

### 3.2.4 Miscellaneous Methods for Measuring Matric or Water Potential

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#### 3.2.4.1 Introduction

A variety of techniques to measure matric potential or water potential in the laboratory and in the field are described in this section. The techniques described herein require equilibration of some medium whose matric or water potential can be determined from previous calibration or can be measured directly. Under equilibrium conditions the matric or water potential of the medium is equal to that of the soil. The techniques can be divided into: (i) those that measure matric potential and (ii) those that measure water potential (sum of matric and osmotic potentials). Matric potential is determined when the sensor matrix is in direct contact with the soil, so salts are free to diffuse in or out of the sensor matrix, and the equilibrium measurement therefore reflects matric forces acting on the water. Water potential is determined when the sensor is separated from the soil by a vapor gap, so salts are not free to move in or out of the sensor, and the equilibrium measurement reflects the sum of the matric and osmotic forces acting on the water.

Seven different techniques are described in this section. Those that measure matric potential include (i) heat dissipation sensors, (ii) electrical resistance sensors, (iii) frequency domain and time domain sensors, and (iv) electro-optical switches. A method that can be used to measure matric potential or water potential is the (v) filter paper method. Techniques that measure water potential include (vi) the Dew Point Potentiometer (Decagon Devices, Inc., Pullman, WA<sup>1</sup>) (water activity meter) and (vii) vapor equilibration.

The first four techniques are electronically based methods for measuring matric potential. Heat dissipation sensors and electrical resistance sensors infer matric potential from previously determined calibration relations between sensor heat dissipation or electrical resistance and matric potential. Frequency-domain and time-domain matric potential sensors measure water content, which is related to matric potential of the sensor through calibration. Electro-optical switches measure changes in light transmission through thin, nylon filters as they absorb or desorb water in response to changes in matric potential. Heat dissipation sensors and electrical resistance sensors are used primarily in the field to provide information on matric potential. Frequency domain matric potential sensors are new and have not been widely used. Time domain matric potential sensors and electro-optical switches are

<sup>1</sup> Use of trade names is for identification purposes only and does not constitute endorsement by the University of Texas at Austin or the U.S. Geological Survey.

new and have not been commercialized. For the fifth technique, filter paper is used as the standard matrix. The filter paper technique measures matric potential when the filter paper is in direct contact with soil or water potential when separated from soil by a vapor gap. The Dew Point Potentiometer calculates water potential from the measured dew point and sample temperature. The vapor equilibration technique involves equilibration of soil samples with salt solutions of known osmotic potential. The filter paper, Dew Point Potentiometer, and vapor equilibration techniques are generally used in the laboratory to measure water potential of disturbed field samples or to measure water potential for water retention functions.

### 3.2.4.2 Heat Dissipation Sensors

#### 3.2.4.2.a Principles

A variety of terms for heat dissipation sensors have been used interchangeably, such as *thermal conductivity sensor* (Fredlund, 1992), *thermal diffusivity sensor*, and *soil matric potential probe* (Campbell Scientific, Inc., Logan, UT). Heat dissipation sensors provide an indirect measurement of the matric potential of soil water. Heat dissipation of a porous matrix in equilibrium with the soil is measured and is related to matric potential of the matrix using a previously determined calibration equation. These instruments have been used for more than 30 yr in agricultural and environmental studies. The historical development and use of these instruments are described in Fredlund (1992).

Heat dissipation sensors consist of a heater and a temperature sensor in a porous matrix material that equilibrates with the surrounding soil. The sensor is generally heated for a fixed time period. The rate of heat dissipation is controlled by the water content of the porous matrix because water conducts heat much more readily than air. The measured temperature increase represents the heat that is not dissipated. Heat dissipation sensors primarily measure the thermal conductivity of the reference matrix, which is a function of its water content (Fig. 3.2.4–1). Because

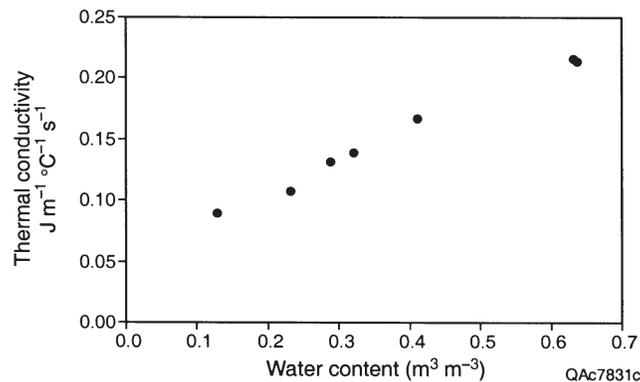


Fig. 3.2.4–1. Thermal conductivity of the porous matrix material of the heat dissipation sensor as a function of water content.

thermal conductivity rather than electrical conductivity is measured, the measurement is not affected by the conductivity of the water. The equilibrium between the sensor and the soil is a matric potential rather than a water-content equilibrium; therefore, the measured heat dissipation is related to the matric potential of the sensor through laboratory calibration. Because water and solutes exchange freely between the sensor and the soil, heat dissipation sensors measure matric potential rather than water potential. Various materials have been used for the reference matrix, including plaster of paris, fired clay, ceramics (Bloodworth & Page, 1957), and gypsum (Phene et al., 1971); however, recent models use porous ceramic. The porous ceramic should be durable for long-term field monitoring, particularly in areas subject to freeze–thaw cycles. Original designs consisted of a heater and temperature sensor installed directly into the soil for thermal conductivity measurements (Shaw & Baver, 1939); however, such instruments required individual calibrations for each soil.

The water content of the ceramic matrix changes with matric potential and causes a corresponding change in the thermal conductivity of the ceramic matrix. The reference temperature is initially recorded prior to heating the sensor. Then a constant current is applied across the heating resistor device. There are currently two basic designs of heat dissipation sensors, one manufactured by Campbell Scientific, Inc. (CSI, Model 229L; Logan, UT) and the other to be manufactured by Unsaturated Soils Technology Ltd. (UST, Saskatoon, Canada; Shuai & Fredlund, 2000). Applied currents range from 50 mA (CSI) to 200 mA (UST). Heat dissipation is generally determined as the difference between two temperatures, one measured after 1 s of heating and the other measured after a heating time that can vary from 20 to 30 s (CSI) to 50 s (UST). Whatever time period is chosen for laboratory calibration should also be used for field monitoring. Most sensors measure the temperature while heating the probe; however, Decagon Devices, Inc. (Pullman, WA) has developed an alternative measurement approach (Thermolink) that supplies a heat pulse (200 mA for 0.5 s) to the CSI heat dissipation sensor and measures the temperature after the probe has cooled for 3 s. The same results are achieved whether temperature is measured during heating or cooling; however, the Decagon method gives a much faster reading but uses more current.

The rate of heat dissipation varies with the thermal conductivity and diffusivity of the ceramic matrix, which is controlled by the water content of the matrix. Thermal conductivity increases with water content (Fig. 3.2.4–1). More heat is dissipated at higher water contents; therefore, the recorded temperature increase is less. The change in temperature will vary depending on the matric potential, the applied current, and the heating time. When a 50-mA current is applied to the heating element for 30 s, which is typical for the CSI model, the temperature increase ranges from about 0.5°C when wet to about 4°C when dry.

The upper measurement range of the sensors is controlled by the air entry pressure (bubbling pressure) of the matrix material of the sensor, which is generally –10 kPa. Unsaturated matric potentials above the air entry pressure (i.e., between 0 and –10 kPa) cannot be measured because the matrix material is essentially saturated. The lower measurement limit is generally considered to be about –1 MPa (Reece, 1996); however, less accurate measurements can be made between –1 and –35 MPa (A. Flint, personal communication, 1999).

The time dependence of temperature,  $T$ , in a line heat source buried in an infinite medium can be approximated (Shiozawa & Campbell, 1990):

$$T - T_0 = (q/4\pi k)\ln(t - t_0) \quad [3.2.4-1]$$

where  $T_0$  is the initial temperature ( $^{\circ}\text{C}$ ),  $q$  is the heat input ( $\text{W m}^{-1}$ ),  $k$  is the thermal conductivity of the medium ( $\text{W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$ ),  $t$  is time (s), and  $t_0$  is an offset time (s). The assumption of an infinite medium is satisfied for heating periods up to about 75 s for the CSI model when heat input is  $\leq 3 \text{ W m}^{-1}$ . A current of 50 mA applied through the 32- $\Omega$  heating element for a period of 20 to 30 s is typical for the CSI model. The new sensor that will be manufactured by Unsaturated Soils Technology Ltd. is larger (28-mm diam., 38 mm long) than the CSI model (15-mm diam., 32 mm long) and can contain the heat pulse provided by a 200-mA current for 50 s, which maximizes the temperature change. Reece (1996) suggested that calibration should be based on sensor thermal conductivity rather than temperature rise because calibrations based on thermal conductivity are independent of the applied current and heating time. However, the increased complexity of the method and the errors associated with determining thermal conductivity, which is generally calculated using the slope method, outweigh the reported benefits of using thermal conductivity. Therefore, most users use temperature rise for calibrations and maintain a constant current and a constant heating time during calibration and monitoring.

