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100 Barr Harbor Dr., West Conshohocken, PA 19428
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Standard Guide for Measuring Matric Potential in the Vadose Zone Using Tensiometers[1]

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1. Scope

1.1 This guide covers the measurement of matric potential in the vadose zone using tensiometers. The theoretical and practical considerations pertaining to successful onsite use of commercial and fabricated tensiometers are described. Measurement theory and onsite objectives are used to develop guidelines for tensiometer selection, installation, and operation.

1.2 The values stated in SI units are to be regarded as the standard. The inch-pound units given in parentheses are for information only.

1.3 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word" Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Terminology

2.1 *Definitions of Terms Specific to This Standard:*

2.1.1 *accuracy of measurement*—the difference between the value of the measurement and the true value.

2.1.2 *hysteresis*—that part of inaccuracy attributable to the tendency of a measurement device to lag in its response to environmental changes. Parameters affecting pressure-sensor hysteresis are temperature and measured pressure.

2.1.3 *precision (repeatability)*—the variability among numerous measurements of the same quantity.

2.1.4 *resolution*—the smallest division of the scale used for a measurement and it is a factor in determining precision and accuracy.

3. Summary of Guide

3.1 The measurement of matric potential in the vadose zone can be accomplished using tensiometers that create a saturated hydraulic link between the soil water and a pressure sensor. A variety of commercial and fabricated tensiometers are commonly used. A saturated porous ceramic material that forms an interface between the soil water and bulk water inside the instrument is available in many shapes, sizes, and pore diameters. A gage, manometer, or electronic pressure transducer is connected to the porous material with small- or large-diameter tubing. Selection of these components allows the user to optimize one or more characteristics, such as accuracy, versatility, response time, durability, maintenance, extent of data collection, and cost.

4. Significance and Use

4.1 Movement of water in the unsaturated zone is of considerable interest in studies of hazardous-waste sites **(1, 2, 3, 4)**[2]; recharge studies **(5, 6)**; irrigation management **(7, 8, 9)**; and civil-engineering projects **(10, 11)**. Matric-potential data alone can be used to determine direction of flow **(11)** and, in some cases, quantity of water flux can be determined using multiple tensiometer installations. In theory, this technique can be applied to almost any unsaturated-flow situation whether it is recharge, discharge, lateral flow, or combinations of these situations.

4.2 If the moisture-characteristic curve is known for a soil, matric-potential data can be used to determine the approximate water content of the soil **(10)**. The standard tensiometer is used to measure matric potential between the values of 0 and −867 cm of water; this range includes most values of saturation for many soils **(12)**.

4.3 Tensiometers directly and effectively measure soil-water tension, but they require care and attention to detail. In particular, installation needs to establish a continuous hydraulic connection between the porous material and soil, and minimal disturbance of the natural infiltration pattern are necessary for

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[2] The boldface numbers in parentheses refer to a list of references at the end of the text.

successful installation. Avoidance of errors caused by air invasion, nonequilibrium of the instrument, or pressure-sensor inaccuracy will produce reliable values of matric potential.

4.4 Special tensiometer designs have extended the normal capabilities of tensiometers, allowing measurement in cold or remote areas, measurement of matric potential as low as −153 m of water (−15 bars), measurement at depths as deep as 6 m (recorded at land surface), and automatic measurement using as many as 22 tensiometers connected to a single pressure transducer, but these require a substantial investment of effort and money.

4.5 Pressure sensors commonly used in tensiometers include vacuum-gages, mercury manometers, and pressure transducers. Only tensiometers equipped with pressure transducers allow for the automated collection of large quantities of data. However, the user needs to be aware of the pressure-transducer specifications, particularly temperature sensitivity and long-term drift. Onsite measurement of known zero and "full-scale" readings probably is the best calibration procedure; however, onsite temperature measurement or periodic recalibration in the laboratory may be sufficient.

5. Measurement Theory

5.1 In the absence of osmotic effects, unsaturated flow obeys the same laws that govern saturated flow: Darcy's Law and the Equation of Continuity, that were combined as the Richards' Equation **(13)**. Baver *et al*. **(14)** presents Darcy's Law for unsaturated flow as follows:

$$q = -K\nabla(\psi + Z) \tag{1}$$

where:

q = the specific flow, $\left[\frac{L}{T}\right]$,

K = the unsaturated hydraulic conductivity, $\left[\frac{L}{T}\right]$,

ψ = the matric potential of the soil water at a point, [L],

Z = the elevation at the same point, relative to some datum, [L], and

∇ = the gradient operator, $[L^{-1}]$.

The sum of $\psi + Z$ commonly is referred to as the hydraulic head.

5.2 Unsaturated hydraulic conductivity, K, can be expressed as a function of either matric potential, ψ, or water content, $\theta[L^3$ of water$/L^3$ of soil], although both functions are affected by hysteresis **(5)**. If the wetting and drying limbs of the $K(\psi)$ function are known for a soil, time series of onsite matric-potential profiles can be used to determine: which limb is more appropriate to describe the onsite $K(\psi)$; the corresponding values of the hydraulic-head gradient; and an estimate of flux using Darcy's Law. If, instead, K is known as a function of θ, onsite moisture-content profiles (obtained, for example, from neutron-scattering methods) can be used to estimated K, and combined with matric-potential data to estimate flux. In either case, the accuracy of the flux estimate needs to be assessed carefully. For many porous media, $\frac{dK}{d\psi}$ and $\frac{dK}{d\theta}$ are large, within certain ranges of ψ or θ, making estimates of K particularly sensitive to onsite-measurement errors of ψ or θ. (Onsite-measurement errors of ψ also have direct effect on $\nabla(\psi + Z)$ in Darcy's Law). Other sources of error in flux estimates can result from: inaccurate data used to establish the $K(\psi)$ or $K(\theta)$ functions (accurate measurement of very small permeability values is particularly difficult) **(16)**; use of an analytical expression for $K(\psi)$ or $K(\theta)$ that facilitates computer simulation, but only approximates the measured data; an insufficient density of onsite measurements to define adequately the θ or ψ profile, which can be markedly nonlinear; onsite soil parameters that are different from those used to establish $K(\psi)$ or $K(\theta)$; and invalid assumptions about the state of onsite hysteresis. Despite the possibility of large errors, certain flow situations occur where these errors are minimized and fairly accurate estimates of flux can be obtained **(6, 17)**. The method has a sound theoretical basis and refinement of the theory to match measured data markedly would improve reliability of the estimates.

5.3 The concept of fluid tension refers to the difference between standard atmospheric pressure and the absolute fluid pressure. Values of tension and pressure are related as follows:

$$T_F = P_{AT} - P_F \tag{2}$$

where:

T_F = the tension of an elemental volume of fluid, $\left[\frac{M}{LT^2}\right]$,

P_{AT} = the absolute pressure of the standard atmosphere, $\left[\frac{M}{LT^2}\right]$, and

P_F = the absolute pressure of the same elemental volume or fluid $\left[\frac{M}{LT^2}\right]$.

