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Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

September 1981

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This work was supported by the Assistant Secretary for Nuclear Energy, Office of Civilian Waste Management of the U.S. Department of Energy under Contract DE-AC03-76SF00098. Funding for this project is administered by the Office of Crystalline Repository Development at Battelle Memorial Institute.
This report is one of a series documenting the results of the Swedish-American cooperative research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U.S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory.

The principal investigators are L.B. Nilsson and O. Degerman for SKBF, and N.G.W. Cook, P.A. Witherspoon, and J.E. Gale for LBL. Other participants will appear as authors of the individual reports.

Previous technical reports in this series are listed below.

2. Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test by Lars Lundstrom and Hakan Stille. (LBL-7052, SAC-02).


33. Numerical Modeling to Assess Possible Influence of the Mine Openings on Far-Field In-Situ Stress Measurements at Striga by T. Chan, V. Guvanasen, and N. Littlestone (LBL-12469, SAC-33).

34. A Field Assessment of the Use of Borehole Pressure Transients to Measure the Permeability of Fractured Rock Masses by C.B. Forster and J.E. Gale. (LBL-11829, SAC-34).


40. Laboratory Investigations of Thermomechanical Properties of Striga Granite by L. Myer and R. Rachiele. (LBL-13435, SAC-40)


43. Thermal Analysis of the Stripa Heater Test Data from the Full Scale Drift by I. Javandel and P.A. Witherspoon. (LBL-13217, SAC-43).


46. Fracture and Hydrology Data from Field Studies at Stripa, Sweden by J.E. Gale. (LBL-13101, SAC-46).


## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xi</td>
</tr>
<tr>
<td>1.0 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2.0 BOREHOLE INSTRUMENTATION DEVELOPMENT</td>
<td>5</td>
</tr>
<tr>
<td>2.1 Pressure Measurement</td>
<td>8</td>
</tr>
<tr>
<td>2.2 Temperature Measurement</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Conductance Measurement</td>
<td>10</td>
</tr>
<tr>
<td>2.4 Setup for Readings Outside the Room</td>
<td>10</td>
</tr>
<tr>
<td>2.5 Packer System</td>
<td>14</td>
</tr>
<tr>
<td>2.6 Modular Borehole Instrumentation</td>
<td>20</td>
</tr>
<tr>
<td>2.7 Final Borehole Instrumentation Layout</td>
<td>24</td>
</tr>
<tr>
<td>2.8 Borehole DBH-2</td>
<td>27</td>
</tr>
<tr>
<td>2.9 Installation Equipment</td>
<td>28</td>
</tr>
<tr>
<td>3.0 VENTILATION SYSTEM DEVELOPMENT</td>
<td>33</td>
</tr>
<tr>
<td>3.1 General Layout</td>
<td>36</td>
</tr>
<tr>
<td>3.2 Bulkhead Wall</td>
<td>36</td>
</tr>
<tr>
<td>3.3 Duct System</td>
<td>37</td>
</tr>
<tr>
<td>3.4 Inlet Duct Heaters</td>
<td>38</td>
</tr>
<tr>
<td>3.5 Room Air Temperature Sensors</td>
<td>38</td>
</tr>
<tr>
<td>3.6 Fans and Heaters</td>
<td>39</td>
</tr>
<tr>
<td>3.7 Air Flow Measurement</td>
<td>39</td>
</tr>
<tr>
<td>3.8 Wet and Dry Bulb Temperature Measurement</td>
<td>41</td>
</tr>
<tr>
<td>3.8.1 Continuous Measurements</td>
<td>41</td>
</tr>
<tr>
<td>3.8.2 Spot Measurements</td>
<td>41</td>
</tr>
<tr>
<td>3.9 Barometric Pressure</td>
<td>42</td>
</tr>
<tr>
<td>3.10 Final Configuration</td>
<td>42</td>
</tr>
<tr>
<td>3.11 Rock Temperature Measurement</td>
<td>42</td>
</tr>
<tr>
<td>4.0 EXPERIMENT INSTALLATION</td>
<td>45</td>
</tr>
<tr>
<td>4.1 Overview</td>
<td>45</td>
</tr>
<tr>
<td>4.2 Ventilation System</td>
<td>47</td>
</tr>
<tr>
<td>4.2.1 Bulkhead Wall</td>
<td>47</td>
</tr>
<tr>
<td>4.2.2 Inlet Duct and Instrumentation</td>
<td>50</td>
</tr>
<tr>
<td>4.2.3 Exhaust Duct and Instrumentation</td>
<td>52</td>
</tr>
<tr>
<td>4.2.4 Air Flow Measurement Calibration</td>
<td>54</td>
</tr>
<tr>
<td>4.3 Continuous Wet and Dry Bulb Temperature Recorders</td>
<td>58</td>
</tr>
<tr>
<td>4.4 Heater Controller</td>
<td>59</td>
</tr>
<tr>
<td>4.5 Room Air Temperature Sensors</td>
<td>61</td>
</tr>
<tr>
<td>4.6 Rock Temperature Sensors</td>
<td>64</td>
</tr>
<tr>
<td>4.7 Packer Field Testing</td>
<td>65</td>
</tr>
<tr>
<td>4.8 Pressure Gauge Calibration</td>
<td>67</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.9 Packer Assemblies</td>
<td>67</td>
</tr>
<tr>
<td>4.9.1 Logistical Considerations</td>
<td>67</td>
</tr>
<tr>
<td>4.9.2 Installation Procedure</td>
<td>72</td>
</tr>
<tr>
<td>5.0 OPERATION OF THE EXPERIMENT</td>
<td>75</td>
</tr>
<tr>
<td>6.0 OPERATIONAL MODIFICATIONS</td>
<td>83</td>
</tr>
<tr>
<td>7.0 CONCLUSIONS</td>
<td>87</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>89</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>91</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Location map</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>Plan view of the entire experiment area and adjacent mine workings</td>
<td>6</td>
</tr>
<tr>
<td>2.2</td>
<td>Borehole layout in the ventilation drift</td>
<td>7</td>
</tr>
<tr>
<td>2.3</td>
<td>Schematic of the temperature transducer circuit</td>
<td>12</td>
</tr>
<tr>
<td>2.4</td>
<td>Schematic of the conductance measurement circuit</td>
<td>13</td>
</tr>
<tr>
<td>2.5</td>
<td>Cobbs packer drawing</td>
<td>15</td>
</tr>
<tr>
<td>2.6</td>
<td>Test setup for packer-induced stress</td>
<td>16</td>
</tr>
<tr>
<td>2.7</td>
<td>Packer-induced stress on a borehole wall</td>
<td>17</td>
</tr>
<tr>
<td>2.8</td>
<td>Relative motion between packer ends and the rubber elements during inflation</td>
<td>19</td>
</tr>
<tr>
<td>2.9</td>
<td>Test setup to measure thrust generated by packer inflation</td>
<td>19</td>
</tr>
<tr>
<td>2.10</td>
<td>Measurement port couplings</td>
<td>21</td>
</tr>
<tr>
<td>2.11</td>
<td>Application of the measurement port couplings</td>
<td>23</td>
</tr>
<tr>
<td>2.12</td>
<td>Final borehole instrumentation layout</td>
<td>25</td>
</tr>
<tr>
<td>2.13</td>
<td>Regulation of inflation pressure for borehole DBH-2</td>
<td>29</td>
</tr>
<tr>
<td>2.14</td>
<td>&quot;Pipe tool&quot; for installing the borehole instrumentation</td>
<td>30</td>
</tr>
<tr>
<td>3.1</td>
<td>Schematic view of the instrumented experiment room</td>
<td>34</td>
</tr>
<tr>
<td>3.2</td>
<td>Schematic of the air-flow measurement system</td>
<td>40</td>
</tr>
<tr>
<td>3.3</td>
<td>Block diagram of the ventilation data collection and control system</td>
<td>43</td>
</tr>
<tr>
<td>4.1</td>
<td>Time-line chart of activities in the ventilation drift during 1979</td>
<td>46</td>
</tr>
</tbody>
</table>
4.2 Partially completed bulkhead as viewed from inside the experiment room .................. 49
4.3 Outside of the partially completed wall .................. 51
4.4 Relative positions of the components of the control system, instrumentation panels and exhaust duct .................. 55
4.5 Air flow calibration curve .................. 57
4.6 Drip system for the wet bulb thermometers .................. 60
4.7 Block diagram of the heater control and electrical system .................. 63
4.8 Detailed drawing of the Cobbs Tri-E1 packer .................. 68
4.9 The borehole installation tally sheet .................. 69
5.1 Ventilation system data sheet .................. 76
5.2 Borehole data sheet for either temperature and pressure or temperature and conductance .................. 77
5.3 Data sheet for temperature hole TG-1 .................. 78
5.4 Data sheet for the wall temperature transducers .................. 79
5.5 Ventilation system field data reduction form .................. 80
6.1 Modified ventilation system for low air-flow measurement ... 84
ABSTRACT

The Macropermeability Experiment was designed to measure both the natural drainage into an underground room and the hydraulic gradient around the room to determine the bulk permeability of a large volume of fractured granite. To achieve this, two instrument systems were developed specifically for the experiment. The first system consisted of an array of instrumented boreholes to measure the hydraulic gradient, and the second consisted of a ventilation system to extract water from the room.

The borehole array consisted of 15 holes divided by packers into ninety-four 5 meter-long intervals. Water pressure and temperature were measured in each interval, and conductance was monitored in 31 intervals.

The ventilation system drew air of known moisture content into the sealed room, where it was heated and circulated to evaporate all moisture, and then drawn back out of the room. The net flow of water into the room was determined from the air-flow rate and the increase in moisture content of the air as it passed through the room. The ventilation system included a moisture-tight wall to seal the room; wet and dry bulb temperature sensors in the inlet and exhaust ducts; heaters in the inlet duct to warm the air; fans within the room to circulate the air; a main fan in the exhaust duct to control the rate of air movement through the room; and an air-flow measurement system.