Thermal conductivity changes with temperature and pressure, primarily as a result of changes in thermal conductivity in the gas phase due to changes in the distillation rate of water within pores in the matrix (Flint et al., 2002). There is no pressure effect on thermal conductivity when the pores are fully saturated or dry.

#### 3.2.4.2.b Equipment

Heat dissipation sensors consist of a heating element and a temperature sensor embedded in a porous matrix. The thermal sensor used by Phene et al. (1971) was a P-N junction diode around which insulated copper wire was wrapped to serve as an external heater. Soiltronics (Burlington, WA) developed a different model of a line heat dissipation sensor that is manufactured and marketed by Campbell Scientific, Inc. (Logan, UT). This sensor consists of a length of resistive wire (heating element) and a copper-constantan thermocouple in a stainless steel hypodermic needle that is in the center of a cylindrical ceramic matrix (Fig. 3.2.4-2). The UST heat dissipation sensor consists of an integrated circuit that uses a silicon semiconductor thermistor in a cylindrical ceramic. Requirements for the matrix material are (i) a pore-size distribution that optimizes measurement sensitivity over the matric potential range of the soil and (ii) that it remains physically and chemically stable with time (i.e., it will not dissolve or deform with time, requiring sensor replacement or repeated calibration). Heat dissipation sensors manufactured by CSI and UST have high porosities ( $\sim 65\%$ ) and wide pore-size distributions that range from 0.05 to 0.0001 mm, which correspond to matric potentials of  $-5$  to  $-1500$  kPa. The water retention functions of the ceramic used in the different heat dissipation sensors are shown in Fig. 3.2.4-3. The strength of the ceramic is also important to ensure that instruments are robust and do not crack during installation, in

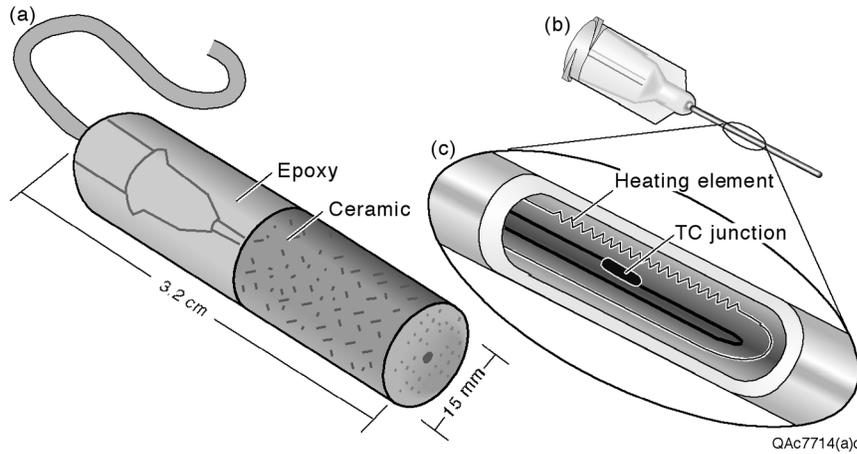


Fig. 3.2.4–2. Heat dissipation sensor (Model 229L, Campbell Scientific, Inc., Logan, UT). TC stands for thermocouple.

shrink–swell soils, or under freeze–thaw conditions. The ceramic for the UST sensor has a compressive strength of about 2100 kPa and a tensile strength of about 600 kPa (Shuai & Fredlund, 2000).

Heat dissipation sensors are connected to measuring instrumentation using individually insulated wires contained in a shielded, burial-grade sheath. An epoxy section is sometimes molded to the ceramic matrix to provide strain relief to the cable (Fig. 3.2.4–2). Temperature changes are typically measured with thermocouples (CSI; Fig. 3.2.4–2) or thermistors (UST). Any data acquisition system that measures in the DC microvolt range with microvolt resolution, such as CSI Model CR10X, CR21X, or CR23X, can be used to make measurements with heat dissipation sensors. A constant current device (e.g., CSI Model CE8 or that by UST) can be used to provide power to the system. Thermolink (Decagon Devices, Inc.) is a self-contained measurement device with a current source, microvolt meter, and

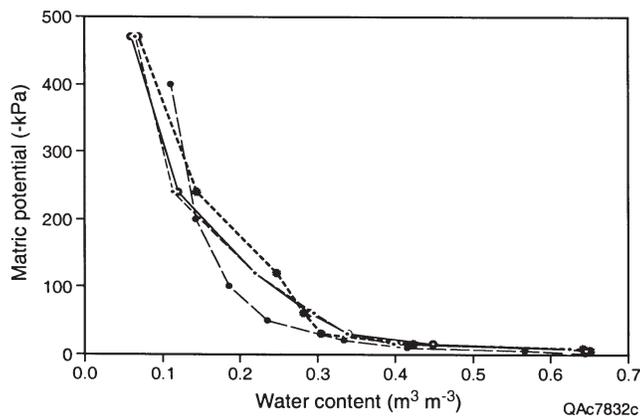


Fig. 3.2.4–3. Typical water retention functions for heat dissipation porous matrix material.

readout. Thermolink is programmed to alternately read sensors, apply calibration and temperature corrections, and then display results in matric potential units. Matric potentials can be monitored automatically and remotely using data loggers. Data can readily be telemetered to other locations.

#### 3.2.4.2.c Calibration and Measurement

The soil matric potential in equilibrium with the water content in the heat dissipation sensor is determined from calibration relationships determined in the laboratory. Measurement and calibration of matric potential by heat dissipation sensors is independent of soil texture because the heat pulse is restricted to the ceramic. It is also independent of salinity because the method is independent of the electrical conductivity. Various levels of calibration can be conducted that depend on the required level of accuracy. Most users suggest that heat dissipation sensors be calibrated individually because of variability of the heat transfer properties of individual sensors. The heat transfer properties of heat dissipation sensors depend on the thermal properties of the different materials (i.e., heating element, porous reference matrix, and other materials used in construction) and of the interfaces between the different materials. For example, in the sensor manufactured by CSI, heat transfer between the stainless-steel needle (which is used to contain the heating element and the temperature sensor) and the ceramic material depends on the density of points of contact between the two different materials. The arrangement of the wires in the hypodermic needle and the amount of contact between the needle and the ceramic cannot be precisely controlled during manufacturing.

The calibration used to relate temperature increase to matric potential of the soil water is strictly empirical, and the functional expression of the relationship can take many forms. An example calibration equation is:

$$\ln(-\psi) = \alpha(\Delta T) + \beta \quad [3.2.4-2]$$

where  $\psi$  is the matric potential,  $\alpha$  is the slope of matric potential vs. temperature difference ( $\Delta T$ ), and  $\beta$  is the intercept. The parameters  $\alpha$  and  $\beta$  are obtained from linear regression of data obtained during calibration. Typical calibration data are shown in Fig. 3.2.4-4. The relation between the natural log of the matric potential of the soil water and temperature increase is linear down to a matric potential of about  $-0.5$  MPa. For calibrations that extend below  $-0.5$  MPa, a power function can be fit to the calibration data:

$$-\psi = \alpha(\Delta T)^\beta \quad [3.2.4-3]$$

where  $\alpha$  and  $\beta$  are fitted parameters.

Reece (1996) evaluated whether a single universal calibration equation could be used for all heat dissipation sensors by examining calibration data from six sensors. He noted that variations in the intercept were not statistically significant and that most of the variability between sensors could be attributed to variations in slope. Normalizing the temperature increase to that measured when the ceramic matrix is dry allowed reduction of all six calibration equations to a single equation. On the basis of these results, Reece (1996) suggested that a single calibration equation could

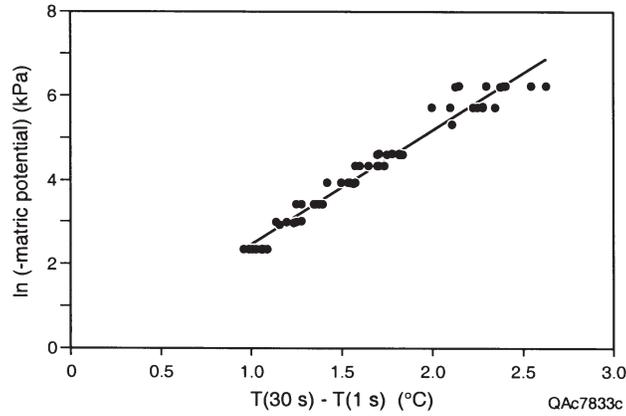


Fig. 3.2.4-4. Typical calibration data and linear fit for eight different heat dissipation sensors (Model 229L, Campbell Scientific, Inc., Logan, UT).

be used instead of different calibration equations for each sensor. Flint et al. (2002) also evaluated calibration equations for six different heat dissipation sensors and suggested normalizing the temperature increase according to:

$$T^* = (\Delta T_d - \Delta T) / (\Delta T_d - \Delta T_w) \quad [3.2.4-4]$$

where  $T^*$  is dimensionless temperature, and subscripts “d” and “w” indicate the temperature increases for a dry and vacuum-saturated ceramic matrix, respectively. This equation results in a range of 0 to 1 for dimensionless temperature. Matric potential was related to dimensionless temperature rise according to:

$$\Psi = \psi_0 (T^{*-n} - 1)^m \quad [3.2.4-5]$$

where  $\psi_0$ ,  $n$ , and  $m$  are fitted parameters. The values obtained for these parameters by Flint et al. (2002) were  $\psi_0 = -56.2 \text{ J kg}^{-1}$ ,  $n = 2.22$ , and  $m = 1.0$ . The mean absolute deviation of measurements from predictions in the range from  $-0.01$  to  $-35$  MPa was 23% for the six calibrated heat dissipation sensors. Therefore, measurement of temperature increases for dry and fully saturated conditions can be used with Eq. [3.2.4-5] to determine matric potentials if that level of accuracy is sufficient. Greater accuracy can be obtained by calibrating heat dissipation sensors individually.