Soil-water tension (or soil-moisture tension) similarly is equal to the difference between soil-gas pressure and soil-water pressure. Thus:

$$T_W + P_G = P_W \tag{3}$$

where:

T_W = the tension of an elemental volume of soil water, $\left[\frac{M}{LT^2}\right]$,

P_G = the absolute pressure of the surrounding soil gas, $\left[\frac{M}{LT^2}\right]$, and

P_W = the absolute pressure of the same elemental volume of soil water, $\left[\frac{M}{LT^2}\right]$.

In this guide, for simplicity, soil-gas pressure is assumed to be equal to 1 atmosphere, except as noted. Various units are used to express tension or pressure of soil water, and are related to each other by the equation:

1.000 bar = 100.0 kPa = 0.9869 atm =
1020 cm of water at 4°C =
1020 g per cm^2 in a standard

gravitational field.

(4)

A standard gravitational field is assumed in this guide; thus, centimetres of water at 4°C are used interchangeably with grams per square centimetre.

5.4 The negative of soil-water tension is known formally as matric potential. The matric potential of water in an unsaturated soil arises from the attraction of the soil-particle surfaces for water molecules (adhesion), the attraction of water molecules for each other (cohesion), and the unbalanced forces across the air-water interface. The unbalanced forces result in the concave water films typically found in the interstices between soil particles. Baver *et al.* **(14)** present a thorough discussion of matric potential and the forces involved.

5.5 The tensiometer, formally named by Richards and Gardner **(18)**, has undergone many modifications for use in specific problems **(1, 11, 19-31)**. However, the basic components have remained unchanged. A tensiometer comprises a porous surface (usually a ceramic cup) connected to a pressure sensor by a water-filled conduit. The porous cup, buried in a soil, transmits the soil-water pressure to a manometer, a vacuum gage, or an electronic-pressure transducer (referred to in this guide as a pressure transducer). During normal operation, the saturated pores of the cup prevent bulk movement of soil gas into the cup.

5.6 An expanded cross-sectional view of the interface between a porous cup and soil is shown in Fig. 1. Water held by the soil particles is under tension; absolute pressure of the soil water, P_W, is less than atmospheric. This pressure is transmitted through the saturated pores of the cup to the water inside the cup. Conventional fluid statics relates the pressure in the cup to the reading obtained at the manometer, vacuum gage, or pressure transducer.

5.6.1 In the case of a mercury manometer (see Fig. 2(*a*)):

$$T_W = P_A - P_W = (\rho_{Hg} - \rho_{H_2O})r - \rho_{H_2O}(h + d) \tag{5}$$

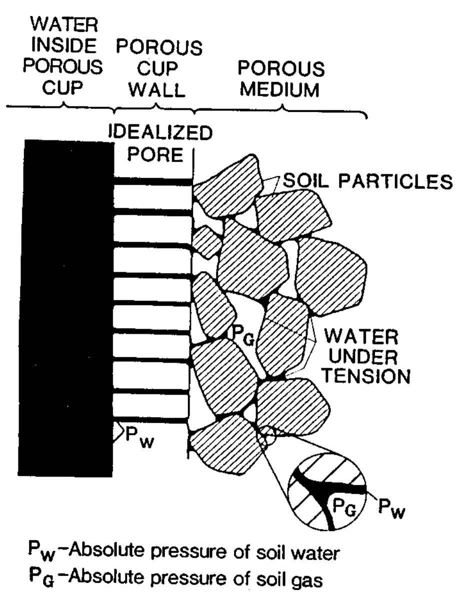

FIG. 1 Enlarged Cross Section of Porous Cup-Porous Medium Interface

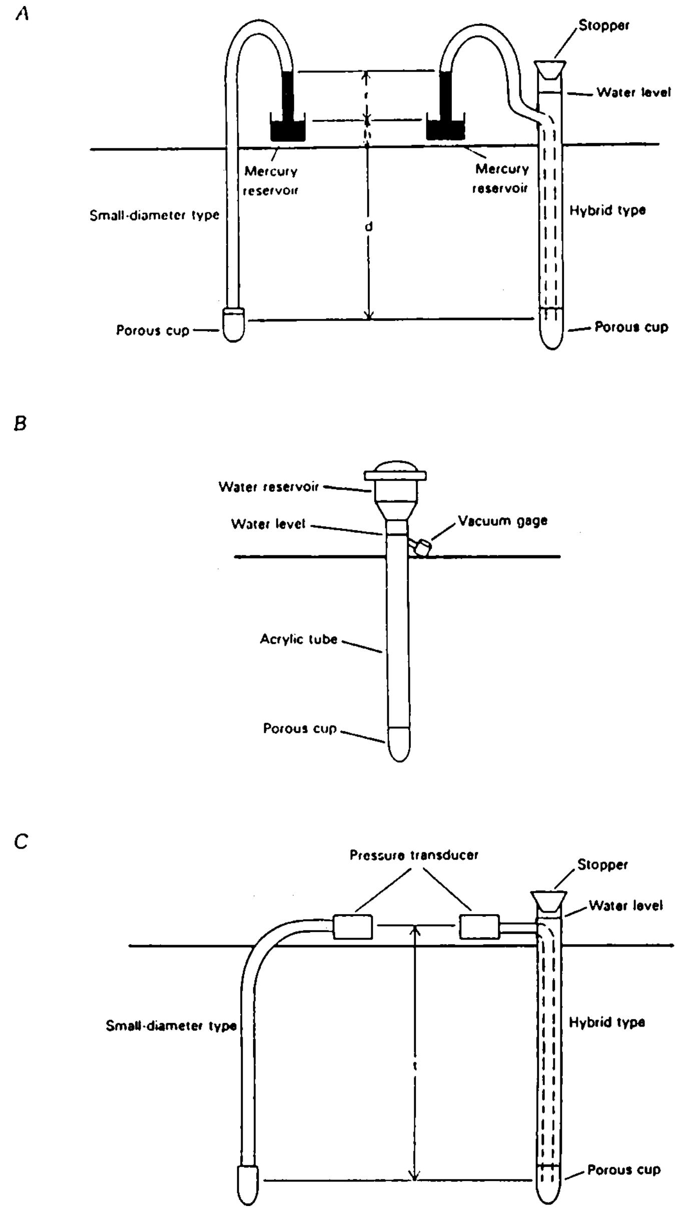

FIG. 2 Three Common Types of Tensiometers: (a) Manometer; (b) Vacuum Gage; and (c) Pressure Transducer

where:

T_W	=	the soil-water tension relative to atmospheric pressure, in centimetres of water at 4°C,
P_A	=	the atmospheric pressure, in centimetres of water at 4°C,
P_W	=	the average pressure in the porous cup and soil, in centimetres of water at 4°C,
ρ_{Hg}	=	the average density of the mercury column, in grams per cubic centimetre,
ρ_{H_2O}	=	the average density of the water column, in grams per cubic centimetre,
r	=	the reading, or height of mercury column above the mercury-reservoir surface, in centimetres,

h = the height of the mercury-reservoir surface above land surface, in centimetres, and
d = the depth of the center of the cup below land surface, in centimetres.

