Designation: D3404 – 91(Reapproved 2004)

Standard Guide for Measuring Matric Potential in Vadose Zone Using Tensiometers[1]

This standard is issued under the fixed designation D3404; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

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 concerns, 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

---

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Groundwater and Vadose Zone Investigations.

Current edition approved July 1, 2004. Published July 2004. Originally approved in 1991. Last previous edition approved in 1998 as D3404 - 91 (1998). DOI: 10.1520/D3404-91R04.

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

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 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, θ[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 atm, except as noted. Various units are used to express tension or pressure of soil water, and are related to each other by the equation:

$$1.000\ \text{bar} = 100.0\ \text{kPa} = 0.9869\ \text{atm} = 1020\ \text{cm of water at } 4°\text{C} = 1020\ \text{g per cm}^2 \text{ in a standard gravitational field.} \quad (4)$$

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*)):

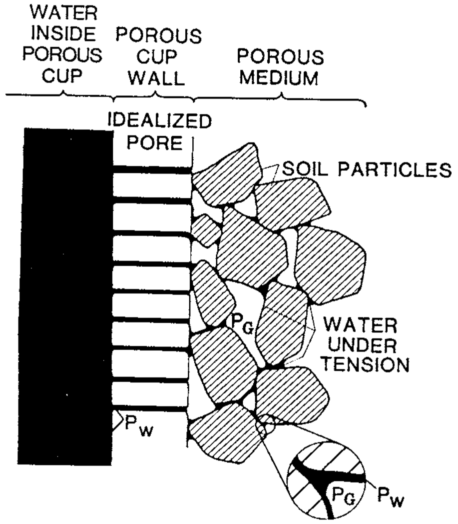
$$T_W = P_A - P_W = (\rho_{Hg} - \rho_{H_2O})r - \rho_{H_2O}(h+d) \quad (5)$$

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,



P_W–Absolute pressure of soil water
P_G–Absolute pressure of soil gas

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

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 8 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

