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MATRIC POTENTIAL MEASUREMENTS IN BANDELIER TUFFS: FIELD TESTS AT LOS ALAMOS TA-54, AREA G, AND TA-49

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1. INTRODUCTION

To be added....

2. OBJECTIVE

In the recent paper by Neeper and Gilkeson titled "The Influence of Topography, Stratigraphy, and Barometric Venting on the Hydrology of Unsaturated Bandelier Tuff," laboratory core data from various holes about Los Alamos were analyzed to evaluate the existence of gradient reversals in matric potential. The profiles from this study indicate specific depth intervals where the gradient is such that moisture would flow upward under capillary forces. These regions are then barriers to downward liquid-phase transport of contaminants due to unsaturated flow processes (Neeper and Gilkeson 1996). The objective of this study is to further evaluate the presence of the gradient reversals by measuring in-situ matric potential from boreholes 54-1002 and 49-700 with use of thermocouple psychrometers and gypsum blocks.

3. METHODOLOGY

3.1 Strap Design

The measurement system comprises an instrumented strap lowered into the borehole and temporarily sealed in place with an inverting membrane borehole liner (SEAMIST™). The strap consists of eleven sections of polyethylene closed-cell foam connected with braided steel rope (see figure 1). The strap extends a total of 110 ft. from top to bottom and is approximately 6 inches in width. It is suspended in the borehole on a wire harness such that the total assembly length is 460 feet. Metal spreaders are located every 10-15 feet to support the steel rope and help prevent twisting of the strap. See figure 2 for a planar view of the spreader. Each foam section, approximately 9 feet in length, contains a thermocouple psychrometer, a gypsum block, and a platinum resistance temperature detector. These instruments are centered vertically and horizontally on the foam panel and protrude approximately 1/8 of an inch outward from the panel. The strap design places each set of instruments located 10-feet apart. See figures 3 and 4 for design details of instrument placement.

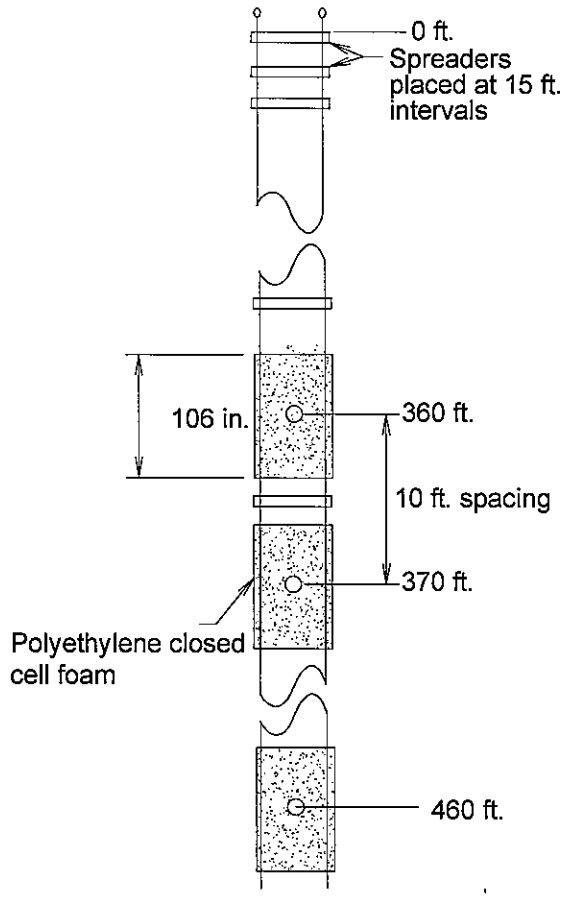


Figure 1. Foam block and spreader assembly.

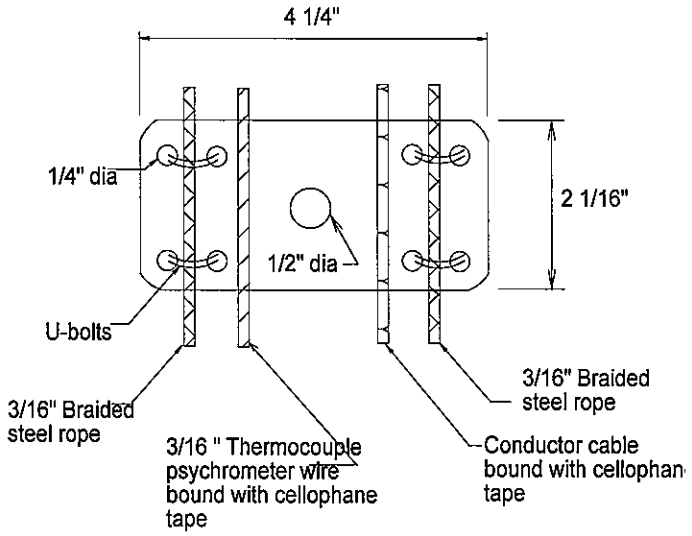


Figure 2. Spreader detail.

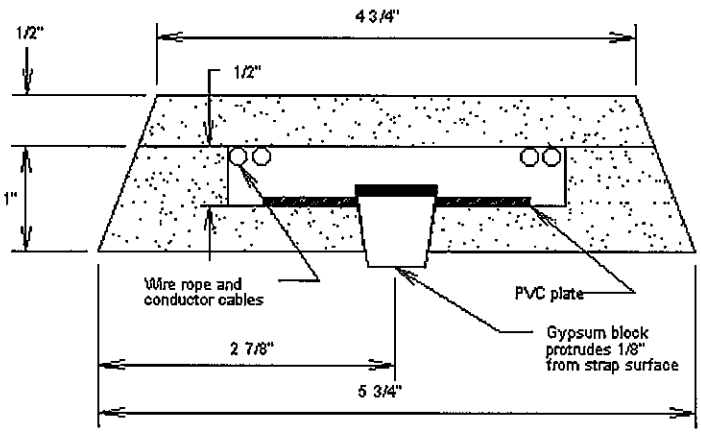


Figure 3. Lateral cross section of strap.

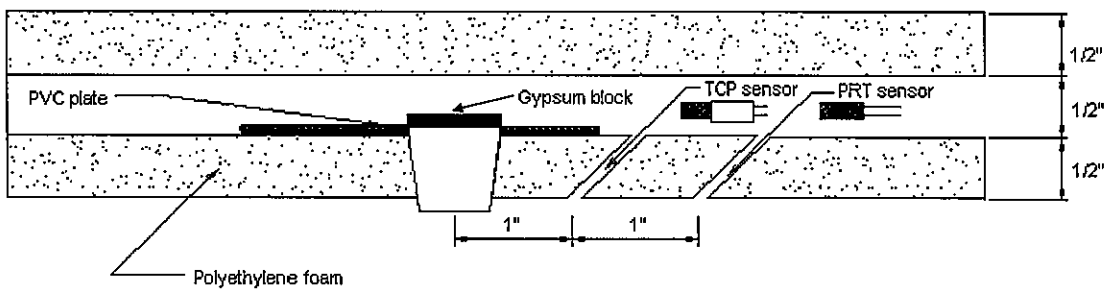


Figure 4. Longitudinal cross section.

The 460-ft. strap assembly is stored on a wooden reel, which rests on a 10-ft. trailer. The trailer allows the strap to be easily transported from one site to another. It also keeps the unused portion of the strap off the ground, while at the site. See figure 5 for a picture of the trailer and reel.

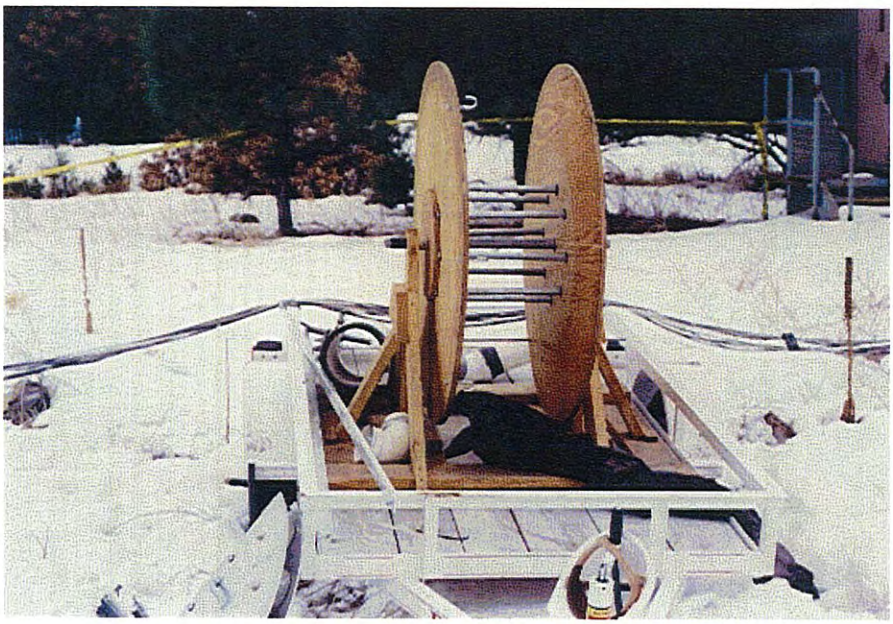


Figure 5. Trailer and reel used to transport and store the strap.

3.2 Strap Installation

The strap installation process is accomplished in one day. Prior to the strap installation, any existing borehole casing must be removed. A short surface casing is left in the hole to support the inverting membrane system. Once the borehole has been cleared, the strap is lowered 15 feet at a time with the use of a crane truck. It is then anchored to the borehole using the metal spreader assembly. Once the strap is in place, the crane is used to lift the inverting membrane canister over the borehole (see figure 6). To employ the membrane, the operator powers up the air pump and turns the canister crank, allowing the membrane to invert and deploy in the borehole under pneumatic pressure. The inflated membrane positions the strap blunt against the borehole wall, so that the instruments establish contact with the soil. See figure 7 for the configuration before and after the inverting membrane installation. The final step involves capping the borehole and attaching the membrane pump to the solar panels (see figure 8).

Figure 6. A crane truck lifts and positions the inverting membrane canister over the borehole.

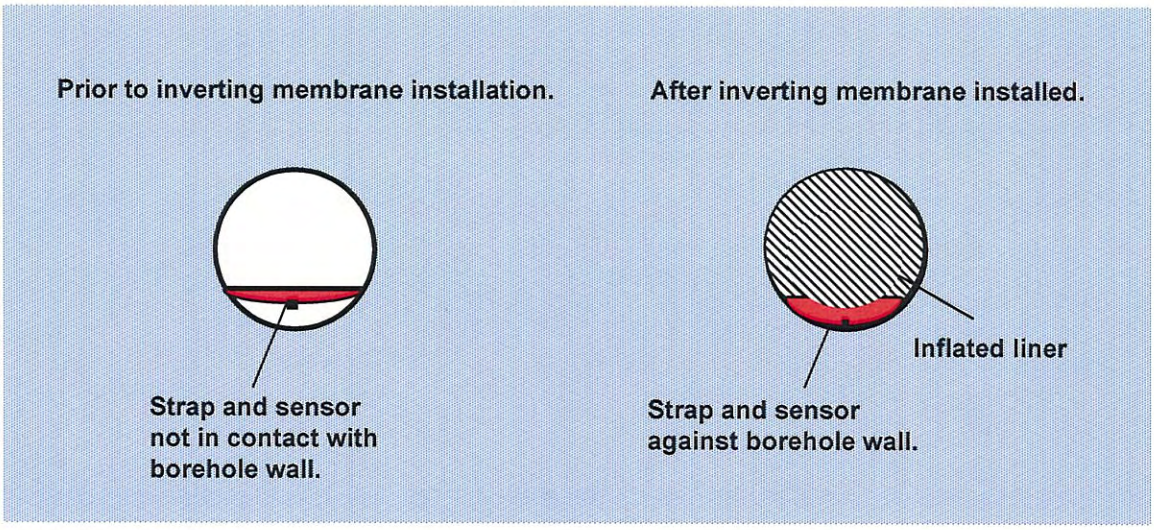


Figure 7. The position of the strap in the borehole before and after the inverting-membrane installation.

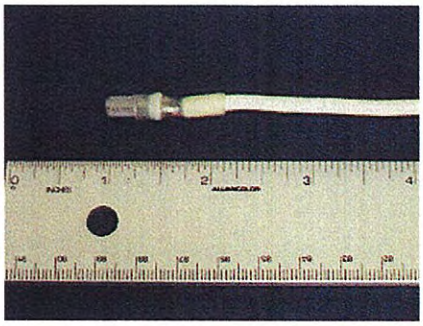
Figure 8. The borehole's surface seal and inverting-membrane pressure gage.

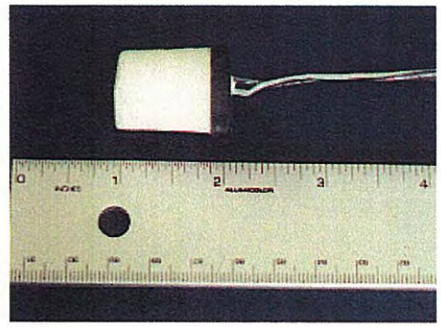
3.3 Strap Instruments

The primary objective of this study is to determine the hydraulic gradient or direction of moisture flow. The hydraulic gradient, a combination of matric suction and osmotic potential, can be determined using two different instruments: a thermocouple psychrometer or a gypsum block. Because the matric potential of soil is affected by temperature gradients, it is also important to accurately measure the temperature changes in the soil. A PRT sensor was the chosen temperature device, because of its ability to record very small changes in temperature and indicate temperature gradients in the borehole. Table 1 lists specifications of the three instruments, which were installed in the psychrometer strap. Figure 9 illustrates the length of each instrument.

Table 1. Instrument specifications.

Instrument	Measures	Supplier	Model #
Thermocouple Psychrometer	Matric potential	Wescor	PST-55-13
Gypsum Block	Matric potential	Campbell Scientific	223
Platinum Resistance Temperature Detector	Temperature	Omega	F3101

a) 

b) 

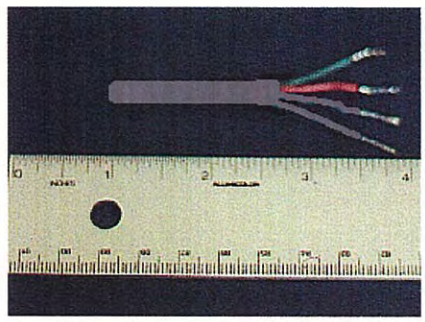
c) 

Figure 9. Photographs of the three instruments installed in the strap. a) thermocouple psychrometer; b) gypsum block; and c) platinum resistance temperature detector.

3.3.1 Thermocouple Psychrometer. Thermocouple psychrometers indicate matrix potential by assuming the pore water is in equilibrium with water vapor in the soil gas. The water or matrix potential is related to relative humidity by the Clausius-Clapyron relationship (osmotic effects are considered negligible):

$$\psi = V \ln\left(\frac{P}{P_s}\right) \qquad \text{(Eq. 1)}$$

where
Ψ = water potential
P = partial pressure of water in vapor phase
P_s = partial pressure of water vapor when at saturated conditions in air
$\overline{v}$ = specific volume of air/water vapor mixture

The ratio of P/P_s is also known as the relative humidity. Under normal conditions of ressure and temperature, this relation is plotted in figure 10. Note that the relative humidity is very high for soil matrix potentials in the range of interest (-20 to 0 bars).

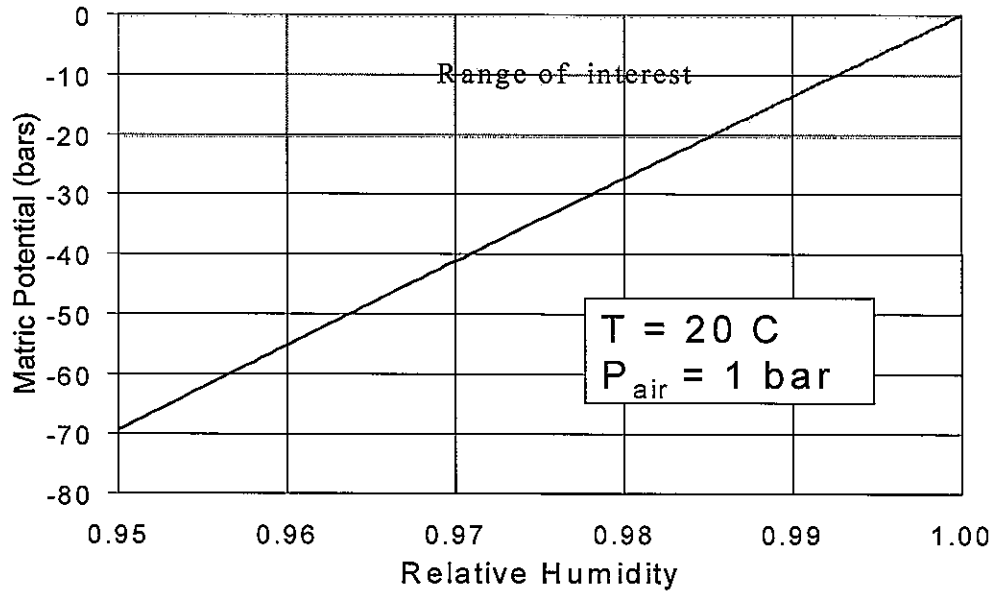


Figure 10. Relationship between relative humidity (P/P_s) and matric potential (ψ).

The thermocouple psychrometer is a delicate device, an inch in length, which contains a copper-constantan thermocouple junction and a chromel-constatan psychrometer junction encased in a fine mesh stainless steel screen. A PVC insulated cable containing the copper and constantan wires is attached to the base of the device and carries input and output voltage signals to and from the psychrometer. See figure 11 for a schematic of a thermocouple psychrometer.

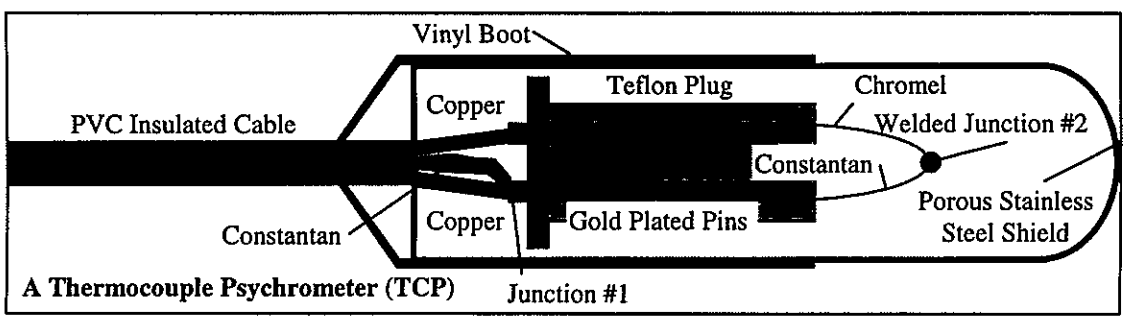


Figure 11. Thermocouple psychrometer schematic.

The Seebeck Effect and the Peltier Effect are the two principles, which govern the thermocouple psychrometer. The Seebeck Effect results in an electric current flow through the thermocouple when two joined wires of dissimilar metals are exposed to different temperatures. The voltage produced in this phenomenon is proportional to the difference in temperature between the junctions (Briscoe 1984). The Peltier Effect goes a step further; when a current is passed through the thermocouple junction, the junction is simultaneously cooled or heated. It is cooled when the electric current is passed through the thermocouple in the same direction as the Seebeck Effect, and is heated if the current is passed in the opposite direction.

The dew point and psychrometric methods are the two procedures used to determine the equilibrium relative humidity, and thus the water potential. The dew point method is the preferred technique because its water potential measurement is affected much less by changes in the ambient temperature and its sensitivity coefficient is twice that of the psychrometric method. It uses a feedback loop to control the Peltier cooling rate, which consequently causes the temperature to remain at the dew point. The wet thermocouple junction "neither loses water through evaporation nor gains water through condensation" (Wescor 1986) at the dew point temperature, since the heat flow is offset by adjustments in the cooling current. The psychrometer's output expresses the matric potential in microvolts. The microvolt value is proportional to the water potential by approximately -75 μvolts / bar (Wescor 1986).

The psychrometric method utilizes the Peltier effect to cool the junction below the dew point temperature, which causes a bead of water to form on the junction. At this point the current is terminated, and the thermocouple output is observed as the temperature of the thermocouple returns to ambient. The temperature (microvolt reading output) should initially drop rapidly until it reaches the wet bulb depression temperature. At this point the evaporation of the bead of water from the junction produces a cooling effect which offsets the heat absorption form the ambient surroundings. The microvolt reading output during the evaporation "plateau" is the psychrometric value which directly corresponds to the water potential. After the evaporation process is complete, the temperature will again drop rapidly until ambient temperature has been reached. Identifying the falling plateau is often difficult, which puts the psychrometric method at a disadvantage to the continuous output process of dew point method. The proportionality constant for the psychrometric method is approximately -0.47 μvolts/bar (Wescor 1986).

Calibrating the psychrometer determines the instrument's specific μvolts / bar relationship. The calibration process involves submerging a psychrometer in several prepared solutions of NaCl with known osmotic potentials (bars) and measuring microvolt output readings. A calibration curve is created by plotting the microvolt reading verses the known matric potential (bars). The μV / bar relationship is linear; therefore, the equation is: microvolt reading = (slope * matric potential) + y intercept.

