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A BOREHOLE INSTRUMENTATION PROGRAM FOR CHARACTERIZATION OF UNSATURATED-ZONE PERCOLATION

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ABSTRACT

A borehole instrumentation and monitoring program has been designed by the U. S. Geological Survey to support site characterization of unsaturated-zone percolation at Yucca Mountain, Nye County, Nevada. This program provides a means of defining the unsaturated-zone fluid flow (liquid and gas) potential field in a setting that incorporates large-scale stratigraphic and structural features, and the influences of geothermal heat flow and atmospheric pressure changes. Data derived from this program will be used to evaluate the suitability of Yucca Mountain as a mined geologic-repository for the storage of high-level, radioactive waste. These data include *in-situ* temperature, pneumatic pressure, and water potential. In addition, the instrumentation program provides facilities for gas-sampling, gas-tracer diffusion testing, water-injection testing, water-level monitoring, neutron moisture-meter monitoring, temperature profiling, and *in-situ* recalibration of the downhole sensors.

The program included testing and development of: 1) precision sensors for measurement, 2) a downhole instrumentation-station-apparatus to house the sensors, recalibrate sensors *in-situ*, and allow access to instrument stations for other testing purposes, and 3) surface-based support and instrumentation facilities.

I. INTRODUCTION

The Yucca Mountain borehole instrumentation program, for characterization of unsaturated-zone percolation, will include approximately 29 deep boreholes with a diameter of 12.25 inches. These boreholes will have an average depth of 500 meters and will penetrate the upper 25 to 90 meters of the saturated zone. The unsaturated zone occurs in the

Tiva Canyon Member and Topopah Spring Member of the Paintbrush Tuff, the Tuffaceous Beds of the Calico Hills, and the Prow Pass Member and Bullfrog Member of the Crater Flat Tuff. Each borehole will be stemmed and instrumented with 16 instrument stations to monitor *in-situ*, unsaturated-zone fluid-flow potentials.

The borehole instrumentation program faced several challenges from its inception. These challenges included development of sensors and methodology to provide accurate and precise measurements of pneumatic pressure, temperature, and water potential at depths of up to 790 meters in boreholes located at remote sites on Yucca Mountain for periods of up to five years. In addition, the instrumentation design of these boreholes had to allow access for other types of experiments including withdrawing gas samples for isotope analysis, injection of gas tracers for diffusion studies, monitoring of water levels, neutron moisture-meter monitoring, and water injection testing.

To meet the diverse requirements of the borehole instrumentation program, four major development efforts were undertaken simultaneously. These efforts included: 1) testing, designing, and evaluating sensors for accurate and precise measurements of temperature, pressure, and water potential, 2) development and testing of *in-situ* recalibration methods, 3) design and construction of a downhole instrument station apparatus to house the sensors and allow access to the borehole, and 4) design and construction of surface-based support and instrumentation facilities.

II. INSTRUMENTATION DESIGN

A simplified diagram of a multiple instrument-station borehole is depicted in Figure 1. Each instrument station is equipped with a Downhole