5.7 Although the density of mercury and water both vary about 1 % between 0 and 45°C, Eq 5 commonly is used with ρ_{Hg} and ρ_{H_2O} constant.

5.7.1 Using $\rho_{Hg} = 13.54$ and $\rho_{H_2O} = 0.995$ (the median values for this temperature range) yields about a 0.25 % error (1.5 cm H_2O) at 45°C, for Tw ≈ 520 cm H_2O. This small, but needless, error can be removed by using the following density functions:

$$\rho_{Hg} = 13.595 - 2.458 \times 10^{-3} (T) \quad (6)$$

and

$$\rho_{H_2O} = 0.9997 + 4.879 \times 10^{-5} (T) - 5.909 \times 10^{-6} (T)^2 \quad (7)$$

where: ρ_{Hg} and ρ_{H_2O} are as defined above, and
T = average temperature of the column, in° C.

5.7.2 Average temperature of the buried segment of water column can be estimated with a thermocouple or thermistor in contact with the tubing, buried at about 45 % of the depth of the porous cup. Air temperature is an adequate estimate for exposed segments.

5.8 Most vacuum gages used with tensiometers are graduated in bars (and centibars) and have an adjustable zero-reading. The zero adjustment is used to offset the effects of altitude, the height of the gage above the porous cup (see Fig. 3(*b*)), and changes in the internal characteristics of the gage with time. The adjustment is set by filling the tensiometer with water and then setting the gage to zero while immersing the porous cup to its midpoint in a container of water. This setting is done at the altitude at which the tensiometer will be used and it needs to be repeated periodically after installation either by removing the tensiometer from the soil or by unscrewing the gage and measuring a tension equal to that used in the original calibration. The gage then reads directly the tension in the porous cup. Use of a vacuum gage without an adjustable zero reading could result in inaccurate measurements because the zero-reading could become negative and, therefore, would be indeterminate.

5.9 Pressure transducers convert pressure, or pressure difference, into a voltage (or current) signal. The pressure transducer can be connected remotely to the porous cup with tubing **(22, 24)** attached directly to the cup **(19, 32)**, or transported between sites **(24)**. An absolute pressure transducer measures the absolute pressure (P_P) in its port. A gage pressure transducer measures the difference between ambient-atmospheric pressure (P_A) and the pressure in its port (P_P), known as gage pressure. When $P_P < P_A$, gage pressure is identical to tension. A differential pressure transducer measures the difference between two pressures; one in each of its two ports. When used with tensiometers, the second port usually is connected to the atmosphere; the unit is used as a gage pressure transducer and it measures tension.

5.10 A calibration equation supplied by the manufacturer, or determined by the user, is used to convert the measured signal into pressure or tension at the pressure-transducer port. The tension in the porous cup and soil is then (see Fig. 3(*c*)):

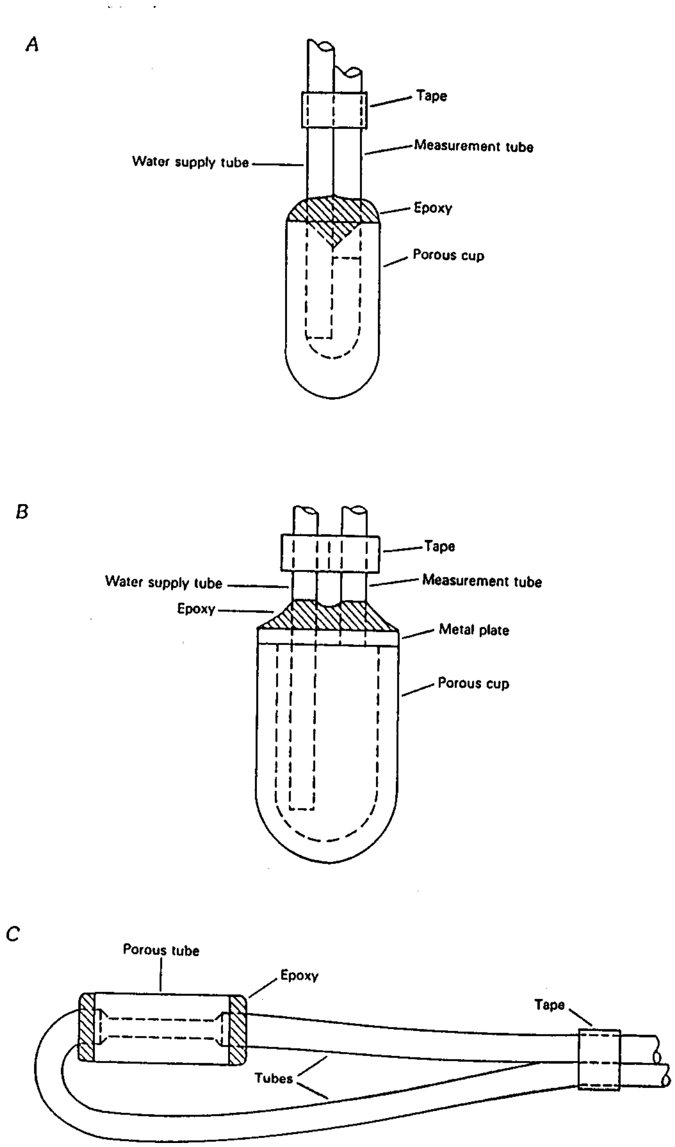

FIG. 3 Porous-Cup and Tube Designs

$$T_W = T_P - t\,(\rho_{H_2O}) \quad (8)$$

where:
T_W = the average tension in the porous cup and soil, in centimetres of water at 4°C,
T_P = the tension in the pressure-transducer port, in centimetres of water at 4°C,
t = the difference in elevation between the pressure-transducer port and the center of the porous cup, in centimetres, and
ρ_{H_2O} = the average density of the water column connecting the porous cup and transducer, in grams per cubic centimetre.

5.11 At 15°C, pure liquid water begins to cavitate (vaporize) if its tension exceeds 969 cm H_2O. If cavitation happens in a tensiometer, liquid continuity is interrupted and tension readings are invalid. Water used in tensiometers is deaerated as completely as practicable, but some impurities and dissolved gases remain that decrease the tension sustainable by liquid water to about 867 cm H_2O **(33)**. Thus, the operating range of tensiometers is described by the following equations:

$$T_C + \Delta h < 867 \text{ cm} \quad (9)$$

and

$$T_C < 867 \text{ cm} \quad (10)$$

where:

T_C = the tension in the porous cup, in centimetres of water at 4°C, and

Δh = the elevation of the highest point in the hydraulic connection between the porous cup and the pressure sensor, minus the elevation of the porous cup, in centimetres.