The thermal conductivity of the heat dissipation sensors is temperature dependent; therefore, measurements that deviate from a reference temperature need to be corrected to the reference temperature. Heat dissipation sensors installed in the field are subjected to daily and seasonal fluctuations in ambient temperature that affect the matric potentials measured by the heat dissipation sensors. The temperature dependence of the sensors is primarily due to temperature effects on latent heat transport. Flint et al. (2002) developed the following equations to correct for temperature variations by calibrating heat dissipation sensors at several different temperatures between 0 and 40°C:

$$T^* = T_0^* - s^*(T - 20) \quad [3.2.4-6]$$

where  $T_0^*$  is the initial estimate of dimensionless temperature, and  $s^*$  is a fifth-order polynomial that was fit to model predictions of the slope of  $T^*$  vs.  $T$  as a function of  $T^*$ :

$$s^* = -0.01337T^{*5} + 0.0559T^{*4} - 0.0747T^{*3} + 0.0203T^{*2} + 0.011T^* + 0.0013 \quad [3.2.4-7]$$

Because  $s^*$  is a function of  $T$ , one must iterate to find a solution. The temperature correction is estimated by calculating an initial estimate of  $T_0^*$  from the measured temperature rise, then calculating  $s^*$  and substituting  $s^*$  into Eq. [3.2.4-6]. This process is repeated until the change in temperature is negligible. The Thermolink (Decagon Devices, Inc.) corrects for temperature using the above equations internally and provides a result in matric potential. Results from Flint et al. (2002) indicate that temperature sensitivity can be up to  $3\% \text{ }^\circ\text{C}^{-1}$ ; therefore, it is important to correct for temperature variations. The following temperature correction was developed by Fredlund et al. (2000) for UST sensors:

$$V_{23^\circ\text{C}} = [(0.0014T + 0.561)/0.593]V_T \quad [3.2.4-8]$$

where  $T$  is soil temperature ( $^\circ\text{C}$ ),  $V_{23^\circ\text{C}}$  is the output voltage at  $23^\circ\text{C}$ , and  $V_T$  is the output voltage at temperature  $T$ . This temperature correction equation was found to be valid over a temperature range from 4 to  $20^\circ\text{C}$ .

A variety of procedures can be used to calibrate heat dissipation sensors. The sole requirement is that the matric potential of the medium surrounding the probe must be known. Either the applied potential can be controlled at a specific value or the matric potential can be independently measured. Hanging water columns, Tempe cells, and pressure plate extractors are typically used. Alternatively, for calibration between  $-10$  and  $-80$  kPa, several heat dissipation sensors can be calibrated in a container where the matric potential of the soil is measured by tensiometers. The soils are generally saturated initially and drained during calibration. Therefore, only the desorption cycle is typically measured.

If the sensors are being calibrated in a pressure plate apparatus, the apparatus should be depressurized prior to measuring the temperature change because of the effect of pressure on heat transfer in the gas phase within the sensor (Phene et al., 1992). To avoid depressurization problems, Tempe cells can be used in the 0 to  $-100$  kPa range (Soilmoisture Equipment, Santa Barbara, CA; Soil Measurement Systems, Tucson, AZ). When pressure plate extractors are used, the sensors are generally placed horizontally in rings that are 6 to 8 cm high. A soil slurry is placed around the sensors. Equilibration at a given pressure during calibration is critical and can be assessed by periodically measuring the change in temperature in the heat dissipation sensor as the sample is dried. Temperature can be measured with a pressure feed-through installed in the wall of the pressure vessel, which allows electrical connections through the vessel. The sensor is assumed to be in equilibrium with

the applied pressure when measured temperature increases reach a constant value. Because calibration of heat dissipation sensors is independent of soil type, any soil can be used for calibration. For high matric potentials (0 to  $-100$  kPa) a coarse material can be used (e.g., sand); however, for lower matric potentials ( $< -100$  kPa) finer soil should be used because it has a higher unsaturated hydraulic conductivity and does not readily desaturate.

Equilibration time increases as matric potential decreases. Equilibration time varies with the applied pressure gradient and unsaturated hydraulic conductivity of the various porous media (reference matrix of the heat dissipation sensor, surrounding soil, and pressure plate). Equilibration times generally range from a few hours for matric potentials of about  $-10$  to  $-50$  kPa to about 1 wk for matric potentials of  $-500$  kPa. Pressure plates are generally not used for lower matric potentials because equilibration would be extremely time consuming and it is uncertain whether equilibration is ever attained at these low matric potentials. Calibration at lower matric potentials can be conducted by placing heat dissipation sensors in soil that is air-dried and measuring water potentials independently using a thermocouple psychrometer sample changer or a water activity meter (Decagon Devices, Inc.). By measuring water potential rather than matric potential, we are assuming that the two are equivalent and that osmotic potential of the soil water is negligible.

As indicated earlier, pressure plate extractors should be depressurized prior to measuring the temperature change. One of the problems with calibration when using pressure plate extractors is that the solution expelled from the soil in the extractor vessel will flow back into the soil when the system is depressurized. To minimize this problem, the effluent tubing should be collapsible and a laboratory clamp used to block flow before depressurization begins. Clamping the effluent tubing may not be sufficient because water beneath the ceramic plate can also flow back into the soil. To minimize this effect readings should be taken as soon as possible after depressurization. Rapid readings are facilitated if all connections are established prior to depressurization. Use of low-flow ceramic plates and sufficient soil thickness beneath the heat dissipation sensor ( $\sim 2$  cm) should also minimize the effects of back flow.

Several data values, which correspond to the matric potentials expected during probe use, should be measured during calibration. If the calibration procedures described in Flint et al. (2002) are used, a vacuum saturated reading should be taken. The next reading could correspond to the air entry value of the sensors ( $\sim -10$  kPa). Additional readings can be taken at 10-kPa intervals to  $-50$  kPa. The intervals between readings are generally increased at lower matric potentials down to  $-500$  kPa. A dry reading should also be taken. The reading of recently manufactured sensors that have not been wetted is suitable for the dry value. Sensors that have been wetted can be air dried and then placed over desiccant in a sealed container. Alternatively, an air-dry reading at a known relative humidity can be taken and corrected to an oven-dry value using an equation in Flint et al. (2002).

Temperature measurements using thermocouples and quality data loggers can be made with an accuracy of  $\pm 0.2^\circ\text{C}$ , and a resolution of  $\pm 0.02^\circ\text{C}$  in the CSI heat dissipation sensors. Shuai and Fredlund (2000) reported an accuracy of  $\pm 0.5^\circ\text{C}$  for temperature measurements using thermistors in the UST heat dissipation sensors.

#### 3.2.4.2.d Errors

The main sources of error in heat dissipation sensors result from (i) the measurement range of the sensors, (ii) calibration, (iii) hysteresis, (iv) poor contact, (v) instrument deterioration with time, (vi) freeze–thaw conditions, and (vi) changing current to the heating element.

A major source of error results from the inability of heat dissipation sensors to measure matric potentials higher than the air entry pressure of the sensor ( $\sim -10$  kPa) because the matrix remains saturated until it reaches the air entry value. Errors also increase at low matric potentials ( $< -1000$  kPa) because the sensors are less sensitive to matric potential changes in this range.

Errors due to calibration can result from lack of equilibration during calibration and back flow of water in pressure plate extractors. Careful monitoring should be conducted during calibration to ensure that equilibration has been reached at each pressure step. The precision of the matric potential measurement can be estimated by comparing repeated calibrations. Data from three independent calibration sequences for 10 heat dissipation sensors (Model 229L, CSI) showed that differences in calibration equations were not statistically significant.

The relations between the sensor's heat dissipation and matric potential is hysteretic; that is, it depends on the saturation history of the sensor. Hysteresis in the heat dissipation–matric potential relations occurs because the measured heat dissipation depends on the sensor water content, and the sensor water content–matric potential relationship is hysteretic. The effect of hysteresis is generally ignored because only desorption curves are usually measured during calibration. However, Feng (1999) conducted detailed studies on the effect of hysteresis on matric potential measurements made by UST sensors and indicated that the maximum possible relative error in matric potential measurements resulting from hysteresis was 30%. The hysteresis curves for their sensors were found to be stable over time, and a hysteresis model was developed to improve matric potential measurements during wetting and drying cycles.