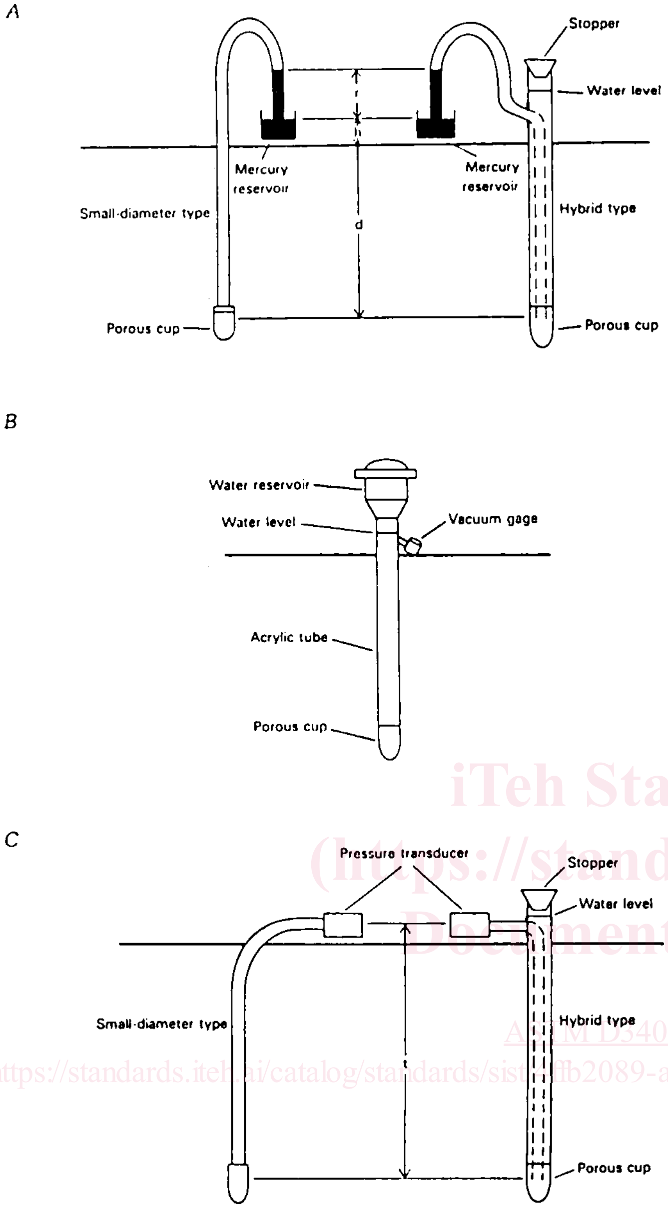


FIG. 2 Three Common Types of Tensiometers: (a) Manometer; (b) Vacuum Gage; and (c) Pressure Transducer

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.

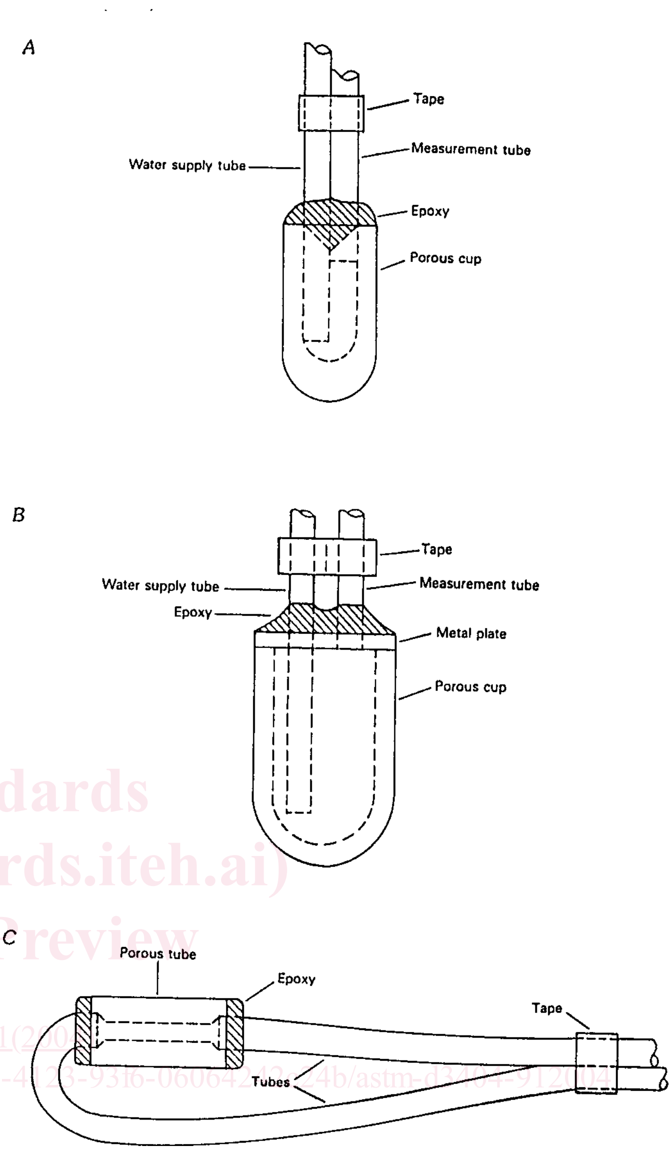


FIG. 3 Porous-Cup and Tube Designs

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*)):

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

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 12 indicates that a "trade-off" occurs between depth of installation of the porous cup and the maximum tension measurable; Eq 13 sets the upper limit of that tension. Eq 12 and Eq 13 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 centimetres^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 centimetres^{-2}.

Also, the porous cup conductance may be expressed as:

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

where:

K_c = the cup conductance, in centimetres^2 second $^{-1}$,
k = the permeability of the cup material to water at the prevailing temperature, in centimetres second^{-1},
A = the average surface area of porous-cup material, estimated as the mean of the inside area and the outside area, in centimetres^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 $\textit{response time}_1 > \textit{response time}_2$. 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 = 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 8 or Eq 11. 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 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

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.