

# **REVIEW OF VADOSE ZONE MEASUREMENT AND MONITORING TOOLS FOR YUCCA MOUNTAIN PERFORMANCE CONFIRMATION PROGRAM**

*Prepared for*

**U.S. Nuclear Regulatory Commission  
Contract NRC-02-02-012**

*Prepared by*

**Dani Or  
Professor of Soil & Environmental Physics  
School of Architectural, Civil and Environmental Engineering  
Ecole Polytechnique Federale de Lausanne  
Lausanne, Switzerland**

**Markus Tuller  
Soil and Land Resources Division  
University of Idaho  
Moscow, Idaho 83844-2339**

**Stuart Stothoff  
Center for Nuclear Waste Regulatory Analyses  
San Antonio, Texas**

**July 2006**

## PREVIOUS REPORTS IN SERIES

Number	Name	Date Issued
CNWRA 2004-06	Performance Confirmation Activities Under 10 CFR Part 63 with Emphasis on Activities Potentially Significant to Waste Isolation	September 2004
CNWRA 2000-06	Assessment of Methodologies to Confirm Container Performance Model Predictions	September 2000

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## ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-02-012. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety. This report is an independent product of CNWRA and does not necessarily reflect the view or regulatory position of NRC.

The authors acknowledge R. Fedors and C. Dinwiddie for their thorough technical review and useful insight, and G. Wittmeyer for his editorial and programmatic reviews. The administrative support provided by J. Gonzalez and P. Houston is greatly appreciated.

## QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

**DATA:** All CNWRA-generated original data contained in this report meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources for other data should be consulted for determining the level of quality for those data. No original data were generated from the analyses presented in this report.

**ANALYSES AND CODES:** No codes were used in the analyses contained in this report.

**PRODUCT DESCRIPTION:** Most methods discussed in this report are illustrated with at least one example to demonstrate how the method is implemented. There is no intent to provide an exhaustive catalog of manufacturers or products. Any use of trade, product, or firm names in this publication is for descriptive or illustrative purposes only and does not imply endorsement by CNWRA or NRC.

## EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004) documents recent DOE intentions for performance confirmation activities at the potential repository at Yucca Mountain. The Performance Confirmation Plan does not represent a final plan for confirmation activities, and technical details of the activities have not been fully developed. A preliminary review of the Performance Confirmation Plan identified several ongoing and planned future performance confirmation activities that would occur in the vadose zone. All of the planned vadose-zone activities are identified as occurring in facilities at the repository horizon. By implication, all characterization and monitoring activities in the vadose zone during performance confirmation will use sensors emplaced in fractured rock (most likely within boreholes drilled from the repository) or cavities in the rock (e.g., drifts, niches, and alcoves). Many of the sensors used for performance confirmation will experience elevated temperatures in the thermally accelerated drifts that will be used to mimic postclosure conditions, in which access for maintenance and upgrades may be severely restricted.

The activities listed in the Performance Confirmation Plan suggest that DOE may wish to use sensors for measuring water content, matric potential, temperature, relative humidity, and water and gas fluxes, and DOE may also wish to obtain pore water for additional analyses. The current state of the art in sensor technology for these applications is reviewed in this document to provide baseline information on the suite of sensors that are available for characterization and monitoring activities in the vadose zone.

The review of available sensor technology suggests that the technology for measuring water content, matric potential, and water and gas fluxes, as well as for obtaining pore water samples, is most fully developed for unconsolidated porous media, as soil science is the primary area of application and development. Findings from the technology review include:

- Water content sensors: A wide variety of approaches are brought to bear on measuring water content. The available methods resolve water content over a wide range in porous media, but some of the methods may not be suitable for fractured rock. Sensor development is proceeding rapidly in some areas. It is not clear how robust these sensors are under elevated temperatures.
- Matric potential sensors: Matric potential is also determined with a variety of methods, but no single method works over the entire range of potentials that may be observed in the field. Each of the methods may be applied to the rock matrix. It is not clear how robust these sensors are under elevated temperatures.
- Pore water samplers: Several sampling techniques are available for extracting pore water. *In situ* techniques may be extremely slow to extract water from the rock matrix.
- Temperature sensors: Temperature sensors infer temperature from the known response of an engineered component to temperature. Industrial applications have provided relatively robust, reliable, and maintenance-free sensors that may be applied over the range of temperatures that may be observed in the field.

- Relative humidity sensors: A variety of methods are used to measure relative humidity. Industrial applications have provided relatively robust, reliable, and maintenance-free sensors. It is not clear how well these sensors perform under elevated temperatures.
- Water flux sensors: Two methods are available to directly measure *in situ* water flux, but significant development is required before either would be applied to fractured rock. It is not clear how well these sensors would perform under elevated temperatures.
- Gas flux sensors: No method exists for directly estimating *in situ* gas flux, although a device is available to estimate transfer between a porous medium and the atmosphere.

Two examples were presented to illustrate how current vadose-zone technology might be deployed to address measurement of percolation fluxes in the subsurface. One example shows how applied tracers might be used to estimate deep percolation fluxes, fast pathways, and lateral diversion. The other example documents several approaches that have been used to estimate shallow infiltration.

The review suggests that measurement activities occurring in fractured vadose-zone rock under ambient temperatures, with time horizons up to perhaps a few years, may be able to use current technology with little modification as long as appropriate maintenance access is available. It is reasonable to expect that the normal pace of technological development will continue to produce enhanced sensors and methodology for the shallow subsurface that may be adapted to hard and fractured rock, even if the rock applications themselves do not drive sensor development.