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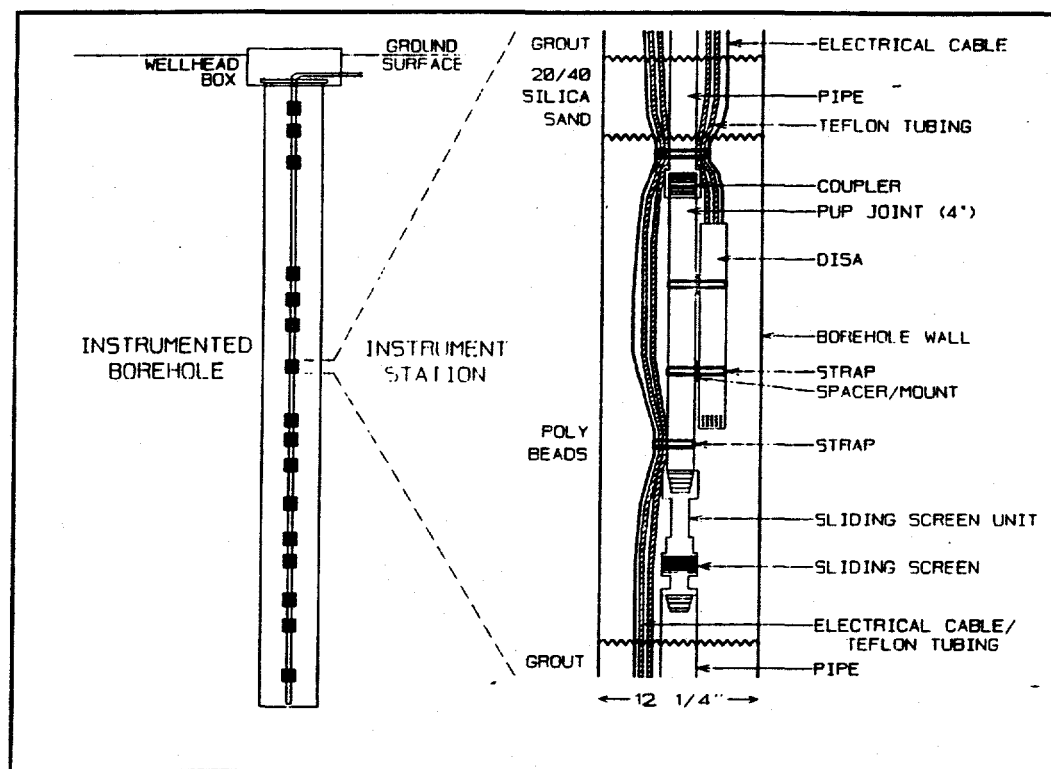


Figure 1. Borehole stemming design with an instrument station.

Instrumentation Station Apparatus (DISA) that houses the sensors used for routine monitoring, and the flow control devices used for gas sampling and *in-situ* recalibration (see DISA discussion below). The DISA's are attached to the outside of a fiberglass pipe, 2.375 inch outside diameter (OD), that is centered in the borehole with three-arm plastic centralizers. Located adjacent to the DISA is an aluminum sliding screen unit that is operated from inside the fiberglass pipe. The fiberglass pipe runs the full length of the borehole and is used to support the electrical cable and tubing during installation of the instrumentation package. In boreholes where the water table is accessible, a well screen is attached to the bottom of the fiberglass pipe and is used to monitor water levels.

The fiberglass pipe, 1.9 inch inside diameter (ID), provides access for continuous profiling or logging of the borehole, and access to the water table. Temperature logs, neutron moisture meter logs, and water-level measurements are thus possible even after the borehole is instrumented. The in-line sliding-screen units provide direct access to the instrument station. A shifting tool, lowered into the central support pipe, is used to open and close individual, or multiple well screens. These well screens are used for: 1) high-volume gas sampling, 2) isolated zone, open-hole, gas-

flow tests, 3) gas-tracer testing, 4) water-injection testing, and 5) as a backup to the DISA in the event of a failure of the solenoid flow-control valves.

Each instrument station is packed in polyethylene beads that are overlain with a 1 meter thick layer of 20/40 mesh silica sand. Polyethylene beads were chosen as a packing material to minimize water potential equilibration times. An expansive, calcium-sulfate based grout is used to isolate individual instrument stations in the borehole and to provide structural support to the entire instrumentation package. The sand layer, at the top of the instrument station, prevents the grout slurry from invading the instrument station during grout emplacement.

At the wellhead, the electrical cable and tubing attached to each DISA is routed underground into an insulated instrument shelter (IIS). The IIS houses the: 1) electronic data acquisition system, 2) power backup and power conditioning system, and 3) heating, ventilating, and air conditioning (HVAC) system (see IIS discussion below).

Up to 16 instrument stations can be established in a 12.25 inch diameter borehole (Figure 1). Smaller diameter boreholes, with a nominal diameter of 6

inches, will also be instrumented with up to 8 instrument stations. Size restrictions in these smaller diameter boreholes require the use of a fiberglass rod in place of a fiberglass pipe, and the elimination of the sliding screen unit and bottomhole well screen from the instrumentation package.