The experiment operated for roughly one year. Groundwater flow rates of 40 to 50 ml/min were measured at nominal room temperatures between 20 and 45°C.
1.0 INTRODUCTION

The Macropermeability Experiment is part of a large series of studies evaluating the possibility of using a large crystalline rock mass as a geologic repository for nuclear waste. The experiment was conducted to measure the permeability of a large volume of low-permeability, fractured granite, information important to estimates of radionuclide transport. This report is the second of two describing the experiment. The first, "Geohydrological Data from the Macropermeability Experiment at Stripa, Sweden," (Wilson et al., 1981), presented the results, and this report describes the design considerations, installation procedures, and operating experience gained.

Standard borehole tests are generally inadequate for measuring average permeability in large volumes of rock because of difficulties in perturbing sufficient volumes and in monitoring the response. In the Macropermeability Experiment, the natural drainage into a mined drift and the hydraulic gradient around the drift were monitored over a 9-month period to determine the average equivalent permeability of 200,000 cubic meters of fractured granite. Water inflow was measured as the net moisture pickup of a controlled ventilation system. With this system, water that entered through the rock was evaporated and removed from the room. The net increase in moisture content of the ventilating air was determined from the air-flow rate and from psychrometric data collected at the inlet and exhaust ducts of a sealed portion of the drift. The hydraulic gradient was measured in 15 boreholes that extended radially and longitudinally from the drift. Each borehole was divided into six monitored zones.

The experiment was performed on the 335 m level of the Stripa iron mine.
in south central Sweden (Fig. 1.1). The test facility was jointly operated by the Swedish Nuclear Fuel Supply Company (KBS) for Sweden and Lawrence Berkeley Laboratory (LBL) for the U.S. Department of Energy (DOE).

The design of the experiment began in October 1978, and field installation was essentially complete in November 1979. Field work was completed in September 1980.

The instrumentation system was developed in an integrated effort from October to December 1978. General responsibilities were divided as follows: S. Lundgren developed the borehole instrumentation and installation equipment; A. DuBois identified and assembled the ventilation system components; G. West designed and assembled the heater controllers; C. Wilson, as Task Investigator, and T. Doe provided borehole instrumentation requirements; and M. McPherson (University of Nottingham) specified the ventilation system requirements. R. Galbraith coordinated these efforts and carried out the actual installation and operation of the experiment. The success of the experiment is due totally to the free exchange of ideas within this group.

The design and operation of the experiment are presented as follows. Section 2 describes the borehole instrumentation system and Section 3 the ventilation system. Installation procedures are reviewed in Section 4, and the operating experience is discussed in Section 5. Problems encountered with installation and operation are highlighted for the benefit of future experiments of this type. Operational modifications required because of an inaccurate early estimate of the groundwater seepage rate into the drift are discussed in Section 6. Conclusions are presented in Section 7.
Fig. 1.1. Location map.
2.0 BOREHOLE INSTRUMENTATION DEVELOPMENT

The Macropermeability Experiment was installed in the ventilation drift of the experimental area, as shown in Fig. 2.1. This figure also shows the 15 boreholes used for measuring the hydraulic gradient. The orientation of these holes may be determined from Fig. 2.2. Five boreholes, HG1 through HG5, extended 30 m from the face of the drift; HG1 was horizontal, and HG2 through HG5 lay on the surface of a cone that diverged with depth. Ten radiating holes, R1 through R10, were arranged in two groups. Holes R1 through R5 lay in a plane roughly 2 m from the face of the drift, and R6 through R10 in a plane roughly 22 m from the face. Of these, R1 and R6 were 40 m long, while the rest were 30 m long. Each hole was 76 mm in diameter.

Borehole DBH-2 was 56 mm in diameter and paralleled the ventilation drift. This borehole extended from the computer drift to a point about 50 m beyond the end of the ventilation drift. While not drilled for this experiment, this borehole was instrumented for water pressure monitoring. The data from this hole were peripheral to those of the 15-borehole primary array.

All isolated intervals in the R and HG boreholes were also monitored for water temperature. In addition, all intervals in the HG holes and interval 4 in R1 were instrumented to measure groundwater conductance for monitoring the migration of a saline tracer.

The borehole instrumentation system had to meet the following basic requirements:

- Water pressure must be measured in six isolated intervals in each borehole.
- Water temperature must be measured in each borehole interval.
- Water conductivity must be measured in selected intervals for a NaCl tracer test.
- As many measurements as possible must be made from outside the room.
Fig. 2.1. Plan view of the entire experiment area and adjacent mine workings.
Fig. 2.2. Borehole layout in the ventilation drift.
The multiple packer system used to divide the boreholes into intervals must be maintained from outside the room.

The borehole instrumentation must be modular to allow for changes in the test plan that might occur while the system was being installed.

The system would have to operate for about one year, measuring very slow rates of change in temperature and pressure.

The data would be read manually once each working day.

The following subsections describe the design of the pressure, temperature, and conductance measurement systems, as well as the special design considerations related to the requirement that all possible readouts be performed outside the sealed room. Design considerations for the packers and modular borehole instrumentation system are presented, along with descriptions of the specialized tools used for installation. A special subsection is devoted to design of the instrumentation in borehole DBH-2.

2.1 Pressure Measurement

A highly reliable system was required to measure fluid pressure in 90 intervals spread over 15 boreholes. Once the instruments were installed, removal for repair or maintenance would perturb the ambient gradients and was to be avoided. For these reasons, it was decided to simplify the downhole equipment as much as possible and to locate all pressure metering instruments where they could be easily replaced. In addition, downhole metering equipment was not considered necessary because of the low transient rates of interest. In the final design, a high-pressure nylon tubing connected each borehole interval to a separate pressure gauge outside the room. This arrangement was both cheaper and more reliable than mounting transducers in each interval. Should continuous pressure measurements later become necessary, transducers could be attached to the backs of the pressure gauges. The tubing also allowed
bleeding of air from the boreholes as the packers were inflated. This was especially important in those boreholes that extended upward.

The pressure gauges were test-quality, Bourdon-tube type with 1 psi scale divisions on a 6-inch dial with a 0-300 psi span. These gauges were read to the nearest one half pound per square inch. Previous work at Stripa had indicated that water pressures would not exceed this range.

2.2 Temperature Measurement

Water temperatures were measured by an integrated circuit temperature transducer mounted in each borehole interval. Unlike thermisters or thermocouples, these transducers were not sensitive to lead length or power supply variations. Using a 4 to 30 V direct-current power supply, the transducer acted as a high-impedance, constant-current regulator calibrated to pass one microamp per degree Kelvin. The temperature of the transducer was read by placing a 1000-ohm resister in the circuit and reading the voltage across the resistor. For example, for 25°C (298.2K) the reading was:

\[ V = (1000 \text{ ohms}) \times (298.2 \text{ K}) \times (1 \times 10^{-6} \text{ A/K}) \]

\[ V = 0.2982 \text{ volts} \]

The temperature was read directly from a calibrated millivolt meter.

For simplicity, a 900-ohm precision resistor was wired in series with a 200-ohm precision trim potentiometer to achieve the 1000-ohm resistance. By adjusting this resistance, slight errors in the manufacture of the transducers were compensated so that all transducers had the same zero point. Since the transducers were linear, no compensation factor needed to be applied to the data.
2.3 Conductance Measurement

The relatively close spacing of the HG holes provided an opportunity to conduct a tracer experiment to measure natural groundwater flow velocities. The tracer was a slug of saturated NaCl solution injected into a selected interval in one of the HG holes. Conductance cells in the other HG holes would detect the arrival of the salt front as it moved outward. Conductance cells were installed in all 30 intervals of the HG holes and in interval 4 of R1.

A mockup of the conductance cell was tested at LBL to determine the method of construction. The iron pipe of the packer system would serve as one electrode. A 9.4 mm diameter steel rod 1 m long and spaced 1 cm from the pipe would complete the cell. The mockup indicated that with a 100 Hz power source operating at 0.4 volts, a 20 ppm change in salinity would be detected as a 1.28 mV change in cell resistance, compared with a known 10-ohm resistor. We also found that the presence in the cell of dissimilar metals such as copper created a large instability in the readings. Nylon pressure tubing was therefore used for the packer inflation line in the intervals where conductance readings were made.

2.4 Setup for Readings Outside the Room

Success required that air temperature and relative humidity in the room be as stable as possible. In addition, at room temperatures of 45°C, it would not be safe for personnel to be in the room for more than a few minutes. An aluminum bulkhead plate with low-pressure compression fittings was built into the room wall to permit data readout outside the room. The pressure tubes and wires from the boreholes were fed out of the room through
these fittings, which formed an airtight seal when tightened. This allowed all pressure, temperature, and conductance readings to be taken outside the room while maintaining the integrity of the bulkhead.

A gauge panel accommodated the instrumentation for each group of five boreholes, HG1 through HG5, R1 through R5, and R6 through R10. The pressure gauges for each borehole were arranged in columns of six with the top gauge being the interval closest to the room. The pressure tube was connected to the gauge through a tee. A valve on the remaining leg of the tee allowed air to be bled from or fluid to be injected into the borehole interval. Additional instrumentation could also be attached to it.

Voltage readings for water temperature were made in a standard double banana socket located to the lower right of each pressure gauge. The trim potentiometer and the resistor were attached to the terminals of this socket. A single switch controlled the power to all the temperature transducers. Figure 2.3 is a schematic of the temperature transducer circuit for a typical borehole. Color coding identified the individual wires.

The conductance readings for the HG holes and interval 4 of borehole R1 were made using a second, differently colored, banana jack located to the lower left of the pressure gauge. Figure 2.4 is a schematic of the conductance measurement circuit. The reference resistor was mounted on a double banana jack so it could be periodically removed from the circuit for calibration. Readings were taken by inserting a shorted double banana jack in the socket next to the gauge. This jack completed the circuit for the cell
Fig. 2.3. Schematic of the temperature transducer circuit.
Fig. 2.4. Schematic of the conductance measurement circuit.

- Oscillator

- $V_I$ Voltage across reference resistor

- $V_V$ Voltage across bore hole cell

- Shorting jack inserted here to make the circuit

- To bore hole electrodes

- To bore hole packer mandrel pipe

XBL 819-11528
in that interval. The voltage was then read across the reference resistor and the cell. The shorted jack was then moved to the next interval and the process repeated.