The eleven psychrometers purchased for the TA-54 borehole were put through a rigorous eight-point calibration with 4 of the 8 points in the –1 bar to –10 bar range. A total of three measurements were taken at each point and the average of these results was used to determine the linear calibration curve. Two calibration curves were produced for each psychrometer; one representing the psychrometric calibration data and the other representing the dew point calibration data. Linear regression statistics revealed that the calibration curves had a high level of integrity. Unfortunately, it was later discovered that the rigorous psychrometer calibration measurements stressed the instruments and caused a high failure rate of the psychrometers in the field. The calibration procedure for the next set of psychrometers was scaled down to three points in the –1 to –10 bar range, so as to decrease the rate of failure. Refer to appendix A for details of the calibration procedure and results.

Several other thermocouple psychrometer properties were noted during both the calibrations and field measurement phases. The dew point measurements produced a strong calibration line. However; this line had a 4-6 μvolt zero offset, which was uncharacteristic of previous calibrations done in the laboratory. The long extension wire

is thought to be the cause of the multiple-point zero offset, since the voltage signal incurs some resistance while traveling through the 400+ ft. of wire to the HR 33T Microvoltmeter. The psychrometric calibrations did not seem to be as affected by the length of the extension wire, therefore their calibration curves have only a slight zero offset. Both the psychrometric and dew point curves showed linear integrity, so both methods were initially used in the field with the idea that one measurement would check the other. During the measurement sequence in the field it was noted that the psychrometric measurements were unable to produce accurate or consistent matric potential results in the –1 bar to –10 bar range. Since the matric potential of the soil near 54-1002 is in that low range, it was concluded that the psychrometric method was not an appropriate method for measuring the matric potential at these two sites. When calibrating the 54-1002 psychrometers only the dew point measurements were considered.

3.3.2 Gypsum Block. Gypsum blocks provide another way of measuring the matric potential by relating the electrical resistance of the porous block to the water content of the soil (assuming the porous block is in liquid equilibrium with the soil water). A gypsum block consists of two concentric electrodes encased inside in gypsum cylindrical block 1 inch in length and ¾-inch in diameter. When the soil is wet, the electrodes measure a low resistance; whereas when the soil is dryer the electrodes measure a higher resistance. The gypsum blocks used in the strap are manufactured by Campbell Scientific and their electrical resistance is measured using a Campbell Scientific 21X Datalogger. The program created to read the gypsum block resistance is located in appendix D.

An advantage of the gypsum block design is that the concentric electrodes restrict the current flow to the interior of the block, which lessens the chance for ground loops. In addition the gypsum material provides a buffer against naturally occurring salts in the soil, that can skew a matric potential reading. Gypsum blocks are at a disadvantage to the thermocouple psychrometer because they are slower to react to matric potential changes, must be in hydrologic contact with the soil, and if the gypsum material dries out, it can become uncoupled with the soil.

Calibration curves relating matric potential to measured resistance are used to determine the matric potential from the measurements. The calibration process for the gypsum blocks, using a pressure plate apparatus, is an advanced procedure that can take 6-8 weeks depending on the drying cycle of the soil. Calibrations were performed by Daniel B. Stephens and Associates. The generated curves are included in appendix B.

3.3.3 Platinum Resistance Temperature Detector. The Platinum Resistance Temperature Detector (PRT) was selected to measure the downhole temperature in the borehole because it is capable of measuring very small changes in temperature. The PRT is a Series F Omega thinfilm element, and is 2 inches in length. It is composed of four strain relieved silver palladium alloy wires encased in a thin flat ceramic cylinder. The nominal resistance of the element at 0°C is equal to 100 ohms. The temperature is indicated by a measurement of change in the resistance of the silver palladium alloy wires. The resistance response was measured in the field using the Campbell Scientific 21X Datalogger.

Initially an Omega-determined standard calibration curve was used for each of the PRTs, which relates the resistance (ohms) to the temperature (°C). When comparing the

depth vs. matric potential curves for measurements taken the week before the strap was pulled up 10 feet (7/16/97) to measurements taken the week after (7/28/97), a consistent 0.5 °C-1.0 °C difference in temperature at all depths was noted. This seemed to indicate that using the standard calibration curve was not generating an accurate representation of the downhole temperatures. After the strap was removed from borehole TA-54, each of the PRT's was individually calibrated and the temperature calculations were adjusted appropriately.

The calibration process involved submersing the PRT sensors in a water bath with a known temperature and measuring the resistance with the Campbell Scientific 21X Datalogger. Each PRT was submersed into two different water baths, one at a temperature near 15°C and another near 20°C, to determine the linear calibration curve. Then a calibration check, which involved measuring the resistance of a water bath with a known temperature, was performed to check each curve's integrity. See appendix c for the calibration procedure and calculations.

4. FIELD TEST CHRONOLOGY

4.1 TA-54-1002

The strap was installed in borehole TA-54-1002 in May of 1997, and measurements were taken on a weekly basis through August of the same year. In the first week of operation, the inverting membrane was unable to hold adequate pressure. This problem was immediately remedied by patching the membrane and replacing a faulty air pump. For the remainder of the testing sequence, all instruments performed well except for the thermocouple psychrometers. These devices had a high rate of failure in the field. By the end of August, five of the eleven psychrometers were not functioning. As discussed earlier, the comprehensive 8-pt calibration is thought to have stressed the instruments and caused their high failure rate. The following table outlines the strap installation and measurement sequence.

Table 2. Time sequence of field installation and measurements.

Date	Event	Notes
5/8/97	Strap installed.	
5/16/97	Data collected.	Noted low membrane pressure.
5/20/97	Membrane patched and new pump installed.	
5/28/97	Data collected.	Membrane pressure back up.
6/3/97	Data collected.	Lost psychrometer @ 132.5 ft.
6/11/97	Data collected.	
6/17/97	Data collected.	
7/7/97	Data collected.	Lost psychrometer @ 192.5 ft..
7/16/97	Data collected.	
7/22/97	Strap pulled up ten ft.	
7/28/97	Data collected.	Lost psychrometers @ 102.5 and 152.5 ft.
8/11/97	Data collected.	Lost psychrometer @ 122.5 ft.

4.2 TA-49-700

Casing removal from borehole 49-700 began the first week of November 1997 and was completed on November 21st. During the casing removal process permeability, anemometry, and caliper measurements were taken at various depths along the borehole wall. On December 6, 1997 the borehole surface seal was installed and on December 12th the strap was installed. The strap did not advance into the borehole with as much ease as it did in borehole 54-1002. It is possible that the strap could have twisted during its decent into the borehole. Also the psychrometer at 327 ft. was lost when its extension cable snapped.

The measurement sequence went smoothly for borehole 49-700. See table 3 for the sequence of events. This time there were no problems maintaining the pressure in the inverted membrane and the psychrometers failure rate was substantially reduced.

Table 3. Time sequence of casing removal, strap installation, and measurements.

Date	Event	Notes
11/7/97	First 100 ft. of casing pulled by Tonto crew.	
11/10/97	Caliper measurements attempted.	Caliper tool not functioning properly.
11/12/97	Anemometry and Packer test run.	Had electrical problems with packer system.
11/13/97	Packer tests run.	Packer system back up and functioning well.
11/18/97	Anemometry tests run.	Anemometry survey completed.
11/21/97	Remainder of the casing pulled.	The last 20 ft. section was left in place for the borehole surface seal installation.
11/25/97	Packer tests run.	Packer membrane over inflated and burst.
12/1/97	Caliper logs taken.	Satisfied with caliper logs.
12/4/97	Packer tests run.	
12/5/97	Packer tests run.	
12/6/97	Borehole surface seal was installed.	
12/7/97	Anemometry measurements completed.	
12/12/97	Strap installed.	Severed one psychrometer during installation, suspect that strap may be twisted.
12/15/97	Strap data collected.	Psychrometer @ 327 ft. identified as being severed.
12/20/97	Strap data collected.	Membrane pressure = 1.1 psi
1/8/98	Strap data collected.	Membrane pressure = 0.95 psi
1/14/98	Strap data collected.	Membrane pressure = 1.1 psi
1/20/98	Strap data collected.	Membrane pressure = 1 psi
1/27/98	Strap data collected.	Membrane pressure = 0.7 psi
2/10/98	Strap data collected.	
2/18/98	Strap data collected.	
2/26/98	Strap data collected.	

3/3/98	Strap data collected.	
3/10/98	Strap data collected.	Membrane pressure = 1.5 psi
3/25/98	Strap data collected.	

5. FIELD MEASUREMENT RESULTS

Plots were created to track thermocouple pyschrometer, gypsum block, and PRT data at eleven different depths over time. Three depth profiles were generated that display depth vs. matric potential for the separate measurement sequences.

5.1 TA-54-1002

5.1.1 Thermocouple Psychrometer Results. The thermocouple psychrometer matric potential data is relatively stable with swings averaging +/- 2 bars over time with an overall measurement range of –4 to –11 bars (see figure 12). The thermal stability of the HR-33T microvoltmeter seems to be the reason for the small swings in matric potential. Since the reference temperature inside the micro voltmeter is located some distance from the terminal block to which the thermocouples are connected; any temperature gradient between the two causes a temperature difference between the terminal block and the reference temperature sensor. This stability issue was evaluated in "Thermocouple Psychrometer Stability Test at Los Alamos TA-54, Borehole 54-1018" (Lowry 1997). For subsequent tests it is recommended to thermally insulate the HR-33T during testing to prevent the discussed temperature gradients and thereby smoothing the matric potential data over time.

The psychrometer depth profiles show a possible gradient reversal between 120 ft. and 135 ft. (see figure 13). Unfortunately, the psychrometer at 130 ft. was one of the first to fail, therefore very little data was available for that depth. However; when the strap was pulled up 10 feet, two measurements were taken at the 130-ft. depth. The matric potential data from 130 ft. was consistent with the previous data and supports the gradient reversal idea. Since the psychrometer failures prevented a thorough collection of data for each depth, a less intensive calibration of the next set of psychrometers is recommended so as to prevent unnecessary stress on the instruments.

5.1.2 Gypsum Block Results. The gypsum block data versus time plots demonstrate that the gypsum blocks are slow to react to changes in moisture. Prior to placing the strap into the borehole, the gypsum blocks were soaked in water, which is responsible for the low matric potential readings in the first week after the installation. It took approximately 35 days for the instruments' readings to stabilize. Even after reaching equilibrium, the gypsum blocks consistently measured lower matric potentials than the psychrometers. This may be a sign that a portion of the gypsum blocks did not have good contact with the borehole wall, which would cause them to dry out and read artificially low matric potentials.

The borehole depth vs. matric potential plots indicated that the matric potential of the soil was much lower nearer the surface of the borehole than suggested by the psychrometers. However, towards the 200-ft. mark both instruments measured comparable matric potentials. Since the gypsum blocks' matric potential measurements seem to swing back and forth throughout the depth profile, there seems to be no way of pinpointing a definite gradient reversal. It is interesting to note that the depth profiles after the strap was pulled up (July 28 and August 11) have the same basic delineation as the profiles before the strap pulled up. This again demonstrates the inability of the gypsum block to measure sudden changes in matric potential.

5.1.2 PRT Results. The plots of the temperature sensor data showed that the temperature of the borehole remained stable, once the membrane was inflated to an acceptable pressure. Even when the membrane was moved up, the profile changed only minutely from the previous profiles. As discussed earlier, the PRTs were calibrated after the strap was pulled from borehole 54-1002 because the general calibration equation was not deemed an acceptable representation of the ohm/^{o}C relationship for the individual instruments. The calibration procedure is recommended for subsequent tests using new PRTs.

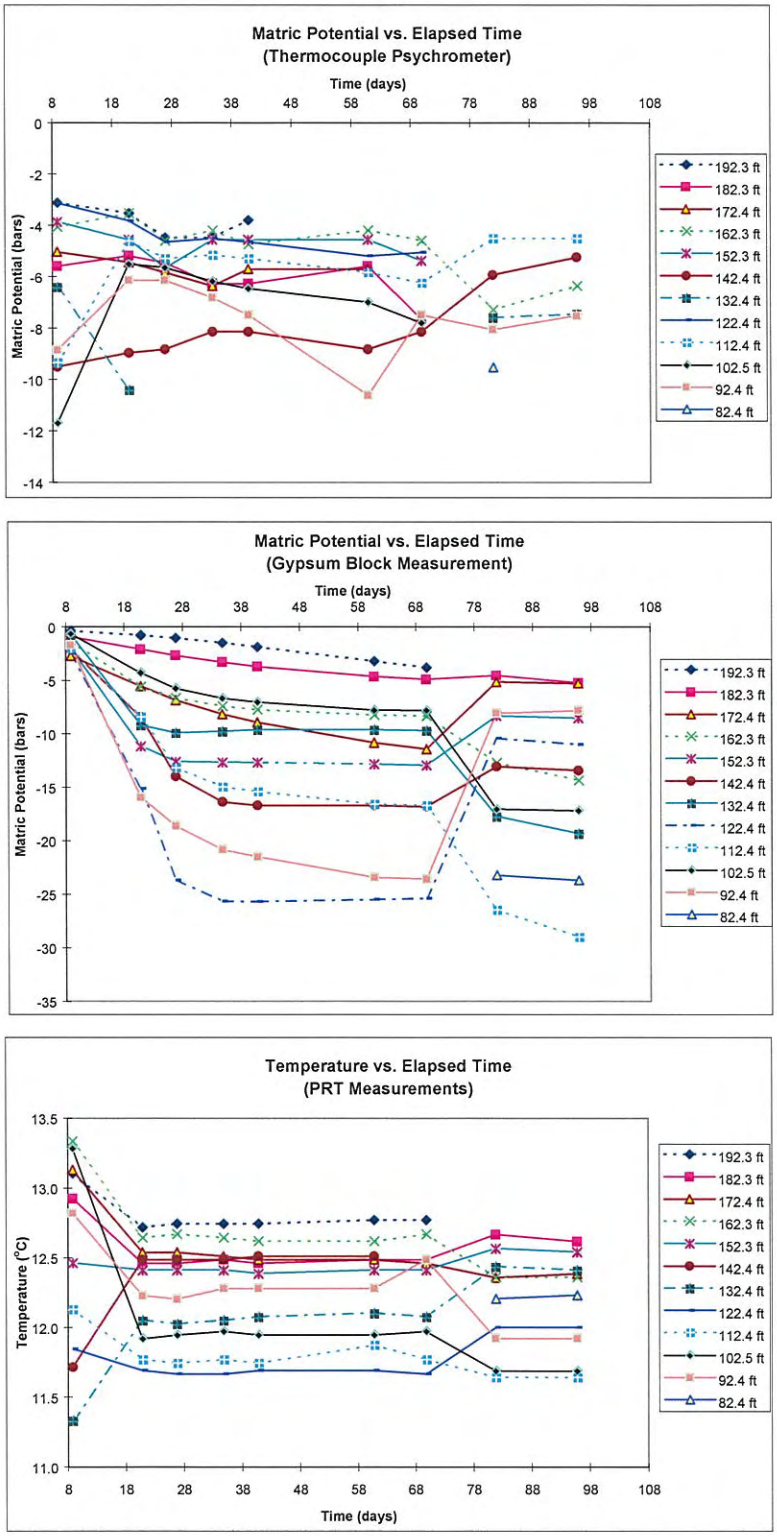


Figure 12. Temperature and matric potential vs time (borehole 54-1002).

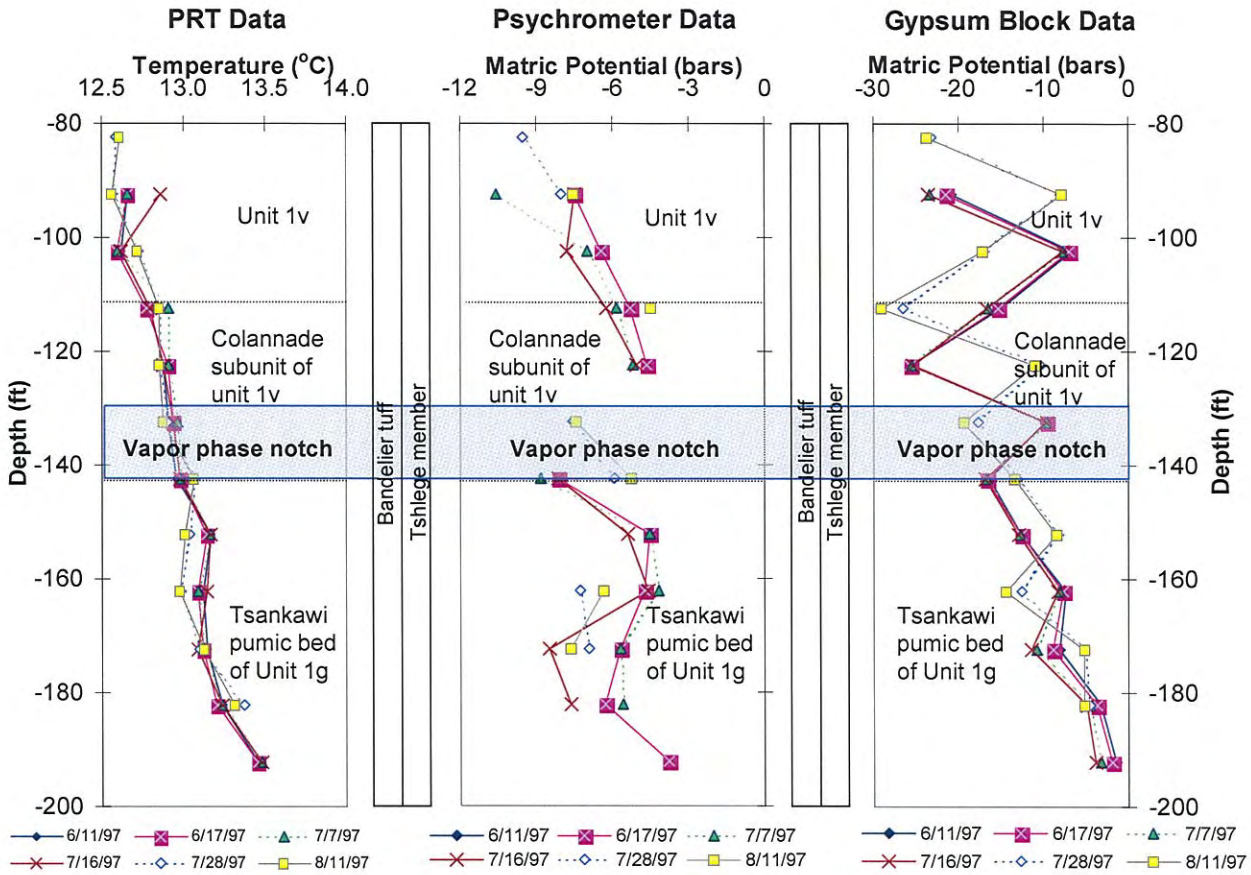


Figure 13. Matric potential and gradients vs. borehole depth over time (borehole 54-1002).

5.2 TA-49-700

5.2.1 Thermocouple Psychrometer Results. The HR-33T was housed in a trailer and remained on site throughout the measurement sequence in order to prevent the high swings in matric potential. The psychrometers seem to have smaller swings in matric potential measurements (+/- 1 bar) than when in borehole 54-1002, where the HR-33T was not thermally insulated. The matric potential range fell between –1 to –4 bars.

The psychrometer depth profiles show a gradient reversal near 375 ft. It is interesting to note that the depth profile of the psychrometer matric potential correlates positively with the lab derived data from the Neeper Gilkeson study (see figure 14). Since it is possible that the strap could be twisted in the borehole, which could prevent the instrumentation from contacting the borehole wall; confidence in data is not high. Further studies, which involve pulling up the strap and reinstalling it are recommended.

5.2.2 Gypsum Block Results. The gypsum blocks responded to the borehole in the same way as in borehole 54-1002. The matric potential dropped off initially indicating that they were equilibrating to the moisture content of the soil. The gypsum block

measurements did not compare well with the thermocouple psychrometer measurements. For future applications of the psychrometer strap, gypsum block will not be used because they require long time to equilibrate and do not respond to sudden changes in matric potential.

5.2.3 PRT Results. The plots of the temperature sensor data showed that the temperature of the borehole remained stable, see the error bar plot on figure 15. The temperature range was between 11.6 and 12.2 °C.