III. CALIBRATION AND OPERATION OF SENSORS

Sensors that are used in the unsaturated-zone borehole instrumentation program at Yucca Mountain are calibrated by the U. S. Geological Survey (USGS) at its Hydrologic Research Facility (HRF) Calibration Laboratory in Area 25, Nevada Test Site (NTS). These sensors are calibrated to an accuracy that is significantly better than manufacturer's specifications. Extreme accuracy is needed to measure what should be (in deep boreholes) minute changes and differences in the fluid-flow potentials at Yucca Mountain. Enhancement of calibration accuracy is achieved by conducting calibrations over a narrow operational range and by carrying temperature as an independent calibration parameter. Sensor calibrations are thus customized for their intended application and for the environment in which the sensors will be deployed. Additional performance enhancement is achieved by using a constant current instead of a constant voltage to provide excitation to the sensor and by using separate, wire leads to excite the sensor, and separate wire leads to read voltage output from the sensor.

When current is used to excite the sensors, voltage is allowed to float to whatever potential (within prespecified voltage compliance limits) is needed to provide a constant current to the sensor. Constant current eliminates measurement errors caused by uncontrolled voltage drops (losses) across lead-wires that are affected by the length of the wire and temperature-induced resistance changes along the wire. Current mode operation also eliminates the need to calibrate the pressure transducers and thermistors, used in this program, with long lead-wires attached. A four-wire sensor configuration, consisting of two sense (voltage output) leads and two source (current input) leads, allows direct measurement of output voltage from the sensor, thus bypassing uncontrolled voltage drops associated with the lead wires.

Output voltage is read with high input resistance (> 1 giga-ohm) multimeters and nanovoltmeters to minimize meter-loading errors (i.e., the difference between the voltage measured by the meter and the true source voltage).

All downhole sensors are deployed in pairs. One sensor is designated as the primary sensor, and the other as the alternate or backup sensor. The alternate sensor is operated periodically to corroborate measurements made by the primary sensor. Operational redundancy is employed, primarily for the purpose of accuracy verification; and secondarily for the purpose of providing a backup measurement capability in the event of a failure of the primary sensor.

IV. SENSOR TYPES

Three types of sensors were chosen to make measurements: 1) thermistors for temperature, 2) pressure transducers for pneumatic pressure, and 3) thermocouple psychrometers for water potential. In some cases, modifications to these sensors were made to increase their measurement precision and accuracy.²

A. Thermistor

A Yellow Springs Instrument Company,^{*} YSI46033, ± 0.1 °C interchangeable, glass encapsulated bead thermistor is used to measure *in-situ* temperature. This sensor has a rated resistance of 2252 ohm at 25 °C, with an operational range of -40 to 100 °C. It is wired in a four-wire measurement configuration, and is calibrated for use in the unsaturated-zone borehole instrumentation program, over a 35 °C temperature span in a range of 5 to 50 °C. Minimum calibration accuracy is ± 0.005 °C (95 percent confidence); though accuracies of 0.003 °C (95 percent confidence) are readily achievable. Measurement sensitivity is on the order of 0.001 to 0.0005 °C. Temperature measurements made with the thermistor are also used to correct the pressure transducer and thermocouple psychrometer measurements for temperature effects.

B. Pressure Transducer

A Druck,^{*} PDCR930U, 0 to 70 kPa, silicon-diaphragm strain-gage, pressure transducer is used to measure *in-situ* absolute pneumatic pressure. This sensor is calibrated and operated in an over-range condition to maximize its sensitivity. The rated burst pressure of this sensor is three times its 70 kPa range. It is calibrated over a pressure range of 70 to 115 kPa and over a 20 °C temperature span in a range of 5 to 50 °C. This sensor does not include internal temperature-compensation circuitry. Instead,

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temperature is carried as an independent calibration parameter, and is measured with the thermistor. Current excitation (normally 2.4 to 2.7 milliamps) is determined independently for each sensor to produce a voltage drop across the strain gage element that is as close as possible to the rated excitation voltage (nominally 10 volts) of the sensor. Minimum calculated accuracy for this sensor is ± 0.035 kPa (95 percent confidence), though accuracies of ± 0.020 (95 percent confidence) are often obtained.