It is critical to maintain good hydraulic contact between sensors and surrounding soil in the field. Good contact may be difficult to attain in very coarse sediments, such as gravel, and in shrink–swell clays because large differences between the pore size of the sensor matrix and the surrounding soil can cause hydraulic decoupling of the two materials. Wet silica flour is often used during installation to ensure good contact between the sensor and surrounding soil; however, use of this approach can be problematic in dry soil. In addition, because of the requirement of hydraulic continuity and good contact between the sensor and the surrounding matrix, sensors cannot be installed in a retrievable manner. Information on the long-term performance of these instruments in the field is generally limited.

Fredlund et al. (2000) evaluated the effect of freeze–thaw conditions on UST heat dissipation sensors. Results of their studies indicated that heat dissipation sensors do not provide reliable matric potential measurements in freezing or thawing soils because the voltage drops as a result of the effect of latent heat of fusion on thermal conductivity. The thermal conductivity of ice and water is different; therefore, it is difficult to interpret voltages measured under freeze–thaw conditions. How-

ever, freeze–thaw cycles did not affect the ability of UST heat dissipation sensors to function upon return to normal conditions because the calibration was not affected by these cycles.

The heat dissipation method as currently applied assumes constant power dissipation at the heating element. The source of power is generally a constant current source with a power capacity of a few watts. A constant voltage source cannot be used in place of a constant current source because there is a voltage drop in the cable; thus, if a voltage source were used, different calibrations for sensors with different cable lengths would be required. Variation in applied power during measurement or between measurements will cause the temperature increase (as sensed by the thermocouple) to change, thus introducing error in application of the calibration. The effect of a changing supply current is greater at lower thermal conductivities. Thermal conductivity of the ceramic matrix decreases as matric potential decreases. A change in current of  $\pm 0.25\%$  would result in  $\pm 1.5$  kPa at  $-50$  kPa and about  $\pm 4.3$  kPa at  $-1000$  kPa in the CSI sensors (Bilskie, 1999).

Advantages of heat dissipation sensors are relatively low cost, ease of operation, ease of data analysis, automated measurements, and remote operation. The heat dissipation sensors cover a greater measurement range than that of any other matric or water potential sensor available. Heat dissipation sensors cover the entire thermocouple psychrometer range. However, unlike thermocouple psychrometers, heat dissipation sensors require good contact with the surrounding soil, which makes it difficult to install them in a retrievable manner. Heat dissipation sensors are generally more robust and easier to use than thermocouple psychrometers. The measurement range of heat dissipation sensors does not extend into the wettest part of the tensiometer range; however, heat dissipation sensors do not require periodic manual water fillings that tensiometers do. Good correspondence was found between matric potentials measured by heat dissipation sensors and tensiometers from  $-10$  to  $-70$  kPa (Reece, 1996; Fredlund et al., 2000) and between heat dissipation sensors and thermocouple psychrometers at matric potentials of less than  $-400$  kPa (Reece, 1996).

Heat dissipation sensors can be used for irrigation scheduling or assessment of soil water status for plant growth (Phene & Howell, 1984; Phene et al., 1992). They can also be used for evaluating the gradient in subsurface matric potential to determine the direction of water movement. Continuous measurements of matric potential in the shallow subsurface (upper 2–3 m) can be used to assess temporal variability in infiltration. Results of monitoring matric potentials at 0.2- and 2-m depth using duplicate heat dissipation sensors (CSI) in an arid site demonstrate the reliability of the instruments and the wide range in matric potentials that can be monitored (Fig. 3.2.4–5). Heat dissipation sensors have been installed at about 50 sites in a statewide meteorologic network in Oklahoma to monitor the status of soil water in the shallow subsurface (upper 2–3 m), which is critical for determining the potential for drought or flooding (Oklahoma Climatological Survey, 2000). Heat dissipation sensors are also being used to evaluate infiltration in artificial recharge systems (Alan Flint, personal communication, 2000). The simultaneous measurements of temperature and matric potential allow both heat and matric potentials to be used to infer recharge at these sites.

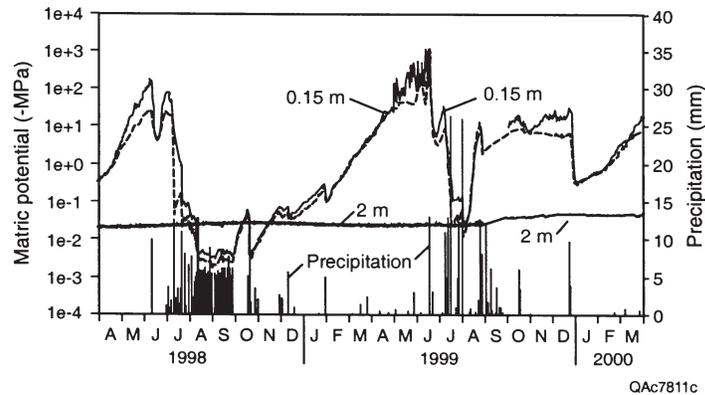


Fig. 3.2.4-5. Variation in matric potentials monitored by duplicate heat dissipation sensors at 0.2- and 2-m depth and measured precipitation and irrigation at an arid site.

### 3.2.4.3 Electrical Resistance Sensors

#### 3.2.4.3.a Principles

Electrical resistance sensors have been used for more than 60 yr in agricultural applications (Bouyoucos & Mick, 1940). These sensors generally consist of porous matrix material that equilibrates with the surrounding soil. During equilibration, water and solutes exchange between the sensor and the soil; therefore, the matric potential of the sensor is the same as that of the soil after equilibration. Although electrical resistance varies primarily with water content, the equilibrium between the sensor and the soil is a matric potential rather than a water-content equilibrium and the measured electrical resistance is related to the matric potential of the sensor through previous laboratory calibration. Although any material with a pore-size distribution that desaturates over the matric potential range of interest can be used, traditional materials for these sensors include gypsum, fiberglass, or nylon. More recently, granular matrix sensors were developed that consist of a gypsum wafer embedded in a granular matrix. Although electrical resistance of the sensors varies primarily with water content, it is also affected by salinity and temperature. In gypsum-based sensors, the gypsum slowly dissolves and the resulting ions provide a buffering capacity that makes this instrument insensitive to salinity variations below the electrical conductivity associated with saturated gypsum ( $\sim 0.2 \text{ S m}^{-1}$ ). Nylon and fiberglass sensors, however, provide no buffering capacity. Resistance measurements can be readily corrected for temperature variations.

The upper measurement range of the sensors is controlled by the air entry pressure (bubbling pressure) of the matrix material in the sensor. Pressures above the air entry pressure cannot be measured because the matrix material remains saturated. For example, the upper limit for granular matrix sensors is about  $-10 \text{ kPa}$  (Thomson & Armstrong, 1987; Spaans & Baker, 1992) and about  $-30 \text{ kPa}$  for gypsum blocks (Bourget et al., 1958). The lower limit depends on the range in smaller pore sizes of the sensor matrix and is about  $-100 \text{ kPa}$  for nylon and granular matrix sensors (Haise & Kelley, 1946; Thomson & Armstrong, 1987; Spaans & Baker,

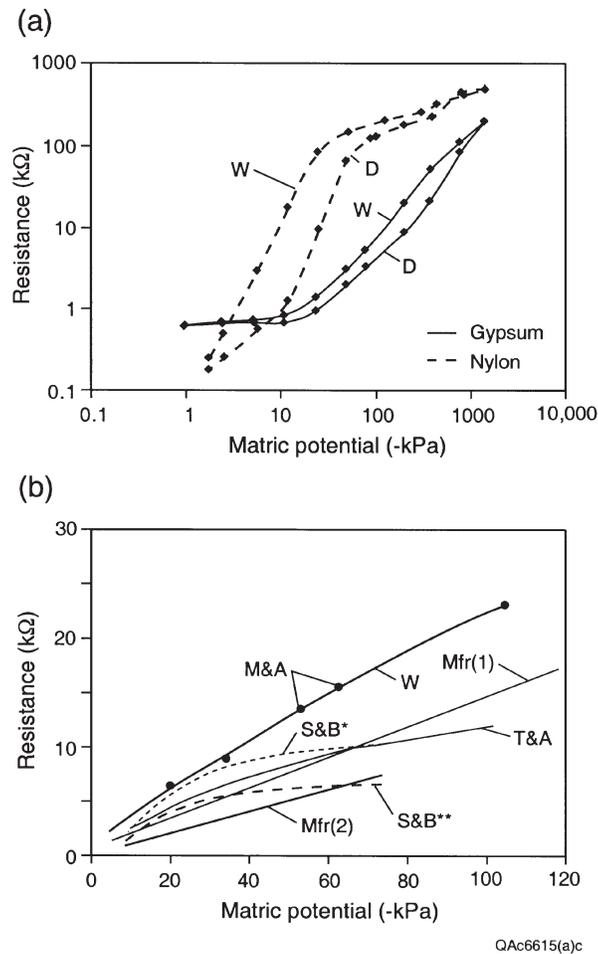
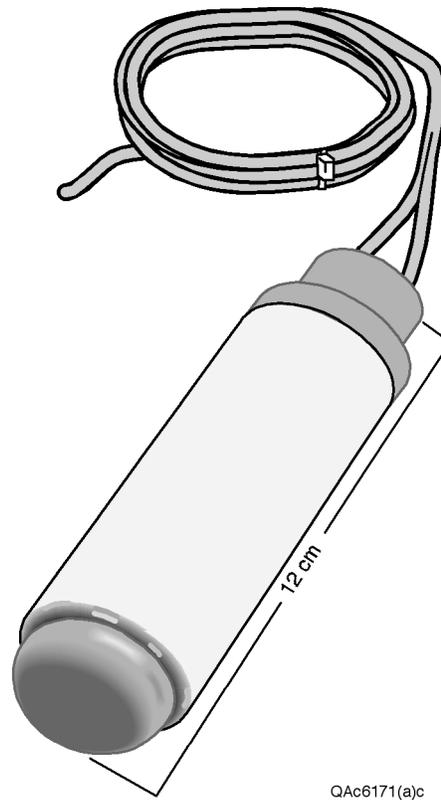