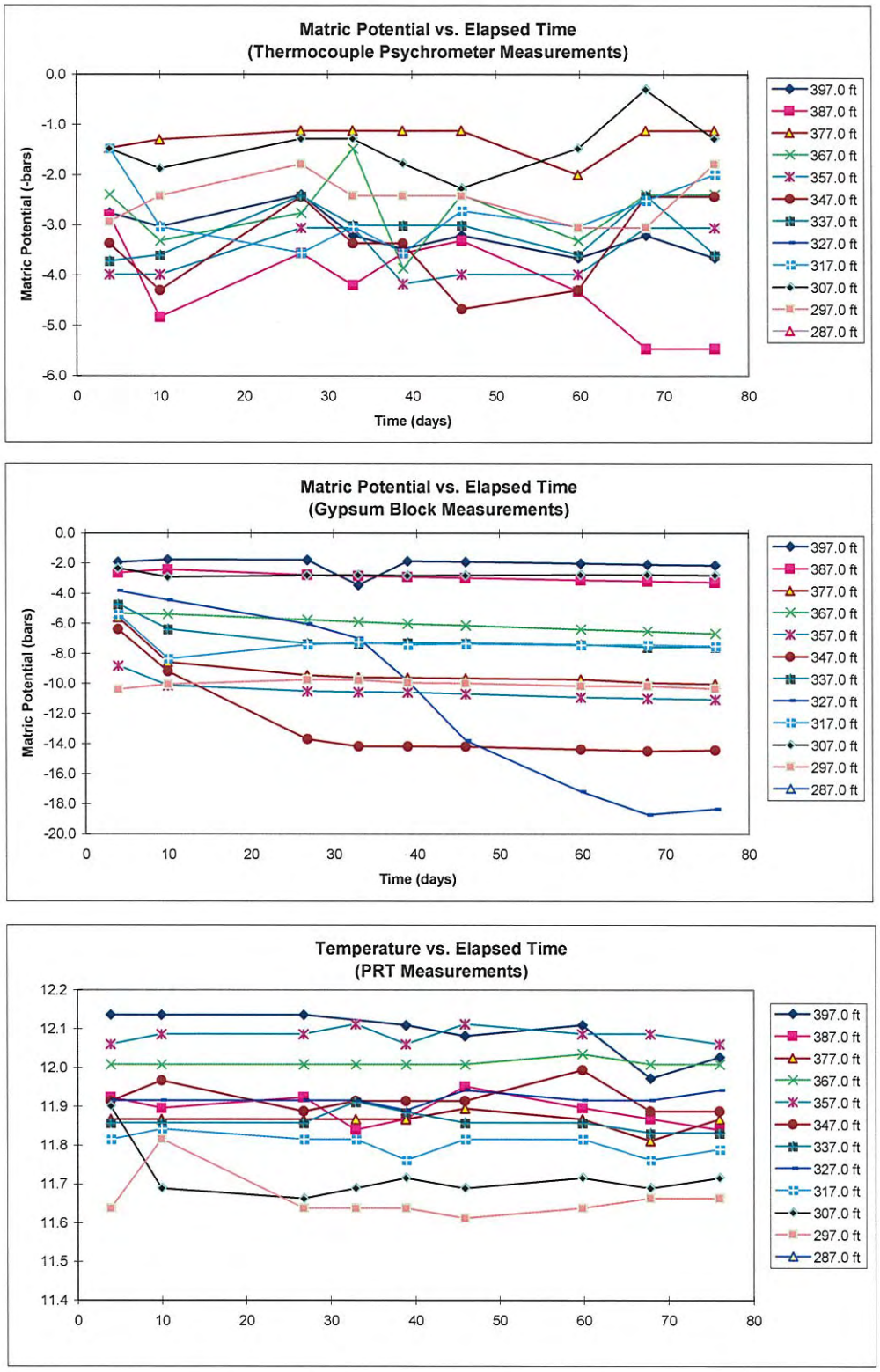


Figure 14. Temperature and matric potential vs time (borehole 49-700).

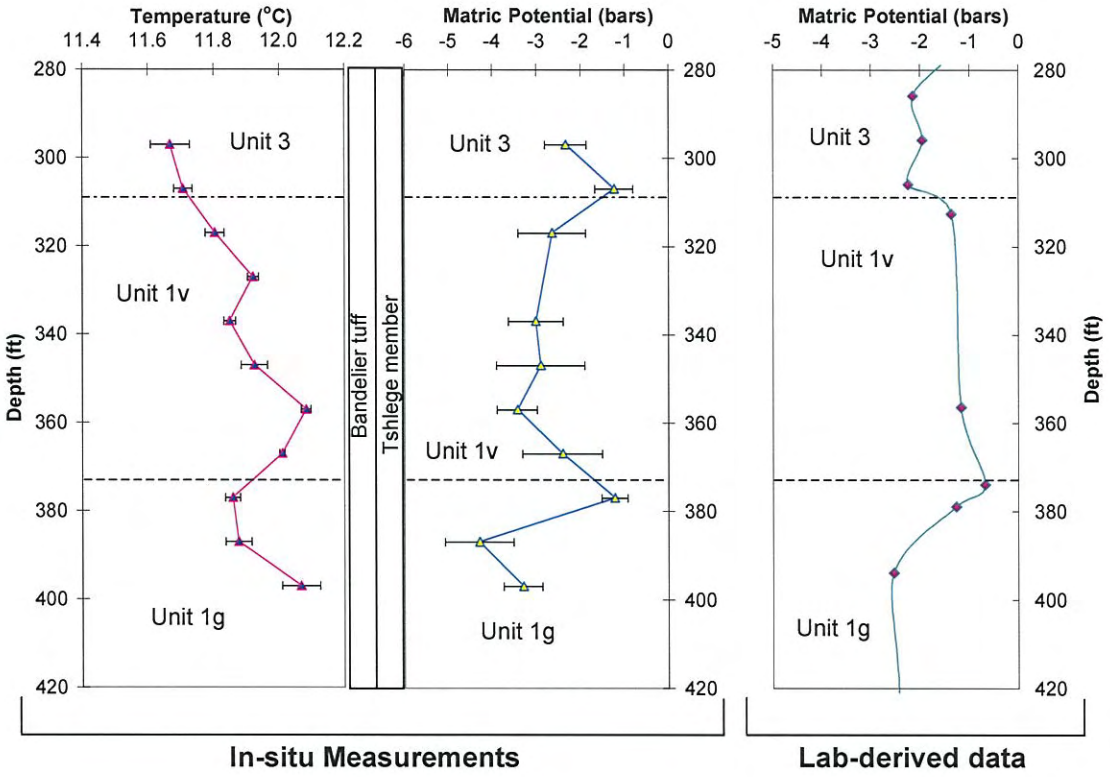


Figure 15. Average matric potential and temperature results with error bars compared with lab derived data from Neeper and Guilkeson study.

6. IMPLICATIONS TO ENVIRONMENTAL RESTORATION PROGRAM

To be completed…..

7. CONCLUSIONS AND RECOMMENDATIONS

- Psychrometers and temperature sensors produced satisfactory results and compared well with laboratory measurments.
- Psychrometer failure can be avoided by reducing calibration cycles.
- Gypsum blocks were difficult to use quantitatively (i.e. slow to stabilize and exensive to calibrate).
- In slanted holes strap emplacement was straight forward.
- In vertical holes, problems with strap/sensor orientation arose due to uncontrolled rotation of strap during emplacement.
- Future work would entail modifying strap to avoid dependence on strap orientation. Reinstall new strap into borehole 49-700.

8. APPENDIX A: THERMOCOUPLE PSYCHROMETER CALIBRATION

8.1 Introduction

Each thermocouple psychrometer has a specific linear relationship between its microvolt output reading and the corresponding matric potential expressed in bars. *Wescor* provides an approximate linear relationship of -0.75 μvolts/bar for the dew point method and -0.47 μvolts/bar for the psychrometric value. These relationships are purely approximations and are not specific to any thermocouple psychrometer. To determine a psychrometer's accurate relationship, it is necessary to perform a calibration. Psychrometers can be calibrated using a series of NaCl dilutions of known osmotic potential. The thermocouple psychrometer calibration curve exhibits the output microvolt reading for each NaCl dilution vs. the known matric potential (bars) of that NaCl dilution. A specific linear relationship is then determined from the recorded calibration points.

The 11 *54-1002* psychrometers were calibrated according to the detailed procedure listed below. The 49-700 psychrometers underwent a simplified version of the following procedure, which included only three points (-2, -3, and –6 bar solutions). Prior to any calibration work each psychrometer was assigned and connected to a reel of extension wire, which will later allow the psychrometer to be lower several hundred feet into a borehole. The extension wire and the corresponding psychrometer were then labeled with an identification number and a data sheet was created to record the identification numbers, Wescor serial numbers, extension wire lengths, and the π_v values determined by *Wescor*). Next laboratory π_v values were determined for the psychrometers (with the wire extension attached) using the *HR 33T* Dew Point Microvoltmeter. These values were recorded on a new data sheet and were used during the calibration procedure. Once the NaCl dilutions were prepared, the psychrometers (5 and 6 at a time) were submersed in the first solution and were left to equilibrate in an insulated box for one hour. Three dew point and a psychrometeric measurements were taken for each psychrometer at one hour intervals for the 54-1002 psychrometers and only one measurement was taken for the 49-700 psychrometers. Data for each NaCl dilution was recorded on a separate raw data sheet.

8.2 Procedure

8.2.1 Materials Needed.

1. Volumetric pipettes → 100 ml, 20 ml, 5ml
2. Mohr pipette → 5 ml
3. Pipette bulb
4. Volumetric flask → 1000 ml
5. Nine glass storage containers (air tight)
6. Wash bottle
7. *Ohaus* Dial-o-gram scale

8. Distilled water
9. Insulated foam chamber (see figure A1))
10. Glass canning jar with silicon rubber diaphram (see figure A1)
11. Eleven *Wescor* thermocouple psychrometers
12. *HR 33T* Dew Point Microvoltmeter (see figure A2)

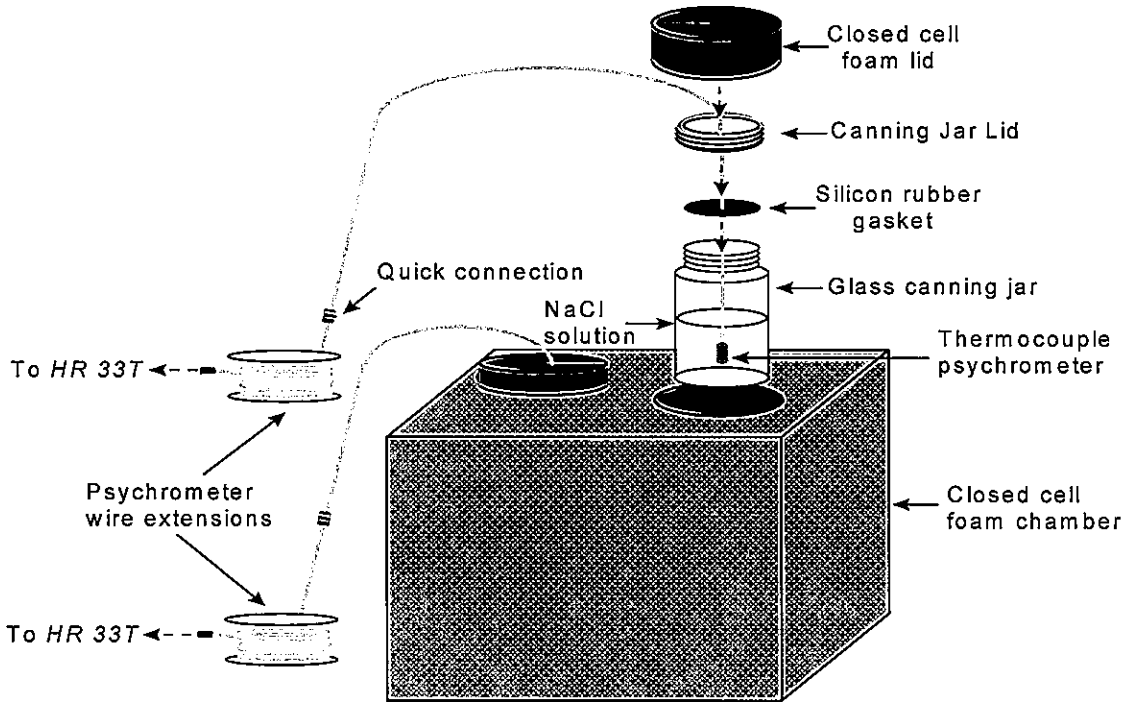


Figure A1. Calibration setup.

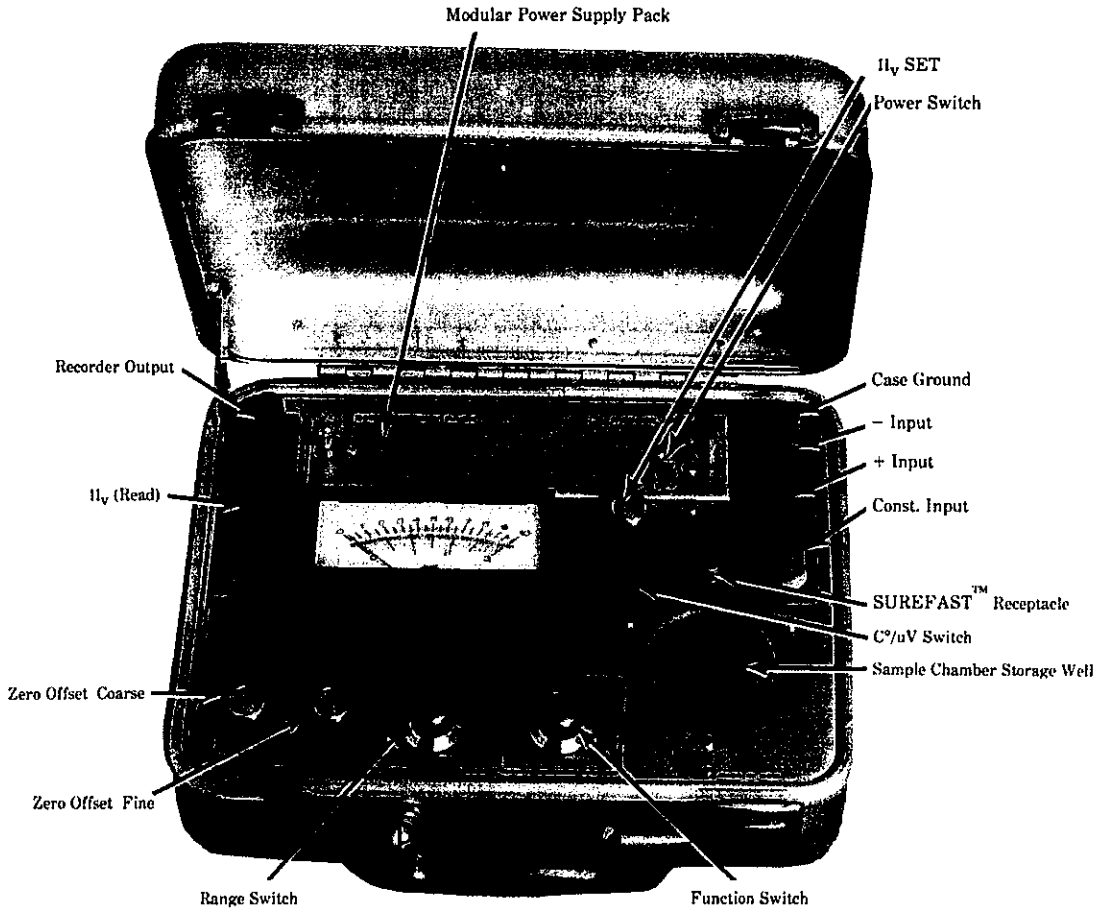


Figure A2. Photograph of the HR-33T (Wescor 1986).

8.2.2 Test Setup.

1. Prepare a 2 M stock solution of NaCl.
   a. Weigh 116.88 gms of NaCl using the 310 g Ohaus Dial-o-gram scale
   b. Dissolve the measured NaCl powder into a 1 L volumetric flask with distilled water and fill the flask with distilled water to the 1 L calibration mark
   c. Mix the solution thoroughly by shaking the volumetric flask
2. Transfer this stock solution to an airtight glass container. From the 2 M stock solution prepare 1 L dilutions with the following molarities: 0.027, 0.071, 0.11, 0.16, 0.22, 0.44, 0.66, and 0.88.
   a. Using a clean volumetric pipette draw the appropriate volume of the 2 M stock solution of NaCl. Table A1 displays volumes of stock solution are needed for dilution preparation.

Table A1. Preparation volumes of stock solutions.

Molar NaCl Solution (@ 25°C)	Volume of Stock Solution Needed (ml)
0.027	13.5
0.071	35.5
0.11	55.0
0.16	80.0
0.22	110
0.44	220
0.66	330
0.88	440

These numbers were obtained using the HP linear interpolation function and Lang's water potential tables (Lang 1967).

b. Release this volume into a clean 1 L volumetric flask, and fill the flask with distilled water to the 1 L calibration mark.
c. Place the lid on the flask and shake vigorously for 30-60 s.
d. Before preparing the next dilution, thoroughly clean all glassware with distilled water.

3. Perform a thorough cleaning of the thermocouple psychrometer, before starting any active calibration procedure.
   a. Rinse the exposed thermocouple and stainless steel covering with near boiling distilled water
   b. Dry the thermocouple by blowing a low pressure air source into the casing
   c. Repeat this procedure between calibrations to eliminate any salt residue
4. Determine the π_v value for each thermocouple pyschrometer.
   a. Allow the thermocouple psychrometer to achieve equilibrium in the dry isothermal foam sample chamber (approximately 20 minutes)
   b. Set the "function" switch to "read" and the range switch to "30 μ V"
   c. Adjust the "zero offset" control until the meter reading is at zero
   d. Set the "π_v/°C" switch to "°C" and record the temperature reading displayed on the meter
   e. Set the "π_v/°C" switch to "π_v"
   f. Turn the "function" switch to "cool"
   g. Wait about 5 seconds and turn the "function" switch to "dew point"
   h. Rotate the "π_v set" knob until the meter holds steady between 15 and 30 μ volts
   i. Depress the "π_v" button and take a μ volt reading from the meter. This value is the π_v value at the corresponding temperature reading for the psychrometer

j. Repeat steps a-i an additional time to determine validity of the measurement

8.2.3 Test Specifications.

1. Temperature changes can affect the calibration slightly, so care should be taken avoid excessive touching of the calibration chamber.
2. The cooling current and cooling time should be a standardized function.
3. The proximity of the thermocouple to the sample in calibration exercises should mirror the proximity in field work. If extensions are needed, calibrations should be completed with the extensions attached.
4. Since the temperature at which a measurement is made affects the voltage output in the psychrometric method, a temperature correction must be applied to the calibration measurements as well as the field measurements.
5. The π_v value should be adjusted according to solution temperature.
6. A portion of lead wire should be within the container to prevent heat flux from traveling along the lead wire to the measuring thermocouple.
7. The psychrometer must be thoroughly cleaned following calibration to eliminate any salt residue.

8.2.4 Calibration Method.

1. Allow the thermocouple psychrometers to equilibrate in a desired NaCl solution
   a. Pour the prepared molar solution of NaCl into the glass thermocouple psychrometer calibration, feed the psychrometer through the silicone diaphram, tighten the metal lid on the jar, and place the jar into the isothermal foam chamber
   b. Allow the chamber to equilibrate for 1.0 hour
2. Determine the temperature of the solution
   a. Plug the thermocouple psychrometer into the *HR 33T*
   b. Set the "Range" knob to "30 μ V" and the "Function" switch to "Read"
   c. Set the "°C/ μV" switch to "°C" and read the temperature directly from the meter
   d. Record this measurement
   e. Determine the temperature corrected π_v value for the psychrometer using the following equation

$$\Pi v_2 = 0.7(T_2 - T_1) + \Pi v_1$$

3. Measure the dew point microvolt and the psychrometric microvolt values
   a. Using the *HR 33T*, set the function switch to READ and set the range switch to the appropriate μ V setting.
   b. Zero the meter by adjusting the zero offset knob.
   c. Depress the π_v button and turn the "π_v set " knob until it reaches the temperature corrected π_v value.
   d. Set the function switch to "cool" and wait until the needle hits the right side of the meter.

e. Set the function switch to "dew point."
f. When the meter converges, record the reading. This is the dew point microvolt value.
g. Turn the knob to "Read." Once the meter again stabilizes, record the value displayed on the meter. This is the psychrometric microvolt value of the solution.
h. Adjust psychrometric values when the solution temperature deviates from 25°C.
i. If the solution temperature is not equal to 25°C while measuring the psychrometric microvolt value, use the following temperature correction equation to adjust the microvolt reading.

Actual μvolt Value = μvolt Reading / (0.325 + 0.027*[Actual Temperature °C])

8.3 Calibration Uncertainties

An uncertainty analysis was performed on the on the thermocouple psychrometer calibration procedure to determine how much error is incurred due to instrument uncertainties. This task was divided into three sections: the liquid measurement uncertainties, the dry measurement uncertainties, and the uncertainties due the HR-33T microvoltmeter. Prior to the calculations, all instruments' specifications were checked and accuracies for each were recorded (see table A2).

Tables A3, A4, A5, and A6 present the results of the measurement uncertainty calculations for various NaCl solutions or μvolts ranges(HR-33T). The method of least squares was used to calculate the cumulative error bar values for each table. Next a calibration curve relating either NaCl molality to bars or μvolts to bars was used to determine the liquid uncertainty effects on the matric potential measurements. See tables A7 and A8.

The results of the uncertainty analysis show that the majority of the measurement error evolves from the liquid measurement uncertainties. It is noted that the greater the molality of the solution, the greater the error associated with a matric potential measurement. Fortunately, since the matric potential range in the field is in the –1 to-10 bar range, the error bar fell below –1 bar.

Table A2. Instrument accuracies.

Instrument	Measurement Uncertainty
Scale	+/- 0.040 gm.
Pipettes	
5ml	+/- 0.03 ml.
20ml	+/- 0.06 ml.
100ml	+/- 0.08 ml.
Mohr	+/- 0.10 ml.
Volumetric flask	+/- 0.60 ml.
HR 33T	+/- 0.60 μv.

8.3.1 Liquid Measurement Uncertainties

Table A3. NaCl solutions uncertainties due to liquid measurements.