Eq 9 indicates that a "trade-off" occurs between depth of installation of the porous cup and the maximum tension measurable; Eq 10 sets the upper limit of that tension. Eq 9 and Eq 10 are approximate; if the water is insufficiently deaerated, the value 867 would be replaced with a smaller value.

5.12 The only tensiometer described thus far that measures absolute soil-water pressure (P_W) directly is the absolute-pressure-transducer type. The others, differential tensiometers, measure the quantity $P_A - P_W$, where $P_A$is ambient atmospheric pressure. The driving forces for liquid water in the unsaturated zone (ignoring osmotic potential) are the absolute pressure gradient in the liquid-water phase and gravity (see Eq 1). If the pressure wave propagates easily through the unsaturated zone, then differential tensiometers can be used directly to determine pressure gradients. However, if a barometric-pressure change is transmitted readily to one differential tensiometer porous cup and not to another (because of an intermediate confining layer), the calculated gradient between the two porous cups would be in error. If a porous cup is isolated from the atmosphere by a confining layer, then a time series of soil-water pressure at the porous cup, calculated with P_A constant, will indicate fluctuations that correlate well with barometric fluctuations. In this case, a recording barometer will provide a record of ambient atmospheric pressure from which absolute soil-water pressure and pressure gradients can be determined. The resulting series of absolute soil-water pressure at the isolated porous cup will be a smoother curve, that will indicate real pressure changes in the water phase.

5.13 Richards **(12)** defined the time constant of a tensiometer as follows:

$$\tau = \frac{1}{K_c S} \quad (11)$$

where:

τ = the time constant, or time required for 63.2 % of a step change in pressure to be recorded by a tensiometer, when the cup is surrounded by water, in seconds,

K_c = the conductance of the saturated porous cup, or the volume of water passing through the cup wall per unit of time per unit of hydraulic-head difference, in centimetre^2 second^{-1}, and

S = the tensiometer sensitivity, or change in pressure reading per unit volume of water passing through the porous-cup wall, in centimetre^{-2}.

Also, the porous cup conductance may be expressed as:

$$K_c = \frac{kA}{W}; \quad (12)$$

where:

K_c = the cup conductance, in centimetre^2 second^{-1},

k = the permeability of the cup material to water at the prevailing temperature, in centimetre second^{-1},

A = the average surface area of porous-cup material, estimated as the mean of the inside area and the outside area, in centimetre^2, and

W = the average wall thickness of the porous cup, in centimetres.

5.14 Richards' **(12)** definition does not apply to a tensiometer buried in a soil because soil conductance (K_s) is in series with K_c and usually $K_s << K_c$. In fact, an onsite time constant cannot be defined **(19)** because the response is not logarithmic due to a varying K_s during equilibration. However, the phrase" response time" is used to describe the rate of onsite response to pressure changes **(33)**. The term is not to be confused with the time constant because two tensiometers with equal time constants emplaced in the same soil can have different response times. For example, if $K_{c_1} = 10\ K_{c_2}$ and $S_2 = 10\ S_1$, then $\tau_1 = \tau_2$; but if $K_s \approx K_{c_2}$, then *response time*$_1$ > *response time*$_2$. Nonetheless, τ as defined here can be used comparatively to help evaluate tensiometer design. Greater sensitivity, large porous-cup surface area and permeability, and thin porous-cup walls are characteristics of a tensiometer with a short response time. Use of a sensitive pressure transducer is the most effective way to decrease response time in a soil of low hydraulic conductivity.

5.15 A bubble that interrupts hydraulic continuity between the porous cup and the pressure sensor will cause a change in the calculated value of P_W as follows:

$$\Delta = (E_P - E_C)\,\rho_{H_2O} \quad (13)$$

where:

Δ = the change in the calculated value of P_W, in centimetres of water at 4°C,

E_P = the elevation of the end of the bubble nearest the pressure sensor, in centimetres,

E_C = is the elevation of the end of the bubble nearest the cup, in centimetres, and

ρ_{H_2O} = the density of water adjacent to the air bubble, in grams centimetre^{-3}.

If bubbles are detected and measured, the above correction(s) can be made to P_W as calculated in Eq 5 or Eq 8. Small bubbles that cling to the wall of the tubing and do not block the entire cross-section do not affect the calculated value of P_W.

6. Procedure

6.1 *Construction and Applications*:

6.1.1 The definitions used to describe the quality of a measurement and used in Table 1 to compare types of tensiometers are given in Section 2.

6.1.2 The operating characteristics of commonly available tensiometers vary (see Table 1) and they need to be matched to the specific installation, cost constraints, and the desired quality of data collection. Complete tensiometers may be purchased from soils and agricultural research companies, made entirely from parts, or made from parts of commercial

TABLE 1 Tensiometer Characteristics

Characteristic	Commercial		Constructed			
	Vacuum Gage	Manometer (Hybrid)	Manometer		Pressure Transducer	
			Small Diameter	Hybrid	Small Diameter	Hybrid
Accuracy	Poor	Excellent	Excellent	Excellent	Good to excellent	Good to excellent
Precision[A]	Poor	Good	Good	Good	Excellent	Excellent
Hysteresis	Poor	Excellent	Excellent	Excellent	Fair to excellent	Fair to excellent
Response time	Poor to excellent	Fair	Fair	Fair	Excellent	Excellent
Versatility of application	Fair	Fair	Excellent	Fair	Excellent	Fair
Durability	Good	Good	Good to excellent	Good	Good	Good
Purging	Seldom	Occasionally	Often	Occasionally	Often	Occasionally
Recalibration	Occasionally	Never	Never	Never	Often	Often
Data-collection method	Manual	Manual	Manual	Manual	Manual or automatic	Manual or automatic
Cost of Five[B]	$260.00	$200.00	$120.00[C]	$150.00	$410.00[D]	$440.00[D]

[A]Precision (repeatability) is rated for either a wetting or drying cycle to distinguish from hysteresis effects.
[B]Estimated for five 0.914 m (3-ft) deep tensiometers.
[C]Does not include cost of deaerating water.
[D]Does not include cost of deaerating water or recording equipment.

units modified to suit the user's needs. The advantages and disadvantages of some of the different types are discussed in the following sub-sections and in Table 1.

6.1.3 Commercially available vacuum-gage-type units (see Fig. 2(*b*)) usually have a large diameter porous cup cemented to a rigid plastic tube of equal diameter (19 or 22 mm). A vacuum gage that indicates from 0 to 100 centibars of tension is screwed into the side of the tube, several centimetres below the top. The space between the vacuum gage and the top of the tube is a reservoir for air (the water may or may not be deaerated beforehand) to collect. When the water level inside the tube approaches the vacuum-gage inlet, the tube cap is unscrewed and the air space is refilled with water. Some vacuum-gage tensiometers have a large water reservoir connected to the top of the tube with a spring-loaded valve to simplify refilling.