Fig. 3.2.4-6. (a) Calibration relations for wetting (W) and drying (D) of five gypsum sensors (mean) and four nylon sensors (mean) (Bourget et al., 1958); (b) calibration relations for granular matrix sensors: T&A—mean seven sensors (Thomson & Armstrong, 1987); W—mean 12 sensors (Wang, 1988); M&A—mean 49 sensors (points) and Mfr(1)—manufacturer's calibration (McCann et al., 1992); S&B range [\*,\*\*] for 36 sensors and Mfr(2) manufacturer's calibration (Spaans & Baker, 1992).

1992) and about  $-1000$  kPa for gypsum blocks (Tanner et al., 1948; Bourget et al., 1958) (Fig. 3.2.4-6).

### 3.2.4.3.b Equipment

Electrical resistance sensors generally consist of two electrodes embedded in a porous matrix. The traditional gypsum sensors consist of cylindrical blocks of gypsum ( $\leq 3$ -cm diam.,  $\leq 3$  cm long). The granular matrix sensors consist of a gypsum tablet in granular material encased in polyvinyl chloride plastic fill (Watermark Sensor, Irrrometer Co., Inc., Riverside, CA) (Fig. 3.2.4-7). A typical fiberglass sensor



QA6171(a)c

Fig. 3.2.4–7. Granular matrix sensor (Watermark Sensor, Irrrometer Co., Inc., Riverside, CA).

consists of a thin (3 mm) perforated metal case surrounding the fiberglass (Colman & Hendrix, 1949). These instruments are marketed by various companies including Campbell Scientific (Logan, UT; gypsum blocks and granular matrix sensors), Delta-T Devices Ltd. (Cambridge, England; gypsum blocks and granular matrix sensors), ELE Soil Test (Lake Bluff, IL; fiberglass sensors), Soilmoisture Equipment Corp. (Santa Barbara, CA; gypsum blocks), and Watermark Sensor (Irrrometer Co., Inc., Riverside, CA; granular matrix sensors). Procedures for constructing gypsum sensors are given in Taylor et al. (1961).

A Wheatstone bridge is generally used to measure resistance. These bridges use alternating current (AC) to avoid polarization at the electrodes in the sensor block. Portable, battery-operated ohmmeters can be used to measure resistance. Goltz et al. (1981) described procedures to construct a meter for measuring sensor resistance. Data loggers can also be used for automated measurements. The data loggers should provide AC rather than DC excitation to avoid polarization in the sensors, although Strangeways (1983) described an option for using short pulses of direct current (DC) for data loggers. Because data loggers are generally grounded and one lead of the sensor is connected to data logger ground to make the measurement, a current path can exist that will destroy the sensor by electrolysis. To

prevent this, a capacitor or switch (multiplexer) should be placed in series with the ground lead of the sensor to break the direct current paths.

### 3.2.4.3.c Calibration and Measurement

Sensors should be soaked initially for about 24 h and oven-dried. This process should be repeated two to three times before calibration and use. Different levels of calibration can be conducted, depending on the accuracy required. Calibrations of electrical resistance sensors provided by manufacturers may be sufficient for some applications. Errors incurred from use of manufacturer's calibrations of granular matrix sensors can be seen in Fig. 3.2.4-6b. Good correspondence was found between the manufacturer's calibration (Fig. 3.2.4-6b) and calibrations developed by Thomson and Armstrong (1987) in the wet range; however, both of these calibrations differed from those developed by McCann et al. (1992) (Fig. 3.2.4-6b). For more accurate matric potential measurements, laboratory calibration is required. Tanner et al. (1948) suggested batch calibrations based on measurements of the electrical resistance of saturated gypsum blocks. Such an approach would greatly reduce the calibration time because only a few instruments from each batch would have to be calibrated. General equations were developed from calibration of different numbers of instruments (7-49) in many studies (Thomson & Armstrong, 1987; Wang, 1988; McCann et al., 1992) (Fig. 3.2.4-6b). McCann et al. (1992) noted a coefficient of variation of 11% based on calibration of 49 instruments in their study. However, Spaans and Baker (1992) suggested that use of a common calibration equation could lead to substantial errors, as shown by the approximate range in individual equations from the 36 instruments calibrated in their study (see S&B\* and S&B\*\* in Fig. 3.2.4-6b). Spaans and Baker (1992) also indicated that repeatability of calibrations was poor. These data suggest that individual calibration is required for greater accuracy.

Sensors are generally calibrated in a pressure plate apparatus (Thomson & Armstrong, 1987; McCann et al., 1992). Modified pressure chambers may be used to allow resistance measurements to be made without releasing the pressure (e.g., Soilmoisture Equipment, Santa Barbara, CA). Sensors are placed in saturated soil in the chamber. When several sensors are calibrated in a single chamber, separate leads for each sensor should be used rather than a single, common lead for all sensors because the soil between the sensors can provide a current path when a single, common lead is used. The drying curve is generally measured because it is difficult to partially saturate a sample. Pressures are increased incrementally, and the samples are allowed to equilibrate at each pressure. Procedures for using the pressure-plate apparatus are described in detail in Section 3.3.2. Sensors can also be calibrated by placing them in soil with other instruments, such as tensiometers, in the laboratory (Spaans & Baker, 1992) or in the field (Eldredge et al., 1993). Sensors can be calibrated indirectly by measuring the resistance and water content of the soil in the laboratory and then relating water content to matric potential by using a previously determined water retention function for the soil (Cannell & Asbell, 1964). This indirect calibration allows many instruments to be calibrated at the same time. Soil from the field site where the instruments are going to be installed should be used for laboratory calibration so that the electrical conductivity of the pore water

is as similar as possible for calibration and field measurements. Use of field soil is especially important for fiberglass and nylon units because there is no chemical buffering in these sensors.

Calibration temperature should be measured, and field measured resistance should be corrected for differences between calibration and field temperatures. Some manufacturers provide a temperature-correction equation. Campbell and Gee (1986) indicated that the correction is generally about 3% per degree Celsius and the following equation can be used:

$$R_c = R_f[1 + 0.03(T_c - T_f)] \quad [3.2.4-9]$$

where  $R_c$  is resistance ( $k\Omega$ ) at calibration temperature ( $T_c$ , °C) and  $R_f$  is the resistance at field temperature ( $T_f$ ) when temperature is above freezing. The 3% per degree Celsius correction is consistent with results of calibrations of granular matrix sensors (Thomson & Armstrong, 1987; Wang, 1988). Discrepancies related to different temperature corrections are negligible compared with other sources of uncertainty.

Electrical resistance sensors are not very accurate in the unsaturated zone and generally provide only a qualitative indication of matric potential. Some studies suggest that the accuracy of the measurements can be improved by installing several sensors at a particular depth and averaging the readings (Taylor et al., 1961). McCann et al. (1992) noted that three to six Watermark granular matrix sensors placed at a given location should yield matric potential within 10% of the actual value with a 90% confidence interval.

Sensors should be resaturated prior to field installation. It is important to maintain good hydraulic contact between the sensor and the surrounding soil. The sensors can be installed in a trench or in an access hole specifically designed for the particular sensor being installed. Field temperature should be measured at the points where the sensors are installed for temperature corrections of measured resistances. Electrical resistance sensors are generally used to measure matric potential of soil; however, they can also be used for evaluating frozen soil conditions because the electrical conductivity goes to almost zero when the water in the block freezes (Colman & Hendrix, 1949; Wilinet al., 1972). Electrical resistance increases sharply when soil freezes because the ions in the sensor become immobile and cannot conduct an electrical current. The temperature associated with frozen soil is generally  $<0^\circ\text{C}$  because the low water potential of the soil depresses the freezing point of water.

#### 3.2.4.3.d Errors

The main sources of error with electrical resistance sensors include (i) the air entry value of the matrix material, (ii) soil salinity effects, (iii) hysteresis, (iv) poor contact, (v) dynamic response of the sensor, and (vi) instrument deterioration with time.

