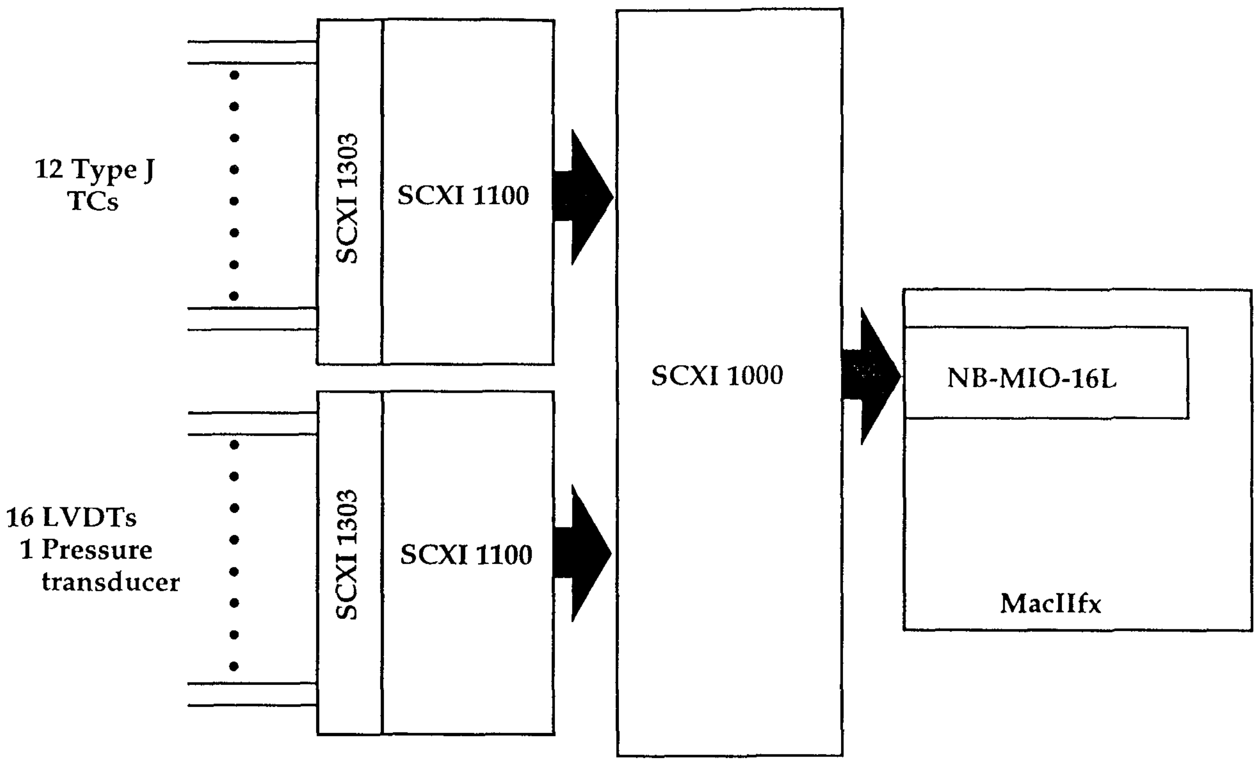

Figure 7. SB3 Data Acquisition System

Results and Discussion

The purpose of Experiment 7051 was to characterize the flow in sample SB3 under its initial conditions: dry, room temperature, and stress at the fracture surface equal to the "lithostatic" stress of about 4 kPa owing to the weight of the top block. Quasi-quantitative observations were made to determine 1) the presence of hydrologic low impedance paths from the point source to the sample boundary; 2) the time required to reach a "steady state" flow under zero applied stress consitions; 3) the efficacy of the procedure used to obtain flow data by collecting fluid at many locations along the perimeter of the horizontal fracture.

The use of a grid of fluid collection ports with spatial resolution greater than the typical hydrologic network path permits quasi-quantitiative analysis of flow at the sample boundary. This method was chosen because channelling is commonly observed in fracture flow experiments (Tsang, et. al., 1984). At steady state, such a network provides lower and upper bounds on the flow under specific temperature and stress conditions. The lower bound, representing flow through the connected porosity of the non-fractured matrix, can be estimated by measuring flow at compressive stresses large enough to close the fracture aperture. The upper bound, representing Darcy flow through an open aperture formed by parallel plane surfaces, can be estimated by extrapolating maximum flow measurements at compressive stresses less than that required to close the fracture aperture. Combining these quasi-quantitative flow data with estimates of the aperture from stress-strain measurements, the surface roughness from direct measurements, and limiting assumptions on the flow path, permits estimates of lower and upper bounds on the permeability. However, flow path assumptions, required to estimate both the length of the flow path from the point source to the collection point and the effective cross sectional area of the flow, are problematic. Tomographic imaging of the volume near the fracture can be used to constrain possible flow paths not in the fracture plane. Nevertheless, the spatial resolution of the collection grid and surface observation of the fracture provide adequate constraints for all but the most pathological flow paths.