The review further suggests that current technology may not be adequate for some measurement activities with time horizons of years to decades, particularly if maintenance access is not available or elevated temperatures will occur. Sensors adapted from industry, such as temperature and relative humidity sensors, may be relatively robust and reliable under these conditions. Sensors with a less wide-spread applicability, such as water content, matric potential, water and gas flux sensors, and pore water samplers, may require significant additional development before the technology is capable of handling extended emplacement, especially under elevated temperatures. As there is a quite limited market for such products, it is reasonable to expect that technological development may only slowly produce enhanced sensors and methodology suitable for these more-demanding conditions.

## Reference

Bechtel SAIC Company, LLC. "Performance Confirmation Plan." TDR-PCS-SE-000001. Rev. 05 ICN 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004.

# 1 INTRODUCTION

Regulations governing the disposal of high-level radioactive waste at 10 CFR 63, Subpart F, require development of a Performance Confirmation Program for a potential repository in Yucca Mountain. The goal of the program is to confirm that the actual subsurface conditions and potential changes in these conditions during construction and waste emplacement operations are within the limits assumed during the licensing review. The Center for Nuclear Waste Regulatory Analyses (CNWRA), at the direction of the U.S. Nuclear Regulatory Commission (NRC), has reviewed the U.S. Department of Energy (DOE) proposed Performance Confirmation Program for long-term monitoring in the vadose zone. The DOE articulated their preliminary Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004) for the Performance Confirmation Program. The preliminary Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004) is referred to as the Performance Confirmation Plan, or Plan for short, throughout this report.

Section 2.1 of the Performance Confirmation Plan summarized the DOE interpretation of the regulatory requirements for the Performance Confirmation Program as

- Confirm that subsurface conditions, geotechnical and design parameters are as anticipated and that changes to these parameters are within limits assumed in the License Application
- Confirm that the waste retrieval option is preserved
- Evaluate information used to assess whether natural and engineered barriers function as intended
- Evaluate effectiveness of design features intended to perform a postclosure function during repository operation and development
- Monitor waste package condition

Vadose zone conditions played an important role in the selection of the potential repository location. Section 3.2 of the Performance Confirmation Plan identified the following vadose zone characteristics as being particularly important:

- A semiarid climate with limited precipitation
- A thickness of rock and soil above the repository of approximately 215 to 450 meters [705 to 1,480 ft]
- Hydrogeologic and geochemical characteristics that limit radionuclide movement
- Depth to groundwater below repository emplacement drifts from more than 215 meters to nearly 365 meters [705 to 1,200 ft]

These characteristics strongly influence the natural and engineered barriers intended to isolate waste, by minimizing contact with naturally occurring water fluxes and by retarding radionuclide

transport (by sorption and drift shadow) in the event of a breach of a waste package at the repository level.

The Performance Confirmation Program is an important component of the overall Yucca Mountain Project, assuring that the potential repository will perform as envisioned. The Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004) articulates the approaches that DOE intends to take for performance confirmation. The Performance Confirmation Plan is the initial attempt by DOE to define the activities that will occur during performance confirmation, and is subject to revision. Although the specific details of each activity remain to be finalized, the Plan suggests that DOE vadose zone performance confirmation activities will focus on *in situ* and in-drift moisture and energy balances at and below the repository horizon, and will consider conditions in and near thermally accelerated drifts. The activities listed in the Performance Confirmation Plan are summarized in Section 2 for reference.

DOE will emplace suites of sensors to carry out the performance confirmation activities. Based on the types of activities listed in the Performance Confirmation Plan, it is reasonable to assume that DOE may wish to consider sensors for water content, matric potential, temperature, relative humidity, and water and gas fluxes, and DOE may also wish to obtain pore water for additional analyses. Section 3, the bulk of this report, is a review of the techniques that are used for performing these types of measurements in the vadose zone, providing a snapshot of the strengths and weaknesses of current technology. Section 4 illustrates some of the capabilities of current technology with examples of hypothetical activities that might occur at a geologic repository, and Section 5 summarizes the findings on vadose zone characterization and monitoring methods.



## 2 VADOSE ZONE ACTIVITIES IN THE PERFORMANCE CONFIRMATION PLAN

The U.S. Department of Energy (DOE) developed a Performance Confirmation Plan (Bechtel SAIC Company, LLC, 2004) to ensure that repository performance lies within estimated or predicted parameters. Section 1.3 of the Performance Confirmation Plan defines eight stages for developing the Performance Confirmation Program:

- (1) Select performance confirmation parameters and test methods
- (2) Predict performance and establish a baseline
- (3) Establish bounds and tolerances for key parameters
- (4) Establish test completion criteria and variance guidelines
- (5) Plan activities, and construct and implement the Performance Confirmation Program
- (6) Monitor, test, and collect data
- (7) Analyze and evaluate data
- (8) Recommend corrective action in the case of variance

DOE narrowed the list of performance characterization activities to eleven ongoing and nine future activities as the basis for their proposed Performance Confirmation Plan, based on an evaluation of various aspects and alternatives related to repository performance and potential impact on total system performance. Sections 2.1 and 2.2 below quote the summary of these processes found in the Executive Summary of the Performance Confirmation Plan [bold italics (added) denote vadose zone processes].