Solution (bars)	Solution (M)	Volumetric Pipettes 5ml	20ml	100ml	Mohr Pipette 5ml	Volumetric Flask 1000ml	Error Bar (+/- ml)	Uncertainty of 1000 ml Solution (%)
0.02	0.027	0.04			0.10	0.85	0.86	0.086
-2.08	0.071	0.05	0.03		0.10	0.85	0.86	0.086
-3.94	0.110	0.05	0.04			0.85	0.85	0.085
-6.32	0.160		0.06			0.85	0.85	0.085
-9.19	0.220	0.04		0.08		0.85	0.85	0.085
-19.68	0.440		0.03	0.11		0.85	0.86	0.086
-30.18	0.660	0.04	0.03	0.14		0.85	0.86	0.086
-40.67	0.880		0.04	0.16		0.85	0.86	0.086
-51.16	1.100	0.04	0.04	0.18		0.85	0.87	0.087

Table A4. Effects of solution uncertainty on the matric potential measurement assuming the bar/molality relationship: y(NaCl concentration) = -0.021*(solution [bars])-0.027.

Solution (bars)	Solution (M)	Total Uncertainty (l)	Solution with Error (M)	Solution with Error (bars)	Error Bar (+/- bars)
0.019	0.027	1.086	0.025	0.121	0.101
-2.079	0.071	1.086	0.065	-1.812	0.267
-3.940	0.110	1.085	0.101	-3.528	0.412
-6.325	0.160	1.085	0.147	-5.727	0.598
-9.187	0.220	1.085	0.203	-8.362	0.825
-19.681	0.440	1.086	0.405	-18.026	1.656
-30.176	0.660	1.086	0.608	-27.679	2.497
-40.670	0.880	1.086	0.810	-37.330	3.340
-51.165	1.100	1.087	1.012	-46.968	4.196

8.3.2 Dry Measurement Uncertainties

Table A5. Uncertainty associated with measurement of dry NaCl.

Weight of NaCL (g)	Uncertainty of Measurement (+/- g)	Uncertainty (%)
116.88	0.04	0.034

Table A6. Effects of dry measurement uncertainties on the matric potential measurements*.

Solution (bars)	Solution (M)	Uncertainty (g)	Solution with Error (M)	Solution with Error (bars)	Error Bar (+/- bars)
0.02	0.027	116.914	0.027	0.020	0.0004
-2.08	0.071	116.914	0.071	-2.079	0.0010
-3.94	0.110	116.914	0.110	-3.938	0.0015
-6.32	0.160	116.914	0.160	-6.323	0.0022
-9.19	0.220	116.914	0.220	-9.184	0.0031
-19.68	0.440	116.914	0.440	-19.675	0.0061
-30.18	0.660	116.914	0.660	-30.167	0.0092
-40.67	0.880	116.914	0.880	-40.658	0.0123
-51.16	1.100	116.914	1.100	-51.149	0.0154

Assumes the molality/bar relationship: y(concentration [molarity]) = -0.021(solution [bars])-0.027

8.3.3 HR-33T Uncertainties

Table A7. Uncertainties due to the HR-33T microvoltmeter.

Scale (μvolts)	Uncertainty (+/- μvolts)	Uncertainty (%)
1-10	0.2	2
1-30	0.6	2

Table A8. Effects of the HR-33T instrument on matric pontential measurements assuming the bar/μvolt relationship: y(bars)= -.7891x(μvolts)*.

Scale (μvolts)	Uncertainty (+/- μvolts)	Error Bar (+/- bars)
1-10	0.2	-0.15782
1-30	0.6	-0.47346

* The error bar calculation changes according to the value of the slope in the dew point calibration curves. The slope represented in this table, is the median value of slopes in the dew point calibrations for borehole 49-700.

8.4 Calibration Results

A spreadsheet was created to formulate a calibration curve for each psychrometer. Included on the spreadsheet are psychrometer identification and serial numbers, a π_v value, the microvolt readings from each trial, an average microvolt value and standard deviation for each NaCl dilution, and the plot of "Average (μ volt) vs. Solution (Bars)". In addition some linear regression statistics, which evaluate the integrity of the best fit line are represented on the spreadsheet. For the 54-1002 psychrometers, two calibration curves were completed for each thermocouple psychrometer; one representing the psychrometric calibration data and the other representing the dew point calibration data. For the 49-700 only the dew point calibration was formulated.

When the strap was pulled from borehole 54-1002 and borehole 49-700, it was taken to the lab where a follow up, one step calibration of the working psychrometers was performed. The results of the calibration recheck are presented in tables A9 and A10.

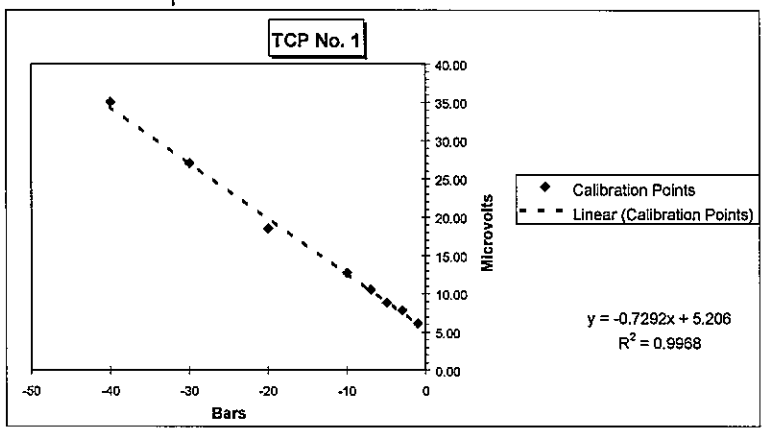
8.3.1 Psychrometer calibration results for borehole 54-1002.

Dew Point Calibration:

TCP Serial No.	36158
TCP ID No.	1
π_v @ 20.0° C	71.5

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	6.3	5.7	6.2	**6.07**	0.32	5.94	0.13	2.22
-3	7.9	7.8	7.6	**7.77**	0.15	7.39	0.37	5.05
-5	8.8	8.5	9.0	**8.77**	0.25	8.85	0.09	0.96
-7	10.5	10.4	10.6	**10.50**	0.10	10.31	0.19	1.84
-10	13.0	12.5	12.5	**12.67**	0.29	12.50	0.17	1.35
-20	18.8	18.2	18.4	**18.47**	0.31	19.79	1.32	6.69
-30	27.0	27.0	27.0	**27.00**	0.00	27.08	0.08	0.30
-40	35.0	35.0	35.0	**35.00**	0.00	34.37	0.63	1.82

Linear Regression Statistics	
No. Observations	8
Standard Error	0.62954361
Equation	y = -0.7292x + 5.206
R^2	0.996820222

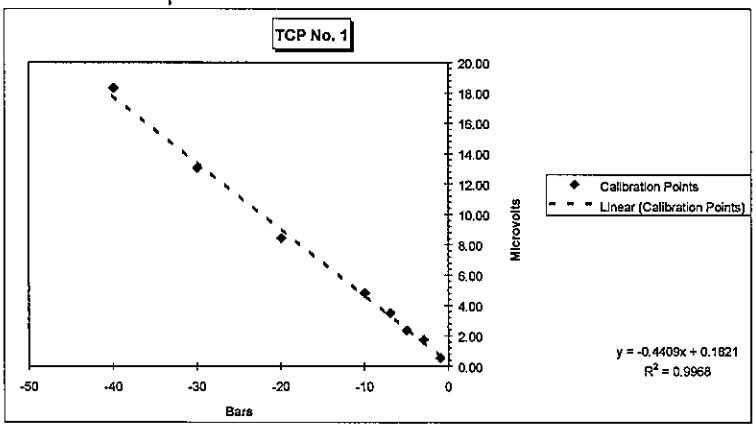


Psychrometric Calibration:

TCP Serial No.	36158
TCP ID No.	1

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.5	0.6	0.6	**0.53**	0.06	0.62	0.10	15.28
-3	1.7	1.7	1.7	**1.72**	0.03	1.50	0.21	14.08
-5	2.3	2.2	2.5	**2.34**	0.11	2.39	0.05	1.94
-7	3.4	3.5	3.6	**3.47**	0.11	3.27	0.21	6.29
-10	5.0	4.7	4.7	**4.80**	0.21	4.59	0.21	4.57
-20	8.7	8.4	8.2	**8.41**	0.25	9.00	0.59	6.52
-30	13.1	13.5	12.5	**13.02**	0.49	13.41	0.39	2.89
-40	18.5	18.5	17.9	**18.30**	0.33	17.82	0.49	2.73

Linear Regression Statistics	
No. Observations	8
Standard Error	0.381596345
Equation	y = -0.4409x + 0.1821
R^2	0.996804136

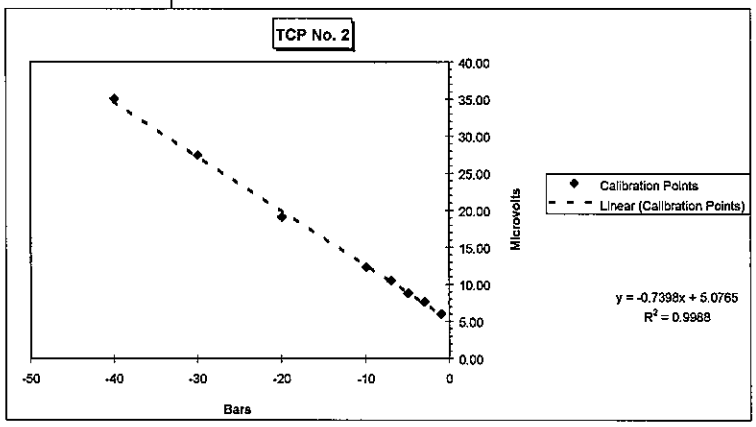


Dew Point Calibration:

TCP Serial No.	35505
TCP ID No.	2
π_v @ 20.0° C	71.5

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	6.5	5.5	5.9	**5.97**	0.50	5.82	0.15	2.59
-3	7.7	7.4	7.6	**7.57**	0.15	7.30	0.27	3.71
-5	8.6	8.7	9.0	**8.77**	0.21	8.78	0.01	0.10
-7	10.5	10.2	10.6	**10.43**	0.21	10.26	0.18	1.74
-10	12.5	12.0	12.3	**12.27**	0.25	12.47	0.21	1.67
-20	19.0	19.2	19.0	**19.07**	0.12	19.87	0.81	4.06
-30	27.1	27.5	27.5	**27.37**	0.23	27.27	0.10	0.35
-40	35.0	35.0	35.0	**35.00**	0.00	34.67	0.33	0.96

Linear Regression Statistics	
No. Observations	8
Standard Error	0.395699344
Equation	y = -0.7398x + 5.0765
R^2	0.998777267

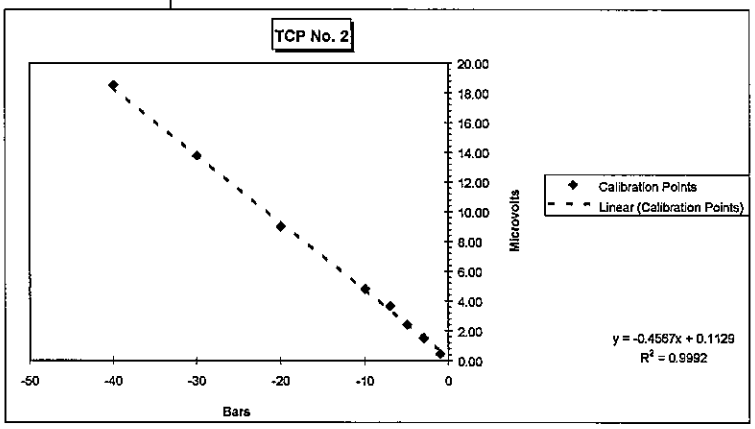


Psychrometric Calibration:

TCP Serial No.	35505
TCP ID No.	2

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.5	0.4	0.3	**0.40**	0.12	0.57	0.17	30.19
-3	1.4	1.4	1.7	**1.49**	0.17	1.48	0.00	0.16
-5	2.4	2.4	2.4	**2.39**	0.04	2.40	0.00	0.18
-7	3.6	3.6	3.7	**3.62**	0.06	3.31	0.31	9.52
-10	5.0	4.6	4.7	**4.76**	0.25	4.68	0.08	1.81
-20	9.1	9.1	8.7	**8.97**	0.23	9.25	0.27	2.96
-30	13.6	13.8	13.8	**13.75**	0.13	13.81	0.07	0.49
-40	18.5	18.5	18.5	**18.50**	0.00	18.38	0.12	0.63

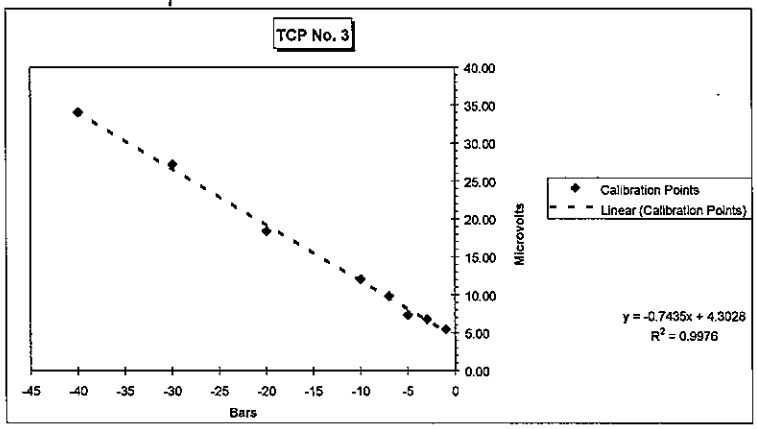
Linear Regression Statistics	
No. Observations	8
Standard Error	0.195387816
Equation	y = -0.4567x + 0.1129
R^2	0.999217321



TCP Serial No.	36166
TCP ID No.	3
π_v @ 20.0° C	75.25

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	5.4	5.2	5.6	**5.40**	0.20	5.05	0.35	7.01
-3	6.9	6.8	6.4	**6.70**	0.26	6.53	0.17	2.55
-5	7.0	7.3	7.6	**7.30**	0.30	8.02	0.72	8.98
-7	9.5	10.0	9.8	**9.77**	0.25	9.51	0.26	2.73
-10	12.0	12.0	12.0	**12.00**	0.00	11.74	0.26	2.23
-20	17.0	19.0	19.0	**18.33**	1.15	19.17	0.84	4.38
-30	27.0	27.5	27.0	**27.17**	0.29	26.61	0.56	2.10
-40	33.5	34.0	34.5	**34.00**	0.50	34.04	0.04	0.13

Linear Regression Statistics	
No. Observations	8
Standard Error	0.551756586
Equation	y = -0.7435x + 4.3028
R^2	0.997648576

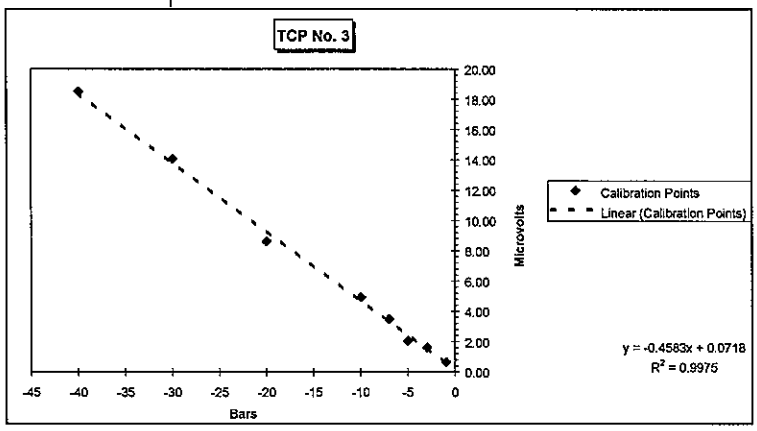


Psychrometric Calibration:

TCP Serial No.	36166
TCP ID No.	3

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.7	0.6	0.6	**0.62**	0.06	0.53	0.09	17.48
-3	1.6	1.6	1.6	**1.59**	0.03	1.45	0.14	9.97
-5	2.0	1.9	2.2	**2.02**	0.14	2.36	0.35	14.70
-7	3.4	3.6	3.5	**3.47**	0.11	3.28	0.19	5.89
-10	4.9	4.9	4.9	**4.91**	0.02	4.65	0.25	5.45
-20	8.1	9.0	8.7	**8.59**	0.45	9.24	0.65	7.03
-30	13.8	14.1	14.1	**14.04**	0.19	13.82	0.22	1.56
-40	18.5	18.5	18.5	**18.50**	0.00	18.40	0.09	0.51

Linear Regression Statistics	
No. Observations	8
Standard Error	0.348470883
Equation	y = -0.4583x + 0.0718
R^2	0.997531602

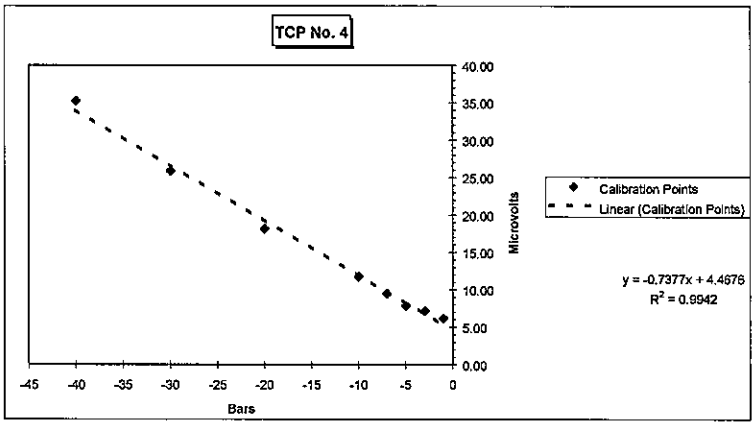


Dew Point Calibration:

TCP Serial No.	36165
TCP ID No.	4
π_V @ 20.0° C	74

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	6.4	6.2	5.8	**6.12**	0.28	5.21	0.91	17.51
-3	7.1	7.0	7.3	**7.13**	0.15	6.68	0.45	6.78
-5	8.0	7.5	8.0	**7.83**	0.29	8.16	0.32	3.96
-7	9.2	9.5	9.6	**9.43**	0.21	9.63	0.20	2.06
-10	12.0	11.5	11.6	**11.70**	0.26	11.84	0.14	1.22
-20	17.8	18.0	18.5	**18.10**	0.36	19.22	1.12	5.84
-30	26.0	25.5	26.0	**25.83**	0.29	26.60	0.77	2.88
-40	34.5	35.0	35.0	**35.17**	0.76	33.98	1.19	3.51

Linear Regression Statistics	
No. Observations	8
Standard Error	0.862368952
Equation	y = -0.7377x + 4.4676
R^2	0.994186106

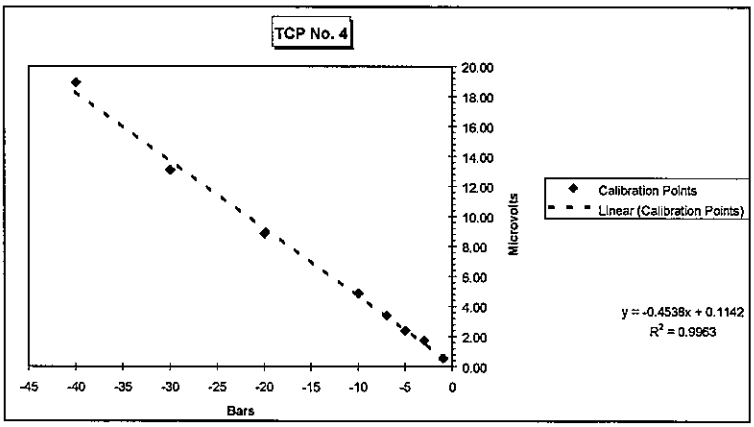


Psychrometer Calibration Data:

TCP Serial No.	36165
TCP ID No.	4

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.5	0.5	0.5	**0.53**	0.01	0.57	0.04	7.43
-3	1.7	1.7	1.7	**1.72**	0.03	1.48	0.24	16.33
-5	2.4	2.2	2.4	**2.35**	0.10	2.38	0.03	1.20
-7	3.3	3.4	3.5	**3.36**	0.11	3.29	0.07	2.13
-10	5.0	4.7	4.8	**4.84**	0.19	4.65	0.19	3.98
-20	8.7	9.0	8.8	**8.82**	0.15	9.19	0.37	4.05
-30	13.6	13.1	12.5	**13.06**	0.54	13.73	0.67	4.88
-40	19.1	19.1	18.5	**18.88**	0.33	18.27	0.62	3.37

Linear Regression Statistics	
No. Observations	8
Standard Error	0.421896475
Equation	y = -0.4538x + 0.1142
R^2	0.996314437

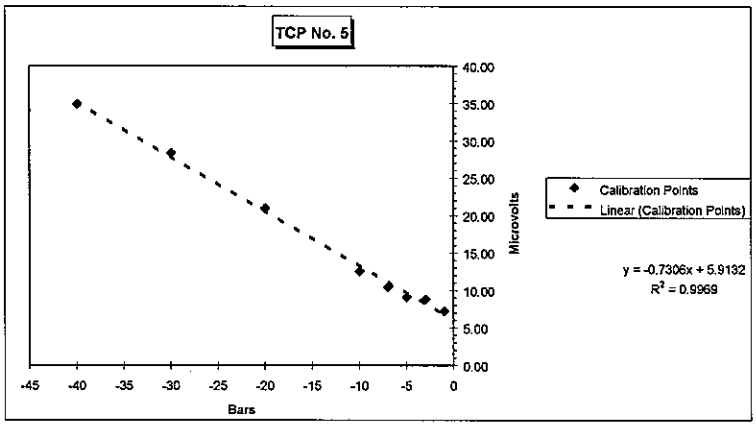


Dew Point Calibration:

TCP Serial No.	36517
TCP ID No.	5
π_v @ 22.5° C	69.5

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	7.0	7.3	7.3	**7.18**	0.16	6.64	0.54	8.12
-3	8.7	8.8	8.8	**8.75**	0.05	8.11	0.65	7.96
-5	9.1	9.0	9.1	**9.07**	0.06	9.57	0.50	5.22
-7	10.1	10.6	10.6	**10.43**	0.29	11.03	0.59	5.39
-10	12.5	12.5	12.6	**12.52**	0.03	13.22	0.70	5.31
-20	20.5	21.0	21.3	**20.93**	0.40	20.53	0.41	1.99
-30	28.0	28.0	29.0	**28.33**	0.58	27.83	0.50	1.80
-40	35.0	34.5	35.0	**34.83**	0.29	35.14	0.30	0.86

Linear Regression Statistics	
No. Observations	8
Standard Error	0.621042511
Equation	y = -0.7306x + 5.9132
R^2	0.996916841

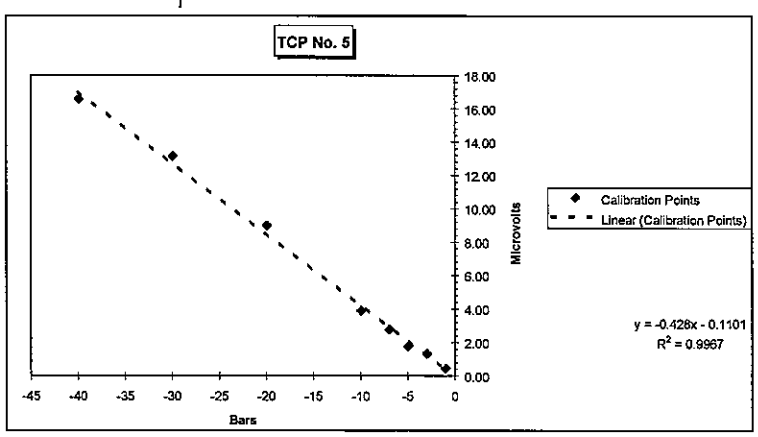


Psychrometric Calibration:

TCP Serial No.	36517
TCP ID No.	5

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.3	0.3	0.6	**0.41**	0.13	0.32	0.10	30.22
-3	1.3	1.3	1.3	**1.30**	0.05	1.17	0.13	10.93
-5	1.8	1.7	1.8	**1.74**	0.07	2.03	0.29	14.33
-7	2.7	2.9	2.8	**2.76**	0.11	2.89	0.12	4.33
-10	3.8	3.9	3.9	**3.88**	0.06	4.17	0.29	6.93
-20	8.9	8.9	9.0	**8.97**	0.05	8.45	0.52	6.20
-30	13.5	12.7	13.3	**13.14**	0.39	12.73	0.41	3.18
-40	16.6	16.6	16.6	**16.57**	0.00	17.01	0.44	2.61

Linear Regression Statistics	
No. Observations	8
Standard Error	0.375467057
Equation	y = -0.428x - 0.1101
R^2	0.996717935

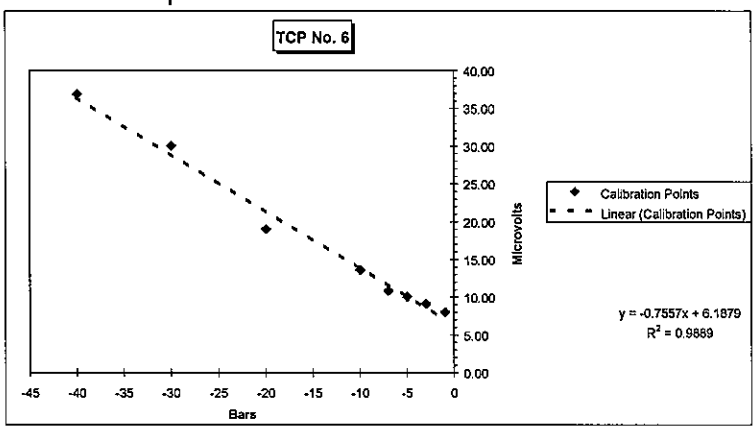


Dew Point Calibration:

TCP Serial No.	36209
TCP ID No.	6
π_v @ 20.0° C	70.5

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	8.0	7.9	8.0	**7.97**	0.06	6.94	1.02	14.73
-3	9.1	9.1	9.0	**9.07**	0.06	8.46	0.61	7.23
-5	10.0	10.0	10.0	**10.00**	0.00	9.97	0.03	0.34
-7	10.6	10.6	11.2	**10.80**	0.35	11.48	0.68	5.91
-10	13.7	13.5	13.5	**13.57**	0.12	13.74	0.18	1.30
-20	18.2	19.0	19.6	**18.93**	0.70	21.30	2.37	11.12
-30	30.0	30.0	30.0	**30.00**	0.00	28.86	1.14	3.95
-40	37.5	37.0	36.0	**36.83**	0.76	36.42	0.42	1.15

Linear Regression Statistics	
No. Observations	8
Standard Error	1.224716103
Equation	y = -0.7557x + 6.1879
R^2	0.988885231

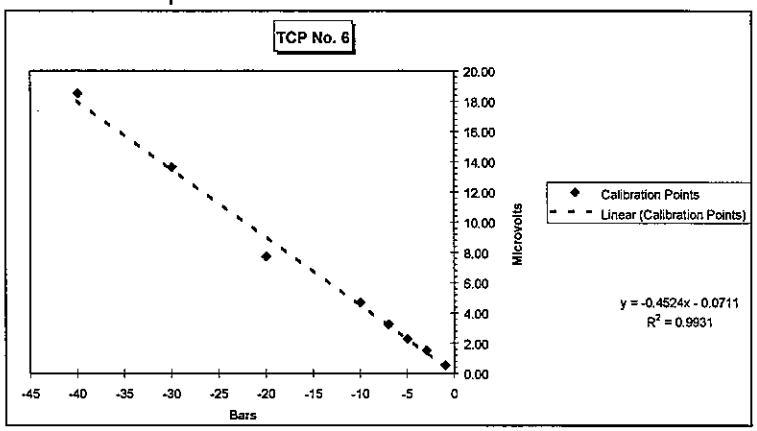


Psychrometric Calibration:

TCP Serial No.	36209
TCP ID No.	6

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.5	0.5	0.5	**0.52**	0.01	0.38	0.14	37.20
-3	1.5	1.6	1.4	**1.49**	0.08	1.29	0.20	15.72
-5	2.3	2.2	2.2	**2.24**	0.07	2.19	0.05	2.40
-7	2.8	3.4	3.5	**3.21**	0.36	3.10	0.12	3.74
-10	4.8	4.7	4.5	**4.65**	0.18	4.45	0.20	4.51
-20	7.2	8.3	7.6	**7.69**	0.57	8.98	1.28	14.30
-30	13.6	13.6	13.6	**13.60**	0.00	13.50	0.10	0.75
-40	18.5	18.5	18.5	**18.50**	0.00	18.02	0.47	2.62

Linear Regression Statistics	
No. Observations	8
Standard Error	0.577014422
Equation	y = -0.4524x - 0.0711
R^2	0.993086922

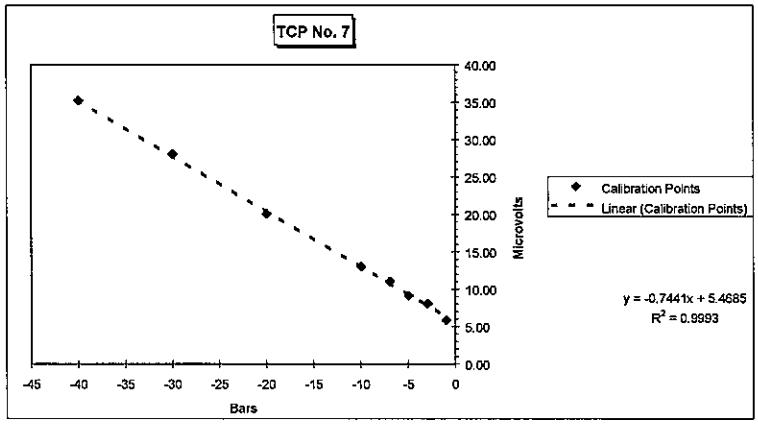


Dew Point Calibration:

TCP Serial No.	35520
TCP ID No.	7
π_v @ 20.5° C	76

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	5.6	5.9	5.9	**5.80**	0.17	6.21	0.41	6.64
-3	8.0	8.1	8.0	**8.03**	0.06	7.70	0.33	4.32
-5	9.0	9.0	9.2	**9.07**	0.12	9.19	0.12	1.33
-7	11.0	11.0	11.0	**11.00**	0.00	10.68	0.32	3.02
-10	13.0	13.0	12.9	**12.97**	0.06	12.91	0.06	0.44
-20	19.6	20.5	20.0	**20.03**	0.45	20.35	0.32	1.56
-30	28.0	28.0	28.0	**28.00**	0.00	27.79	0.21	0.75
-40	35.5	35.0	35.0	**35.17**	0.29	35.23	0.07	0.19

Linear Regression Statistics	
No. Observations	8
Standard Error	0.303218632
Equation	y = -0.7441x + 5.4685
R^2	0.999289912

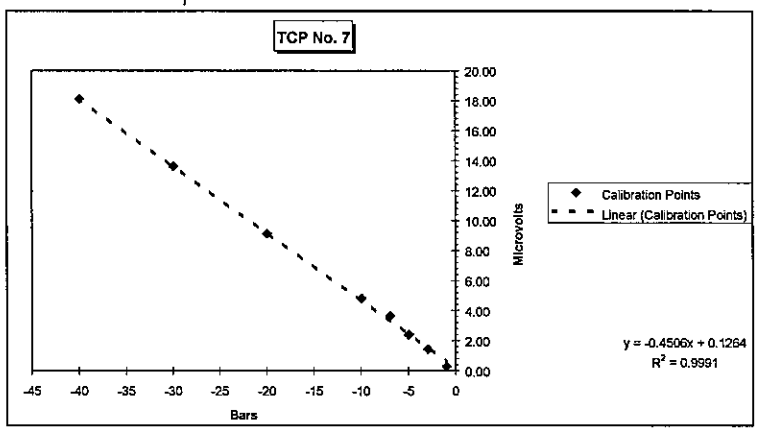


Psychrometric Calibration:

TCP Serial No.	35520
TCP ID No.	7

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.2	0.3	0.3	**0.27**	0.03	0.58	0.31	54.01
-3	1.4	1.5	1.3	**1.41**	0.09	1.48	0.07	4.94
-5	2.3	2.4	2.5	**2.38**	0.08	2.38	0.00	0.08
-7	3.6	3.6	3.7	**3.62**	0.06	3.28	0.34	10.49
-10	4.8	4.9	4.7	**4.79**	0.11	4.63	0.16	3.35
-20	9.0	9.3	9.0	**9.10**	0.18	9.14	0.04	0.40
-30	13.6	13.6	13.6	**13.60**	0.00	13.64	0.04	0.31
-40	18.5	17.9	17.9	**18.11**	0.33	18.15	0.04	0.21

Linear Regression Statistics	
No. Observations	8
Standard Error	0.204012193
Equation	y = -0.4506x + 0.1264
R^2	0.99912332

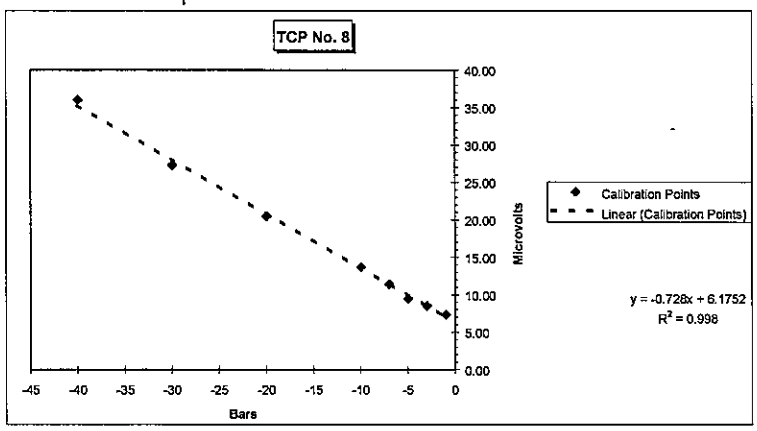


Dew Point Calibration:

TCP Serial No.	36518
TCP ID No.	8
π_v @ 22.0° C	70.25

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	7.3	7.3	7.3	**7.28**	0.03	6.90	0.38	5.51
-3	8.0	8.7	8.7	**8.43**	0.38	8.36	0.07	0.89
-5	9.6	9.2	9.6	**9.47**	0.23	9.82	0.35	3.55
-7	11.5	11.3	11.3	**11.37**	0.12	11.27	0.10	0.85
-10	13.9	13.5	13.5	**13.63**	0.23	13.46	0.18	1.33
-20	20.3	20.6	20.4	**20.43**	0.15	20.74	0.30	1.45
-30	27.0	27.3	27.4	**27.23**	0.21	28.02	0.78	2.79
-40	36.0	36.0	36.0	**36.00**	0.00	35.30	0.71	2.00

Linear Regression Statistics	
No. Observations	8
Standard Error	0.501912997
Equation	y = -0.728x + 6.1752
R^2	0.997969922

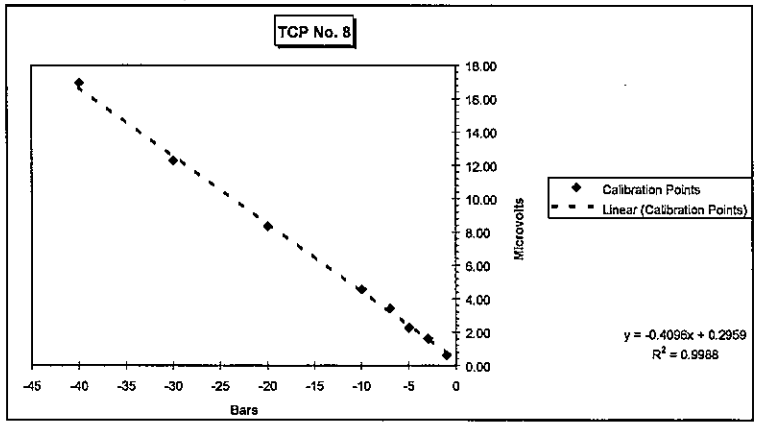


Psychrometric Calibration:

TCP Serial No.	36518
TCP ID No.	8

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.6	0.6	0.6	**0.60**	0.03	0.71	0.11	15.25
-3	1.5	1.6	1.7	**1.59**	0.10	1.52	0.06	4.26
-5	2.2	2.2	2.3	**2.25**	0.06	2.34	0.10	4.20
-7	3.3	3.4	3.4	**3.39**	0.06	3.16	0.22	7.07
-10	4.6	4.6	4.4	**4.54**	0.09	4.39	0.15	3.35
-20	8.3	8.4	8.3	**8.32**	0.07	8.49	0.17	2.03
-30	12.3	12.3	12.1	**12.27**	0.11	12.58	0.31	2.49
-40	16.6	17.1	17.1	**16.93**	0.32	16.68	0.25	1.52

Linear Regression Statistics	
No. Observations	8
Standard Error	0.219617599
Equation	y = -0.4096x + 0.2959
R^2	0.998771037

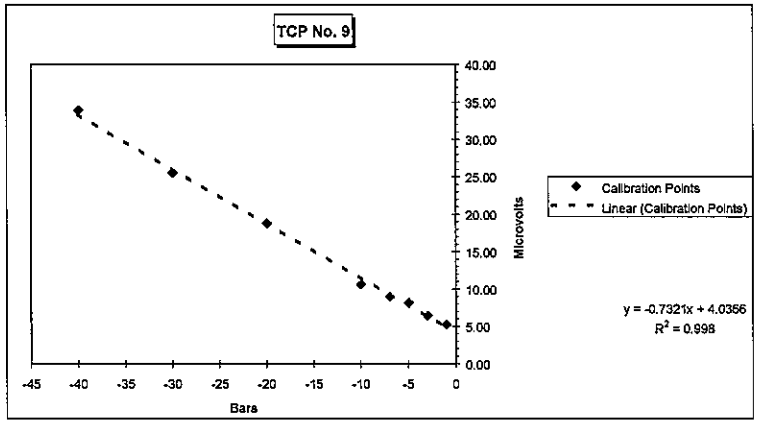


Dew Point Calibration:

TCP Serial No.	36164
TCP ID No.	9
π_v @ 21.5° C	70.25

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	5.1	5.2	5.2	**5.15**	0.05	4.77	0.38	8.00
-3	6.4	6.4	6.5	**6.40**	0.05	6.23	0.17	2.68
-5	8.1	8.0	8.2	**8.10**	0.10	7.70	0.40	5.23
-7	8.9	9.0	8.9	**8.93**	0.06	9.16	0.23	2.49
-10	10.5	10.2	11.0	**10.57**	0.40	11.36	0.79	6.96
-20	18.5	18.8	18.9	**18.73**	0.21	18.68	0.05	0.29
-30	25.0	25.5	26.0	**25.50**	0.50	26.00	0.50	1.92
-40	33.0	33.5	35.0	**33.83**	1.04	33.32	0.51	1.54

Linear Regression Statistics	
No. Observations	8
Standard Error	0.50475674
Equation	y = -0.7321x + 4.0366
R^2	0.997969792

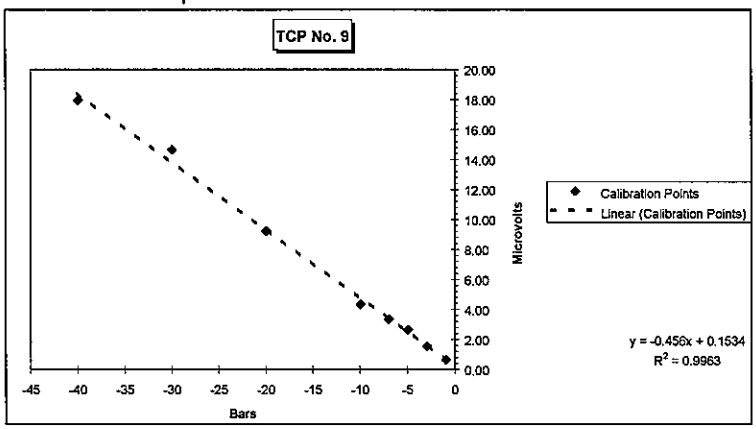


Psychrometric Calibration:

TCP Serial No.	35520
TCP ID No.	9

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.6	0.6	0.6	**0.62**	0.00	0.61	0.01	1.18
-3	1.5	1.5	1.6	**1.53**	0.03	1.52	0.01	0.71
-5	2.6	2.6	2.6	**2.61**	0.02	2.43	0.18	7.41
-7	3.3	3.3	3.3	**3.31**	0.00	3.35	0.03	0.97
-10	4.1	4.4	4.4	**4.30**	0.18	4.71	0.41	8.70
-20	8.9	9.4	9.2	**9.19**	0.23	9.27	0.08	0.86
-30	13.6	15.3	15.0	**14.63**	0.90	13.83	0.80	5.78
-40	17.9	17.3	18.5	**17.92**	0.58	18.39	0.47	2.58

Linear Regression Statistics	
No. Observations	8
Standard Error	0.422706121
Equation	y = -0.456x + 0.1534
R^2	0.996336098

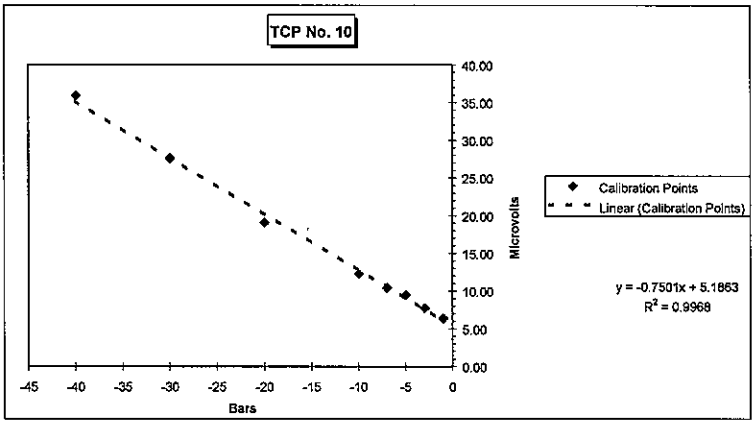


Dew Point Calibration:

TCP Serial No.	36137
TCP ID No.	10
π_v @ 20.5° C	72

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	6.3	6.3	6.3	**6.30**	0.00	5.94	0.36	6.12
-3	7.7	7.6	7.7	**7.67**	0.06	7.44	0.23	3.09
-5	9.5	9.5	9.4	**9.47**	0.06	8.94	0.53	5.93
-7	10.2	10.4	10.5	**10.37**	0.15	10.44	0.07	0.67
-10	12.3	12.0	12.3	**12.20**	0.17	12.69	0.49	3.84
-20	18.1	19.5	19.5	**19.03**	0.81	20.19	1.15	5.72
-30	27.7	27.5	27.5	**27.57**	0.12	27.69	0.12	0.44
-40	36.5	35.7	35.5	**35.90**	0.53	35.19	0.71	2.02