2.5 Packer System

The choice of packers was made largely on the basis of cost. Cobbs Tri-El NX packers, developed for use in coal mining under a contract with the U.S. Bureau of Mines (Cobbs, 1971), appeared to be the cheapest suitable for the experiment (Fig. 2.5) These packers, use a hydraulically activated piston to longitudinally squeeze three solid rubber rings, causing them to expand radially to form a seal between the packer mandrel and the borehole wall.

To confirm their suitability, these packers were tested in the laboratory. One experiment evaluated the sealing mechanism. A test packer was pressurized inside a 3-inch inner diameter aluminum tube. The outer surface of the tube was fitted with six strain gauges arranged in orthogonal pairs and spaced to lie opposite the rubber packer rings, (Fig. 2.6). One end of the tube was capped and fitted to allow fluid to be pumped in against the pressurized and seated packer.

The packer inflation pressure was increased in 250 psi increments, and the strain gauges were read after each increase. Figure. 2.7 shows the induced stress for each strain gauge. Circumferential gauges 1 and 3 show that the radial force exerted by the outer rubber rings increased linearly with packer inflation pressure. Circumferential gauge 2 was opposite the center ring and produced a line parallel to 1 and 3 but with an initial offset. Rearrangement of the rings on the packer and a repeat of the text showed this
Fig. 2.5. Cobbs packer drawing.
Fig. 2.6. Test setup for packer-induced stress.
Fig. 2.7. Packer-induced stress on a borehole wall.
offset to be the effect of one ring being of a harder grade rubber than the other two. The test showed that a radial force between 4000 and 7000 psi could be generated with this packer at an inflation pressure of 1000 psi. This was more than adequate for the experiment at Stripa, where the water pressure was expected to be less than 300 psi.

The longitudinal gauges 4 through 6 (Fig. 2.7) reflect a shortening of the rubber rings as the packer was inflated. Gauge 4, the closest to the piston, went from negative to positive, indicating that the rubber ring had moved out from under the gauge and that tension rather than compression was being applied at that gauge location. The greatest compression occurred under gauge 5 and was only slightly less under gauge 6. This indicates that the net longitudinal displacement of the packer during inflation was small.

Figure 2.8 illustrates the relative motion between the packer and the borehole as the packer was inflated. The piston works against one end of the packer and squeezes the rubber rings against the opposite end of the packer. The rubber rings displace by sliding along the central mandrel pipes. Once the rubber has expanded enough to grip the wall of the hole, additional longitudinal compression of the rubber rings can occur only if the ends of the packer move with respect to the center ring. Since some two to three inches of additional movement were observed in the lab experiments, a serious problem might have arisen if several packers were mounted in opposite directions in the same borehole, so this arrangement was avoided.

A different experiment determined the magnitude of the thrust generated by packer movement. Figure 2.9 illustrates the test setup. A packer was placed inside a 3-inch I.D. steel pipe. To simulate a borehold and improve the packer
Fig. 2.8. Relative motion between packer ends and the rubber elements during inflation.

Test Assembly: Axial Force

Fig. 2.9. Test setup to measure thrust generated by packer inflation.
grip, the inside of the pipe had been roughened by cutting a fine screw thread on its surface. A load cell was placed between the piston end of the packer and a rigid stop. A similar stop was placed against the pipe. As the packer was inflated, the thrust generated was measured with the load cell. Repeated tests showed that a 2000 to 2500 psi longitudinal pressure was generated by an inflation pressure of 500 to 1000 psi. This load is sufficiently high to conclude that all packers in a string should be oriented the same way.

These experiments confirmed that Cobbs packers could be used for the Macropermeability Experiment and provided information on their characteristics. The design allowed multiple packers to be placed in one borehole, so long as they were oriented in the same way, and the inflation pressure could be maintained from outside the room.

2.6 Modular Borehole Instrumentation

To place several packers in the same borehole, a simple, watertight method of passing tubing or wires from the water-filled borehole to the interior of the packer pipe string was needed. The method had to accommodate one or more nylon or copper tubes, the temperature transducer leads, and the lead for the conductance cell. The system had to be flexible so as to accommodate changes in the configuration that might occur as the equipment was installed. The solution was to modify a standard 3000 psi, black iron, 1 1/2-inch by 3/4-inch NPT reducer.

Figure 2.10a illustrates these modifications. A blind hole was drilled and tapped for a 1/8-inch pipe thread. A smaller, concentric hole was drilled to the interior of the coupling. This arrangement allowed the temperature
Fig. 2.10. Measurement port couplings.
transducer to be housed in the larger part of the hole and held with a pipe plug while the electric leads were passed through the small hole to the interior of the pipe. Figure 2.10b shows a coupling with the maximum number of ports for any borehole interval in this experiment. One port was for the temperature transducer. The other three were drilled through to the interior of the coupling and tapped for 1/8-inch pipe threads. These holes accommodated a bored-through tube fitting for the pressure tube or a wire for the conductance electrode. While this experiment required a maximum of four ports, as many as eight could have been drilled in the coupling. The external groove shown in Fig. 2.10 was machined the length of the coupling to hold the packer inflation tube and protect it from being pinched against the borehole wall. Figure 2.10c shows the bushing that completed the instrument housing and reconnected to the 3/4-inch mandrel pipe.

Figure 2.11 illustrates the application of these port couplings in the instrument string and their flexibility. Figure 2.11a shows the pressure measurement tube mounted in its compression fitting and the temperature transducer in its receptacle. The brass fitting provided the necessary watertight seal as the tube passed from inside the pipe to the borehole. Figure 2.11b shows the waterproof, single-conductor bulkhead connector as it was installed for the conductance cell electrode. The electrode was held away from the pipe by two plastic spacers and kept in place with plastic cabling straps. Figure 2.11c shows the special arrangement for the deepest interval at the end of the packer string. A single temperature-port coupling was used, and the pressure measurement tube was installed in the end of the pipe with a bushing. For intervals with conductance cells, a two-port coupling with an appropriate length of pipe supported the electrode. Two pressure tubes were
a. Pressure and temperature measurement.

b. Conductance measurement.

c. Special case at the end of the pipe assembly.

Fig. 2.11. Application of the measurement port couplings.
installed in the deepest intervals of several HG holes by using a three-port coupling. The extra tube allowed a tracer to be circulated into the borehole interval through the tube at the coupling and out through the tube at the end of the pipe.

An O-ring-sealed union between the measurement port coupling and the pipe already in the hole simplified installation. A standard instrumentation module thus consisted of a packer, a measurement port coupling, and an O-ring-sealed union. Pipe lengths between these components depended solely on the required packer spacing in the borehole.

The number of modules that could be installed in any borehole was limited by the space available inside the pipe for wires and tubes. In this experiment, 3/16-inch O.D. tubing was used for the pressure measurements. Although smaller tubing would have allowed more modules to be installed, such tubing would have had too much resistance to flow for some of the secondary experiments being planned. The packer mandrel had the smallest inner diameter in a module and allowed no more than seven tubes in any borehole. The wires for the temperature and conductance measurements were placed between the tubes and did not add to the space requirements.

2.7 Final Borehole Instrumentation Layout

Figure 2.12 shows the final borehole instrumentation system. The packers divided each borehole into approximately 5 m long intervals. Boreholes R1 and R6 were 40 m long and thus had 8 intervals. The remaining boreholes were 30 m long and had 6 intervals. Almost all intervals were monitored for pressure and temperature. The exceptions were the pair of intervals closest to the room in
Fig. 2.12. Final borehole instrumentation layout.
both R1 and R6, which were not instrumented. The intervals were numbered sequentially from the room outwards.

As mentioned previously, conductance cells were installed in all intervals in the HG holes and in interval 4 of borehole R1. Since this latter interval produced almost half of the water draining from the 15 boreholes prior to instrumentation, it was felt that a tracer introduced into the rock was likely to show up in it. Interval 6 in boreholes HG1, HG3, and HG5, as well as interval 4 in R1, were equipped with two pressure tubes to allow the tracer to be introduced. The final selection of the tracer injection interval depended on the hydraulic gradients that would develop after all packers were inflated.

Each of the 94 packers was kept at the same pressure with a single nitrogen bottle and regulator supplying a distribution manifold, as shown in Fig. 2.12. The inflation pressure was read at the manifold with a Bourdon-tube, 6-inch dial, 0-1000 psi, test-quality gauge with 5-psi scale divisions. A ball valve and a check valve controlled the flow of gas. The ball valve was opened to supply each borehole as it was instrumented. The check valve prevented a leak in any one borehole from reducing packer pressure in other boreholes.

A single, 1/8-inch copper tube connected the packers in each borehole to the distribution manifold. At the borehole, a tee and two ball valves divided the inflation tube into two legs. One leg supplied the packer nearest the room, packer 1. The other leg passed inside the mandrel pipe past packer 1, out into the borehole at the first measurement port coupling, and connected to packer 2. Packer 2 and the rest of the packers were connected in series as indicated in Fig. 2.12.
The independent operation of packer 1 was necessary for filling the borehole and pressure tubes with water. This was especially true for the upwardly inclined holes R1, R2, R6, R7, HG2, and HG5, as well as the horizontal borehole HG1. When packer 1 was inflated, natural seepage from the rock was allowed to fill the hole. Trapped air was removed by opening the valve at the gauge to bleed each pressure line.

After all air had been displaced from the hole, the remaining packers were inflated. This inflation caused a net increase in packer volume, raising the water pressure in the borehole. Care was taken to bleed off this pressure during the inflation process. Once the packers had reached the final inflation pressure, all water pressure measurement tubes were bled back to less than 25 psi, and data collection began.

2.8 Borehole DBH-2

Borehole DBH-2 provided another opportunity to obtain pressure measurement data, but it also posed a problem because it formed a conduit parallel to the wall of the ventilation drift. The 56 mm diameter of DBH-2 was also too small for the packers used in the other boreholes. However, several packers were available from other completed experiments, and similar port couplings were made from smaller diameter reducers. The reduced hole diameter was accommodated by measuring only water pressures and instrumenting only five intervals. For this purpose, 1/8-inch pressure tubing was adequate. The intervals, divided by five pneumatic packers, were roughly 10 m long.