### 2.1 Ongoing Activities

- (1) Precipitation monitoring (precipitation quantities and composition measured at the Yucca Mountain site)
- (2) ***Seepage monitoring (seepage monitoring and analysis in alcoves on the repository intake side and in repository thermally accelerated drifts)***
- (3) ***Subsurface water and rock testing (chloride mass balance and isotope chemistry analysis of water samples collected at selected underground locations)***
- (4) ***Unsaturated zone testing (field testing of transport and sorptive properties of unsaturated zone rock in an ambient seepage alcove or a drift with no waste packages emplaced)***
- (5) Saturated zone monitoring (measurements of water level, electrochemical potential, hydrogen potential, and background radionuclide concentrations in saturated zone wells at the repository site and in Nye County)
- (6) Saturated zone alluvium testing (tracer testing of alluvium transport properties in the Alluvial Test Complex)
- (7) ***Subsurface mapping (mapping of fractures, faults, stratigraphic contacts and lithophysal characteristics of rock in the underground openings)***

- (8) Seismicity monitoring (monitoring of regional seismic activity and observation of fault displacements following significant seismic events)
- (9) Construction effect monitoring (measurement of construction deformation of underground openings/confirmation of related rock mechanical properties)
- (10) Corrosion testing (laboratory samples testing of waste package, waste package pallet, and drip shield materials corrosion behavior in the range of expected repository environments)
- (11) Waste form testing (laboratory testing of waste form dissolution and waste package coupled effects including use of scale mockups of waste package)

## **2.2 Future Activities (Post Construction/Operation)**

- (12) Saturated zone fault zone hydrology testing (hydraulic and tracer testing in fault zones)
- (13) Drift inspection (periodic inspection of emplacement drifts and thermally accelerated drifts using remote inspection and measurement techniques)
- (14) ***Thermally accelerated drift near-field monitoring (monitoring of rock mass and water properties in the near-field of a thermally accelerated emplacement drift)***
- (15) Dust buildup monitoring (monitoring and laboratory evaluation of the quantity and composition of dust on engineered barrier surfaces and samples)
- (16) ***Thermally accelerated drift environment monitoring (monitoring and laboratory evaluations of environmental conditions in a thermally accelerated drift including gas and water compositions, temperatures, film depositions, microbes, radiation and radiolysis effects using remote techniques)***
- (17) Thermally accelerated drift thermal-mechanical effects monitoring (monitoring of drift and invert degradation in a thermally accelerated drift)
- (18) Seal testing (testing of effectiveness of borehole seals in the laboratory, shaft and ramp seals in the field, and backfill emplacement techniques)
- (19) Waste package monitoring (monitoring of integrity of waste packages using visual inspection and/or internal pressure measurement employing remote monitoring techniques)
- (20) Corrosion testing of thermally accelerated drift samples (laboratory testing of waste package, waste package pallet, and drip shield samples obtained from a thermally accelerated drift)

## **2.3 Observations**

The Performance Confirmation Plan conceptually describes repository performance as attributable to three barriers: (i) the Upper Natural Barrier, including infiltration, unsaturated zone flow, ambient seepage, and thermal seepage; (ii) the Engineered Barrier System; and (iii) the Lower Natural Barrier, including unsaturated zone flow, radionuclide transport in the unsaturated zone, saturated zone flow, and saturated zone transport. Each of the activities summarized in Sections 2.1 and 2.2 are intended to help confirm that one or more of the barriers is performing within the limits assumed during the License Application. The Upper and Lower Natural Barriers both have components within the vadose zone.

The activity descriptions in the Plan appear to focus on quality assurance and safety issues, and the technical details of the planned activities are not fully determined. Aside from precipitation observations, hydrology-related performance confirmation activities listed in the Plan are either activities related to near-drift processes or activities related to the saturated zone. Most of the proposed near-drift activities are intended to consider processes in and near thermally accelerated drifts. By omission, it appears that DOE intends to not perform activities confirming that infiltration rates and unsaturated zone fluxes from the ground surface to the repository are within the limits assumed during the License Application.

Based on the activities described in the Performance Confirmation Plan, many vadose zone measurement sensors used for performance confirmation will be placed within boreholes drilled into fractured rock from drifts, alcoves, and niches. The remaining sensors would be placed directly within drifts, alcoves, and niches. Many of the sensors will encounter high temperatures in and near thermally accelerated drifts, which are drifts that will be heavily instrumented, closed to ventilation using bulkheads, and allowed to heat up prior to closure in order to examine system responses to conditions expected in the repository during the postclosure thermal period. There is no activity described in the Plan that would place vadose zone measurement sensors within an unconsolidated porous medium.

### 3 VADOSE ZONE SENSING TECHNOLOGY

Vadose zone sensing technology largely has been driven by soil scientists, although industrial activity has also driven sensor development in some areas (e.g., temperature and humidity sensors). Vadose zone sensing technology has only rarely been applied within rock masses (e.g., Yucca Mountain), and typically these applications are modifications of techniques developed for soil science. Most vadose zone sensing methodologies can be applied to soil, rock, and industry-specific porous media. All such media are generically referred to as porous media in this report.

The sensor methods discussed in this report are divided into eight general sensor categories: (i) water content measurement, (ii) matric potential measurement, (iii) pore water extraction, (iv) indirect water content measurement, (v) temperature measurement, (vi) relative humidity measurement in cavities, (vii) in situ water flux measurement, and (viii) *in situ* gas flux measurement. Several sensors may be used to measure more than one physical quantity, and in some cases multiple sensors are bundled into one probe. Sensors with multiple capabilities are presented in the section related to the most advanced of the sensor's capabilities. Characteristics of methods with wide exposure and particular applicability to the Yucca Mountain Project are summarized in a Summary Box.

Most methods discussed in this report are illustrated with at least one example to provide a visual example of how the method is implemented. There is no intent to provide an exhaustive catalog of commercial products, and any use of trade, product, or firm names in this publication is for descriptive or illustrative purposes only and does not imply endorsement by the Center for Nuclear Waste Regulatory Analyses or the U.S. Nuclear Regulatory Commission.