Linear Regression Statistics	
No. Observations	8
Standard Error	0.653320048
Equation	y = -0.7501x + 5.1863
R^2	0.99676385

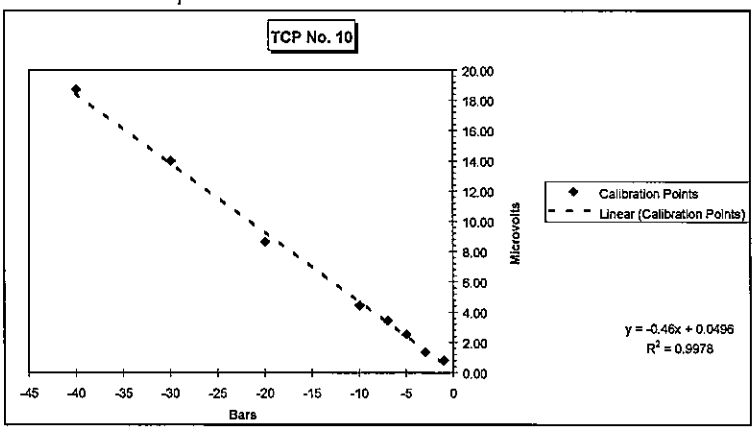


Psychrometer Calibration Data:

TCP Serial No.	36137
TCP ID No.	10

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.8	0.8	0.8	**0.79**	0.01	0.51	0.28	54.78
-3	1.3	1.3	1.5	**1.33**	0.11	1.43	0.10	6.72
-5	2.5	2.5	2.5	**2.50**	0.04	2.35	0.15	6.58
-7	3.3	3.5	3.6	**3.44**	0.17	3.27	0.17	5.11
-10	4.5	4.4	4.5	**4.43**	0.06	4.65	0.22	4.83
-20	8.2	9.0	8.7	**8.62**	0.40	9.25	0.63	6.82
-30	13.6	14.1	14.1	**13.96**	0.31	13.85	0.11	0.83
-40	19.1	18.5	18.5	**18.69**	0.33	18.45	0.24	1.30

Linear Regression Statistics	
No. Observations	8
Standard Error	0.33107696
Equation	y = -0.46x + 0.0496
R^2	0.997788428

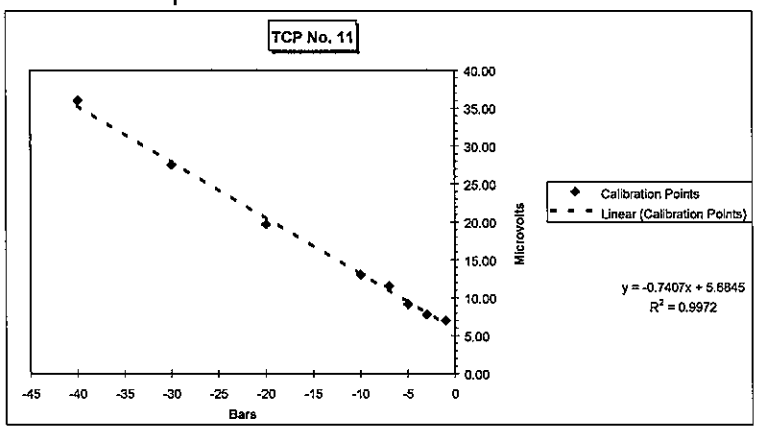


Dew Point Calibration:

TCP Serial No.	36213
TCP ID No.	11
π_v @ 20.5° C	76

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	6.9	6.9	7.1	**6.93**	0.14	6.43	0.51	7.91
-3	7.8	7.7	7.7	**7.73**	0.06	7.91	0.17	2.19
-5	9.5	8.8	9.0	**9.10**	0.36	9.39	0.29	3.07
-7	11.5	11.5	11.5	**11.50**	0.00	10.87	0.63	5.80
-10	13.0	13.0	13.0	**13.00**	0.00	13.09	0.09	0.70
-20	19.5	20.0	19.4	**19.63**	0.32	20.50	0.87	4.22
-30	27.0	27.0	28.5	**27.50**	0.87	27.91	0.41	1.45
-40	36.5	35.5	36.0	**36.00**	0.50	35.31	0.69	1.95

Linear Regression Statistics	
No. Observations	8
Standard Error	0.600387549
Equation	y = -0.7407x + 5.6845
R^2	0.997196308



Psychrometric Calibration:

TCP Serial No.	36213
TCP ID No.	11

Solution(bars)	Solution(μ volts) Trial 1	Trial 2	Trial 3	Average (μ volts)	Stan. Deviation. (+/-)	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-1	0.3	0.3	0.6	**0.41**	0.13	0.33	0.08	24.94
-3	1.0	1.0	1.1	**1.07**	0.05	1.23	0.16	13.04
-5	2.3	2.4	2.3	**2.32**	0.03	2.13	0.19	9.00
-7	3.5	3.5	3.6	**3.51**	0.06	3.02	0.49	16.11
-10	4.4	4.4	4.5	**4.39**	0.06	4.37	0.02	0.39
-20	8.1	8.9	7.3	**8.07**	0.78	8.86	0.79	8.92
-30	12.0	13.1	13.6	**12.88**	0.83	13.36	0.48	3.59
-40	18.5	18.5	18.5	**18.50**	0.00	17.85	0.65	3.64

Linear Regression Statistics	
No. Observations	8
Standard Error	0.513761886
Equation	y = -0.4492x - 0.1202
R^2	0.99443226

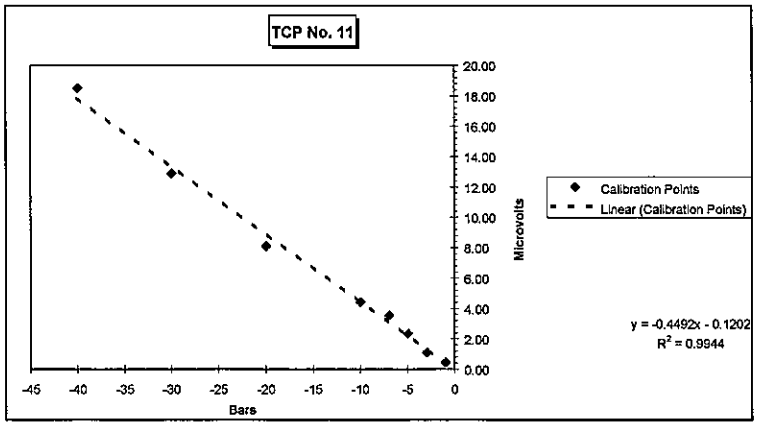


Table A9. Recalibration results of the remaining 54-1002 psychrometers.

TCP ID No.	Actual Matric Potential (bars)	Measured Matric Potential (bars)
1	-7	-9.3
3	-7	-7.0
5	-7	-7.6
6	-7	-6.4
8	-7	-7.3
9	-7	-7.8

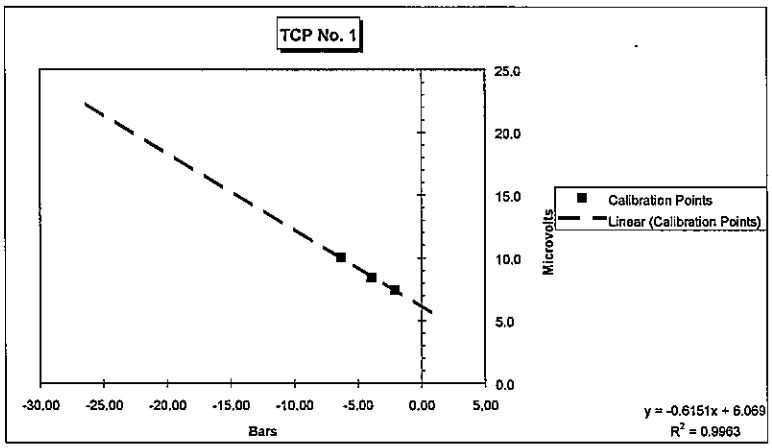
8.3.2 Psychrometer calibrations for borehole 49-700.

Dew Point Calibration:

TCP Serial No.	37060
TCP ID No.	1
π_v @ 20.0° C	71.8

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.08	7.4	7.35	0.05	0.71
-3.94	8.4	8.49	0.09	1.09
-6.32	10.0	9.96	0.04	0.41

Linear Regression Statistics	
No. Observations	3
Standard Error	0.113470548
Equation	y = -0.6151x + 6.069
R^2	0.996257103

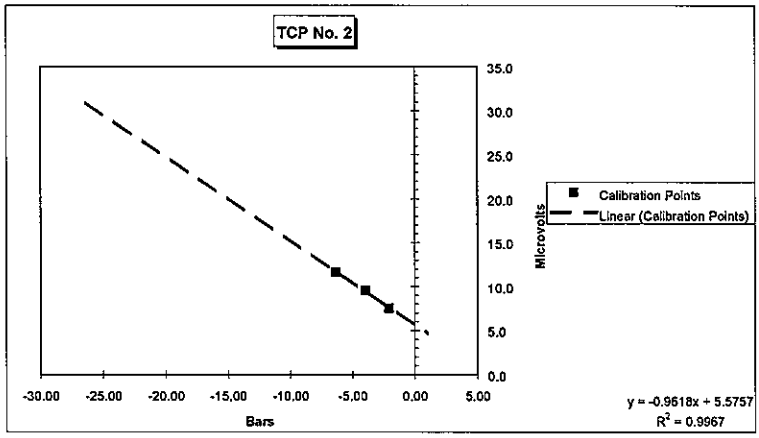


Dew Point Calibration:

TCP Serial No.	37062
TCP ID No.	2
π_v @ 20.0° C	71

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.08	7.5	7.58	0.08	1.00
-3.94	9.5	9.37	0.13	1.44
-6.32	11.6	11.66	0.06	0.51

Linear Regression Statistics	
No. Observations	3
Standard Error	0.165630396
Equation	y = -0.9618x + 5.5757
R^2	0.996736706

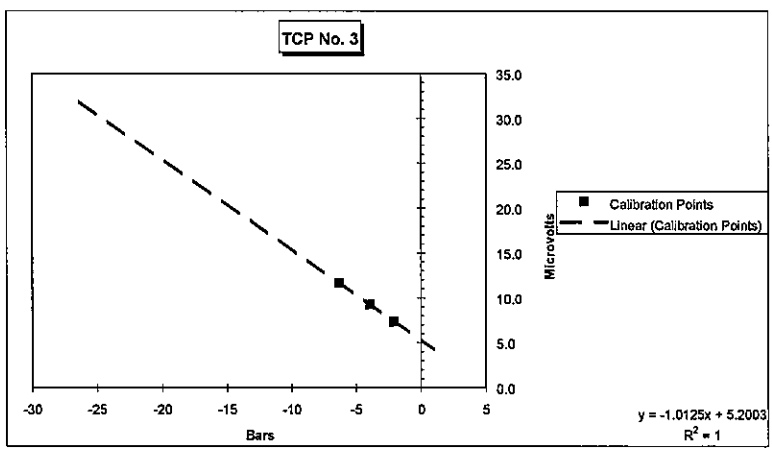


Dew Point Calibration:

TCP Serial No.	37097
TCP ID No.	3
π_v @ 20.0° C	71.5

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	7.3	7.31	0.01	0.08
-3.939864211	9.2	9.19	0.01	0.12
-6.324957198	11.6	11.60	0.00	0.04

Linear Regression Statistics	
No. Observations	3
Standard Error	0.012811191
Equation	y = -1.0125x + 5.2003
R^2	0.999982327

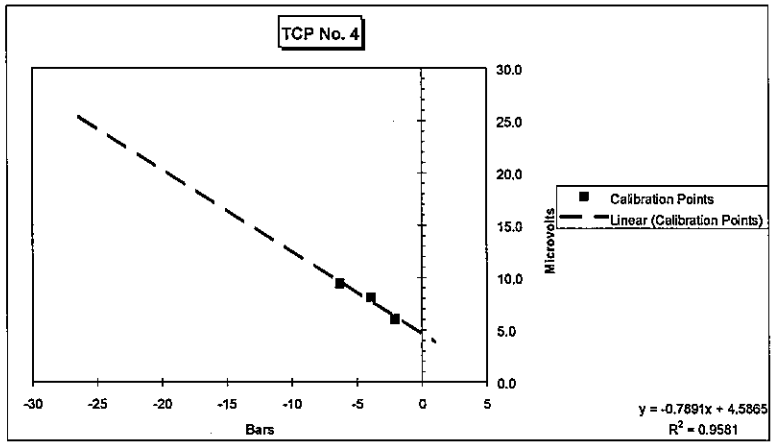


Dew Point Calibration:

TCP Serial No.	37064
TCP ID No.	4
π_v @ 20.0° C	74.3

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	6.0	6.23	0.23	3.65
-3.939864211	8.1	7.70	0.40	5.26
-6.324957198	9.4	9.58	0.18	1.85

Linear Regression Statistics	
No. Observations	3
Standard Error	0.496891189
Equation	y = -0.7891x + 4.5865
R^2	0.958057613

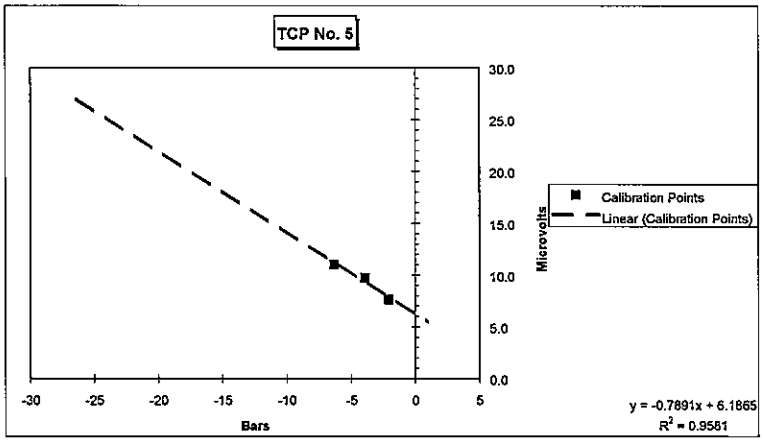


Dew Point Calibration:

TCP Serial No.	37068
TCP ID No.	5
π_v @ 20.0° C	71.8

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	7.6	7.83	0.23	2.91
-3.939864211	9.7	9.30	0.40	4.35
-6.324957198	11.0	11.18	0.18	1.59

Linear Regression Statistics	
No. Observations	3
Standard Error	0.496891189
Equation	y = -0.7891x + 6.1865
R^2	0.958057613

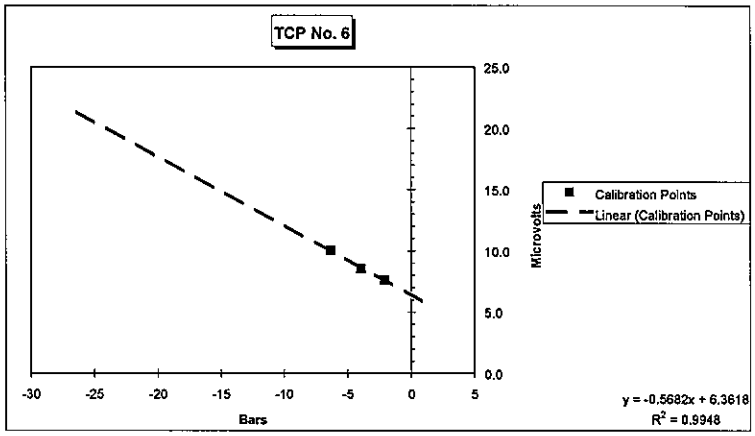


Dew Point Calibration:

TCP Serial No.	37098
TCP ID No.	6
π_v @ 20.0° C	84.4

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	7.6	7.54	0.06	0.75
-3.939864211	8.5	8.60	0.10	1.17
-6.324957198	10.0	9.96	0.04	0.45

Linear Regression Statistics	
No. Observations	3
Standard Error	0.123536484
Equation	y = -0.5682x + 6.3618
R^2	0.994809094

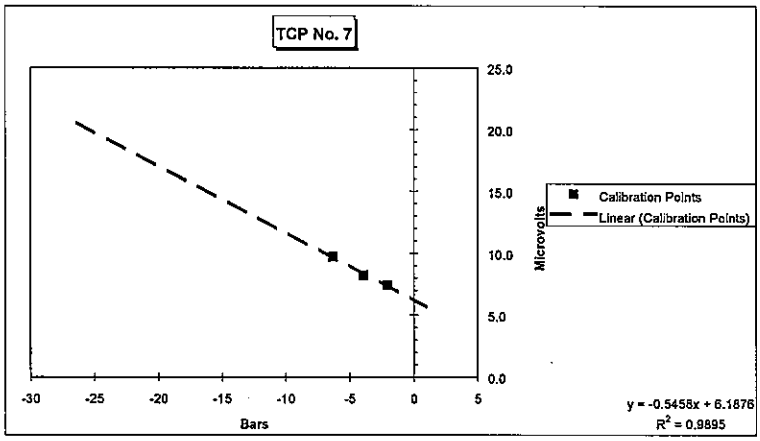


Dew Point Calibration:

TCP Serial No.	37074
TCP ID No.	7
π_v @ 20.0° C	76.8

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	7.4	7.32	0.08	1.06
-3.939864211	8.2	8.34	0.14	1.65
-6.324957198	9.7	9.64	0.06	0.62

Linear Regression Statistics	
No. Observations	3
Standard Error	0.169290737
Equation	y = -0.5458x + 6.1876
R^2	0.989489235

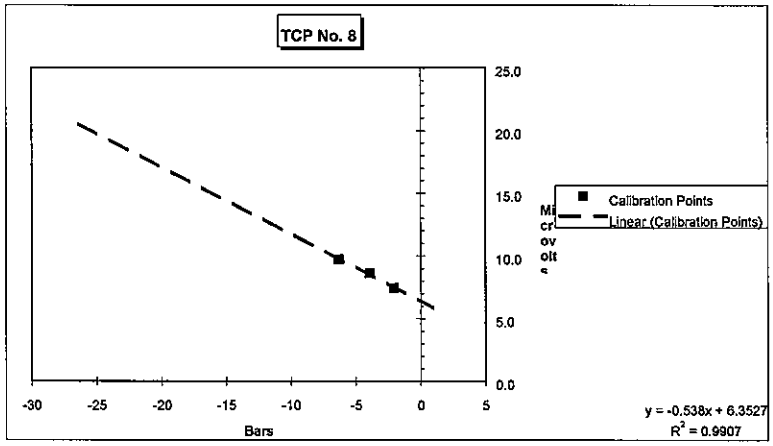


Dew Point Calibration:

TCP Serial No.	37078
TCP ID No.	8
π_v @ 20.0° C	72.3

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	7.4	7.47	0.07	0.96
-3.939864211	8.6	8.47	0.13	1.51
-6.324957198	9.7	9.76	0.06	0.57

Linear Regression Statistics	
No. Observations	3
Standard Error	0.156479546
Equation	y = -0.538x + 6.3527
R^2	0.99074842

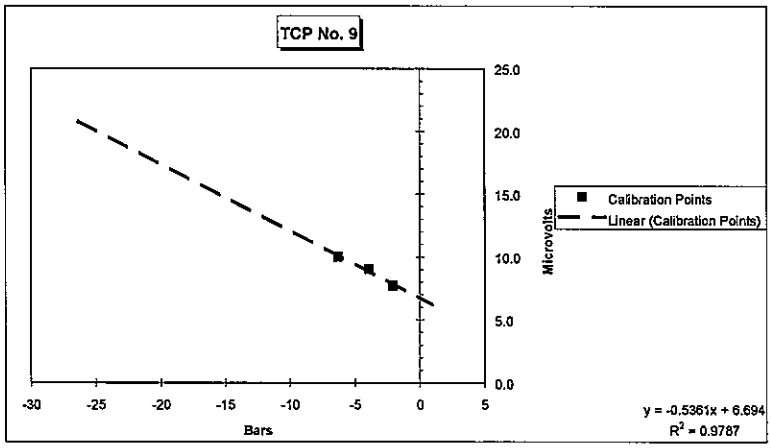


Dew Point Calibration:

TCP Serial No.	37091
TCP ID No.	9
π_v @ 20.0° C	72.3

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	7.7	7.81	0.11	1.39
-3.939864211	9.0	8.81	0.19	2.20
-6.324957198	10.0	10.08	0.08	0.84

Linear Regression Statistics	
No. Observations	3
Standard Error	0.237922116
Equation	-0.5361x + 6.694
R^2	0.978719198

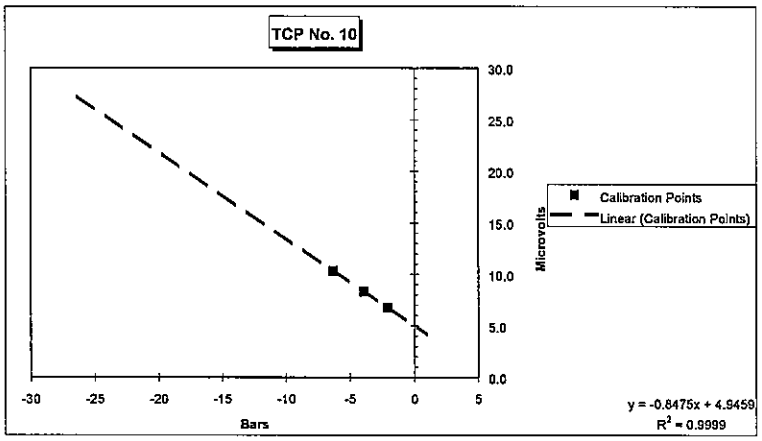


Dew Point Calibration:

TCP Serial No.	37094
TCP ID No.	10
π_v @ 20.0° C	74.6

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	6.7	6.71	0.01	0.12
-3.939864211	8.3	8.28	0.02	0.18
-6.324957198	10.3	10.31	0.01	0.06

Linear Regression Statistics	
No. Observations	3
Standard Error	0.018301701
Equation	y = -0.8475x + 4.9459
R^2	0.999948522



Dew Point Calibration:

TCP Serial No.	37096
TCP ID No.	11
π_v @ 20.0° C	74.5

Solution(bars)	Solution (μ volts) *Trial 1*	Estimated (μ volts) from Linear Fit	Fit Error (+/-)	Fit Error (%)
-2.079491681	7.8	7.72	0.08	1.02
-3.939864211	9.7	9.77	0.07	0.71
-6.324957198	12.5	12.40	0.10	0.84

Linear Regression Statistics	
No. Observations	3
Standard Error	0.129942079
Equation	y = -1.1101x + 5.432
R^2	0.998489719

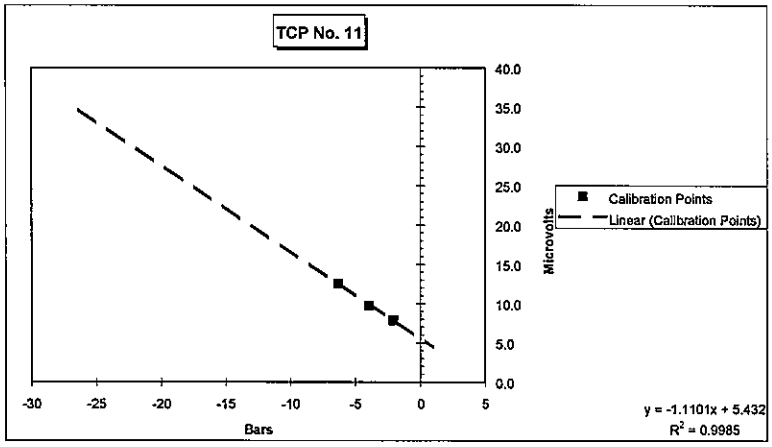


Table A10. Recalibration results of the 49-700 pyschrometers.