6.1.4 The advantages of vacuum-gage tensiometers include simplicity of use, relatively low cost, and the maintenance of a hydraulic connection between the porous cup and gage, even with large quantities of air present. However, this last advantage is typically offset by the use of a vacuum gage with a resolution of 0.5 centibar (5 cm H_2O) and an overall accuracy of 3 centibars (31 cm H_2O). Response time is excellent immediately after removing all air, but it slows rapidly as the air reservoir fills up. Efforts can be made to minimize thermal effects on the air column by shielding it from the sun. The construction is fairly durable, but its rigidity can transfer shock and actually damage the porous cup, cup-tube bond, or hydraulic connection with the soil if the top is impacted after installation. Although the tube usually is installed vertically, it can be inclined to a nearly horizontal orientation as long as the zero adjustment of the vacuum gage is made at the same inclination. Installations greater than 45° from the vertical are more likely to have air accumulation problems.

6.1.5 A vacuum-gage tensiometer is used predominantly for irrigation scheduling where extreme accuracy is not necessary. It is not recommended for measurement of unsaturated hydraulic gradients **(33)**. However, replacement of a standard vacuum gage with a more accurate, higher-resolution gage, or with an accurate pressure transducer, would improve the usability of the tensiometer.

6.1.6 In this guide, a tensiometer with a large diameter cup-tube assembly connected to the pressure sensor with small-diameter (3.2 mm, for example) tubing is referred to as a hybrid tensiometer (see Fig. 2(*a*)). Hybrid tensiometers, like vacuum-gage tensiometers, have a space at the top of the large tube to collect air. Hydraulic continuity is not broken, unless air bubbles block an entire cross-section of the small-diameter tubing.

6.1.7 Commercial manometer-type tensiometers commonly are hybrid types. Almost all of the air that enters the tensiometer through the porous cup collects harmlessly at the top. However, air also tends to be liberated from solution near the top of the manometer, where the maximum tension occurs; use of deaerated water minimizes air production.

6.1.8 A mercury manometer is probably the most accurate pressure-sensor commonly used in tensiometers and it never needs calibrating (a water manometer, usable only in special cases, is more accurate because of a better resolution). Hysterisis in a manometer tensiometer (from surface tension at the interface) or pressure-transducer tensiometer is usually much less than that in a vacuum-gage tensiometer. Thus, the hybrid-manometer tensiometer and pressure-transducer tensiometer combine fairly maintenance-free operation with excellent accuracy.

6.1.9 The major advantages of constructing a manometer tensiometer with small-diameter tubing are the versatility of onsite application, accuracy, and low cost. Flexible nylon tubing can be routed around obstructions, connecting a porous cup to a gage hundreds of feet away. Installation orientation is limited only by backfilling capabilities. A typical design **(30)** employs two 3.2 mm-diameter (nominal ⅛-in.-diameter) nylon tubes cemented with epoxy directly to a 9.5 mm-diameter (nominal ⅜-in.-diameter) porous cup (see Fig. 3(*a*)). The water-supply tube is connected via a shutoff valve to a deaerated water supply and the measurement tube is routed directly to the mercury reservoir. Manometer sensitivity (*S*, see Eq 11) is the reciprocal of the cross-sectional area of the manometer tubing; response time is minimized by using small-diameter tubing. The design is simple, but the epoxy-nylon-tube bond is somewhat susceptible to rupture, from differential movement of the nylon tubes. A more robust design (see Fig. 3(*b*)) uses a larger porous cup and a metal plate to separate the nylon tubes, allowing the epoxy to form a stronger bead around the tubes. A third design (see Fig. 3(*c*)) uses a porous tube, made by cutting the rounded end off a 6.4 mm-diameter (nominal ¼-in.-diameter) porous cup. One of the nylon tubes is molded into a "U" shape with heat, to produce the design in Fig. 3(*c*). The third design is extremely durable and versatile. The porous tube can be purged of air in any orientation, which is not entirely true of designs (*a*) and (*b*).

6.1.10 Tensiometers tend to collect air bubbles onsite that originate from the following: insufficiently deaerated water; air that diffuses through the water-filled pores of the porous cup; dissolved gases in the soil moisture that flow into the porous cup during a wetting cycle; and air that diffuses through the tubing material.

6.1.11 The major disadvantage of the small-diameter designs is that air bubbles can easily block the entire cross-section of the tubing, interrupting hydraulic continuity. Thus, small-diameter designs require frequent purging of air—especially at large tensions. Use of a thick-walled tubing decreases diffusion through the tube wall. Some plastics (such as polyethylene) are relatively permeable to air and are unsatisfactory tubing material. Use of metal tubing almost eliminates air diffusion through the tube wall, however, other adverse affects can occur from the use of materials that have a high thermal conductivity.

6.1.12 A hybrid-manometer tensiometer can be constructed for two-thirds to three-fourths the price of a commercial unit. The cost in Table 1 was determined for five "cup-tube kits" purchased at a supply company and outfitted with a manometer made from parts. A cup-tube kit consists of a porous cup cemented to a stoppered acrylic tube with a fitting to accept 1.6 mm-diameter (nominal 1⁄16-in.-diameter) manometer tubing. The manometer tubing extends to the bottom of the acrylic tube. The cost could be decreased further by assembling the entire unit from basic parts.

6.1.13 Tensiometers equipped with pressure transducers are well-suited to collect large quantities of data. Measurements can be made often and recorded automatically by a data logger or a strip-chart recorder. The extreme sensitivity of the pressure transducer results in the shortest time constant obtainable, making this type of tensiometer ideal for tracking wetting fronts. However, the extreme sensitivity also results in the transducer becoming susceptible to measuring transient-temperature effects **(34)**, caused by thermal expansion and contraction of water or air, or both, in the tensiometer. Water that freezes inside a pressure-transducer cavity will affect the calibration, and it can rupture the unit. Pressure transducers (and above-ground connecting tubing) can be enclosed in an insulated (and, if need be, heated) shelter or surface pit to minimize temperature fluctuations. The shelter or pit needs to be located so that it does not disturb the natural flow field at the porous cup(s).

6.1.14 Sensing elements of a typical pressure transducer are semiconductive resistors, embedded in a diaphragm that moves from applied pressure(s). As the resistors shorten or lengthen, their resistances change. Inherently, the resistance is a nonlinear function of pressure (or pressure difference) and temperature. The resistors are included in a modified Wheatstone bridge, excited by a regulated voltage (or current) source. The output of the bridge is a nearly linear function of pressure that is independent of temperature; however, all pressure transducers retain some nonlinearity and a slight temperature dependence **(35)**. In addition, the zero offset and, to a lesser extent, the sensitivity may change with time (known as drift), possibly requiring recalibration at regular intervals **(35)**. Other sources of error are repeatability and pressure and temperature hysteresis effects **(35)**. Onsite application determines required pressure-transducer specifications; for example, gradient-measurement normally warrants a more accurate transducer than simple pressure measurement does.