#### 3.1 Water Content Measurement

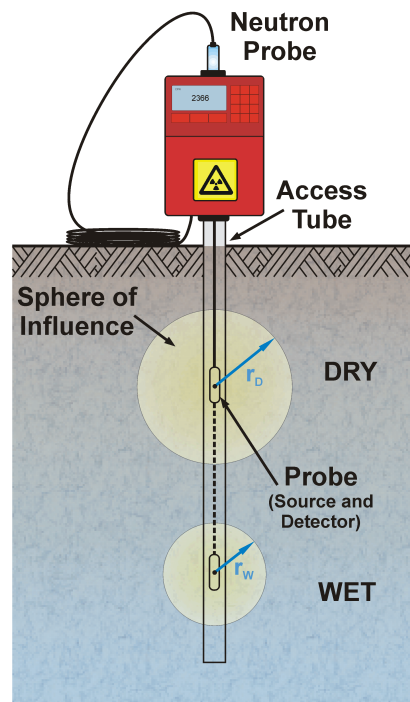
The amount of water in a porous medium and the forces by which water is held in the pores (matric or capillary potential) are important attributes of liquid water in a porous medium. These attributes are related to each other through a characteristic curve. The liquid-phase characteristics affect the gaseous phase in the pore space and the rates of exchange between the liquid and gas phases; these characteristics also affect other transport properties such as hydraulic conductivity.

Many geotechnical and hydrologic practices and studies require knowledge of the amount of water contained in soil or in rock formations. Some of the methods used to determine water content are described in this section, focusing on methods for performing continuous and measurements relevant to long-term monitoring and the U.S. Department of Energy (DOE) Performance Confirmation Plan. The neutron scattering approach emits neutrons into the porous medium and measures characteristics of reflected neutrons. The remaining methods are all based on measurement of the bulk dielectric permittivity or the dielectric constant ( $\epsilon_b$ ) of the porous medium (Hilhorst, et al., 2001). The dielectric constant of rock and soil is dominated by the presence of liquid water, due to its high dielectric constant (~81) relative to other constituents such as soil and rock minerals (2 to 5), frozen or bound water (~3), and air (1). Dielectric methods rely on interactions between porous media and applied electromagnetic waves or fields to deduce the dielectric permittivity of the medium under study. These methods include time domain reflectometry, capacitance and frequency domain methods, impedance sensors, phase transmission sensors, and ground-penetrating radar.

### 3.1.1 Neutron Scattering

The neutron scattering method is commonly used for field measurement of volumetric water content and in some industrial and construction applications (e.g., see applications at [www.berthold.com](http://www.berthold.com)). The method is based on the propensity of hydrogen nuclei to slow (thermalize) high energy fast neutrons. A typical neutron moisture meter consists of (i) a probe containing a radioactive source that emits high-energy (2 to 4 MeV) fast {1,600 km/s [994 mi/s]} neutrons and a detector of slow neutrons; (ii) a scaler to monitor the flux of slow neutrons, and, optionally, (iii) a datalogger for storing and retrieving data. The neutron probe method is illustrated in Figure 3-1. The radioactive source commonly contains a mixture of Americium-241 and Beryllium in 10 to 50 millicurie amounts. The alpha particles emitted by the decay of the Americium-241 collide with the light Beryllium nuclei, resulting in emission of fast neutrons.

Fast neutrons are emitted spherically from the radioactive source into the surrounding medium, where they collide with various atomic nuclei. Collisions with most nuclei are virtually elastic (i.e., resulting in only minor losses of kinetic energy by the fast neutrons). However, collisions with light hydrogen nuclei, which have mass similar to neutrons, cause significant loss of kinetic energy and slow the fast neutrons. When the speed of fast neutrons diminishes to that of particles at ambient temperature {approximately 2.7 km/s [1.7 mi/s]}, with corresponding energies of approximately 0.03 eV, the neutrons are called thermalized or slow neutrons. Thermalized neutrons rapidly form a “cloud” of nearly constant density near the detector that measures the return flux of the slow neutrons. The average kinetic energy loss (the relative number of slow neutrons returning to the detector) is linearly dependent on the amount of



**Figure 3-1. An Illustration of a Neutron Probe Lowered Into an Access Tube for Repetitive *In Situ* Water Content Measurements. Note the Different Sphere of Influence for Measurements in Wet and Dry Soil.**