9. APPENDIX B: GYPSUM BLOCK CALIBRATION

9.1 Introduction

Calibration curves relating matric potential to measured resistance are used to determine the matric potential from the measured resistance. A five-point gypsum block calibration was performed by Daniel B. Stephens on each of the 15 gypsum block. The results of these calibrations and analysis of the integrity of each curve follow. See tables B1 and B2 for the calibration data and corresponding calibration equation.

Regression statistics were performed on all the calibration data received from Daniel B. Stephens to determine the integrity of the produced curves. Two statistical methods were used to determine the usefulness of the calibration curves: the f test and the coefficient of determination (r^2). An F-test returns the one-tailed probability that the variances of the actual x and y values are not significantly different from the x and calibration predicted y values. The coefficient of determination measures the contribution of x in predicting y. If the integrity of the calibration curves is good both the r^2 test and the f-test value should produce a number near 1.

9.2 Calibration Results

Table B1. Daniel B. Stephen's gypsum block calibration data.

Probe Number	Matric Potential (-bars)	Resistance (kohms)
1	0.00	0.2770
	1.00	1.0420
	2.92	4.7350
	6.00	8.8920
	8.75	13.8010
2	0.00	0.2560
	1.00	1.1300
	2.92	4.9550
	6.00	10.1300
	8.75	16.8230
3	0.00	0.2740
	1.00	0.7620
	2.92	1.5080
	6.00	2.5690
	8.75	4.7290
4	0.00	0.2700
	1.00	1.2230
	2.92	3.0520
	6.00	5.2010
	8.75	8.9330
5	0.00	0.2710
	1.00	0.9780
	2.92	1.9180
	6.00	3.3210
	8.75	6.4030
6	0.00	0.2650
	1.00	0.9090
	2.92	1.9710
	6.00	3.0180
	8.75	5.0970
7	0.00	0.2640
	1.00	1.0560
	2.92	4.8990
	6.00	8.2670
	8.75	12.6240
8	0.00	0.2620
	1.00	0.8350
	2.92	1.7890
	6.00	2.8160
	8.75	4.7790

Table B1. Daniel B. Stephen's gypsum block calibration data (continued).

Probe Number	Matric Potential (-bars)	Resistance (kohms)
9	0.00	0.2630
	1.00	1.0460
	2.92	3.4690
	6.00	5.8010
	8.75	9.4360
10	0.00	0.2790
	1.00	1.2370
	2.92	8.9090
	6.00	18.6310
	8.75	29.4080
11	0.00	0.2720
	1.00	1.0930
	2.92	6.8310
	6.00	14.0010
	8.75	25.8180
12	0.00	0.2550
	1.00	0.5640
	2.92	1.5830
	6.00	2.9580
	8.75	5.7920
13	0.00	0.2610
	1.00	0.3420
	2.92	0.7290
	6.00	1.2190
	8.75	2.1950
14	0.00	0.2630
	1.00	1.2880
	2.92	7.8860
	6.00	17.3050
	8.75	28.8000
15	0.00	0.2600
	1.00	1.3580
	2.92	9.0560
	6.00	20.2370
	8.75	31.0720

Table B2. Daniel B.Stephen's summary of gypsum block calibrations.
Fitted Parameters $Y = A + Bx^c$
Y = Matric Potential (-bars)
X = Resistance (kohms)

Probe Number	A	B	C	R^2
1	-0.0722	0.7605	0.9359	0.9959
2	-0.2386	0.9507	0.7982	0.9971
3	-1.9347	3.9417	0.6541	0.9862
4	-0.6801	1.5643	0.8290	0.9905
5	-1.6143	3.1423	0.6548	0.9817
6	-0.9293	2.3607	0.8795	0.9845
7	0.0186	0.6244	1.0440	0.9927
8	-1.0655	2.6865	0.8413	0.9864
9	-0.3458	1.1818	0.9154	0.9923
10	0.1100	0.4353	0.8844	0.9953
11	-0.2406	0.9151	0.7060	0.9930
12	-2.0951	4.2293	0.5432	0.9920
13	-6.1735	10.8572	0.4132	0.9924
14	-0.0530	0.6301	0.7858	0.9966
15	0.1133	0.4206	0.8784	0.9965

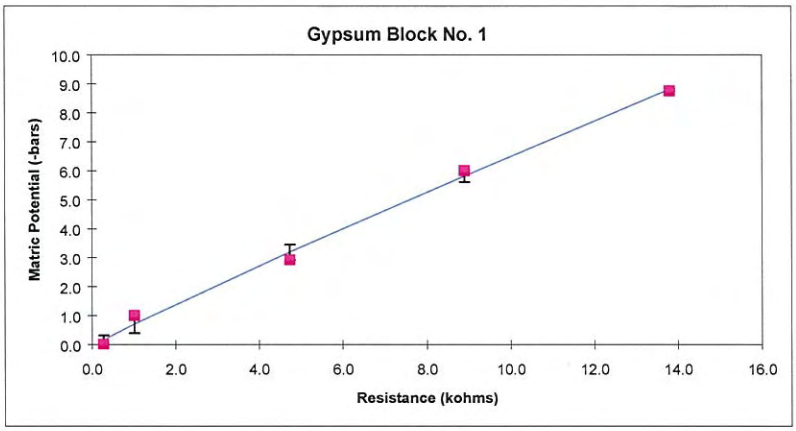
Block No. 1:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2770	0.00	0.1565	0.1565	200.0000
1.0140	1.00	0.6983	0.3017	35.5352
4.7350	2.92	3.1872	0.2672	8.7488
8.8920	6.00	5.8063	0.1937	3.2810
13.8010	8.75	8.7982	0.0482	0.5490

Usefulness of Model Checks:

R^2	0.9959
Ftest	0.9995



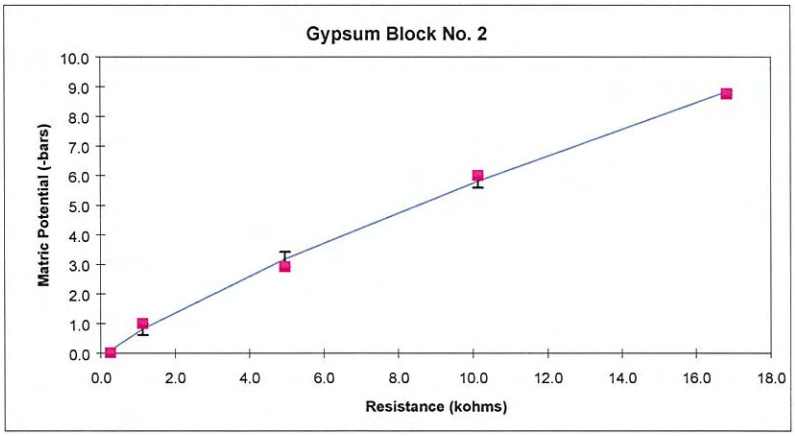
Block No. 2:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2560	0.00	0.0818	0.0818	200.0000
1.1300	1.00	0.8095	0.1905	21.0532
4.9550	2.92	3.1720	0.2520	8.2723
10.1300	6.00	5.7970	0.2030	3.4414
16.8230	8.75	8.8095	0.0595	0.6782

Usefulness of Model Checks:

R^2	0.9971
Ftest	0.9993



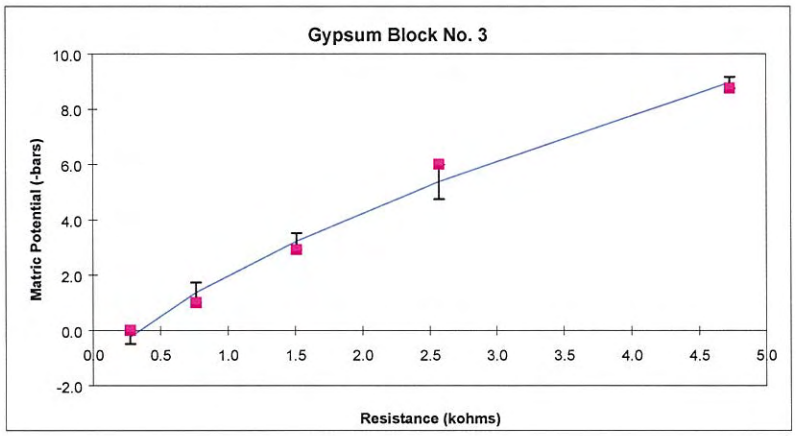
Block No. 3:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2740	0.00	-0.2446	0.2446	200.0000
0.7620	1.00	1.3650	0.3650	30.8646
1.5080	2.92	3.2220	0.3020	9.8354
2.5690	6.00	5.3718	0.6282	11.0481
4.7290	8.75	8.9559	0.2059	2.3253

Usefulness of Model Checks:

R^2	0.9862
Ftest	0.9884



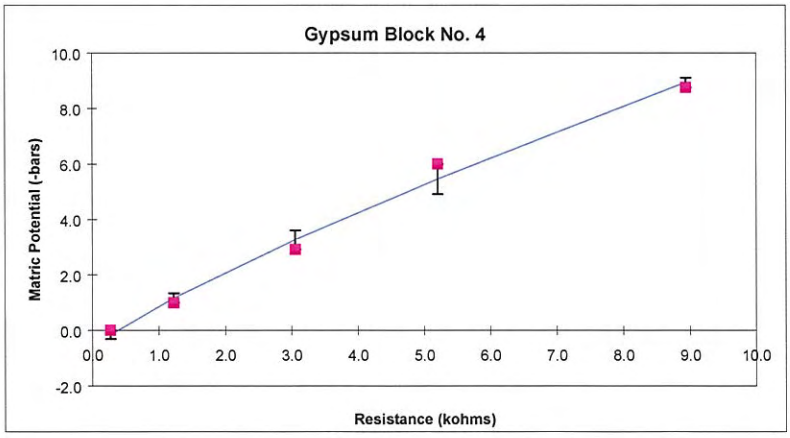
Block No. 4:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2700	0.00	-0.1518	0.1518	200.0000
1.2230	1.00	1.1683	0.1683	15.5239
3.0520	2.92	3.2648	0.3448	11.1512
5.2010	6.00	5.4569	0.5431	9.4808
8.9330	8.75	8.9293	0.1793	2.0285

Usefulness of Model Checks:

R^2	0.9905
Ftest	0.9940



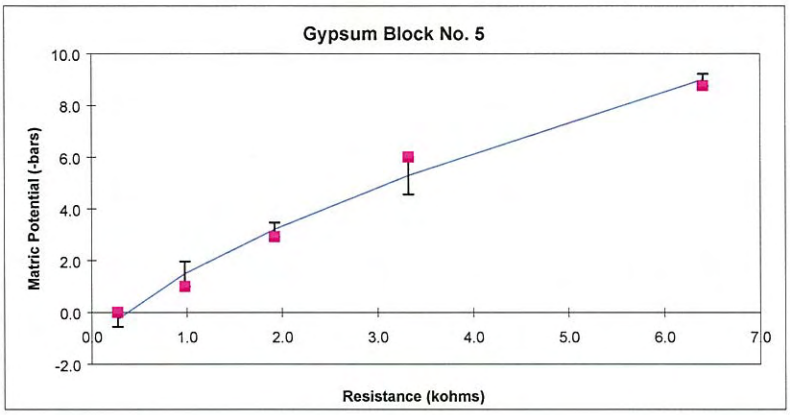
Block No.5:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2710	0.00	-0.2778	0.2778	200.0000
0.9780	1.00	1.4826	0.4826	38.8760
1.9180	2.92	3.1992	0.2792	9.1240
3.3210	6.00	5.2813	0.7187	12.7407
6.4030	8.75	8.9848	0.2348	2.6475

Usefulness of Model Checks:

R^2	0.9817
Ftest	0.9858



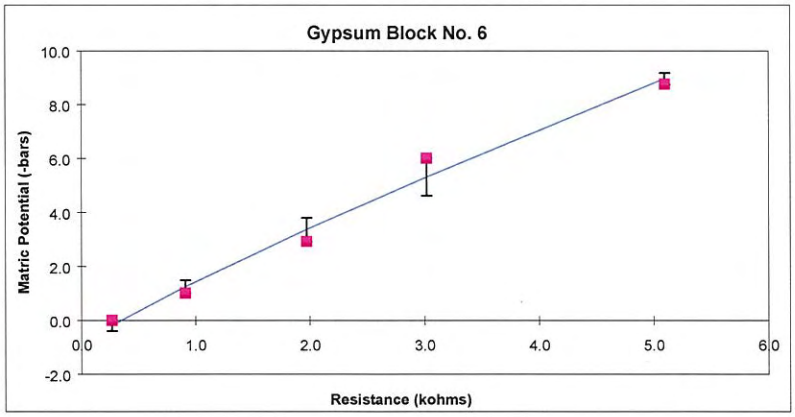
Block No. 6:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2650	0.00	-0.1951	0.1951	200.0000
0.9090	1.00	1.2414	0.2414	21.5393
1.9710	2.92	3.3583	0.4383	13.9634
3.0180	6.00	5.3074	0.6926	12.2507
5.0970	8.75	8.9591	0.2091	2.3610

Usefulness of Model Checks:

R^2	0.9845
Ftest	0.9870



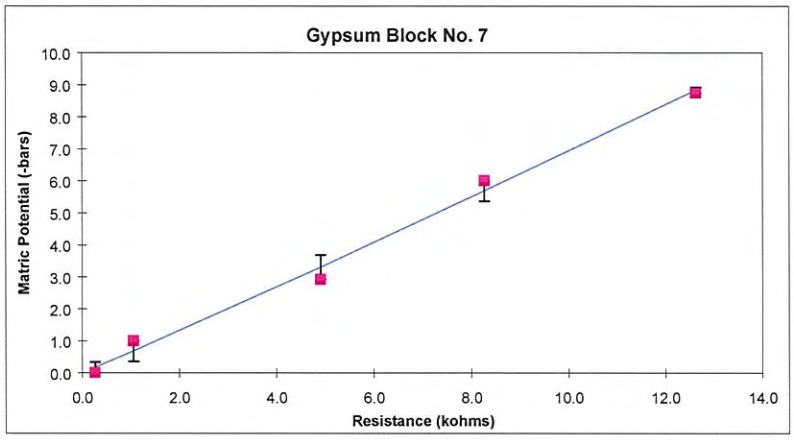
Block No.7:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2640	0.00	0.1741	0.1741	200.0000
1.0560	1.00	0.6795	0.3205	38.1592
4.8990	2.92	3.2991	0.3791	12.1903
8.2670	6.00	5.6833	0.3167	5.4220
12.6240	8.75	8.8314	0.0814	0.9257

Usefulness of Model Checks:

R^2	0.9927
Ftest	0.9972



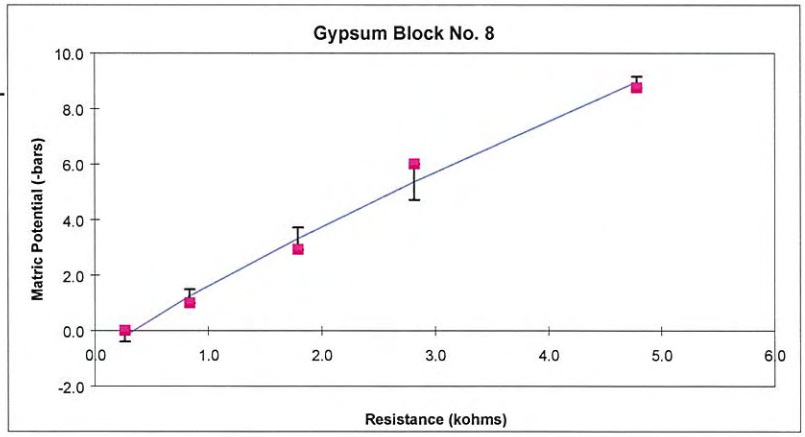
Block No. 8:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2620	0.00	-0.1949	0.1949	200.0000
0.8350	1.00	1.2429	0.2429	21.6555
1.7890	2.92	3.3169	0.3969	12.7262
2.8160	6.00	5.3534	0.6466	11.3898
4.7790	8.75	8.9509	0.2009	2.2703

Usefulness of Model Checks:

R^2	0.9864
Ftest	0.9883



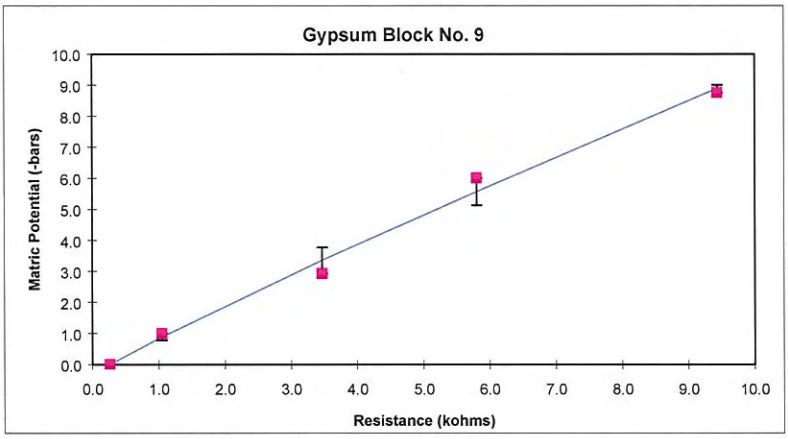
Block No. 9:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2630	0.00	0.0022	0.0022	200.0000
1.0460	1.00	0.8857	0.1143	12.1264
3.4690	2.92	3.3444	0.4244	13.5488
5.8010	6.00	5.5624	0.4376	7.5695
9.4360	8.75	8.8770	0.1270	1.4415

Usefulness of Model Checks:

R^2	0.9923
Ftest	0.9958



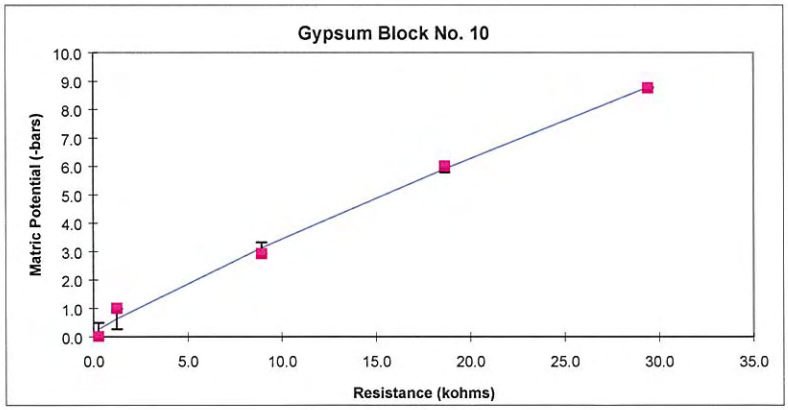
Block No. 10:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2790	0.00	0.2508	0.2508	200.0000
1.2370	1.00	0.6354	0.3646	44.5902
8.9090	2.92	3.1217	0.2017	6.6782
18.6310	6.00	5.8934	0.1066	1.7921
29.4080	8.75	8.7696	0.0196	0.2241

Usefulness of Model Checks:

R^2	0.9953
Ftest	0.9965



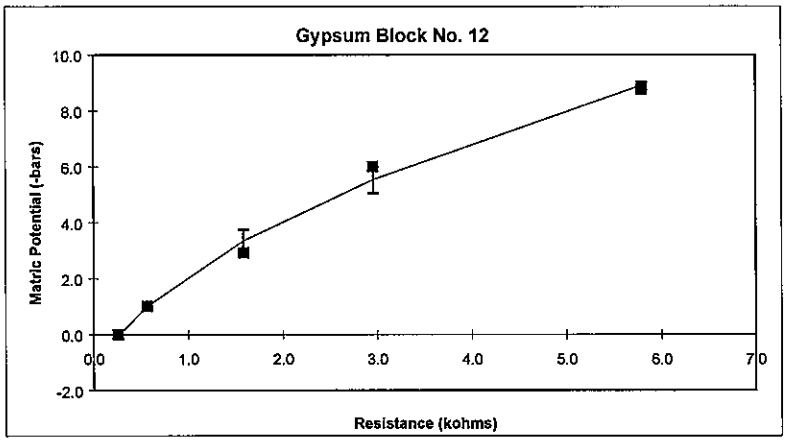
Block No. 12:

Power Fit:

Resistance (kohms)	Matric Potential (-bars)	Estimated Matric Potential from fit (-bars)	Fit Error (+/-)	Percent Difference (%)
0.2550	0.00	-0.0818	0.0818	200.0000
0.5640	1.00	1.0035	0.0035	0.3478
1.5830	2.92	3.3327	0.4127	13.2017
2.9580	6.00	5.5277	0.4723	8.1941
5.7920	8.75	8.8858	0.1358	1.5398

Usefulness of Model Checks:

R^2	0.9930
Ftest	0.9934



10. APPENDIX C: PRT CALIABRATION

10.1 Introduction

Each PRT has a specific calibration curve which relates its measured resistance to a temperature in Celcius. The equation is found by measuring the resistance output of the PRT, while it is submersed in several different water baths of known temperature. The following write up outlines the procedure and results of the PRT calibrations.