Results for Experiment 7051

Experiment 7051 was conducted under conditions of effectively zero fracture interface stress and at room temperature to establish the fiducial for subsequent experiments at elevated stresses and temperatures. Beginning with the unsaturated sample, unreported flow data for driving pressures up to 2.5 Psig for 22 hours and then increases in pressure to 29 Psig over 6 hours indicate 1) imbibition is the primary fluid sink mechanism at early times (capillary pressures typically are significantly larger than one atmosphere) and 2) the fracture surface in SB3 has no natural hydrologic short circuits (a fluid pressure of 29 Psi acting over an area of about 2 in^2 is enough to lift the top block and create a zero impedance flow path).

Using the assembly shown in Figure 6, we obtained the results shown in Table 2 and Figure 8. Flow at collection points not shown in Table 2 was zero. Some flow, most likely through the fracture surface, passed through imperfections in the manifold-rock sealing surface and was not collected in the manifold. Modifications to the manifold-rock sealing technique will be made in subsequent experiments, permitting a quantitative accounting of fluid into and out of the sample.

Data reported in Table 2 and Figure 8 permit some quasi-quantitative observations.

1. Essentially all of the measured flow at zero stress is through the fracture and into 8 of the 38 channels. Three-fourths of the channels reported no flow for the nominally isotropic fracture aperture. No flow through the faces of the blocks away from the fracture plane was observed in this short experiment. This is consistent with the analyses of pore structure in this material (Pena, et. al., 1995; Price, et. al., 1985).

2. Recorded flow was dominated by paths generally in the E-W direction, which may owe to the anisotropy of the rock fabric.

3. The maximum measured flow rate[1] of water at room temperature and zero fracture interface stress at 9 Psig driving pressure through a single flow path is about 5 gms/min, with an average measured flow for all paths under those conditions of about 6 gms/min.

4. The impedance of a flow path may change with time, as seen for channels N2 and W2.

5. Relatively low driving pressures (about 14 feet of hydrostatic head) are sufficient to cause flow through this smooth fracture at zero axial stress.

6. Measured flow through channel E6 is proportional to the source pressure: at 9 Psig, flow is 5.2 gm/min; at 6 Psig, flow is 3.2 gm/min.

Finally, after modifying the manifold-rock sealing surfaces to capture all of the fluid passing through the fracture, collecting fluid at many discrete locations along the fracture boundary appears to be a promising method of quantifying fluid flow through a fracture. In particular, we expect to be able to make quasi-quantitative measurements of the effect of the anisotropic rock fabric on the flow as a function of compressive stress and temperature.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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[1] Flow through the fracture comparable to the measured flow was observed at eleven locations (N2, N5, N10-W1, W2, W3, W6, W9, S10-E1, S3-S4, S4, S5). This flow was not collected in a channel because of an inadequate seal between the manifold and the rock or because of a natural fracture that was purposefully left unsealed for this experiment.

Table 2. Flow in grams of tap water for Experiment 7051. T ≈ 23°C. $\sigma_1 \approx 4$ kPa. $\sigma_2 = \sigma_3 = 0$. P ≡ Pressure at the point source in the fracture. N1, N2, ... are collection points around the perimeter of the fracture (see Figure 6). Flow at collection points not shown in this table is zero.

Time (Min)	Pressure (Psig)	N1	N2	N4	N5	W1	W2	W4	W6	E5	E6	E8	E9	E10
0	29	0.0	79.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60	29	0.0	142.8	11.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
120	29	0.0	220.1	11.6	0.0	52.1	0.0	1.7	0.8	0.0	0.0	2.4	0.0	0.0
120	9	0.0	220.1	11.6	0.0	52.1	0.0	1.7	0.8	0.0	0.0	2.4	0.0	0.0
240	9	0.0	293.1	11.6	33.1	60.1	0.0	1.7	0.8	10.0	0.0	36.7	2.8	0.0
253	9	18.7	362.0	11.6	72.5	60.1	84.6	1.7	0.8	79.4	0.0	89.2	2.6	9.2
273	9	36.8	364.2	15.0	95.9	60.1	174.6	1.7	0.8	145.5	106.5	114.6	4.0	9.5
285	9	36.8	364.2	15.0	95.9	60.1	174.6	1.7	0.8	145.5	196.7	114.6	4.0	9.5
300	9	36.8	364.2	15.0	95.9	60.1	174.6	1.7	0.8	145.5	283.0	114.6	4.0	9.5
308	9	65.5	364.2	18.5	110.1	62.2	278.7	1.7	0.8	171.0	283.0	134.9	5.2	10.0
313	0	65.5	364.2	18.5	110.1	62.2	278.7	1.7	0.8	171.0	283.0	134.9	5.2	10.0
333	0	65.5	364.2	18.5	110.1	62.2	278.7	1.7	0.8	171.0	283.0	134.9	5.2	10.0
333	9	65.5	364.2	18.5	110.1	62.2	278.7	1.7	0.8	171.0	283.0	134.9	5.2	10.0
352	9	65.5	364.2	18.5	110.1	62.2	278.7	1.7	0.8	171.0	384.7	134.9	5.2	10.0
373	9	66.5	416.6	37.1	110.1	62.2	363.3	1.7	0.8	171.0	479.3	139.3	5.2	10.0
388	9	66.5	416.6	37.1	110.1	62.2	363.3	1.7	0.8	171.0	569.1	139.3	5.2	10.0
389	6	66.5	416.6	37.1	110.1	62.2	363.3	1.7	0.8	171.0	569.1	139.3	5.2	10.0
413	6	66.5	416.6	37.1	110.1	62.2	363.3	1.7	0.8	171.0	631.7	139.3	5.2	10.0
483	6	72.6	448.7	37.1	110.1	62.2	369.6	1.7	0.8	182.6	631.7	140.1	6.7	10.0
598	6	79.4	448.7	38.2	110.1	62.8	439.9	1.7	0.9	182.6	1000.1	140.1	6.7	10.0
718	6	84.1	448.7	38.2	110.1	63.4	521.8	1.7	0.9	203.4	1387.7	140.1	6.7	10.0