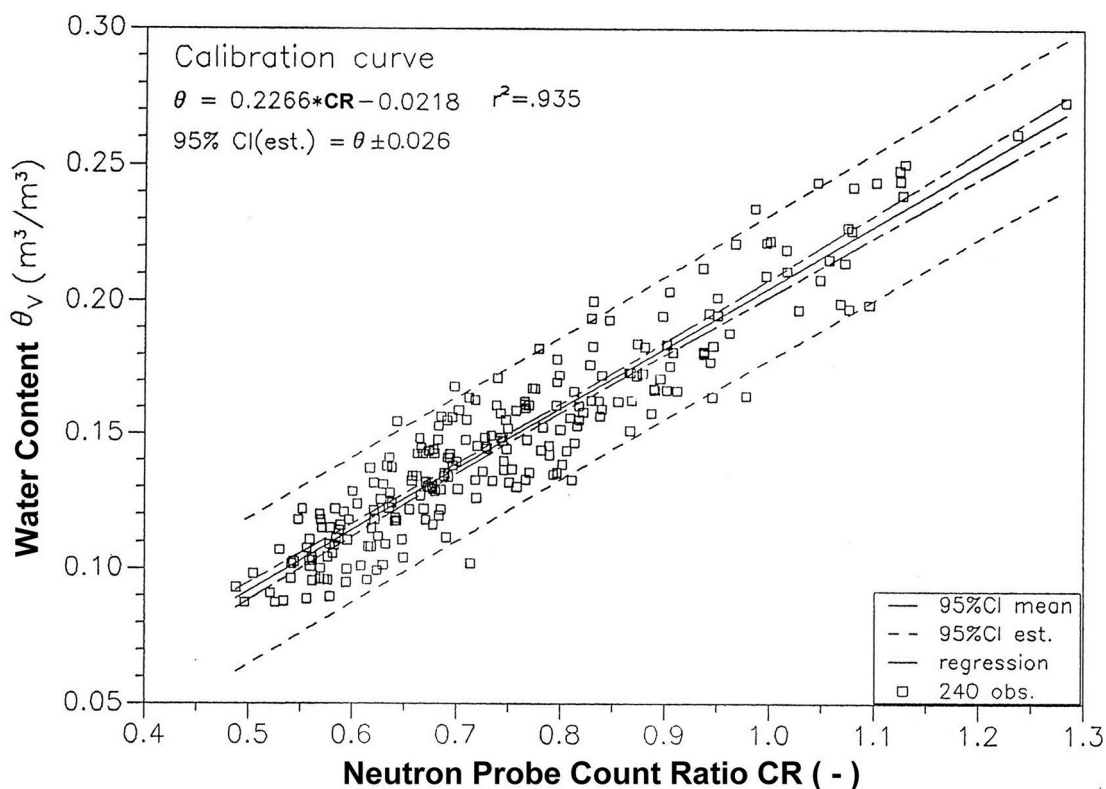
hydrogen nuclei in the soil, and the primary source of hydrogen in soil (and the most variable in time) is water. Several other nonhydrogen substances effectively thermalize fast neutrons and are present in trace amounts in some media; these substances generally may be compensated for using medium-specific calibration.

Calibration of the neutron probe to account for background hydrogen sources and other local effects (e.g., local bulk density, trace neutron attenuators, etc.) is conveniently achieved by simultaneous measurement of water content (from samples acquired during installation of an access tube or from nearby destructive sampling) and actual neutron probe counts at the same locations. The calibration curve (Figure 3-2) is typically linear and relates volumetric water content,  $\theta_v$ , to slow neutron counts or count ratio

$$\theta_v = a + b \text{ (CR)} \quad (3-1)$$

where

CR — ratio of slow neutron counts at a specific location in the soil to a standard count obtained with the probe in its shield  
 $a$  and  $b$  — fitting constants



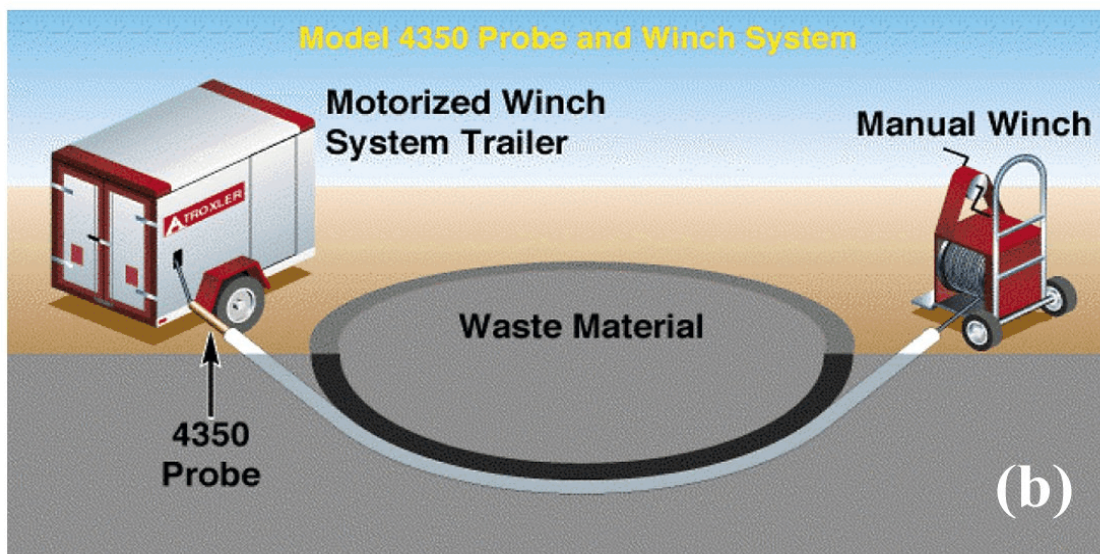
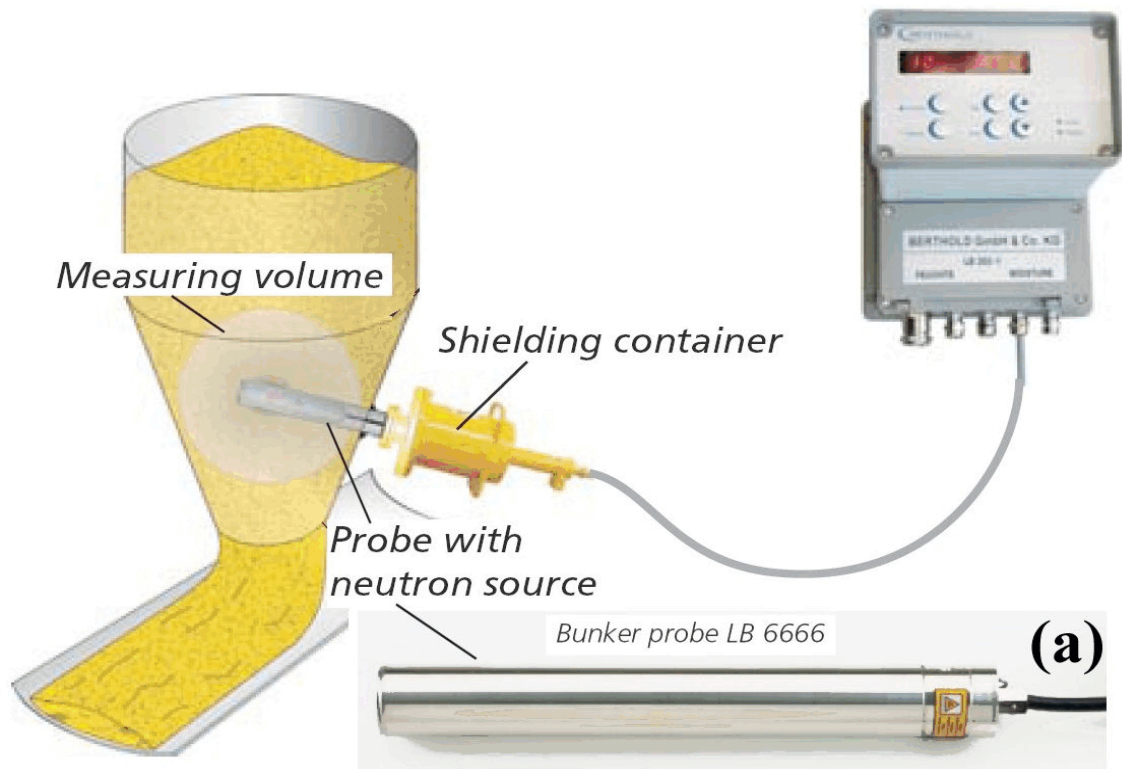
**Figure 3-2. Calibration Curve for CPN 502 Neutron Probe in Millville Silt Loam Soil, Logan, Utah. The Dashed Lines Represent the 95 Percent Confidence Interval About the Regression Line. [Reproduced From Or (1990) With Permission]**