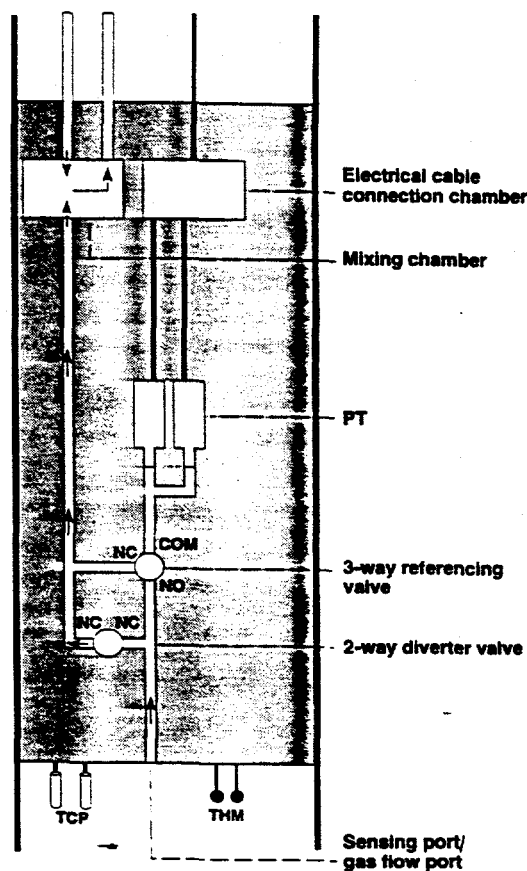
C. Thermocouple Psychrometer

A JRD Merrill Specialty Equipment Company,^{*} modified, 6-wire, Peltier-type thermocouple psychrometer, was developed by the USGS to measure *in-situ* water potentials.¹ This thermocouple psychrometer consists of a wet-bulb chromel-constantan sensing junction and a separate dry-bulb copper-constantan reference junction. The sensor is calibrated over a 20°C temperature span between a temperature of 10°C to 40°C. Six salt solutions ranging from 0.02 molal (*m*, -90 kPa) to 1.5 *m* (-7,500 kPa) are used to calibrate these sensors. The calibrated accuracy of this sensor is 10% at -90 kPa, and 1% at -7,500 kPa (both at 95% confidence). The sensitivity of the sensor is on the order of 5 kPa. Details of this sensor are discussed at length in a companion paper to this proceedings¹.

V. DOWNHOLE INSTRUMENT STATION APPARATUS (DISA)

The DISA is a multipurpose device that was developed by the USGS specifically for use in the unsaturated-zone borehole instrumentation program at Yucca Mountain (Figure 2). The DISA houses two pressure transducers, two thermistors, and two thermocouple psychrometers. It also houses two solenoid valves and is connected to a pair of teflon FEP (tetrafluoroethylene hexafluoropropylene copolymer) tubes, 0.25 inch ID, that run from the ground surface to the downhole instrument station and back to the ground surface. These tubes are used for: 1) sampling formation rock gases, 2) verifying downhole measurements of water potential made with the thermocouple psychrometers,² 3) introducing tracer gases for gas tracer diffusion tests, 4) *in-situ* recalibration of the downhole pressure transducers, and 5) uphole measurements of the pneumatic pressure inside the instrument station in the event of a failure of

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PT = pressure transducer

TCP = thermocouple psychrometer

THM = thermistor

NC = normally closed (de-energized state)

NO = normally open (de-energized state)

COM = common referencing point

→ = flow direction of gas during gas sampling

Figure 2. Downhole instrument station apparatus (DISA)

both downhole pressure transducers. These multipurpose capabilities are made possible by energizing one or both of the two solenoid valves housed inside the DISA.

A two-way valve (diverter) is used to gain access to the instrument station for: 1) vacuum withdrawal of formation rock gases, 2) introducing gas tracers, and 3) uphole measurements of the pneumatic pressure inside

the instrument station. A three-way, no-flow, referencing valve is used to regulate communication of the pressure transducers between the instrument station and the teflon sampling tubes (Figure 2). When energized, the three-way valve isolates the pressure transducer from direct communication with the instrument station allowing measurement of pressure inside the sampling tubes. When the three-way valve is energized, the pressure transducers are used to: 1) measure the pressure drop of gases entering the DISA during gas sampling (two-way valve energized) or, 2) measure pressure applied at the ground surface to one end of the sampling tubes to recalibrate the pressure transducers *in-situ* (two-way valve de-energized, see Figure 2).