A virtually continuous, relatively low pressure packer was designed to seal the portion of the hole opposite the drift, preventing the borehole from either draining the rock mass or providing a flow path parallel to the room. The packer was fabricated in three sections at LBL from 1/2-inch pipe and
rubber sleeves. The sleeves were fit over the pipe, clamped at the ends to form an airtight seal, and inflated through holes drilled in the pipe wall by pressurizing the inside of the pipe. The individual sections were then connected in series to fill the first 45 m of the borehole.

The packer mandrel was pressurized through an additional measurement port coupling attached to the end of the pipe outside the borehole, (Fig. 2.13). This coupling allowed all five pressure tubes and the high-pressure inflation line to exit the closed mandrel through sealed fittings. A pressure regulator provided 500 psi inflation pressure for the five packers in the deeper part of the hole. It also supplied a second regulator that maintained a 150 psi pressure in the mandrel to inflate the 45-meter-long packer.

2.9 Installation Equipment

The borehole instrumentation was made of steel, brass, copper, rubber, and plastic. Approximately 600 to 800 pounds of material was to be installed in holes with orientations that ranged from vertically downward to 55° upward. Further, the borehole collars were located between ground level and 4 m above the floor of the drift. Working space in front of the R holes was limited by the width of the room. Special equipment clearly was required to install the pipe and packers in these holes. In addition, a clamp was needed to hold the equipment in place when the packers were not inflated.

A special machine called the "pipe tool" was designed and fabricated by LBL for this task (Fig. 2.14). Attached to brackets on the wall (section AA), it was supported at the motor end by two adjustable legs. A trolley with a pipe clamp was driven back and forth with a ball screw mechanism. The trolley rode between and was guided by the channels that formed the sides of the tool.
Fig. 2.13. Regulation of inflation pressure for borehole DBH-2.
Fig. 2.14. "Pipe tool" for installing the borehole instrumentation.
It could travel 82 inches. The ball screw was driven by a reversible, variable-speed electric motor with an internal brake that was automatically activated when the motor was off. This feature was very important because the brake held the trolley in place whenever the motor was turned off.

The controls for the motor were in a hand-held box on a cable that allowed the operator to stand anywhere along the machine while it was operating. The controls included direction and speed as well as on-off. For safety, limit switches automatically stopped the trolley when it reached either end of the machine. As a further safety feature, an electronic shear pin was included in the motor controller. This device turned off the motor if current demand exceeded that required to generate a thrust of 1000 pounds, thus preventing damage if an obstruction was encountered in the borehole or the limit switches failed to operate. The shear pin could be reset with a button on the motor controller box.

The wall brackets were attached to the rock wall with anchor bolts inserted in the same holes that had been used to hold the drilling machine in place. These holes did not have a fixed spacing around the boreholes so the brackets had to accommodate any possible three-point attachment. The brackets are shown in Fig. 2.14. Two bars were attached to the wall with the three anchor bolts. Two aluminum "I" beams were clamped to the bars. These I-beams guided a pair of jaws that clamped around the mandrel pipe. These jaws were lever-actuated and were used alternately with the clamp on the trolley to hold the pipe and packers as sections were added during installation. Once installation was completed, the jaws were bolted together against the pipe to hold the instrumentation in place when the packers were not inflated.
3.0 VENTILATION SYSTEM DEVELOPMENT

The ventilation system was used to monitor the very low rate of groundwater seepage into the drift. Figure 3.1 shows its primary components. Part of the ventilation drift was isolated by building an airtight and watertight bulkhead 33 m from the drift face. A dedicated ventilation system controlled the environment within the room and pumped moisture from it. Wet and dry bulb temperatures were continuously measured in both the inlet and exhaust ducts, and the air flow rate was continuously measured in the exhaust duct. An air heater was included in the inlet duct to distribute heat evenly to the room. It also evaporated inflowing water and allowed the experiment to be run at room temperatures up to 45°C.

The ventilation system was operated by adjusting the heater power level and the fan speed until the rate at which water entered the room was exactly matched by the rate at which water was transported from it. Once these conditions were established and the rate of seepage determined, the room temperature was increased and the fan speed adjusted to repeat the measurement of inflow at a higher room temperature.

The range of heater power and fan speeds required to conduct the experiment was highly dependent on the unknown seepage rate. This rate had to be estimated in order to design the equipment to be used. The open HG and R boreholes drained 800 ml/min of water into the room. Almost half of this, 300 ml/min, came from borehole R1. When these holes were packed off, the total inflow was expected to decrease. On the basis of this limited information, it was decided to conservatively assume a seepage rate of 600 ml/min as a maximum design condition.
Fig. 3.1. Schematic view of the instrumented experiment room.
The following general design and layout were adopted for the ventilation system:

- A moisture-tight bulkhead keyed into the rock to prevent leaks through blast-induced fractures.
- A fan in the exhaust duct to assure a relatively lower air pressure within the room so that any air leakage across the bulkhead would be into the room.
- Instruments to measure air-flow rates in the exhaust duct so that any leakage into the room would be included in the measurement.
- Instruments to measure the moisture content of the air as it enters and again as it exits the room to determine the net moisture pickup.
- Electric heaters in the inlet duct to warm the incoming air, thus providing the heat necessary to evaporate the moisture in the room and to compensate for heat loss in the rock walls.

Since the air-flow rate and heater power requirements were calculated on the basis of an assumed water inflow of 600 ml/min, the fan was required to move one cubic meter of air per second against a back pressure of 4.5 inches of water. The back pressure was due to frictional losses within the fan and duct system. Warming the air, vaporizing the water, and heating the rock walls were estimated to require 100 kW of heater power.

The rate of evaporation was determined from psychrometric measurements and calculations. First, the air moisture content was determined at both the inlet and exhaust ducts through wet and dry bulb temperature measurements and barometric pressure readings. The moisture content times the air-flow rate indicated how much water was transported per unit time. At steady state, the evaporation rate from the room was the difference between the moisture transport rates of the air entering the and leaving the room. Before the start of the experiment, the air temperature in the drift was 12 to 14°C, and the relative humidity was 65%.
3.1 General Layout

See Fig. 3.1 for the orientation and location of the ventilation system components. The fan was located in the exhaust duct, as required. The air-flow measurement system was also located in the exhaust duct, about 1.5 m from the wall. Between the air-flow measurement point and the wall were two sets of wet and dry bulb thermometers. One set monitored absolute wet and dry bulb temperatures in the exhaust duct, and the other combined with a similar set in the inlet duct to provide a continuous record of the differential temperatures between the ducts. The heaters were located in the inlet duct just inside the room. The inlet duct extended almost the length of the room and had several side ports with sliding covers. These ports and six 1.5 m diameter ceiling fans distributed the heated air evenly around the room to maximize moisture pickup from all surfaces. Three air temperature sensors, equally spaced along and centered on the axis of the room, monitored air temperature.

All recorders and controllers were located outside the room, next to the borehole instrumentation panels. Four 7-day circular charts recorded the absolute exhaust wet and dry bulb temperatures, the differential wet and dry bulb temperatures, the air-flow rate, and the three room air temperature sensors. A watt-hour meter on the heater controller console displayed the cumulative total electrical energy supplied to all devices in the room, including lights, fans, and heaters.

3.2 Bulkhead Wall

The wall was constructed with a heavy wood frame anchored to the rock with pins. A 2 cm thick plywood sheathing covered the frame and extended
into a 20 cm deep key slot drilled into the rock around the circumference of the drift. A 3 mil sheet of polyethylene covered the plywood and served as a moisture barrier. Six inches of fiber glass insulation was also added to the exterior wall to prevent thermal loss or condensation on the inner side. The key slot was sealed with a liquid plastic foam that hardened and expanded upon contact with the air. An insulated cold-storage locker door with a window allowed access. To the left of the door was the aluminum plate that provided ports for the instrumentation cables.

To further prevent the loss of moisture through seepage beneath the wall, a trench was cut in the floor of the room about one meter from the wall. This trench intercepted any lateral flow that might occur along fractures in the floor. The bottom and side of the trench nearest the wall were sealed, and, if necessary, a pump could have been placed in the trench to remove excess water. The trench remained dry throughout the experiment.

3.3 Duct System

Standard 360 mm diameter air duct was used throughout. The inlet duct was flange-mounted to the wall and supported by adjustable steel legs along its length. The exhaust duct was similarly mounted and was slung from the ceiling with chains. It extended outside the room to a point 100 m from the wall to minimize recirculation of warm moist air to the inlet duct. The exhaust duct was insulated for 50 m from the wall to prevent condensation and avoid adding heat to the air. Air filters on the mouths of both ducts prevented dirt from clogging the sleeves on the wet bulb thermometers.
3.4 Inlet Duct Heaters

Although the assumed 600 ml/min seepage rate called for 100 kW of heater power, only 45 mW were available at the start of the experiment from the mine power supply. More power, however, would become available as the demands of the other experiments decreased.

A 45 kW heater was thus initially installed in the inlet duct just inside the room. This heater was divided into three 10 kW and three 5 kW sections. More sections could have been added if necessary and as power became available. The 10 kW sections and one 5 kW section were manually controlled and either on or off. The other two 5 kW sections had continuously variable power controls, one of which could be thermostatically actuated by a room air temperature sensor. Power to the heater was supplied through voltage regulators that smoothed line voltage variations from the mine. These regulators, borrowed from other experiments, reduced the power available to the 10 kW heaters to about 8 kW.

3.5 Room Air Temperature Sensors

The room air temperature was monitored by nickel resistance temperature detectors (RTD's) at three equally spaced points along the axis of the room. The RTD's were connected, through pneumatic transmitters, to a three-pen recorder and a thermostatic controller. A manifold at the chart recorder allowed any one RTD to control one 5 kW heater. In this manner, heater control could be shifted to the most thermally unstable part of the room simply by closing one valve and opening another. By placing the thermostat on the variable-control 5 kW heater, the maximum power level fluctuations were reduced to the power level of the smallest heater element.
3.6 Fans and Heaters

Because seepage was not evenly distributed over the walls, electrical outlets were provided for small fans or heaters that could be placed anywhere in the room. These provided air mixing or local additional heat to prevent puddles from forming. The six ceiling fans with variable speed controls kept the air in the room in constant motion to distribute the hot air evenly and enhance evaporation.