The calibration coefficients are similar for many soils. The sphere of influence of the radiation source, which varies from approximately 15 cm [0.49 ft] (wet soil) to approximately 70 cm [2.3 ft] (very dry soil), depends on how far fast neutrons travel before becoming thermalized (see illustrated sphere of influence in Figure 3-1). An approximation for the radius of influence,  $r$  (in centimeters), as a function of ambient water content is given by

$$r = 15 (\theta_v)^{-1/3} \quad (3-2)$$

The neutron scattering method is unsuitable for measurements near the soil surface or rock cavities because a portion of the neutrons may escape. Reliable measurements are typically obtained at depths (or distances from a rock wall) exceeding 15 to 20 cm [0.49 to 0.66 ft]. Figure 3-3 depicts typical applications of the neutron scattering method for monitoring water content. Characteristics of the method relevant to performance confirmation are summarized in Summary Box 1.

Summary Box 1. The Neutron Scattering Method	
<b><u>Measurement Range</u></b>	
<ul style="list-style-type: none"> <li>Entire range of water contents</li> </ul>	
<b><u>Accuracy</u></b>	
<ul style="list-style-type: none"> <li>±2 percent volumetric water content with calibration</li> </ul>	
<b><u>Limitations</u></b>	
<ul style="list-style-type: none"> <li>Radiation hazards and licensing requirements</li> <li>Requires site specific calibration</li> <li>Variable volume of measurement</li> <li>Not suitable for near-surface measurements</li> <li>Provides “snap shots”</li> <li>Difficult to automate</li> <li>Installation and measurements are labor intensive</li> </ul>	
<b><u>Advantages</u></b>	
<ul style="list-style-type: none"> <li>Repetitive and nondestructive measurements at the same locations</li> <li>Reliable and robust measurements (following calibration)</li> <li>Cost effective: one device can serve many access tubes</li> <li>Measurement of total water content for entire <math>\theta</math> range is not sensitive to phase and energy state of water (liquid, bound, and frozen water)</li> </ul>	
<b><u>Applicability for the Performance Confirmation Program</u></b>	
<ul style="list-style-type: none"> <li>May be used for monitoring near-field variations in water content</li> <li>May be used to independently quantify percolation flux in the shallow subsurface in combination with deep (advanced) tensiometers</li> </ul>	



**Figure 3-3. Applications of Neutron Scattering for Monitoring Water Content:**  
 (a) A Stand-Alone Probe in Industrial Applications, and (b) Automated Scanning Through a Horizontal Access Tube With a Manual or Motorized Winch.  
 [Illustration (a) Courtesy of Berthold Technologies U.S.A., LLC; (b) Reproduced with Permission from T. Burford, Sandia National Laboratories]



### 3.1.2 Time Domain Reflectometry

Time domain reflectometry is a relatively new method for water content measurement (Topp, et al., 1980). The main advantages of the time domain reflectometry method over other methods for repetitive water content measurement (e.g., neutron scattering) are (i) accuracy to within 1 to 2 percent of volumetric water content, (ii) minimal calibration requirements—in many cases medium-specific calibration is not needed, (iii) no radiation hazard, (iv) good spatial resolution, (v) measurements are simple to obtain, and (vi) the method is capable of providing continuous water content measurements through automation and multiplexing.