The DISA is constructed of schedule 80 polyvinyl chloride (PVC). Electrical connections for the pressure transducers, thermistors, and solenoid valves are made-up inside the DISA in a water-tight, vapor-tight compartment. Housed in the DISA is a small chamber where dry carrier-gas is mixed with nearly vapor-saturated formation rock gases to prevent condensation of the nearly vapor-saturated formation rock gases during gas sampling.² Mixing inside this chamber occurs by forcing the two gas streams into turbulent flow at the point where the two gas streams meet.

VI. SURFACE SUPPORT FACILITIES

Surface support facilities at the borehole include a shelter to house data acquisition instruments that are connected with electrical cable to sensors in the DISA, and gas-sampling instruments that are connected with teflon tubing to the DISA.

A. Insulated Instrument Shelter (IIS)

An IIS, which serves as a surface support facility, was designed by the USGS. The IIS provides a controlled temperature environment, as well as protection from lightning, electro-magnetic noise, and other elements of a harsh desert environment. An IIS is installed at each borehole field site, and it is capable of supporting up to three instrumented (16 station) boreholes. Each IIS provides a controlled environment for the personal computer (PC) based data-acquisition-system and gas-sampling-system instruments.

Two uninterruptible power supplies (UPS's) with line conditioners, isolation transformers, converters, and battery packs provide on-line protection for measuring equipment, computers, and environmental controls. The battery supply is designed to provide power to all systems in the shelter for at least 24 hours if main

power is lost.

B. Data Acquisition System

A PC-based data acquisition system is housed in the IIS and is connected to the downhole sensors. It includes the following electronic components: 1) a Hewlett-Packard,^{*} HP3497A signal multiplexer and HP3498A extender with relay switching option cards, and an HP3457A multimeter to measure voltage output from the sensors, and 2) a Keithley,^{*} K220 programmable current generator for current excitation of the sensors, a K182 nanovoltmeter for measurement of voltage output from the psychrometer, and a K706 scanner with K7168 nanovolt relay switching cards. Two computers connected, in a peer-to-peer network are used; one for data acquisition, and one for control and communication.

Routine monitoring of temperature, water potential, and pneumatic pressure is accomplished at each instrument station by scanning the primary sensors once every three to five hours, and the alternate sensors occasionally.

VII. FIELD TRIALS AND RESULTS

A. Field Trials

In 1991, three 12.2 meter deep holes located adjacent to the HRF in Area 25, NTS were instrumented with 78 sensors.³ This test facility consists of an IIS, a data acquisition system, and three cased, screened, and stemmed boreholes, dry-augured in unsaturated zone alluvium. Sensors have been monitored every 3 to 5 hours for over two years. Results indicate that the sensors have performed well.

Figures 3-5 illustrate typical performance histories for the thermistor, pressure transducer, and thermocouple psychrometer. Two years of measurements, obtained from two of each type of sensor (one primary and one alternate) located at a depth of 12.2 meters in HRF Borehole #1, are shown in these figures. The curves cover a 20,000 hour sampling period. The primary sensor record represents over 4,000 duty cycles and the alternate sensor record represents about 1,000 duty cycles.

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B. Results

The small inset in Figure 3 shows primary and alternate thermistor curves over 50 hours of concurrent operation; for the most part, the curves agree with each other to within 0.001°C in a 0.005°C band. The primary and alternate pressure transducers (Figure 4) performed in a similar manner. The inset shows two curves over a 50 hour period of operation; the curves agree with each other to within differences that are on the order of ± 0.010 kPa. Figure 5 shows the results of the primary and alternate thermocouple psychrometers. The inset shows that the sensitivity of these sensors is on the order of ± 5 to 10 kPa (0.05 to 0.10 bars).

VII. SUMMARY AND CONCLUSIONS

A borehole instrumentation and monitoring program was designed for reliable, long-term (3 to 5 years) monitoring of *in-situ* pneumatic pressure, temperature, and water potential in deep, unsaturated-zone boreholes at Yucca Mountain, Nye County, Nevada. Sensor redundancy and multiple *in-situ* recalibration options insure that the data will be verifiable and that measurements can continue to be made in the event of premature sensor failures. The instrumentation design for the 12.25 inch diameter

boreholes also allows access for other types of experiments including: 1) gas sampling, 2) gas tracer diffusion studies, 3) water level monitoring, 4) isolated zone, open-hole gas-flow tests, 5) temperature profiling, 6) water injection testing, and 7) neutron moisture-meter monitoring. Size restrictions in 6 inch diameter, instrumented boreholes limit the scope of additional experimentation to gas sampling and gas tracer diffusion studies.