A major source of error results from the inability of electrical resistance sensors to measure matric potentials higher than the air entry pressure of the sensor

because the matrix remains saturated until matric potentials decrease to the air entry pressure. The air entry pressure is about  $-10$  kPa for granular matrix sensors (Thomson & Armstrong, 1987; Spaans & Baker, 1992) and about  $-30$  kPa for gypsum blocks (Bourget et al., 1958).

Errors due to salinity are high for nylon and fiberglass sensors, whereas salinity errors may be reduced for gypsum sensors because of the buffering capacity of the ions provided during dissolution of the gypsum. Scholl (1978) developed a specialized sensor for highly saline soils that also incorporates a salinity sensor. Field salinity measurements allow the measured resistance to be corrected for salinity by using previously determined calibration data.

The relation between the sensor's electrical resistance and matric potential is hysteretic; that is, it depends on the saturation history of the sensor. Hysteresis in the resistance–matric-potential relation occurs because the measured resistance depends on the sensor water content, and the sensor water content–matric potential relation is hysteretic. Bourget et al. (1958) indicated that gypsum blocks are less affected by hysteresis than are nylon sensors (Fig. 3.2.4–6a). To minimize the effects of hysteresis, wetting and drying in the native sediments should be matched with wetting and drying calibration curves for the sensors. However, field soil will generally not be on a main wetting or drying curve but on a scanning curve. These instruments are generally considered only qualitative indicators of matric potential; therefore, errors due to hysteresis may be incorporated into the measurements.

It is critical to maintain good hydraulic contact between the sensors and the surrounding soil in the field. Good contact may be difficult to attain in very coarse sediments, such as gravel, and in shrink–swell clays because large differences between the pore size of the sensor matrix and the surrounding soil can cause hydraulic decoupling of the two materials.

The dynamic response of the sensors can vary with changing soil moisture. McCann et al. (1992) noted that the dynamic response of Watermark granular matrix sensors was good during typical soil water drying cycles after complete rewetting, but was poor during rapid drying or partial rewetting of the soil. The sensor response was improved by using a finer-textured material with a corresponding higher unsaturated hydraulic conductivity in the transmission portion of the sensor.

Electrical resistance sensors generally deteriorate with time. Instrument deterioration can be rapid if sensors are connected directly to a data logger without a current switch (multiplexer) or capacitor. Other causes of deterioration result from gypsum dissolution and decomposition of nylon or fiberglass. England (1965) evaluated deterioration of fiberglass units over a 10-yr period and noted significant deterioration caused by migration of soil constituents into the units.

The low cost and ease of operation make electrical resistance sensors useful as a qualitative indicator of matric potential. Thus, they are used for irrigation scheduling or crude assessment of soil water status for plant growth. They are not sufficiently accurate to evaluate hydraulic gradients to calculate water fluxes through soil. For more precise measurement in the 0 to  $-80$  kPa range, tensiometers are preferred.

### 3.2.4.4 Frequency Domain and Time Domain Matric Potential Sensors

#### 3.2.4.4.a Principles

Matric potential can be measured by combining a water content measuring device (either frequency domain or time domain reflectometry (see Section 3.1.3.3) with a matrix material whose water retention function has previously been determined. Examples of this type of instrument include the Equitensiometer (Delta-T Devices, 1999), and the TDR-Matric (TM) sensor proposed by Or and Wraith (1999). The Equitensiometer consists of a frequency domain water content probe (ThetaProbe) embedded in a specially formulated matrix material. The TM instrument consists of porous disks with different known maximum pore sizes that are stacked in a coaxial cage. Matric potential of the porous material in the sensor equilibrates with that of the surrounding soil, and the change in water content is detected by the frequency domain or time domain probe. The measured water content is then converted to matric potential using a previously determined calibration relationship between sensor matric potential and water content. The upper measurement limit of these instruments is based on the air entry pressure of the matrix material in the sensor ( $\sim -2$  kPa for the Equitensiometer,  $\sim -2.5$  kPa for prototype TM sensors). The lower measurement limit is reported to be  $-1000$  kPa for the Equitensiometer and depends on the finest porous disk used in the TM sensor ( $-500$  kPa for prototype TM sensors).

#### 3.2.4.4.b Equipment

The Equitensiometer consists of a 100-MHz frequency domain water content probe in matrix material. The instrument is 40 mm in diameter and 210 mm in length. Equitensiometers can be directly powered by Delta-T data loggers by using their internal batteries. An external power supply is recommended if several sensors are being measured.

The prototype TM sensors consist of stacked porous disks with different maximum pore sizes in a coaxial cage. The sensor may be fabricated to variable dimensions, subject to a minimum length of about 150 mm for reliable TDR measurements. The prototype sensor is 28.5 mm in diameter and 175 mm in length. The TDR probe can be connected to a Tektronix (Beaverton, OR) TDR cable tester that is controlled by a data logger or a computer.

#### 3.2.4.4.c Calibration

Each Equitensiometer is marketed with a factory calibration. Two calibration equations are provided, one linearizing the full range (0 to  $-1000$  kPa) and the other linearizing the range from 0 to  $-350$  kPa, which provides greater resolution in the wet range. The manufacturer indicates that the factory calibration should be stable for about 2 yr. This calibration can be checked by inserting the probe in deionized water and checking the reading against the calibration value.

The TM sensor can be calibrated by using a pressure chamber apparatus. The prototype sensors were calibrated in two ways. First, the individual disks were calibrated separately, and a composite water retention function was determined from individual disk water retention functions and the relative volume that each disk oc-

cupied in the porous matrix. Second, the sensor was calibrated as a single unit on a pressure plate apparatus. Poor agreement was obtained between the two calibrations, and the single unit calibration is preferred (Or & Wraith, 1999).

#### 3.2.4.4.d Errors

These instruments cannot be used in the very wet range ( $> \sim -2$  to  $-2.5$  kPa) because the matrix remains saturated at matric potentials greater than its air entry value. The reported accuracy of the Equitensiometers is  $\pm 10$  kPa from 0 to  $-100$  kPa and  $\pm 5\%$  of reading from  $-100$  to  $-1000$  kPa. The moisture hysteresis problem for these sensors is similar to that described for the electrical resistance sensors. Because of the large mass of matrix material in these sensors and the associated large water storage capacity of this material, the dynamic response of the instrument may be delayed. The time lag between matric potential changes in the surrounding soil and the response of the sensors is greatest when the matric potential is changing rapidly and at low matric potentials. These sensors have not been tested in saline soils. The Equitensiometer manual provides procedures for correcting readings to a common temperature, so temperature calibration is not required. The Equitensiometer and TM sensors have not been used in frozen soil. It is important to maintain good hydraulic contact between the instrument and the surrounding soil. Hydraulic decoupling will be of greatest concern in coarse-textured soil and shrink–swell soil.

#### 3.2.4.5 Electro-Optical Switches

The principle of the electro-optical switch method for measuring matric potential is based on the air entry value of a thin matrix material, such as a nylon filter, and variations in light transmission through this material with water content (Cary et al., 1991). Nylon filters are translucent to infrared light when saturated. When the matric potential decreases below the air entry value of the nylon filter, the filter starts to desaturate and the light transmission decreases abruptly, resulting in a large voltage change and opening of the switch. The narrow pore-size distribution of the filters results in an abrupt signal change. The matric potential corresponding to the pore size of the filter can be calculated using the capillary rise equation and assuming a zero contact angle.

The instrument developed by Cary et al. (1991) consists of an infrared light-emitting diode, a nylon filter disk through which the light passes, and a photodiode to capture the light that passes through the nylon filter. The nylon filter extends into the soil and equilibrates with the matric potential of the soil. Attenuation of the light beam registers as an output voltage. The measurement range of the instrument depends on the pore size of the nylon filter. A range of matric potentials can be measured by combining filters of different pore sizes. The upper limit of matric potential measurement is controlled by the air entry value of the coarsest nylon filter, and the lower limit is controlled by the nylon filter with the smallest pore size.

The sensor has been tested from near saturation ( $-0.004$  MPa) to about  $-2.5$  MPa and is not commercially available. The electro-optical sensor essentially functions as an on–off switch and may prove useful for irrigation scheduling. The advantages of the sensor are low cost, physical stability, reliability, rapid response

because of the low water capacity of the nylon material, and ability to be monitored automatically.

### 3.2.4.6 Dew Point Potentiometer

#### 3.2.4.6.a Principles

The Dew Point Potentiometer (Decagon Devices, Inc., Pullman, WA) (or water activity meter) uses the chilled mirror dew point technique to measure the water potential of a soil or rock sample in the laboratory. The instrument was developed by Decagon Devices, Inc. The current model (WP4) is designed specifically for measurement of water potential in soils and rocks and represents a modification of previous meters termed *water activity meters* (Models CX1 and CX2; AquaLab, Decagon Devices, Inc.), which were also used in the food industry and are described in Gee et al. (1992). The main modifications to the original water activity meter are a reduction in measurement range (from 0 to  $-316$  MPa to 0 to  $-40$  MPa), greater precision (from  $\pm 0.4$  MPa to  $\pm 0.1$  MPa), and measurement output in terms of water potential rather than water activity. Water activity is synonymous with equilibrium relative humidity, that is, the relative humidity of the air space in equilibrium with soil under isothermal conditions in a sealed container. Water potential ( $\psi$ , Pa) can be calculated from water activity ( $A_w$ ) expressed as a fraction, by using the Kelvin equation,

$$\psi = (RT/V_w)\ln(A_w) \quad [3.2.4-10]$$

where  $R$  is the ideal gas constant ( $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ ),  $T$  is temperature (K), and  $V_w$  is molar volume of water ( $1.8 \times 10^{-5} \text{ m}^3 \text{ mol}^{-1}$ ).