6.1.15 A large degree of accuracy may be achieved in a variety of ways. A sophisticated pressure transducer costing seven to eight hundred dollars typically has an overall accuracy of 1 cm H_2O, at 23°C, and a temperature coefficient of 0.07 cm $H_2O\ °C^{-1}$. Without temperature correction, a worst-case error (at 0°C) of 2.6 cm H_2O could result. At the other extreme, a simple pressure transducer may be purchased for about fifty dollars and its output may be corrected for nonlinearity and temperature dependence by measuring temperature and applying a second-order polynomial fit to the measured data **(36)**. The decreased linearity and temperature errors, combined with a typical repeatability and hysteresis error of 1.5 cm H_2O, produce a root-sum-square error of 1.8 cm H_2O. Such a transducer is listed in Table 1. Of course, the same curve-fitting procedure can be applied to a pressure transducer with better repeatability and hysteresis to achieve greater accuracy.

6.1.16 Accuracies determined in the two examples discussed in 6.1.15 further are degraded by drift or lack of long-term-stability. If a long-term-stability specification cannot be supplied by the pressure-transducer manufacturer, much of the data collected may be inaccurate. A long-term-stability specification is used to determine how often a transducer needs to be recalibrated to maintain desired accuracy. A hanging column of water or mercury (or a calibrated vacuum source) is used for initial and then periodic recalibration.

6.1.17 Air that collects in an automated-tensiometer system can be purged manually or automatically at regular intervals using solenoid valves triggered by a data logger. Air collects more rapidly when tension is greater; onsite experience will determine the necessary time interval to maintain desired accuracy. The time interval can be maximized by using horizontal sections of tubing at high points in the system. Bubbles that collect in these horizontal sections do not cause errors but they do increase the response time.

6.1.18 Porous cups used in tensiometers remain saturated during normal operation. If the difference between air pressure outside the porous cup and water pressure inside the cup exceeds the bubbling pressure of the cup, air will displace the water in the largest pores and eventually will enter the interior of the cup. The more commonly used tensiometer cups have a bubbling pressure of 1 bar (1020 cm H_2O). Porous cups with bubbling pressures of 2, 3, and 5 bars are available, but they only have applications in the laboratory. If onsite tensions are known to not exceed 0.5 bar, a porous cup with a 0.5-bar bubbling pressure can be used to decrease response time.

However, a better way to decrease response time is by the use of commonly available, "high-flow" porous cups, made with a pore-size distribution that emphasizes the larger pores. (Cost of a porous cup is between two and fifteen dollars. Larger porous cups are more expensive than smaller ones, and high-flow-cups are more expensive than standard-flow-cups.)

6.1.19 Specialized tensiometers have been developed to address specific onsite problems. Peck and Rabbidge **(35)** extended the upper limit of measurable tension by using a reference solution with a low osmotic potential and a porous cup coated with a semipermeable membrane. Using a pressure transducer, soil-water tensions as large as 153 m H_2O (15 bars) can be measured. The solution in the tensiometer usually is under positive pressure, thus decreasing the problem of air invasion. However, the pressure can be quite large and it could cause permanent "creep" of the transducer diaphragm. Depolymerization of the solute and subsequent loss through the membrane also could cause creep. Ambient temperature affects the osmotic potential directly (as qualitatively predicted by van't Hoff's law) and indirectly by causing flow of water through the membrane. Thus, an osmotic tensiometer is valuable for measuring extremely low matric potentials, but some sources of measurement error are unique to it.

6.1.20 The U.S. Forest Service developed an inexpensive recording tensiometer for use in remote areas where electric power is unavailable **(31)**. This instrument can record as much as 1 month of continuous data on a battery-driven raingage chart. Oaksford **(27)** designed a unit based on a coaxial water manometer that provides maximum sensitivity at depths as deep as about 6 m. This unit uses a calibrated wire and ohmmeter to sense a below-ground, free-water surface inside the unit.

6.1.21 Fluid-scanning switches have been used successfully **(20, 34, 37, 38)** to connect as many as 22 tensiometers sequentially to a single pressure transducer. The approach minimizes cost and removes the bias between tensiometers caused by using different pressure transducers. Equally relevant, this network has the capability of measuring a zero and a full-scale calibration tension before each scan. This capability removes measurement errors from hysteresis, temperature dependence, and long-term drift. However, if the pressure transducer fails, data from all its tensiometers are lost. Also, the scanning switch is made with precise tolerances and it may develop leaks over time.

6.1.22 Another approach to efficient data collection with large numbers of tensiometers **(25, 39)** is to connect a portable pressure transducer to each tensiometer using a hypodermic needle and septum. The needle tip is inserted in an air space above the tensiometer fluid. A small change in tensiometer pressure is caused by the connection, probably affecting measurements by a few cm H_2O. Also, changes in the fluid-surface elevation, although small, affect measurements directly unless the changes are accounted for.

6.1.23 A small proportion of water in a frozen soil may remain liquid and, therefore, mobile. Measurement of tension in frozen soils can be accomplished using a pressure transducer and ethylene glycol **(26)** as a tensiometer fluid. The pressure transducer minimizes exchange of fluid between the soil and tensiometer, but slight bulk flow and diffusive flux do occur that decrease the freezing point of the soil fluid. The osmotic tensiometer probably will work well in frozen soils.

6.1.24 Porous cups have been connected directly to pressure transducers; the internal cavity has been filled with deaerated fluid and the entire assembly has been buried in a soil, with no provisions for purging of the fluid **(19, 32)**. Although this approach provides a stable temperature environment, the pressure transducer cannot be recalibrated readily for drift. Also, soil gas diffusing through the porous cup creates an air pocket in the cavity. Because this pocket is at a pressure less than that of the soil gas, air will continue to diffuse through the porous-cup wall, eventually emptying the cup of water. A purging system is needed for extended undisturbed operation.

6.1.25 The specialized tensiometers developed thus far have resulted from insight and persistence of researchers faced with particular problems. Most of these solutions require extra effort, care, and expense; review of the cited report(s) is needed before implementation.

6.2 *Installation*:

6.2.1 Continuous hydraulic connection between the porous cup and soil **(18)**, and minimal disturbance of the natural flow field are essential to collection of accurate tensiometric data. When a hole is made to accept the tensiometer, the cuttings need to be preserved in the order they were removed if the hole is to be backfilled.

6.2.2 Hydraulic connection can be established in several ways. Commercial tensiometers fit snugly into holes made with a coring tool (available as a tensiometer accessory) or made with standard iron pipe. The porous cup is forced against the hole bottom and no backfill is used. When the soil is rocky, or when a small-diameter tensiometer is installed, a hole larger in diameter than the porous cup is excavated. If the soil at the bottom of the hole is soft, the porous cup may be forced into the soil. A hard soil sometimes can be softened with water. If the porous cup will not penetrate the moistened soil, the last cuttings from the hole need to be used to backfill around the cup, either by making them into a slurry or by careful tamping. A tremie pipe ensures clean delivery of cuttings or slurry to the bottom of the hole. Gaps between the porous cup and soil increase the tensiometer response time by reducing the effective area of the porous cup. In the worst case, no hydraulic connection occurs and the tensiometer will not indicate the soil-water tension.