3.7 Air Flow Measurement

Two principal types of air flow measurement devices were used. The first consisted of an air straightener of Hexcell material with both total and static pressure sensors and was used for larger flow rates (Fig. 3.2). Each set of pressure sensors was spaced to provide an equally weighted pressure reading over the cross section of the duct. The sets were also manifolded together to provide an average total and an average static pressure. The manifolds were connected to a pneumatic transmitter that converted the pressure difference to a 3 to 15 psi output, which was linear with respect to velocity head. This output went to a pneumatic square-root extractor that had a 3 to 15 psi linear output with respect to flow volume. The output of the square-root extractor then drove a pen on a 7-day chart recorder.

The second principal type of air flow measurement device employed a circular orifice to create a pressure drop proportional to the velocity head. During the period of time the orifice was used, the Hexcell was removed from the exhaust duct and the orifice installed in its place. The orifice was designed to create pressure drops within the same range as that of the first device, thus permitting use of the same differential pressure converter, pneumatic square root extractor, and chart recorder as the first device.
Fig. 3.2. Schematic of the air-flow measurement system.
3.8 Wet and Dry Bulb Temperature Measurement

3.8.1 Continuous Measurements

The wet and dry bulb temperatures in the exhaust duct and the differential wet and dry bulb temperatures between the inlet and exhaust ducts were continuously recorded using standard industrial-process, liquid-expansion, thermally compensated systems. One recorder was driven directly by two absolute temperature sensors in the exhaust duct. The wet bulb sensor was housed in a continuously wetted, porous ceramic sleeve. Evaporation of water cooled the sleeve and produced the wet bulb temperature. The differential readings were made with a pair of sensors connected through a "Y" block. Bellows within the block permitted the differential pressure between the two input lines to be transmitted to a recorder by the output line. Each of the porous sleeves was equipped with an independent, filtered water supply. To reduce the rate of clogging in the ceramic sleeves a deionizing column removed salts from the water. The continuous measurements provided a record of system stability but were not used to calculate transport because of their relatively low accuracy.

3.8.2 Spot Measurements

The vapor transport calculations were based upon spot temperature measurements made with a spring Assman psychrometer. This device has two thermometers mounted in air ducts and an internal fan that draws the same amount of air over each thermometer. The wet bulb thermometer has a cotton sleeve that was moistened immediately before each reading. The spring was fully wound, and the first reading was taken by hanging the psychrometer at the mouth of the inlet duct until stable temperatures were attained. The temperatures were read and the psychrometer was moved to the mouth of the exhaust duct, where a
second set of temperature measurements was made. These temperature readings were considered more accurate than the continuous readings because of a greater instrument precision and a more consistent wetting of the wet bulb.

3.9 Barometric Pressure

The air pressure must be known to compute the moisture content of the air streams. For the inlet air stream, the air pressure was read directly from a barometer near the intake of the inlet duct. Because of the fan in the exhaust duct, the pressure in the room was slightly lower than the pressure at the inlet. This difference was read from a differential pressure gauge mounted across the wall. The air pressure in the exhaust duct was therefore equal to the barometric pressure less the differential pressure.

3.10 Final Configuration

Figure 3.3 schematically represents all components of the ventilation system and control interconnections. The recorders served as monitors of the stability of the system. Except for the air-flow measurement, the manufacturer's calibration or calibration procedures were accepted. The air-flow measurement systems were calibrated in the field. The Hexcell device was operated near the lower end of its range, where the accuracy of the manufacturer's calibration decreased. The orifice devices were fabricated by LBL and were not calibrated prior to installation.

3.11 Rock Temperature Measurements

A network of integrated transducers monitored temperatures both on the rock surfaces and in a borehole at various radial distances from the drift. These data permitted an evaluation of heat transfer from the air into the rock. Transducers were cemented to the surface of the rock at boreholes R1,
Fig. 3.3. Block diagram of the ventilation data collection and control system.
R2, R4, R6, R7, R9, and at the temperature measurement hole, TG-1. The temperature hole was percussion-drilled to a depth of 10 m at a location 15 m from the end of the drift, along the midplane of the room. Temperature transducers were mounted with a geometric spacing of 0.15, 0.30, 0.60, 1.25, 2.5, 5.0, and 10 m in a plastic tube assembly grouted into the hole. Readings were taken at the R6-R10 gauge panel. The transducers were read in the same way as the transducers in the boreholes.
4.0 EQUIPMENT INSTALLATION

4.1 Overview

Installation of the Macropermeability Experiment was the joint responsibility of LBL and KBS. KBS provided the material for the wall, duct work, exhaust fan, and instrument area platform. It also supplied the labor for constructing the wall, drilling the wall slot, excavating the trench inside the room, drilling the temperature hole TG-1, and installing the ducting and exhaust fan. LBL provided and installed all the instrumentation, including the special duct sections for flow and psychrometric measurements and heaters.

Installation was scheduled to begin in January 1979 with the wall, trench, and duct work. University of Waterloo (Canada) personnel were completing their single-fracture and pressure-pulse testing in the R and HG boreholes during this activity, finishing in mid-July. The R holes became available for the Macropermeability Experiment first and were instrumented as the University of Waterloo work continued in the HG holes.

Figure 4.1 shows how these activities overlapped. The upper part is a time line showing the progress of the wall and ventilation system installation while the lower part shows the progress of borehole activities, including the initial LBL packer testing and temperature-probe assembly. The packers were field-tested for competence in May and June, and again in August after replacement parts were received from the manufacturer. About one-third of the packers were pre-tested at LBL in July and August before shipment to Stripa.
Fig. 4.1. Time-line chart of activities in the ventilation drift during 1979.
Part of Fig. 4.1 is labeled "Univ. of Waterloo Activities." In this portion, each borehole has a series of bars showing when tests were being conducted. After the Waterloo activities, a short bar indicates the time required to install the borehole instrumentation. The following blank indicates the time it took for the boreholes to fill with water after the number one packer had been inflated. The long solid lines extending to the right indicate when all the packers were inflated and pressure data collection began. Borehole R10 shows an interruption in data collection in November when several leaks in the packer inflation system developed. The instruments had to be reinstalled in an attempt to stop the leaks.

4.2 Ventilation System

4.2.1 Bulkhead Wall

The first step in installing the ventilation system was to cut a 20 cm deep key slot in the granite for the bulkhead wall. The primary purpose of the slot was to minimize air leakage around the wall through blast-induced fractures. This measure was considered necessary even though a smooth wall-blasting technique (developed at Stripa) had been used to make the tunnel (Anderson, 1978), and test cores had shown that fractures penetrated less than 20 cm from the blastholes.

A slot drilling technique, developed at Stripa to recover very large cores, was employed to make the key slot. First, the location of the slot was marked on the rock around the circumference of the drift. Then two
rows of 51 mm diameter, 20 cm deep percussion holes were drilled parallel to this line. Hole spacing was maintained with a guide that fit into the previously drilled hole. The holes overlapped so that the resulting slot had a corrugated edge and a width of 3 to 4 cm.

The same method was used to cut the edge of the floor trench closest to the wall. A single row of 25 mm diameter holes was drilled into the granite, and a hydraulically driven wedge broke the rock into the slot opening. This enlarged and deepened the trench with a minimum of disturbance to the surrounding granite. One end of the trench was deepened to form a sump. The side of the trench nearest the wall was sealed with epoxy, and additional epoxy was used to seal and smooth the trench floor to assure that water would be retained by the sump.

The bulkhead wall was constructed within a perimeter frame of 15 x 15 cm wooden beams. This frame was secured to the granite with 25 mm diameter, 40 cm long steel pins. This heavy support was necessary because of the large force exerted against the wall during the experiment from the reduced air pressure within the room.

Figure 4.2 shows the partially completed wall from inside the room. The perimeter beams are visible at the upper left and along the base of the wall. The vertical 10 by 15 cm beams and the 5 by 10 cm lattice framing that supports the 2 cm thick plywood are clearly visible in the center. The aluminum plate containing the airtight wire and tube feedthroughs was installed in the rectangular hole near the right edge of the photograph. The sealed wall of the trench is visible along the lower right.
Fig. 4.2. Partially completed bulkhead as viewed from inside the experiment room.
Once the plywood cover was in place, the normal mine ventilation for the room was blocked. To assure proper ventilation, the mine duct was temporarily diverted directly into the inlet duct opening in the wall. When the exhaust fan was turned on, starting the experiment, this diversion was eliminated.

Figure 4.3 shows the outside of the wall, the plastic moisture barrier held in place with wooden wedges, and the foam that sealed the slot. After the plastic was secured to the wall, the slot was filled with an expanding plastic foam. This foam both filled the open space in the slot and formed a seal between the plastic and the rock. Air leakage was further minimized by rubber gaskets around the openings for the inlet ducts in the wall. A cold-storage locker door with a window in the wall allowed both access and visual inspection of the room. Finally, the outside wall surface was covered with two layers of 8 cm thick fiber glass insulation. The insulation permitted the inner side of the wall to be warmed by the room air during the experiment, reducing the potential for condensation.

4.2.2 Inlet Duct and Instrumentation

The heaters were installed in the inlet duct inside the room. This duct was extended to within 4 m of the end of the drift. Four 15x15 cm openings were cut in the side of the duct and fitted with sliding doors. These openings were adjusted during the experiment to achieve even and complete distribution of inlet air. The entire length of the duct inside the room was covered with fiber glass insulation to protect personnel from the heater and to assure that hot air would be distributed to the far end.
Fig. 4.3. Outside of the partially completed wall.
Ports for the wet and dry bulb thermometers and a viewing window were installed in the 3 m length of inlet duct mounted outside the room. The mouth was fitted with a housing for a 24-inch square by 1-inch thick furnace filter. The filter housing included a hook from which the Assman psychrometer was hung. The hook was located so that the inlet of the psychrometer would be centered on the duct inlet.

The performance of the wet bulb sleeve was monitored through the duct viewing window. Proper performance of the wet bulb thermometer depended on a steady supply of water to a porous ceramic sleeve that surrounded the temperature element. The water flow had to be periodically adjusted to compensate for changes in the porosity of the sleeve due to precipitation and for changes in the humidity of the passing air. A visual inspection was sufficient for the operator to know if any adjustment was necessary.