The propagation velocity,  $v$ , of an electromagnetic wave along a transmission line (probe or waveguide) of length  $L$  (Figure 3-4) embedded in a porous matrix is determined from the time response of the system to a pulse generated by the time domain reflectometry cable tester. The propagation velocity ( $v = 2L/t$ ) is a function of the bulk dielectric constant ( $\epsilon_b$ ) according to

$$\epsilon_b = \left( \frac{c}{v} \right)^2 = \left( \frac{ct}{2L} \right)^2 \quad (3-3)$$

where

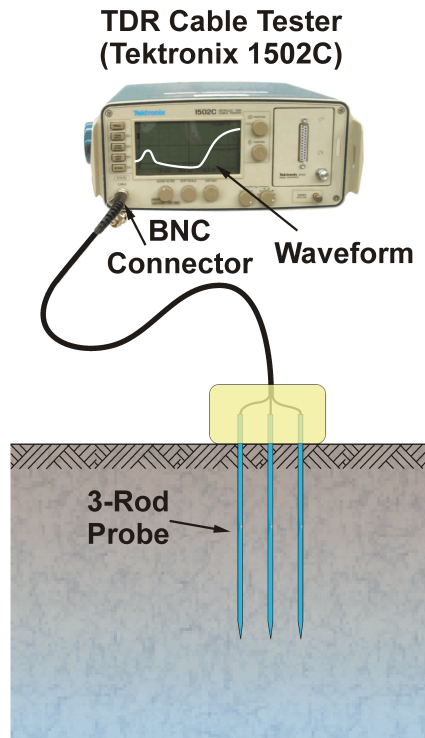
$c$  — velocity of electromagnetic waves in vacuum ( $3 \times 10^8$  m/s)  
 $t$  — time for a wave to traverse the length of the embedded waveguide and return (out and back distance =  $2L$ )

The definition of the dielectric constant is given in Eq. (3-3); this equation states that the dielectric constant of a medium is the squared ratio of wave propagation velocity in vacuum to the propagation velocity in the medium. The method is relatively insensitive to soil composition and texture because the bulk dielectric constant ( $\epsilon_b$ ) is controlled by the dielectric constant of liquid water, thus is a good method for measuring liquid water content. The bulk dielectric permittivity is determined from analyses of time domain reflectometry waveforms (reflection coefficient versus time or distance) as depicted in Figure 3-5.

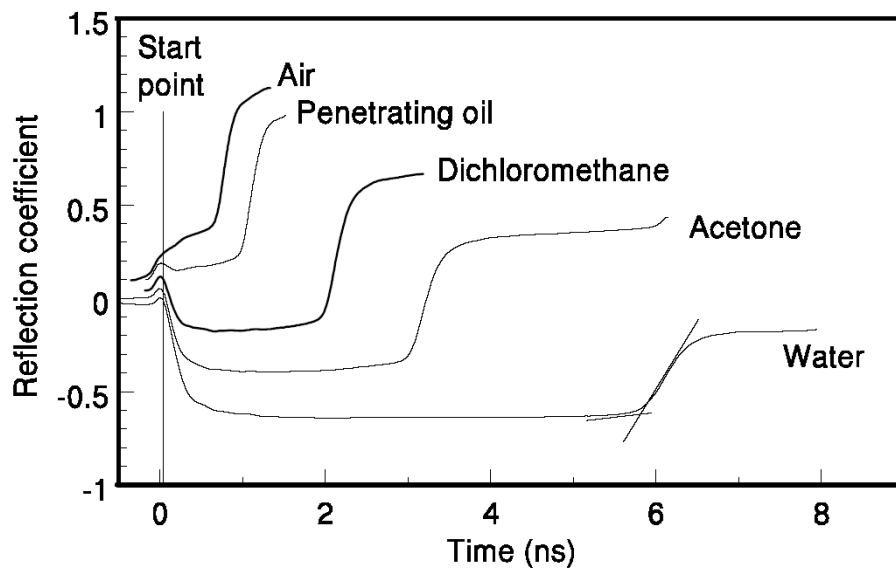
Two basic approaches are used to establish the relationships between  $\epsilon_b$  and volumetric water content ( $\theta_v$ ). The first approach is empirical, whereby mathematical expressions are simply fitted to observed data without using any particular physical model. Such an approach was employed by Topp, et al. (1980), who fitted a third-order polynomial to the observed relationships between  $\epsilon_b$  and  $\theta_v$  for multiple soils (Figure 3-6a). The second approach is physically based, using a mixing model of the dielectric constants and the volume fractions of each of the soil components to derive a relationship between the composite (bulk) dielectric constant and the amount of soil water (i.e., a specific component). Dielectric mixing models were developed by Birchak, et al. (1974), Dobson, et al. (1985), and Roth, et al. (1990).

Time domain reflectometry calibration establishes the relationship between  $\epsilon_b$  and  $\theta_v$ . For example, calibration might be conducted in a fairly uniform soil without abrupt changes in water content along the waveguide. The empirical relationship for mineral soils (soils with low organic matter content), as proposed by Topp, et al. (1980), is