Measurement of water potential with the WP4 is based on equilibrating liquid-phase water of a soil or rock sample with vapor-phase water in the air space above the sample in a sealed chamber, and then measuring the dew point temperature of the air and the temperature of the sample. Water potential measurements of a sample are rapid ( $\leq 5$  min.). A chilled mirror is used to measure the dew point of the water vapor. A Peltier cooling device is used to cool the mirror until dew forms and then to heat the mirror to eliminate the dew. Temperature of the sample is measured with an infrared thermometer. The vapor pressure of the air is equal to the saturation vapor pressure at the dew point temperature, by definition of the dew point. Therefore, the vapor pressure of the air ( $P$ ) is calculated from the dew point temperature ( $T_d$ , °C). Saturated vapor pressure ( $P_0$ ) is calculated from the sample surface temperature ( $T_s$ , °C) according to:

$$P_0(T_c) = a \exp[bT_s/(T_s + c)] \quad [3.2.4-11]$$

where  $T_c$  is temperature (°C), and  $a$ ,  $b$ , and  $c$  are constants (Buck, 1981). The water activity is calculated as follows:

$$\begin{aligned} A_w &= \frac{P}{P_0(T_s)} = \frac{a \exp[bT_d/(T_d + c)]}{a \exp[bT_s/(T_s + c)]} \\ &= \exp \left( \frac{bT_d}{T_d + c} - \frac{bT_s}{T_s + c} \right) = \exp \left[ \frac{bc(T_d - T_s)}{(T_d + c)(T_s + c)} \right] \end{aligned} \quad [3.2.4-12]$$

Water potential is related to dew point depression as follows (inserting Eq. [3.2.4–12] into Eq. [3.2.4–10]):

$$\Psi = \frac{RT}{V_w} \left[ \frac{bc(T_d - T_s)}{(T_d + c)(T_s + c)} \right] \quad [3.2.4-13]$$

where  $T_d$  is the dew point temperature ( $^{\circ}\text{C}$ ). An algorithm in the WP4 computes water potential from  $T_s$  and  $T_d$  using Eq. [3.2.4–13].

### 3.2.4.6.b Equipment

The equipment required for the measurements includes a Dew Point Potentiometer (Model WP4, Fig. 3.2.4–8) or water activity meter (Model CX1 or CX2, or Aqualab), and sample cups. The meters include a chilled mirror sensor to measure the dew point temperature of the air, a fan to circulate air in the sensing chamber and speed up vapor equilibration, and an infrared thermometer to measure the sample temperature specifically. The dew point temperature is measured by cooling a stainless-steel mirror by Peltier cooling, monitoring the mirror reflectance with an optical sensor to detect condensation at the dew point, and measuring the temperature of the mirror at that time. The sample cups have a capacity of 15 mL and are 40 mm in diameter and 11.5 mm tall. The measurements can be recorded manually or by a computer.

### 3.2.4.6.c Measurement

The WP4 meter, or equivalent, is used to measure water potentials of disturbed field soil or rock samples or to measure water potential of samples that have been wetted or dried for water retention functions. The sample cup should be filled to 50% capacity to minimize the potential of contaminating the chamber. The sample can be compressed with a no. 7 rubber stopper (Gee et al., 1992). Water potential



Fig. 3.2.4–8. Dew Point Potentiometer (WP4) (Decagon Devices, Inc., Pullman, WA).

readings can be taken continuously or at predefined intervals. The time series of readings should be examined in the early stages of the study to determine when to record the water potential. When the readings have stabilized, the instrument will display the water potential of the sample. The system can be connected to a computer, and software is available to record the measurements. Detailed measurement procedures are provided in the operator's manual.

#### 3.2.4.6.d Errors

The main source of error when measuring water potential of disturbed field samples in the laboratory results from sample drying during collection and measurement. This problem is greatest for coarse-textured soils and dry soils. Great care should be taken to minimize water loss during sample collection. A variety of procedures can be used to collect samples. If sample tubes are used in drilling, these should be capped and sealed as quickly as possible after collection. Transfer of samples to air-tight containers at the surface may result in more water loss than use of sample tubes. Data analysis should consider any water redistribution in the sample tube during sample storage, and the vertical dimension of the tubes should be chosen for the desired vertical resolution of water potential measurements. Water loss during measurements by the meter should be minimal because measurements are made in a sealed chamber and are rapid ( $\leq 5$  min). Sample transfer and measurements can also be conducted in a humidified glove box as described in Section 3.2.3.

The performance of the instrument should be checked prior to sample measurements by measuring the water potential of a salt solution with a known osmotic potential. Salt solution standards are available from the manufacturer, or they can be prepared according to information provided in Table 3.2.3-1 of Section 3.2.3. If the instrument readings are offset from standard solution readings, the linear offset of the meter should be corrected. It is important to avoid contamination of the instrument. If necessary, the mirror and fan can be cleaned according to procedures outlined in the operator's manual.

Temperature control is important. To attain an accuracy of  $\pm 0.1$  MPa, the measured difference between dew point and sample temperatures must be accurate to  $\pm 0.005^\circ\text{C}$ . This accuracy is most readily attained when the sample and chamber temperatures are about the same (within  $\pm 0.5^\circ\text{C}$ ). An error of  $1^\circ\text{C}$  in the measured difference between dew point and sample temperatures would result in an 8-MPa error in measured water potentials. The chamber temperature will generally be 2 to  $3^\circ\text{C}$  warmer than the ambient temperature because of heat generated inside the case by the instrument circuitry. If the sample is cooler than the chamber, equilibration will take longer. If the sample is warmer than the chamber, condensation will occur in the chamber. The instrument will warn the user if the sample temperature is above the chamber temperature. Because the chilled mirror dew point technique is a primary measurement method of relative humidity, detailed calibration is not required. However, operationally the instrument offset should be verified periodically by using a calibrating salt solution to check for instrument drift with time.

There are several differences between the Dew Point Potentiometer (WP4) and the thermocouple psychrometer sample changer (such as the Tru Psi, Decagon

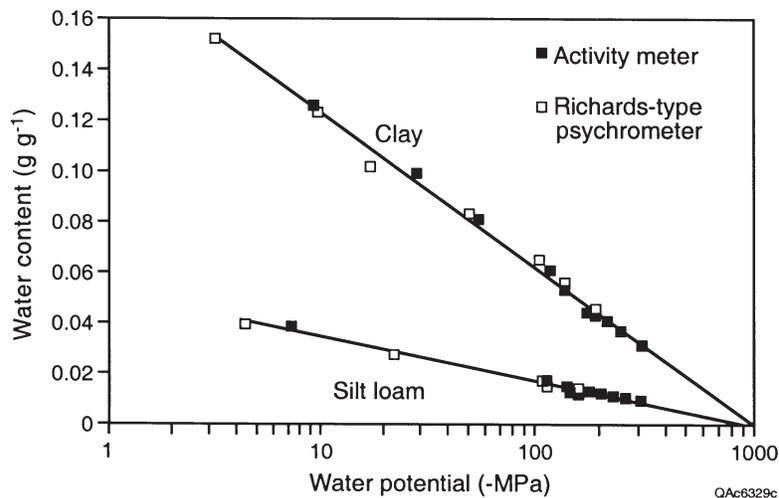


Fig. 3.2.4-9. Comparison of water potentials measured with a water activity meter (Model CX1) and a Richards' thermocouple psychrometer (Model SC10) (from Gee et al., 1992).

Devices, Inc., Pullman, WA) described in Section 3.2.3. The time required to complete a sample measurement is much shorter for the WP4 (~ <5 min per sample) than for the sample changers (~15–30 min for thermal and vapor equilibration prior to sample measurement plus ~2–3 min per sample). Measurement accuracy is less for the WP4 ( $\pm 0.1$  MPa) than for Tru Psi ( $\pm 0.03$  MPa). The capacity of the sample cups is much greater for the WP4 (15 mL) than for Tru Psi (1.5 mL). Water potential measurements made with older models of these two instruments compare favorably (Fig. 3.2.4-9) (Gee et al., 1992). Thus, the Dew Point Potentiometer is a very robust instrument that is suitable for rapid, accurate laboratory measurements of water potential. The instrument is generally used to measure water potential of soil samples; however, water potential and water retention of rock samples have also been measured with the WP4 (Flint et al., 1999).

### 3.2.4.7 Filter Paper Technique

#### 3.2.4.7.a Principles

Filter paper can be used to measure the energy status of water in unsaturated media in the laboratory. The filter paper is either placed in direct contact with the soil for matric potential measurements or it is separated from the soil by a vapor gap for water potential measurements. Direct contact between the filter paper and soil allows water in the liquid phase and solutes to exchange freely, whereas separation between the filter paper and the soil by a vapor gap limits water exchange to the vapor phase and prohibits solute movement. The soil samples containing filter papers are allowed to equilibrate for several days in an airtight, isothermal container. After equilibration, the change in mass of the filter paper is measured and is related to the matric potential or water potential through a previously determined calibration curve.