4.2.3 Exhaust Duct and Instrumentation

The exhaust duct extended 3 m into the room and was equipped with a filter housing and psychrometer hook similar to that on the inlet duct. Because the exhaust duct was mounted near the ceiling, a small elevated platform was built under its intake for the psychrometer. The platform was 2 m above the floor and allowed the experiment operator to read the psychrometer after its thermometers had stabilized. The platform frame was welded 25 mm O.D. pipe with a floor of expanded metal with a large amount of open space. This provided a strong platform with a minimum of impedance to the air circulation in the room. The platform also provided a support for the end of the duct.
The permanent instrumentation in the exhaust duct was located just outside the wall. The temperature measurement station contained four ports for two pairs of wet and dry bulb thermometers, and a viewing window on the lower side of the duct. The air-flow measurement station was just downstream of the temperature measurement station. A flexible joint separated the air measurement station from the rest of the exhaust duct. Figure 4.4 shows the components of the exhaust duct system.

The exhaust duct fan was mounted on the floor of the drift. Three standard 4 m duct sections and two 45° elbows were required to clear the instrument and control panels and reach the fan. A 12 x 12 cm opening was cut in the duct just upstream from the fan and fitted with a sliding cover. This opening let air that had not passed through the room to enter the fan, allowing the flow through the room to be lower than the slowest speed setting of the fan. Additional fan speed control was provided by multiple fan belt pulley combinations between the fan and the motor, and by a shutter door on the exhaust side of the fan.

A flexible connection was placed between the fan and the long downstream duct that carried the exhaust air out of the experiment area. This duct originally extended to a point just past the Luleå drift (see Fig. 1.2) where the air was expected to be carried away with the normal return air stream of the mine. However, it was found that when some of the ventilation fans were turned off in the general experiment area, the inlet air temperature would rise because of air recirculating from the exhaust duct. This condition was corrected by extending the exhaust duct to the cross tunnel at the entrance to the experiment drift.
Except for the fan itself, the exhaust duct was insulated from the bulkhead wall to a point outside the time-scaled experiment drift, a distance of about 50 m. This insulation was intended to prevent condensation inside the air duct that might interfere with the instrumentation or the fan. A sump with a drain was installed in the duct just upstream from the fan. Again, a small window in the duct allowed visual checks for condensation.

The main fan control unit was installed in the instrument area and a safety switch was placed inside the door to the room. At high fan speeds, the pressure drop across the door was so great that the door could not be opened from the inside. The safety switch would allow someone inside the room to turn off the fan.

4.2.4 Air Flow Measurement Calibration

A detailed analysis of the theory, operation, calibration, and reliability of the air-flow measurement system has been given by McPherson (1981). The calibration for the first part of the experiment is briefly described in this section. This work established the technique used in subsequent calibrations.

Figure 4.4 shows the relative positions of the exhaust duct, the fan, the air-flow measurement station, its instrument cabinet, and the circular chart recorders. The air-flow calibration measurements were made in the inclined portion of the exhaust duct as indicated in the figure. This location was both upstream of the fan and at a point where the air stream was least affected by bends or leaks in the duct. Orthogonal holes were drilled in the duct to permit pitot tube or anemometer traverses to measure the
Fig. 4.4. Relative positions of the components of the control system, instrumentation panels and exhaust duct.
velocity head. The six measuring points of each traverse were determined by logarithmically spacing them across the diameter of the drift. A pitot tube 400 mm long by 7 mm diameter was used for the calibration.

The calibration was conducted by setting the fan speed, making two measurement traverses through each hole in the duct, and noting the average reading on the circular chart. The fan speed was then changed and the process repeated. The psychrometric measurements were also used to compute the ambient density of the air, permitting the calibration to be referenced to a standard air density. As a result of these readings, it became obvious that the moisture pickup from the room was roughly an order of magnitude less than the 600 ml/min upper limit assumed in the experimental design. Parts of the experiment therefore had to be run at lower fan speeds than expected. A Wallac hot-wire anemometer was obtained and the calibration range was extended to very low air-flow rates.

The initial calibration resulted in the chart in Fig. 4.5. This figure was used by the operator to convert the chart readings to true air-flow with respect to a standard air density. To use this chart, the operator would:

- Determine the exhaust duct pressure using the barometer and the pressure drop across the wall.
- Read the wet and dry bulb thermometers at the inlet of the exhaust duct.
- Calculate from these readings the actual density of the air in kg/m$^3$.
- Read the air-flow chart recorder in chart divisions.
- Using the calibration chart, convert this reading to a standardized reading for an air density of 1.2 kg/m$^3$.
Fig. 4.5. Airflow calibration curve.

The equation for the calibration curve is:

\[ Q_{\text{st}} = 0.14371 + 0.01224 \times (\text{CH}) \]

for \( \text{CH} > 15 \)
-58-

- Compute the actual air flow \( Q \) from the equation

\[
Q = Q(\text{standard}) \left( \frac{1.2 \text{ kg/m}^3}{\text{actual density}} \right)^{1/2}
\]

The procedure for data collection and analysis in the field is covered in Section 5.

4.3 Continuous Wet and Dry Bulb Temperature Recorders

Since the experiment operator spent only a few hours each working day actually monitoring the experiment, the continuous temperature recorders provided assurance of temperature stability. As previously mentioned, the moisture transport calculations were made from the Assman psychrometer readings and not from these records.

The wet and dry bulb air temperature in the exhaust duct and the differential temperatures between the inlet and exhaust ducts were continuously recorded on circular charts. The sensors were installed as the ducts were completed, and continuous records were kept from late September 1979 to the end of the experiment. Since precision was not important, the manufacturer's calibration was accepted after it was confirmed that the sensor readings agreed with a reference thermometer to within \( \pm 1^\circ \text{C} \). One chart recorded the exhaust duct wet and dry bulb temperatures and the other recorded the respective differential temperatures between the inlet and exhaust ducts.

The liquid-filled differential sensors produced a true differential output for the recorder. The sensors were labeled hot and cold by the manufacturer to designate the polarity of the system. Early in the experiment, before the heaters were turned on, the inlet air was warmer than the exhaust air because
of the heat losses due to evaporation in the room. When the heaters were
turned on, the differential sensors had to be reversed to maintain the proper
polarity.

The three wet bulb sensors were kept wet by inserting them in porous
ceramic sleeves. Water was supplied to the sleeves at a sufficient head and
rate to keep them moist but not so great as to cause dripping. Figure 4.6
shows the drip system. The height of the open tube determined the head, and
the needle valve controlled the flow rate. The drip rate from the overflow
tube gave the operator a visual indication of the flow rate.

This drip system, while simple in concept, was the single most trouble­
some component in the air-flow measurement system. The sleeves were suscep­
tible to clogging by dirt in the air as well as by minerals precipitating
from the water. Filters were therefore put on the duct intakes and a de­
onizing column was plumbed into the water line. These measures alleviated
the gross problems, leaving only the subtle adjustment of the head and flow
rate. The exact flow rate required depended upon the porosity of the sleeve
and the rate of evaporation from the surface of the sleeve. The rate of
evaporation was very low and an adjustment in the flow rate took several hours
to equilibrate. Adjustments made in the morning often resulted in the sleeve
either flooding or drying out several hours later, after the end of the working
day. If such a system were to be employed again, it should include a very fine
screw valve for the head adjustment.

4.4 Heater Controller

The heater controls were fabricated at LBL and shipped to Stripa as a
unit. Installation consisted of connecting the controls to the mine power
Fig. 4.6. Drip system for the wet bulb thermometers.
circuit and of connecting cables from the controls to the heaters in the duct. The power cables ran from the controllers to the heaters through the wall in a 10 cm length of 6 cm I.D. pipe that was then sealed with a duct sealing compound. The heaters were protected from overheating by an air-flow switch in the duct and internal overheat circuit breakers. If the fan should fail, stopping the airflow, the heaters would be turned off by the air-flow switch. If the fan was not moving the air fast enough to dissipate the heat, the internal circuit breakers would shut off the power. The circuit breakers would automatically reset, turning on the heaters again when they had cooled to a safe operating temperature.

The sail on the air-flow switch came off twice during the experiment, turning off the heaters even though the fan was still operating. The switch was replaced quickly each time, so that the heat loss was of little consequence to the experiment. The overheat protection was very valuable because the low moisture flow into the room required greatly reduced fan speeds and increased the possibility of overheating.

4.5 Room Air Temperature Sensors

Three nickel resistance temperature detectors (RTDs) were placed in the room to monitor the heat distribution from the inlet duct. These sensors assured the operator that the heat was evenly distributed, and any one of them could be used as a thermostatic control for the smallest heater element if required to achieve stability.

Pneumatic transmitters remotely actuated a three-pen circular chart recorder. The sensors worked very well once the air supply was set to assure
an adequate flow rate for the transmitters. The air supply was controlled by a single pressure regulator at the supply point and by metering valves to regulate the flowing pressure at each transmitter. The sensors were calibrated using an LBL-fabricated resistance box that provided mid-span and end-point readings for the 0 to 70°C span of the chart recorder.

The operator periodically reviewed the circular charts to assure that all three pens were on the same line, indicating an even heat distribution throughout the room. If temperatures varied, the doors on the sides of the inlet duct were adjusted to redirect the air flow.

For computational purposes, the room temperature was determined by the Assman psychrometer reading at the mouth of the exhaust duct. The thermostatic heater control was used as little as possible. Even though the smallest element of the heater could be automatically controlled, the 2° to 3° range of the control cycle was not desirable. We found that except for periods when rapid temperature increases were required to reach the next higher experimental temperature, the heater output was best controlled by manually adjusting the power supplied to each heater element.

Figure 4.7 is a block diagram of the electrical system for the experiment. The diagram shows the interconnections of the heaters and safety switches, the room air temperature thermostatic controller, the fan control, and the total power meter. This meter recorded the cumulative electrical energy use in the room, which included all fans, space heaters, resistance to pneumatic transmitters, and other electrical devices powered through the circuit labeled lights and outlets.
Fig. 4.7. Block diagram of the heater control and electrical system.
4.6 Rock Temperature Sensors

The rock temperature was measured at boreholes R1, R2, R4, R6, R7, R9, and TG-1. These sensors were set to a common zero by hanging them next to the reference thermometer on the R6-R10 gauge panel and adjusting the individual trim pots until they all read the same as the reference thermometer. A general purpose epoxy was used to cement them to the rock.