10.2. Procedure

10.2.1 Materials Needed

1. Glass container
2. Electric stirrer
3. Precise thermometer
4. Clamp stand
5. Water
6. PRT sensors
7. Campbell Scientific datalogger

10.2.2 Test Setup.

1. Fill glass container with water
2. Set container on stirrer platform, insert the magnet, and plug stirrer into outlet
3. Set the clamp stand over the glass container
4. Clamp thermometer so that it is submersed in the water

10.2.3 Calibration Method.

1. Submerse a PRT sensor in the water bath
2. Connect the PRT sensor to the Campbell Scientific datalogger
3. Measure and record the temperature on a data sheet
4. Record the resistance displayed in the datalogger window, when the number has stabilized (takes approximately 1-2 minutes)
5. Check the temperature of the water again to assure that it has not changed
6. Repeat steps 1-5 for the remainder of the PRT sensors
7. Obtain a second water bath with a different temperature
8. Repeat steps 1-6
9. Plot the temperatures versus the measured resistance to determine the slope and y-intercept
10. Check the calibration by repeating steps 1-6 again with a new water bath

10.3. Calibration Results

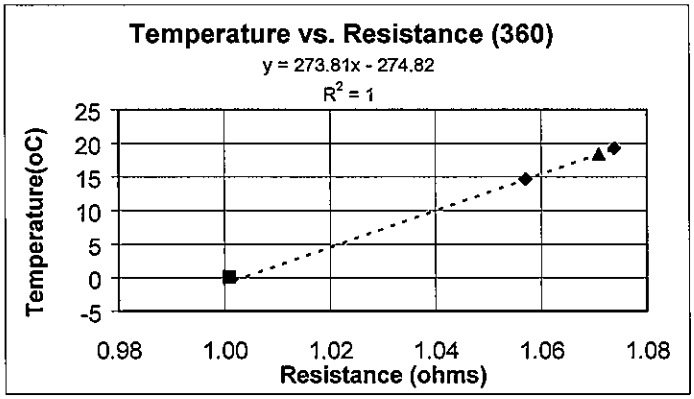
A spreadsheet was created to formulate a calibration curve for each PRT. Each calibration curve had a high level of integrity and was reproducible during the calibration check. See table C1 and C2 for results.

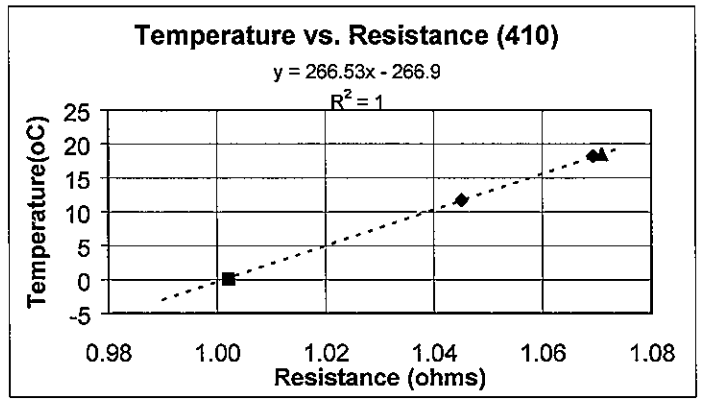
Table C1. PRT calibration data.

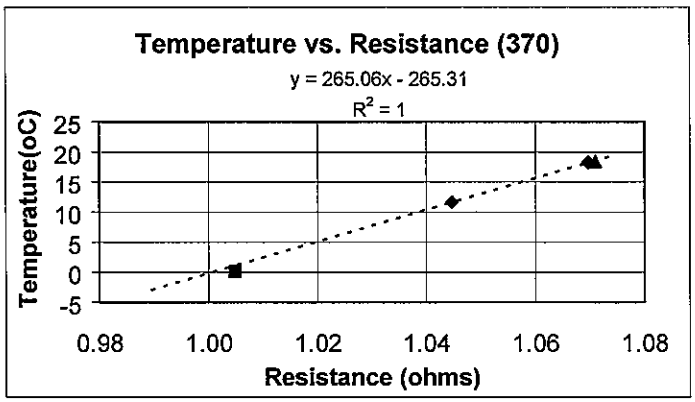
TCP Number	Measured Resistance (kohms)	Thermometer Reading (°C)
360	1.0009	0.1
360	1.0570	14.6
360	1.0738	19.2
360	1.0709	18.4
370	1.0049	0.1
370	1.0447	11.6
370	1.0696	18.2
370	1.071	18.4
380	1.003	0.1
380	1.0463	12
380	1.0704	18.4
380	1.0705	18.4
390	1.0047	0.1
390	1.0468	12
390	1.0714	18.4
390	1.0713	18.4
400	1.0008	0.05
400	1.0576	14.7
400	1.0741	19.2
400	1.071	18.4
410	1.0021	0.05
410	1.0451	11.65
410	1.0693	18.1
410	1.0709	18.4
420	1.0035	0.05
420	1.0447	11.7
420	1.0692	18
420	1.0692	18
430	1.0029	0.1
430	1.057	14.5
430	1.0745	19.2
430	1.0717	18.5
440	1.0031	0.1
440	1.0573	14.55
440	1.0745	19.3
440	1.0716	18.55
450	1.0041	0.05
450	1.0564	14.5
450	1.0745	19.2
450	1.0719	18.5
460	1.0053	0.05
460	1.0566	14.6
460	1.075	19.3
460	1.071	18.4

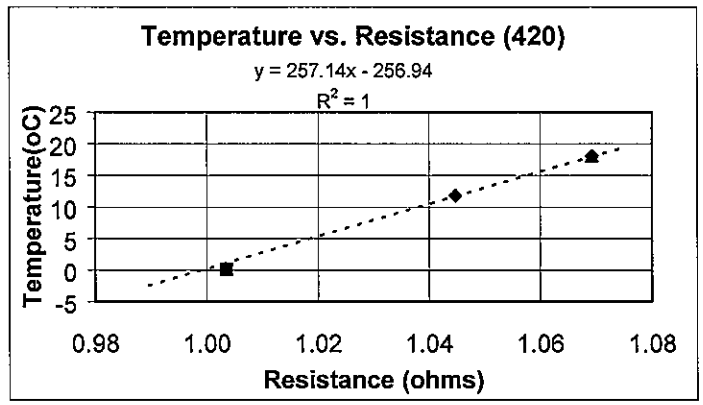
Table C2. TCP calibration check.

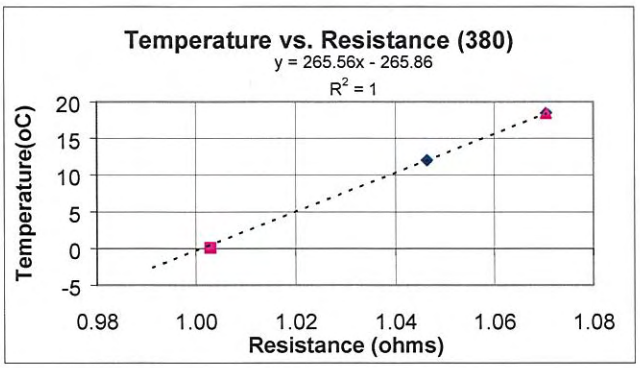
TCP No.	X	Y	Slope	Y Intercept	Predicted Y	Fit Error (+/-)	Zero Offset
360	1.0709	18.4	273.81	-274.82	18.4031	0.0031	1.0037
370	1.0710	18.4	265.06	-265.31	18.5693	0.1693	1.0016
380	1.0705	18.4	265.56	-265.86	18.4220	0.0220	1.0012
390	1.0713	18.4	260.16	-260.34	18.3694	0.0306	1.0006
400	1.0710	18.4	272.73	-273.74	18.3538	0.0462	1.0035
410	1.0709	18.4	266.53	-266.90	18.5270	0.1270	1.0019
420	1.0717	18.6	257.14	-256.94	18.6369	0.0369	0.9994
430	1.0717	18.5	268.57	-269.38	18.4465	0.0535	1.0028
440	1.0716	18.6	276.16	-277.44	18.4931	0.0569	1.0044
450	1.0719	18.5	259.67	-259.81	18.5303	0.0303	1.0007
460	1.0710	18.4	255.43	-255.29	18.2755	0.1245	0.9990

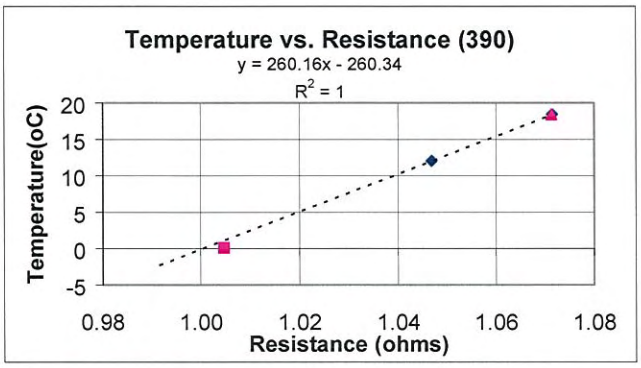


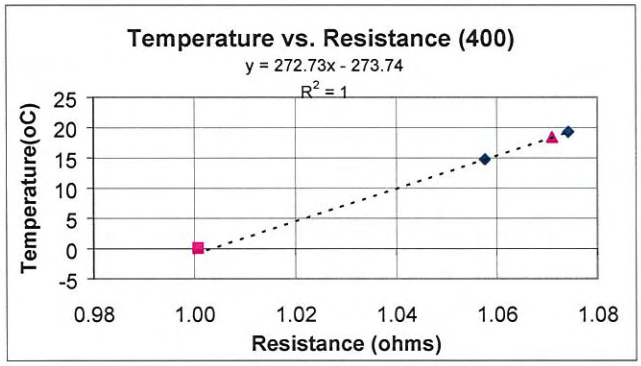


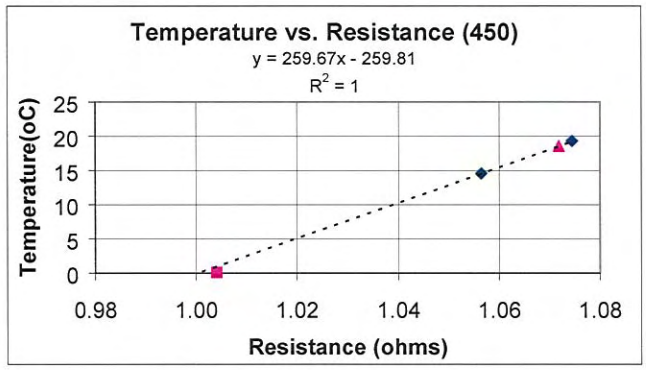


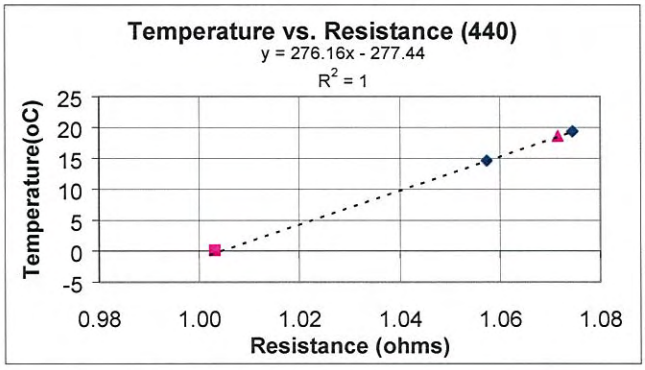



Temperature vs. Resistance (380)
y = 265.56x - 265.86
R2 = 1
Temperature(oC)
20
15
10
5
0
-5
0.98
1.00
1.02
1.04
1.06
1.08
Resistance (ohms)

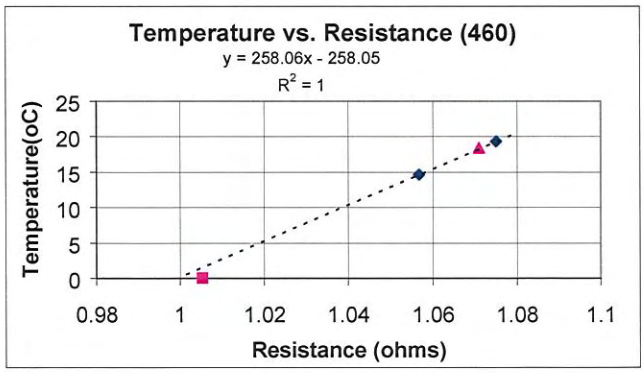

Temperature vs. Resistance (390)
y = 260.16x - 260.34
R2 = 1
Temperature(oC)
20
15
10
5
0
-5
0.98
1.00
1.02
1.04
1.06
1.08
Resistance (ohms)


Temperature vs. Resistance (400)
y = 272.73x - 273.74
R2 = 1
Temperature(oC)
25
20
15
10
5
0
-5
0.98
1.00
1.02
1.04
1.06
1.08
Resistance (ohms)


Temperature vs. Resistance (430)
y = 268.57x - 269.38
R2 = 1
Temperature(oC)
25
20
15
10
5
0
-5
0.98
1.00
1.02
1.04
1.06
1.08
Resistance (ohms)


Temperature vs. Resistance (440)
y = 276.16x - 277.44
R2 = 1
Temperature(oC)
25
20
15
10
5
0
-5
0.98
1.00
1.02
1.04
1.06
1.08
Resistance (ohms)

Temperature vs. Resistance (450)
y = 259.67x - 259.81
R2 = 1
Temperature(oC)
25
20
15
10
5
0
0.98
1.00
1.02
1.04
1.06
1.08
Resistance (ohms)


Temperature vs. Resistance (460)
y = 258.06x - 258.05
R2 = 1
Temperature(oC)
25
20
15
10
5
0
0.98
1
1.02
1.04
1.06
1.08
1.1
Resistance (ohms)

11. APPENDIX D: PSYCHROMETER STRAP

11.1 Datalogger Operation

The data acquisition program Strap.dld is loaded into the datalogger memory using the program TELCOM and a PC. To start the program running, press *0 on the 21X. Then, press *6 to display the data. The temperature measurement is located at memory location 1, which is displayed by pressing A on the face of the 21X. This location will display -9999 until 10 seconds have passed, at which time the average reading will be displayed. This is the number to record. Pressing A again moves to memory location 2, which is the resistance of the gypsum block. This value is not averaged, and may be written down promptly. Pressing B decrements the memory location, for example going from location 2 to location 1.

Data for each sensor suite on the strap is acquired by mating the connector on the datalogger to the connector on the strap corresponding to the desired depth of measurement. When the displayed value changes in memory location 1, from –9999 to a measured resistance, the values may be written down.

11.2 Datalogger Program

The program used to acquire and process data on the 21X datalogger, Strap.dld, is displayed in table D1. The temperature sensor readings are computed using a 10-sample average, while the gypsum block readings are not averaged.

Table D1. Programs

01:	2	Sec. Execution Interval
01:	P9	Full BR w/Compensation
01	1	Rep
02:	2	15 mV slow EX Range
03:	2	15 mV slow BR Range
04:	3	IN Chan
05:	3	Excite all reps w/EXchan 3
06:	500	mV Excitation
07:	20	Loc :
08:	1	Mult
09:	0	Offset
02:	P5	AC Half Bridge
01:	1	Rep
02:	14	500 mV fast Range
03:	1	IN Chan
04:	1	Excite all reps w/EXchan 1
05:	250	mV Excitation
06:	2	Loc :
07:	1	Mult
08:	0.0000	Offset
03:	P59	BR Transform Rf[X/(1-X)]
01:	1	Rep
02:	2	Loc :
03:	1	Multiplier (Rf)
04	P51	Spatial Average
01:	10	Swath
02:	11	First Loc
03:	1	Avg Loc :
05:	P54	Block Move
01:	9	No. of Values
02:	Source Step	
04	: 11	First Destination Loc :
05	: 1	Destination Step
06:	P86	Do
01:	10	Set high Flag 0 (output)
07:	P70	Sample
01:	1	Rep
02:	1	Loc

11.3 Datalogger Wiring Diagrams

Figures D1 and D2 are the wiring diagrams for the PRT temperature sensor and the gypsum blocks as connected to the Campbell Scientific 21X Datalogger. The labels on each line at the left of the diagrams are the connection points to the 21X.

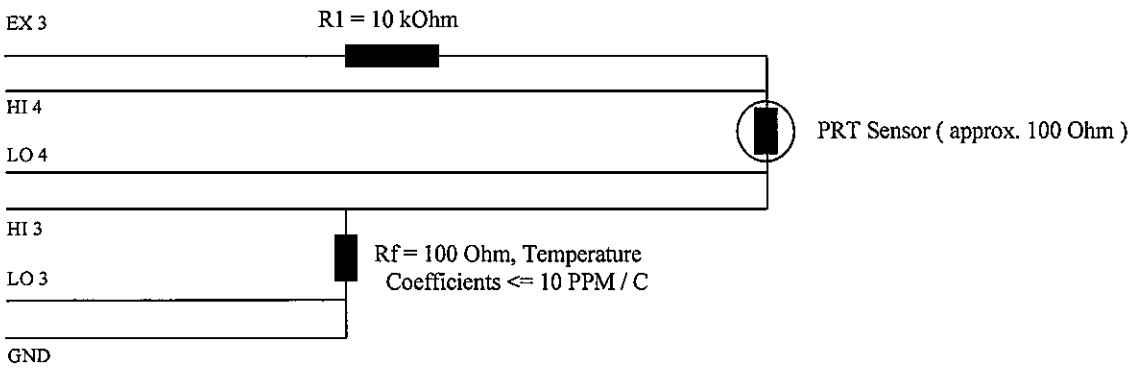


Figure D1. PRT configuration.

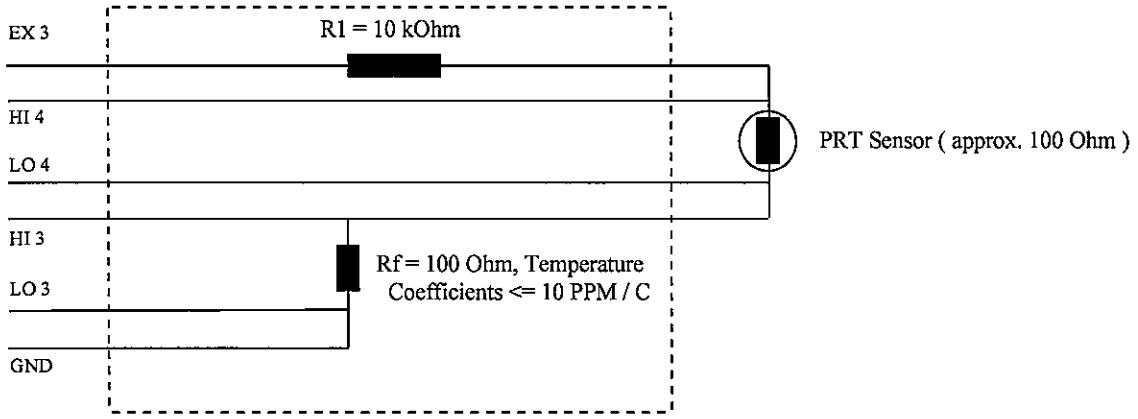


Figure D2. Gypsum block configuration.

12. REFERENCES

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Wescor. 1986. *HR 36 Dew Point Microvoltmeter: Instruction/Service Manual.* NEED MORE INFO HERE