### 3.2.4.7.b Calibration

Detailed studies of filter paper calibrations were conducted by Hamblin (1981), Al-Khafaf and Hanks (1974), and Deka et al. (1995). Calibrations have been conducted using tensiometers and thermocouple psychrometers (Deka et al., 1995), hanging water columns, pressure chambers, and salt solutions (Al-Khafaf & Hanks, 1974). Deka et al. (1995) found reasonable agreement between calibration curves developed for different batches of Whatman no. 42 filter papers (Fisher Scientific, Pittsburgh, PA), indicating that their general calibration curves can be used for this type of filter paper. The regression relationship between log (matric potential) measured by the filter paper technique against measurements by tensiometers and thermocouple psychrometers between  $-0.001$  to  $-10$  MPa gave an  $r^2$  of 0.995 (Fig. 3.2.4–10). Calibration curves are generally divided into two parts, the wet region where capillary forces are dominant, and the dry region, where adsorptive forces are dominant. Potential is generally plotted on a log scale and the relationships are linear. The calibration curves developed by Deka et al. (1995) were combined with those from Chandler and Gutierrez (1986), Fawcett and Collis-George (1967), and Greacen et al. (1987) to develop generalized calibration equations for Whatman no. 42 filter paper:

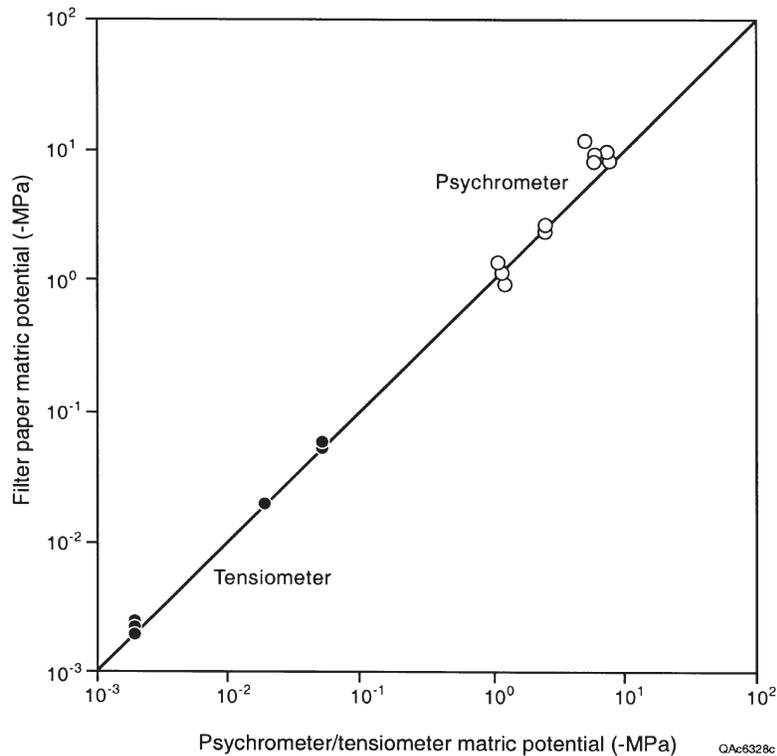


Fig. 3.2.4–10. Comparison of water potentials measured by filter paper with those measured by tensiometer ( $\geq -0.01$  MPa) or thermocouple psychrometer ( $< -0.01$  MPa) (from Deka et al., 1995). The 1:1 line is also shown.

$$\begin{aligned}\log_{10}(-\psi_m) &= 5.144 - 6.699w & \psi_m < -51.6 \text{ kPa} \\ \log_{10}(-\psi_m) &= 2.383 - 1.309w & \psi_m > -51.6 \text{ kPa} \quad [3.2.4-14]\end{aligned}$$

where  $\psi_m$  is the matric potential (kPa) and  $w$  is the gravimetric water content ( $\text{g g}^{-1}$ ). For more accurate measurements, calibration equations should be developed specifically for the filter papers being used. When calibration equations from the literature are used, care should be taken to ensure that the same type of filter paper is used and that the same parameter is being measured (matric potential or water potential).

### 3.2.4.7.c Measurement

The measurement procedure is outlined in detail in ASTM D 5298-94 (American Society for Testing and Materials, 1994). The most commonly used filter paper is Whatman no. 42 (Fisherbrand 9-780A), although Whatman no. 1 and Schleicher and Schuell No. 589 White Ribbon (Schleicher & Schuell, Dassel, Germany) have also been used. The diameter of the filter paper is generally 5.5 cm. Filter papers may be pretreated with a 2% concentration of formaldehyde to prevent microbial growth or decomposition of the filter paper. Prior to measurement, filter papers are oven-dried and placed in a desiccation chamber. Sample containers should be able to hold about 100 g of soil and should be of sufficient diameter so the filter paper does not touch the wall of the container and absorb moisture that may condense on the wall.

For liquid equilibration where direct contact is required, the filter paper is generally surrounded by the soil sample to facilitate equilibration from both sides. To prevent soil from adhering to the filter paper, the filter paper to be measured is generally separated from the soil by placing it between additional filter papers. For vapor equilibration, the filter paper is placed on a steel screen on top of the soil sample. The lid is then placed on the sample container and Parafilm may be used to ensure an air-tight seal. It is important to minimize temperature gradients; therefore, the sample container is placed in an insulated box, the box is separated from the laboratory bench, and fluctuations in room temperature should be minimized. Sample equilibration will vary depending on the texture and the matric potential or water potential of the sample. Equilibration times range from 2 d (Al-Khafaf & Hanks, 1974) to as long as 7 to 14 d (McQueen & Miller, 1968). After equilibration, the filter paper is removed from the soil using tweezers and placed in a separate container for weight measurements. The filter paper is weighed, oven-dried for 24 h at 105°C, and reweighed to measure the water content of the filter paper. Transferal of the filter paper from the soil sample to the weighing container should be done in a humid environment, such as a glove-box lined with wet paper towels to minimize water loss. Nonpowdered vinyl surgical gloves should be used to prevent body oils from affecting the measurements.

### 3.2.4.7.d Errors

The main sources of error in the filter paper technique include (i) lack of filter paper equilibration, (ii) errors in measuring the water content of the filter paper,

and (iii) errors in the water potential or matric potential versus water content calibration equation. When the filter paper technique is used to measure water potential or matric potential of field soils, water loss during sample collection and measurement can also be a problem, as described in Section 3.2.3. If the filter papers are not allowed to equilibrate for a sufficient time period, then the water content and corresponding water potential of the soil will be underestimated. Liquid phase equilibration is fairly rapid in the wet range (high potential) and generally requires only a few days. In contrast, vapor equilibration is slow in the wet range because a large amount of water needs to be transferred. Thermal equilibration is also important. Temperature gradients in the sample can result in liquid flow. In addition, temperature gradients can result in large errors when vapor exchange is used for equilibration; a 1°C temperature difference between the soil and the filter paper will result in a water potential error of 8 MPa.

### 3.2.4.8 Vapor Equilibration

#### 3.2.4.8.a Principles

Vapor equilibration can be used to determine the relationship between water potential and water content of soils, which is termed the *water retention function*. To reach different water potentials, soil samples are equilibrated across a vapor gap with different salt solutions, or agar gels, of known osmotic potential. The soil sample absorbs or desorbs water until water potential equilibrium is reached. At equilibrium, the water potential of the soil sample is set by the known osmotic potential of the salt solution and the water content of the soil samples can be determined by oven-drying.

#### 3.2.4.8.b Measurement

Place open containers of soil and salt solutions of known osmotic potential in an insulated container. Temperature gradients are critical because a 1°C temperature difference between the soil sample and the salt solution will result in an 8 MPa difference in water potential. Therefore, the insulated container should consist of a cooler that is insulated from the laboratory bench and placed in a room that has minimal diurnal temperature fluctuations. The mass of the soil sample should be measured initially and after equilibration, to calculate the water content change. Procedures for measuring the water content of soil samples are outlined in Section 3.1. Osmotic potentials of saturated salt solutions are provided in Robinson and Stokes (1959). Concentrations of NaCl, KCl, and LiCl required to obtain different water potentials are given in Section 3.2.3, Campbell and Gee (1986), and Rawlins and Campbell (1986), respectively. Separation distance between the soil sample and the salt solution should be minimized to reduce the possibilities of temperature differences. A partial vacuum can also be used to speed up vapor equilibration. Equilibration time will depend on the water potential and type of soil and can be checked periodically by measuring the water content of the soil samples. Even though saturated salt solutions should maintain a constant osmotic potential after water loss to the sample, other salt solutions may become concentrated and should be replaced periodically.

### 3.2.4.8.c Errors

The primary source of error results from temperature gradients in the sample during equilibration. Lack of equilibration will also result in errors in water potential measurements.

### 3.2.4.9 References

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