The probe for TG-1 was assembled at LBL and shipped to Stripa. The temperature transducers were mounted in 3-inch lengths of Plexiglas rod so that the top surface of each transducer was exposed through the side of the rod. The rod segments were connected together with 1-inch O.D. soft plastic tubing. The transducers were set to a common reading by suspending the assembly in the room and setting each transducer to the temperature indicated by a glass thermometer at that location. The joints were reinforced and sealed with epoxy and the assembly was ballasted with lead shot at the bottom. The assembly was then lowered into the hole and cemented in place with grout. Air was squeezed out of the assembly while the grout was being pored into the hole. Despite this loss of volume, the density of the grout was sufficiently great to cause the assembly to float up in the hole during installation, so the assembly was held in place until the grout set.

The trim potentiometers and output jacks for the borehole probe assembly were located in a box mounted on the R6-R10 gauge panel. Readings from the deeper transducers eventually became erratic, and finally these transducers failed. This was probably the result of water working its way into the probe through a bad joint.
4.7 Packer Field Testing

The packers were expected to remain inflated and not leak for a period of one to two years. To improve their performance, each packer was disassembled and cleaned, and the O-ring surfaces were polished and lubricated with a silicone-base stopcock grease. After reassembly, each packer was inserted into a 25 cm long length of 76 mm I.D. pipe, placed in a tank of water, and inflated to 900 psi. If no leaks developed in 24 hours, the packer was judged to be good and was used in the experiment. If the packer leaked, it was fixed and the test repeated. This was a harsh test because the operating packer pressure for the experiment was only 650 psi.

Figure 4.8, a detailed mechanical drawing of the packer, indicates all the locations of potential leaks. There are three pairs of O-rings and four welded joints as well as a plug at one end. Leaks were found at least once at all of these locations. Leaks at welds were sealed by rewelding. The plug was usually replaced after the threads in the hole were refurbished. Sometimes the plugs were also welded to stop leaks. The O-ring leaks were usually repaired with additional polishing of the seal surface and installation of a new set of O-rings and backup rings.

The major problem was with the main cylinder. The cylinders for the initial shipment of packers were made from welded tubing that had a longitudinal seam. Although the cylinder was chrome-plated inside and out to provide a protective finish, the plating did not completely fill the seam at the weld. Thus, on roughly one-third of the first 60 packers received, this seam provided a longitudinal leakage path past the O-rings. These cylinders were returned to the manufacturer for replacement with units made from
Potential locations of leaks

1. Threaded fittings
2. "O" ring seals
3. Welds

Fig. 4.8. Detailed drawing of the Cobbs Tri-El packer.
seamless tubing. A second order of 40 packers was pressure-tested at LBL before shipment to Stripa. Testing of the initial packer shipment resumed at Stripa when the replacement cylinders arrived.

4.8 Pressure Gauge Calibration

The pressure gauges were calibrated against a Heise reference gauge traceable to the U.S. Bureau of Standards. Each panel of 30 gauges was calibrated as a unit. The gauges were connected in series with the reference gauge and a nitrogen bottle, and all the gauges were read at each calibration pressure. Calibration pressures started at 50 psi and increased in 50 psi increments to 250 psi. If there was an error of more than 1 psi in the initial test, the gauge was adjusted to read 50 psi. The gauge was again checked at 50 psi at the end of the calibration. The gauges all performed within the 1 psi error limit claimed by the manufacturer.

4.9 Packer Assemblies

4.9.1 Logistical Considerations

The working space in the drift required that the borehole instrumentation be assembled as it was installed. This made it impossible to test the assembly for leaks before to installation. Each assembly was therefore performed carefully and systematically, using reliable materials and procedures.

To reduce the chance of error, the wires for the temperature transducers and conductance cells were color-coded for depth and a larger wire size was used for the conductance cells. The pressure tubes were labeled with numbered adhesive strips and checked for these labels whenever a new
tube was added. After installation each packer assembly module—consisting of a measurement port, packer and O-ring sealed coupling—was installed, all temperature transducers were checked. If a water leak had occurred, the leads to the deepest transducer would be short-circuited and the reading would be close to the supply voltage. When such leaks were detected, the partial assembly was pulled out and the leak fixed. This test only applied to the downward inclined holes. The upward-inclined holes did not fill with water until after the packers were installed and the first packer inflated. The location of each packer was determined at LBL from a study of the core photographs, fracture logs and results from the University of Waterloo testing in these holes. The packers and measurement ports were then installed with the aid of the tally sheet shown in Fig. 4.9. (These sheets are discussed in the next subsection.)

Three to five days were required to completely install the packers in a borehole. Installation began with setting up the "pipe tool" and continued until all tubes and wires had been connected to the gauge panel and the number one packer inflated. This work was generally done by one person, with occasional help in stringing out the pressure tubes and wires from the borehole to the gauge panel. Two people working together would not have significantly reduced the installation time because all wires and tubes had to be fed through each pipe or packer as it was added to the assembly. Only after that was accomplished could the proper length for the next piece be measured, and these time-consuming tasks could effectively use only one person.

Packer installation was greatly facilitated by the "pipe tool." This machine with its two clamps, variable speed, and automatic stops did more to
MACROPERMEABILITY TALLY SHEET

Deepest packer depth

<table>
<thead>
<tr>
<th>Zones</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
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<tbody>
<tr>
<td>C</td>
<td></td>
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<td></td>
<td></td>
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<td>D</td>
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<tr>
<td>E</td>
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<td></td>
<td></td>
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<tr>
<td>(C+D)</td>
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<td></td>
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<tr>
<td>(C+D+E)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Packer Depth

- (C+D)
- 1
- 2
- 3

Next Packer Depth

- F +1
- +2
- +3

Total F

(F+E)

Corrections and Explanations:

Final packer depths

<table>
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<tr>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
</table>

Final port depths

|   |   |   |   |   |   |

Fig. 4.9. The borehole installation tally sheet.
help install the packer assemblies than any other item. The tool controlled
the descent of the packer assemblies into the vertical holes and drove the
assemblies into the upward-inclined holes. For boreholes HG2 and HG5, the
machine was inverted and braced against the ceiling in a position above the
borehole. For HG5 in particular, this was the only position that left room
for the operator because the hole was close to the ceiling.

Several simple problems in installation should be recounted for the
benefit of future experiments. On several occasions, subtraction errors
were made in the calculations on the tally sheet. These errors resulted
in a slight shift in the location of the packers from their specified
positions, and all packers installed subsequent to an error were affected
by it. Fortunately, none of these shifts put packers over a fracture, and
all shifts were less than 10 cm.

A second problem was the water pipe supplied in Sweden and used in
assembling the packer strings. This pipe was longitudinally welded and,
unlike U.S. welded pipe, had a sharp fin of metal on the inside along the
weld. On several occasions, this fin shaved the insulation off the tempera-
ture transducer wires, which probably contributed to the failure of several
transducers. This damage was repaired when detected, but all repairs had then
to be fed through the pipe, again exposing the wire to possible damage.

Finally, the installer twice neglected to tighten the brass compression
fitting around the pressure tube at a measurement port. In each case, this
caused a one-day delay while the flooded assembly was pulled out of the
borehole, dried, and reinstalled.
The installation procedure for any borehole first required assembling all the parts that would go into the borehole. These included:

- Six or eight tested packers.
- The measurement port couplings with the correct number of ports for each interval.
- Five O-ring-sealed unions.
- Six temperature transducers with the six-inch color-coded leads attached.
- Six bulkhead connectors with color-coded leads (if conductance was to be measured in the hole).
- Spools of 20 AGW and 18 AGW color-coded wire for the temperature and conductance circuits.
- Compression fittings for the 3/16-inch pressure tubes and the 1/8-inch packer inflation tubes.
- Pairs of wrenches for each size of compression fitting.
- A 500-foot roll of 3/16-inch nylon tubing. There was no room in the pipe for a union to join two pieces of tubing.
- Two 50-foot lengths of copper or, if conductance was to be measured, a 500-foot roll of 1/8-inch nylon tubing.
- Pipe-cutting and threading tools, pipe vise and bench, Teflon pipe sealant, one pair of 18-inch pipe wrenches, and a set of open-end wrenches for the unions and measurement-coupling bushings.
- Thirty-meters of 3/4-inch pipe.
- Rosin core solder, soldering iron, heat-shrink tubing, heat gun, wire strippers and cutters to make the electrical splices.
- The tally sheet with the hole depth and packer locations indicated on it.

Only two assemblies could be made before installing anything in the hole. A standard 1.5 m length of pipe could be installed between the measurement port coupling and one side of the union. These were laid out in the order they would be needed. Also, a 15 cm length of pipe could be
installed between the other side of the union and the piston end of the packer. All other materials had to be added piece by piece.

4.9.2 Installation Procedure

The packers were installed so that the prescribed depth coincided with a point 10 cm from the end of the packer. This point was roughly in the center of the rubber elements after the packer was inflated. Placement was aided by the tally sheet (Fig 4.9), which served two functions: first, it was structured to guide the installer in properly locating the packers and pressure ports in the borehole; second, it provided a record of the installation in each borehole.

Installation started with the deepest measurement port coupling in the borehole. Pressure tubing 2 m longer than the borehole was connected to the coupling. Length "A" on the tally sheet was the length of tubing extending beyond the coupling. The temperature transducer was then mounted in its receptacle, and the common ground (black) and positive (red) wires were soldered to it. All solder connections were protected by heat-shrink tubing. These wires were then laid out next to the pressure tube and cut to the same length as the tube. An appropriate length of pipe was then added to position the port coupling within the open interval of borehole between the deepest packer and the end of the borehole. This was length "B" on the tally sheet. A packer assembly with a 15 cm pipe and half of a union was then added, followed by the other half of the union and the 1.5 m pipe with the next measurement port coupling. These were the lengths "C" and "D" entered on the tally sheet.