6.2.3 If water is used to establish hydraulic connection, the tension adjacent to the porous cup will be reduced, and it will recover asymptotically as the added water is dispersed in the soil. The rate of dispersal will depend on the K (see Eq 1) of the soil and a time series of tension will indicate when natural conditions are restored sufficiently.

6.2.4 If vertical profiles or gradients of pressure are to be measured, multiple small-diameter tensiometers can be installed in a single hole. Ideally, the original lithology is duplicated (except that gravel larger than 6 mm in diameter and cobbles and boulders can be removed) by using the cuttings in reverse order for backfilling. A backfill that is more compacted than the undisturbed soil will tend to shed infiltrating water, but, after a short time, the tension in the undisturbed soil and in the backfill will be in equilibrium. A backfill that is less compacted than the surrounding soil, or one with excessive gaps, will be a conduit for infiltrating water, resulting in abnormally low tensions in the backfill and in the undisturbed soil. Therefore, compaction of the backfill to a slightly greater bulk density than that of the undisturbed soil is desirable. Less permeable layers (such as clay lenses) need to be reproduced or even exaggerated by importing a fine-grained material.

6.2.5 Deep installation of tensiometers can be accomplished by drilling horizontal holes radially from a central caisson hole. This method also preserves undisturbed conditions above and below each porous cup. Backfilling horizontal holes with a tamping rod is painstaking. An alternative is to backfill in the vicinity of the porous cup and to fill the remainder of the hole with an expanding insulation foam. Pressure transducers work particularly well in caisson holes. If the entire length of tubing connecting the porous cup to the pressure transducer is horizontal, air bubbles do not cause errors. Also, the problem of transducer sensitivity to temperature change is minimized, because temperature in the caisson hole remains relatively constant. A caisson hole allows use of water manometers for improved precision because the entire manometer can be placed below the level of the porous cup.

6.3 *Operation*:

6.3.1 Testing the porous cup, the porous cup-tubing interface, all fittings, and the measurement and recording device(s), before installation, is desirable. After saturating the porous cup, apply air pressure to the interior of the tensiometer while the parts to be tested are submersed. If bubbles appear at a gage pressure substantially less than the bubbling pressure of the porous cup, the unit is faulty and the appropriate parts need to be repaired or replaced.

6.3.2 Water used in tensiometers is deaerated in a carboy by applying a vacuum or heat, or both. Excellent results have been obtained using a pump that generates 970 cm H_2O vacuum with a heated magnetic stirrer for 48 h. Insufficiently deaerated water requires frequent onsite purging, or, in the worst case, allows bubbles to form before a tensiometer has reached equilibrium, preventing accurate data collection. The deaerated water is siphoned (to minimize reaeration) from the carboy to a collapsible plastic container (available at a sporting goods store) for onsite use. Although the air above the water is forced out of the spout immediately, the water reaerates slowly by diffusion of air through the container wall. Proper fittings should be used to connect the container spout to the tensiometer supply tube. Use of water native to the soil being measured will minimize the effect of osmotic potential across the cup on the measured matric potential.

6.3.3 Purge a small-diameter tensiometer by connecting the water supply container to the water supply tube and raising it above the top of the tensiometer, while opening the supply valve. Several tensiometers can be connected in a "tee" network to simplify multiple purging. Purging instructions for vacuum-gage and hybrid tensiometers are supplied by the manufacturer. These instructions can be modified if use of deaerated water is desired. Purging time needs to be short to minimize wetting of the soil immediately surrounding the porous cup. When purging is complete, the system is closed and the soil draws water through the porous cup until equilibrium is established. The pressure inside the porous cup approaches the soil-water pressure asymptotically at a rate determined by the time constant and the unsaturated hydraulic conductivity of the soil. When equilibrium is reached, make the measurement. Record a single value of pressure when using a vacuum-gage or pressure transducer; a manometer requires measurement of the mercury column and reservoir elevations.

6.3.4 The most reliable data are obtained by purging a tensiometer and allowing it to equilibrate before recording the measurement. However, wet soils, lack of wetting fronts, low permeability tubing, or thoroughly deaerated water tend to prevent air accumulation for long periods; these conditions, either singly or in combination permit reliable data collection without purging.

6.3.5 Dry soils or inadequate manometer design, or both, occasionally result in mercury being pulled over the top of the manometer and into the porous cup. The porous cups shown in Fig. 3 may be purged of mercury by applying pressure to the measurement tube, forcing mercury out the supply tube. Pressure applied to the top of a hybrid tensiometer will force the mercury out the measurement tube.

6.3.6 Porous cups that are removed from a soil to be reused need to be washed with warm water to prevent plugging of the pores. A porous cup with plugged pores possibly can be restored by sanding or rinsing in a weak HCl solution **(33)**.

REFERENCES

(**1**) Healy, R. W., Peters, C. A., DeVries, M. P., Mills, P. C., and Moffett, D. L., "Study of the Unsaturated Zone at a Low-Level Radioactive-Waste Disposal Site near Sheffield, Ill.," *Proceedings*, National Water Well Association Conference on Characterization and Monitoring of the Vadose Zone, Los Vegas, NV, Dec. 1983, pp. 820–831.

(**2**) McMahon, P. B., and Dennehy, K. F., "Water Movement in the Vadose Zone at Two Experimental Waste-Burial Trenches in South Carolina," *Proceedings*, National Water Well Association Conference on Characterization and Monitoring of the Unsaturated (Vadose) Zone, Denver, CO, Nov. 1985, pp. 34–54.

(**3**) Ripp, J. A., and Villaume, J. F., "A Vadose Zone Monitoring System for a Flyash Landfill," *Proceedings*, National Water Well Association Conference on Characterization and Monitoring of the Unsaturated (Vadose) Zone, Denver, CO, Nov. 1985, pp. 73–96.

(**4**) Ryan, B. J., DeVries, M. P., Garklavs, George, Gray, J. R., Healy, R. W., Mills, P. C., Peters, C. A., and Striegl, R. G., "Results of Hydrologic Research at a Low-Level Radioactive-Waste Disposal Site Near Sheffield, Illinois," *U.S. Geological Survey Water-Supply Paper 2367*, 1991.

(**5**) Lichtler, W. F., Stannard, D. I., and Kouma, E., "Investigation of Artificial Recharge of Aquifers in Nebraska," *U.S. Geological Survey Water-Resources Investigations Report 80-93*, 1980.

(**6**) Sophocleous, Marios, and Perry, C. A., "Experimental Studies in Natural Groundwater Recharge Dynamics: Analysis of Observed Recharge Events," *Journal of Hydrology*, Vol 81, 1985, pp. 297–332.

(**7**) Anderson, E. M., "Tipburn of Lettuce. Effect of Maturity, Air and Soil Temperature, and Soil Moisture Tension," Cornell Agricultural Experimental Station, *Bulletin*, No. 829, Cornell University, New York, 1946.