Attainment of extremely accurate and precise measurements is achieved by: 1) calibrating sensors over a narrow operational range, 2) carrying temperature as an independent calibration parameter, 3) operating all sensors in a four-wire configuration, 4) using constant current to excite the sensors, and 5) using precision electronic systems that are maintained in a temperature controlled environment (IIS). Accuracy is confirmed by using an alternate sensor to independently verify the reading of the primary sensor. *In-situ* recalibration is used to ascertain the correct measurements whenever there are discrepancies in the readings of these two sensors.

Field trials, in instrumented boreholes located adjacent to the Hydrologic Research Facility in Area 25, NTS, have demonstrated that the stability characteristics

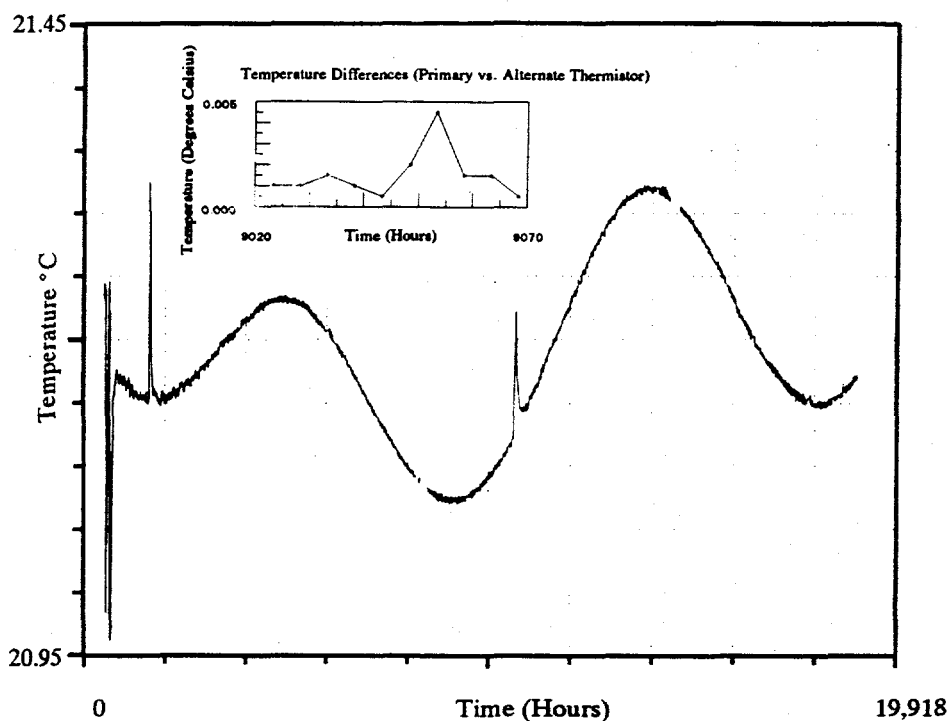


Figure 3. Primary and alternate thermistor measurements at the U.S. Geological Survey test facility.