The next water pressure tube was then installed in the coupling. Length
"E" is the distance the pressure tube extends beyond the end of the coupling. This pressure tube was laid out beside the first tube, cut to the same length, and labeled. The temperature transducer was secured in its socket, and the black transducer lead was soldered to the common ground wire. The appropriate colored wire was then soldered to the positive transducer lead, laid out along the pressure tubes, and cut to the same length. Using the data on the tally sheet, the length of the next piece of pipe required to place the next packer at its specific location was computed by first adding the lengths "C" and "D" together and subtracting the total from the difference in depths between the two adjacent packers. The result should be the length "F." The lengths of the measurement port coupling (0.1 m) and the packer end and coupling (0.145 m) were then subtracted from the length "F" to get the length of pipe necessary for this interval. The pipe was then cut, threaded, and added to the system. As a check, the actual length "F" was directly measured and recorded on the tally sheet. The inflation tube was connected between the packers and the entire assembly moved into the borehole.

This sequence was repeated for each interval until all the packers were in the borehole. At the last measurement port, the packer inflation tube was diverted inside the mandrel pipe and a separate inflation tube was attached to the last packer. The length "H" between a convenient measurement point on the wall bracket and the rock wall was measured, and this was added to the depth of the last packer, "G," to get the length of the last pipe in the assembly. For boreholes with conductance cells, the procedure was the same except that the conductance hardware was installed after the temperature transducer. Only one wire was needed for the conductance cell because the pipe provided the common strand for the circuit.
The inflation pressure tube for the packers was then strung from the inflation manifold outside the wall to the borehole. There, a tee divided the line, and two ball valves were installed to control gas flow to either the collar packer or the other packers in the hole. The collar packer was inflated first to allow the hole to fill with groundwater and force the air from the pressure lines. The water pressure lines were then individually strung from the proper gauge to the borehole one at a time and connected to the tubes coming from the borehole. Finally, the wires for the temperature transducers and the conductance cells were also strung one at a time through the bulkheads and connected to the proper readout points.

As the water pressure in the boreholes increased, air was bled from the pressure tubes. The order in which the tubes filled with water served as a check that the tubes were correctly labeled and connected. After all the air had been expelled from the tubes, the packers were inflated in stages. Inflation pressure was increased slowly because the change in shape of the packers caused the water pressure to rise in some intervals. When the water pressures reached about 200 psi, inflation was stopped and the intervals were bled back to less than 25 psi. Inflation then resumed until the packer pressure reached 650 psi. At this point, the installation was complete. The water pressure in the intervals was bled back to less than 25 psi, and data collection began.
5.0 OPERATION OF THE EXPERIMENT

The primary responsibility of the experiment operator was to collect the data on a daily basis and assure that the experimental conditions were being maintained as specified by the task investigator. To achieve this, forms were developed to list in a logical format all the data to be collected and read.

Only two forms were needed to record all ventilation and borehole data. Figure 5.1 shows the form for data pertaining to the ventilation system. This form contains all the information necessary to compute the psychrometric parameters and provided a complete statement of the ventilation aspects of the experiment. The form was structured to contain one week of data.

Figure 5.2 shows the form for collecting either borehole pressure and temperature or temperature and conductance data. Each sheet could contain a complete reading of data from one gauge panel. The operator supplied the date, the data category, and the time of day. The borehole was identified at the top of each column. A separate column was provided for the two 40 m boreholes, R1 and R6, in where the instrumented zones were numbered 3 through 8. The format for data entry was indicated at the bottom of the form, and the formula for calculating conductance from the data was also provided.

Other forms (Figs. 5.3 and 5.4) were used for the temperature sensors in borehole TG-1 and the sensors mounted on the walls of the experiment room. These forms also hold the data for one week of operation.

A field data reduction form (Fig. 5.5) was used to compute the net moisture pickup of the ventilation system. Relative humidity and net water
**Fig. 5.1. Ventilation system data sheet.**
Fig. 5.2. Borehole data sheet for either temperature and pressure or temperature and conductance.
Fig. 5.3. Data sheet for temperature hole TG-1.
<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Wall Temperature at Borehole (°K)</th>
</tr>
</thead>
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<td></td>
<td></td>
<td>R-1</td>
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Fig. 5.4. Data sheet for the wall temperature transducers.
<table>
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<tr>
<th>Date</th>
<th>Time</th>
<th>$t_w$ (°C)</th>
<th>$t_d$ (°C)</th>
<th>$P$ (mb)</th>
<th>$t_w$ (°C)</th>
<th>$t_d$ (°C)</th>
<th>$\Delta P$ (in H$_2$O)</th>
<th>Qair (chart div)</th>
<th>Total Water Inflow (cm$^3$/min)</th>
<th>Relative Humidity (%)</th>
<th>Total Water Outflow (cm$^3$/min)</th>
<th>Relative Humidity (%)</th>
<th>Air Flow Rate (m$^3$/s)</th>
<th>Net Water Outflow (cm$^3$/min)</th>
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Fig. 5.5. Ventilation system field data reduction form.
outflow were monitored to determine if any adjustments in the heater power levels or in the air-flow rate were required to maintain steady-state conditions.

Data was collected at the start of each working day, beginning with an inspection of the system to assure that it was operating properly. The four chart recorders were checked for any interruption or disturbance. The Assman psychrometer was then wetted, wound, and hung on the inlet duct. While the psychrometer was coming into equilibrium with ambient wet and dry bulb air temperatures, the chart recorders, barometric pressures, heater control temperature, and mine air temperature were read. The Assman psychrometer was then read, rewound, and hung opposite the inlet to the exhaust duct inside the room. As the psychrometer again came to equilibrium, the room was inspected for changes in the size or location of drips and damp spots. The psychrometer was then read and the room was not entered again until the next day.

The psychrometric data was analyzed using a HP67 programmable calculator to produce the data for Fig. 5.5. The ventilation system was then adjusted if necessary, and any comments on the state of the experiment were entered in the log book.

Pressure readings from the boreholes were made after the psychrometric data had been collected. Temperature readings were initially made on a daily basis. However, the changes in temperature were so slow that a reading once a week was adequate until the rock started to warm up. Once temperatures started to rise in a zone, the readings were taken daily, with all the temperatures recorded at least once a week. Conductance measurements were also made weekly before the tracer was injected into a borehole. After that, the
conductance readings were taken daily. Once a week, the charts on the
recorders were replaced and all data mailed to LBL. Copies were also
sent to M. J. McPherson at the University of Nottingham, U. K., and to
J. E. Gale at the University of Waterloo, Canada. On the same day, the
experiment operator reviewed the events of the week with the task inves­
tigator over the telephone and telexied the reduced ventilation data to
him. In this way, the experiment was monitored by all the principal parties
involved.
6.0 OPERATIONAL MODIFICATIONS

The net moisture pickup from the room proved to be an order of magnitude lower than expected. This meant that during the higher temperature tests the experiment had to be run at much lower air-flow rates than the original measurement system permitted. During the first stage of the experiment, when the initial 20°C room temperature test was under way, plans were made and equipment ordered to modify the ventilation system. The primary modifications were made in the air-flow measurement system and in the inlet-duct heaters.

The air-flow measurement system was modified by replacing the original pitot tube measurement unit in the exhaust duct with a 100 mm orifice plate inside a 150 mm pipe. Initially, a differential pressure gauge was used to read the pressure drop across the orifice plate until we verified that the original signal conditioning equipment could still be used to operate the chart recorder. This change required a recalibration of the chart recorder and a slight change in the field data reduction programs. Because the air flow was now more than an order of magnitude lower, calibration within the 360 mm diameter duct became much more difficult. This duct was therefore replaced with a section 4 m long and 165 mm diameter. The reduced diameter increased the air velocity at the calibration station to a point where the calibration could be done accurately. Figure 6.1 shows the modifications to the duct work that were in effect during the 30° and 45° temperature tests. Baffles were also installed in the duct at the thermometers to increase the air velocity across the wet bulbs and assure accurate readings. The duct was restored to its original configuration for the cool-down test, which required greater air flows.
Fig. 6.1. Modified ventilation system for low air-flow measurement.
A temporary air-flow measuring system was used for 2 weeks before the orifice plate was completed. The temporary system consisted of a 76 mm diameter, 305 mm long duct and baffle installed within the original 360 mm duct. This temporary system was calibrated using the original 360 mm duct.

The lower air-flow rate caused overheating of the inlet duct heaters because of the lower rate of heat transfer to the air. This problem was overcome by removing a 1.5 m section of duct between the inside wall and the facing heater and adding a duct fan to the mouth of this heater. This fan recirculated room air through the heaters at a rate sufficient to keep them from overheating. The main experiment fan continued to control the rate at which air was drawn into the room. Since warm room air rather than cool mine air was circulating over the heaters, the maximum power of the heaters was also reduced. This was not a problem because the energy to heat the cooler mine air drawn into the room was also reduced.
7.0 CONCLUSIONS

The Macropermeability Experiment worked. It was designed to measure the groundwater seepage into and the water pressure gradient surrounding a large underground opening in low permeability fractured granite, and that result was achieved. The experiment employed a novel ventilation technique as a pump to both transport and measure the total groundwater flow into the room. Although this flow rate turned out to be 40 to 50 ml/min, nowhere near the maximum 600 ml/min planned for in the initial design, only rather simple modifications were required to accommodate this difference.

Fifteen boreholes were divided into ninety 5 m zones instrumented for pressure and temperature. Thirty-one zones were also instrumented for conductance readings. This was accomplished with inexpensive materials that proved to be reliable over the one-year operating life of the experiment. A modular system of packer and measurement port couplings was developed that allowed almost unlimited flexibility in the placement of packers in the boreholes. This system would be applicable to any borehole instrumentation requiring multiple packers and a variety of measurements in each isolated interval.

The most serious reliability problems concerned the leaks that occasionally developed in the borehole packer inflation system. The presence or suspected presence of leaks created uncertainty in some of the water pressure readings. During the year of operation of the packer system, however, there were very few detected leaks compared to the large number of measurement points, and the overall reliability of the experimental data was maintained. Operating this or any similar system for longer periods of time would very likely result in a steadily increasing uncertainty in the water pressure.
measurements. Future long-term experiments with retrievable downhole equipment should use a packer system that can be "set" and then mechanically locked in position without continuous reliance on pressurized fluid, and then released on command at some later date. This design problem must be addressed before truly reliable long-term studies can be made.
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