(**8**) Richards, L. A., and Neal, O. R., “Some Field Observations with Tensiometers,” *Proceedings*, Soil Science Society of America (1936), Vol 1, 1937, pp. 71–91.

(**9**) Richards, S. J., Willardson, L. S., Davis, Sterling, and Spencer, J. R., “Tensiometer Use in Shallow Ground-Water Studies,” *Proceedings*, American Society of Civil Engineers, Vol 99, No. IR4, 1973, pp. 457–464.

(**10**) McKim, H. L., Walsh, J. E., and Arion, D. N.,“ Review of Techniques for Measuring Soil Moisture In Situ,” *U.S. Army Corps of Engineers, Cold Regions Research and Engineering Lab Special Report 80-31*, 1980.

(**11**) Richards, L. A., Russell, M. B., and Neal, O. R., “Further Developments on Apparatus for Field Moisture Studies,” *Proceedings*, Soil Science Society of America, Vol 2, 1938, pp. 55–64.

(**12**) Richards, L. A., “Methods of Measuring Soil Moisture Tension,” *Soil Science*, Vol 68, 1949, pp. 95–112.

(**13**) Richards, L. A., “Capillary Conduction of Liquids through Porous Mediums,” *Physics 1*, 1931, pp. 318–333.

(**14**) Baver, L. D., Gardner, W. H., and Gardner, W. R., *Soil Physics*, Wiley, New York, 1972, pp. 291–296.

(**15**) Brooks, R. H., and Corey, A. T., “Hydraulic Properties of Porous Media,” *Hydrology Papers*, No. 3, Colorado State University, Fort Collins, CO, 1964.

(**16**) Marshall, T. J., “Relations Between Water and Soil,” Commonwealth Bureau of Soil Science, England, *Technical Communication* No. 50, 1960.

(**17**) Haverkamp, R., Vauclin, M., Touma, J., Wierenga, P. J., and Vachaud, G., “A Comparison of Numerical Simulation Models for One-Dimensional Infiltration,” *Soil Science Society of America Journal*, Vol 41, 1977, pp. 285–294.

(**18**) Richards, L. A., and Gardner, W., “Tensiometers for Measuring the Capillary Tension of Soil Water,” *Journal of American Society of Agronomy*, Vol 28, 1936, pp. 352–358.

(**19**) Bianchi, W. C., “Measuring Soil Moisture Tension Changes,” *Agricultural Engineering*, Vol 43, 1962, pp. 398–404.

(**20**) Bianchi, W. C., and Tovey, Rhys, “Continuous Monitoring of Soil Moisture Tension Profiles,” *Transactions*, American Society of Agricultural Engineers, Vol 11, No. 3, 1968, pp. 441–447.

(**21**) Colman, E. A., Hanawalt, W. B., and Burck, C. R., “Some Improvements in Tensiometer Design,” *Journal of the American Society of Agronomy*, Vol 38, 1946, pp. 455–458.

(**22**) Healy, R. W., deVries, M. P., and Striegl, R. G., “Concepts and Data-Collection Techniques Used in a Study of the Unsaturated Zone at a Low-Level Radioactive-Waste Disposal Site Near Sheffield, Illinois,” *U.S. Geological Survey Water-Resources Investigations Report 85-4228*, 1986.

(**23**) Hunter, A. S., and Kelley, O. J., “Changes in the Construction of Soil Moisture Tensiometers for Field Use,” *Soil Science*, Vol 61, 1946, pp. 215–218.

(**24**) Klute, A., and Peters, D. B., “A Recording Tensiometer with a Short Response Time,” *Proceedings*, Soil Science Society of America, Vol 26, 1962, pp. 87–88.

(**25**) Marthaler, H. P., Vogelsanger, W., Richard, F., and Wierenga, P. J., “A Pressure Transducer for Field Tensiometers,” *Soil Science Society of America Journal*, Vol 47, 1983, pp. 624–627.

(**26**) McKim, H. L., Berg, R. L., McGraw, R. W., Atkins, R. T., and Ingersoll, J., “Development of a Remote-Reading Tensiometer Transducer System for Use in Subfreezing Temperatures,” *Proceedings*, American Geophysical Union Second Conference on Soil-Water Problems in Cold Regions, Edmonton, Alberta, 1976, pp. 31–45.

(**27**) Oaksford, E. T., “Water-Manometer Tensiometers Installed and Read from the Land Surface,” *Geotechnical Testing Journal*, Vol 1, No. 4, 1978, pp. 199–202.

(**28**) Peck, A. J., and Rabbidge, R. M., “Design and Performance of an Osmotic Tensiometer for Measuring Capillary Potential,” *Proceedings*, Soil Science Society of America, Vol 33, 1969, pp. 196–202.

(**29**) Richards, L. A., “Soil Moisture Tensiometer Materials and Construction,” *Soil Science*, Vol 53, 1942, pp. 241–248.

(**30**) Stannard, D. I., “Theory, Construction, and Operation of Simple Tensiometers,” *Ground Water Monitoring Review*, Vol 6, No. 3, 1986, pp. 70–78.

(**31**) Walkotten, W. J., “A Recording Soil Moisture Tensiometer,” *U.S.D.A. Forest Service Research Note PNW-180*, 1972.

(**32**) Watson, K. K., “A Recording Field Tensiometer with Rapid Response Characteristics,” *Journal of Hydrology*, Vol 5, 1967, pp. 33–39.

(**33**) Cassel, D. K., and Klute, A., “Water Potential: Tensiometry,” American Society of Agronomy—Soil Science Society of America, *Agronomy Monograph* No. 9 (Second Edition). *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, 1986, pp. 563–596.

(**34**) Rice, Robert, “A Fast-Response, Field Tensiometer System,” *Transactions*, American Society of Agricultural Engineers, Vol 12, 1969, pp. 48–50.

(**35**) Omega Engineering, Inc., *Omega 1987 Complete Pressure, Strain and Force Measurement Handbook and Encyclopedia*, Dec 1986.

(**36**) Micro Switch, Freeport, Illinois, *Pressure Sensors, Catalog 15*, 1985.

(**37**) Fitzsimmons, D. W., and Young, N. C., “Tensiometer-Pressure Transducer System for Studying Unsteady Flow Through Soils,” *Transactions*, American Society of Agricultural Engineers, Vol 15, No. 2, 1972, pp. 272–275.

(**38**) Williams, T. H. Lee, “An Automatic Scanning and Recording Tensiometer System,” *Journal of Hydrology*, Vol 39, 1978, pp. 175–183.

(**39**) Haldorsen, Sylvi, Petsonk, A. M., and Torstensson, B. A., “An Instrument for In Situ Monitoring of Water Quality and Movement in the Vadose Zone,” *Proceedings*, National Water Well Association Conference on Characterization and Monitoring of the Unsaturated (Vadose) Zone, Denver, CO, Nov. 1985, pp. 158–172.

(**40**) Mualem, Yechezkel, “A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media,” *Water Resources Research*, Vol 12, No. 3, 1976, pp. 513–522.