SB3 Experiment 7051

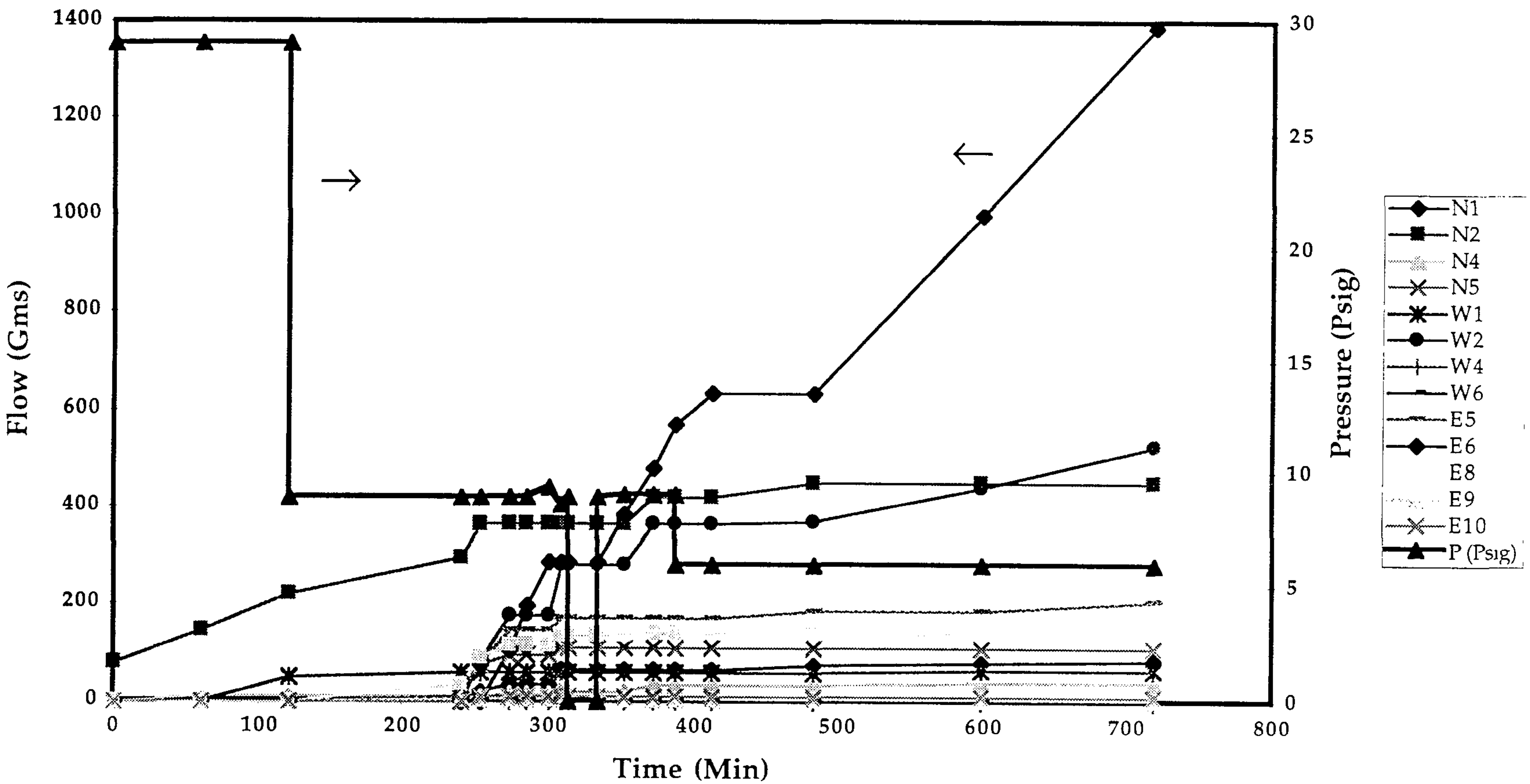

Figure 8. Flow and driving pressure data for Experiment 7051.

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