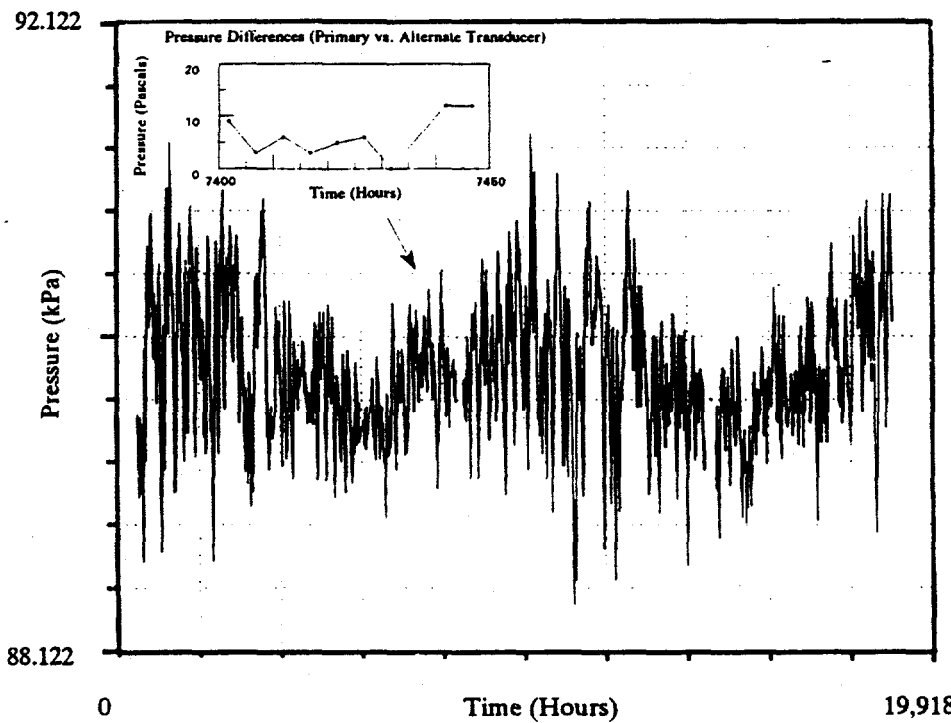


Figure 4. Primary and alternate pressure transducer measurements at the U.S. Geological Survey test facility.

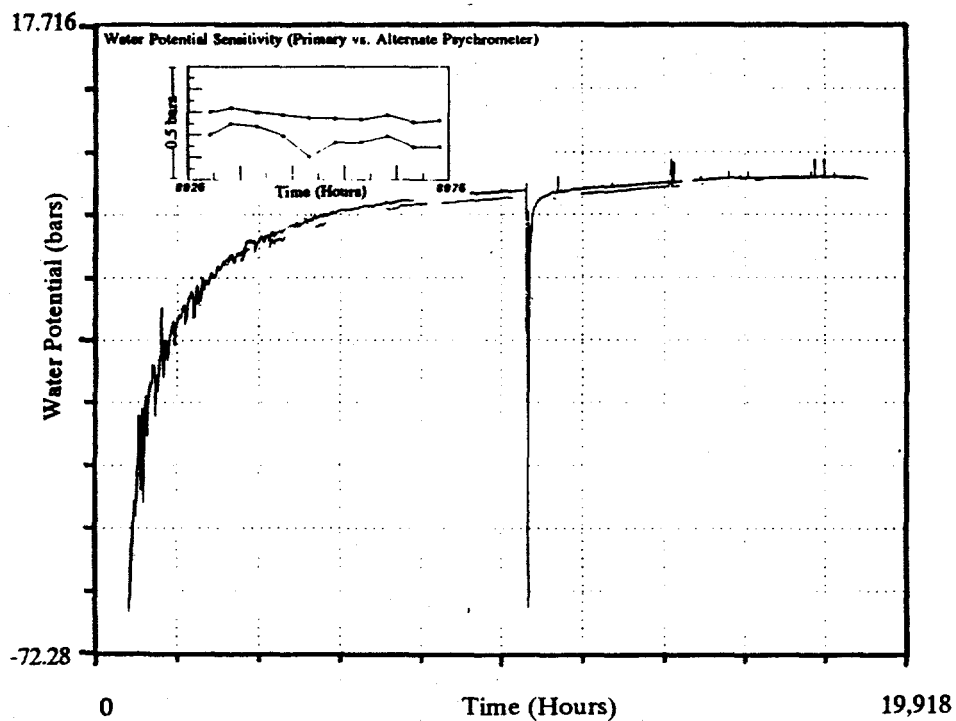


Figure 5. Primary and alternate thermocouple psychrometer measurements at the U.S. Geological Survey test facility.

of the sensors selected for use at Yucca Mountain will satisfy the long-term monitoring needs of this program. After over two years of continuous operation, the performance of these sensors is comparable to that observed during their original calibration and early monitoring history.

VIII. ACKNOWLEDGMENTS

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