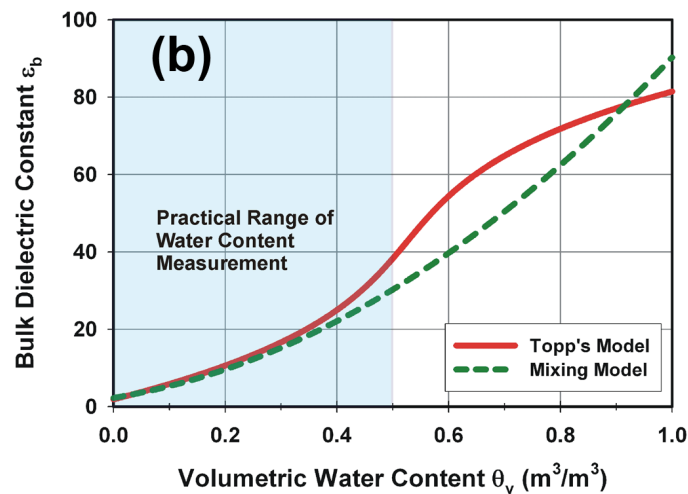
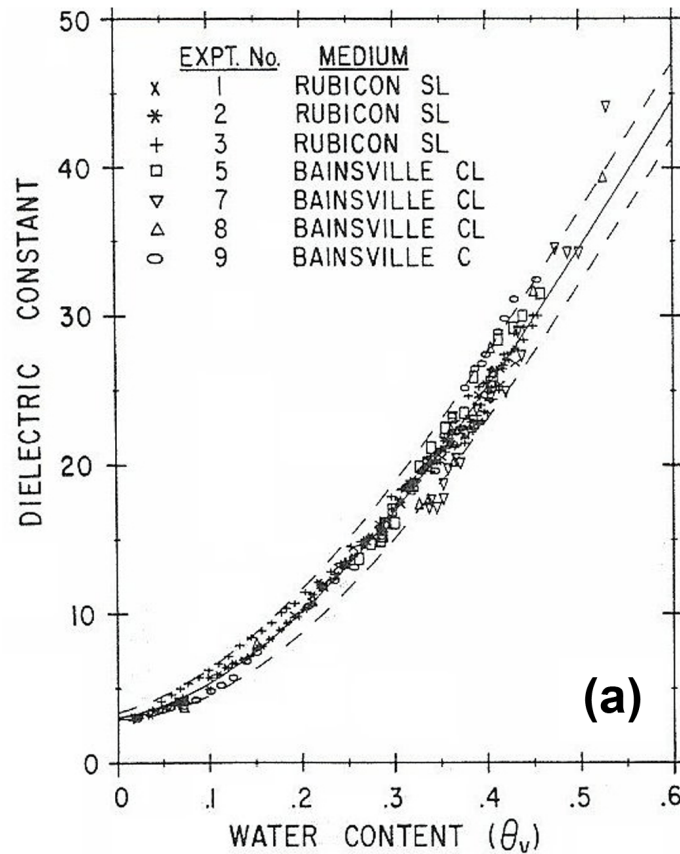
$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \epsilon_b - 5.5 \times 10^{-4} \epsilon_b^2 + 4.3 \times 10^{-6} \epsilon_b^3 \quad (3-4)$$



**Figure 3-4. Time Domain Reflectometry Cable Tester With Three-Rod Probe Embedded Vertically in Surface Soil Layer**



**Figure 3-5. Time Domain Reflectometry Waveforms Increase in Travel Time as the Permittivity of the Fluid Medium Increases. Travel Time for the Water Waveform is Determined Using The Intersection of the Two Tangent Lines.**  
 [Reproduced From Robinson, et al. (2003) With Permission]



**Figure 3-6. Calibration Approaches for Establishing Relationships Between Bulk Dielectric Permittivity and  $\theta_v$ :** (a) The Empirical Expression of Topp, et al. (1980) Fitted to Experimental Results; and (b) Comparison Between Topp's Empirical Expression and a Physically-Based Dielectric Mixing Model.

Note: SL—Silt and CL—Clay

[(a) Reproduced From Topp, et al. (1980) With Permission]

This relationship provides adequate description for water contents less than 0.5 (covering most of the range of interest in many soils), with an estimation error for  $\theta_v$  of approximately 0.013. However, Eq. (3-4) does not adequately describe the relationship between  $\epsilon_b$  and  $\theta_v$  for water contents exceeding 0.5 and for soils containing appreciable amounts of organic matter (see Figure 3-6b).

A physically-based calibration model employing dielectric mixing of the constituents and their geometric arrangement expresses the bulk dielectric constant of a three-phase system (Roth, et al., 1990) as:

$$\epsilon_b = \left[ \theta_v \epsilon_w^\beta + (1-n) \epsilon_s^\beta + (n - \theta_v) \epsilon_a^\beta \right]^{1/\beta} \quad (3-5)$$

where

$n$	—	soil porosity
$1-n$	—	volume fraction of the solid phase: $(1-n) = V_s/V_T$ , where $V_s$ is volume of solids and $V_T$ is total sample volume
$\theta_v$	—	volume fraction of the aqueous phase: $\theta_v = V_w/V_T$ , where $V_w$ is volume of water
$n - \theta_v$	—	volume fraction of the gaseous phases: $(n - \theta_v) = V_a/V_T$ , where $V_a$ is volume of air
$\epsilon_s$	—	dielectric constant of the solid phase
$\epsilon_w$	—	dielectric constant of the aqueous phase
$\epsilon_a$	—	dielectric constant of the gaseous phase
$\beta$	—	factor summarizing the geometry of the medium relative to the axial direction of the wave guide ( $-1 \leq \beta \leq 1$ ; $\beta = 1$ for an electric field parallel to soil layering, $\beta = -1$ for a perpendicular electrical field, and $\beta = 0.5$ for an isotropic two-phase mixed medium)

Note that the volume fractions sum to unity.

Rearranging Eq. (3-5) and solving for  $\theta_v$  yields

$$\theta_v = \frac{\epsilon_b^\beta - (1-n) \epsilon_s^\beta - n \epsilon_a^\beta}{\epsilon_w^\beta - \epsilon_a^\beta} \quad (3-6)$$

which links  $\theta_v$  to the value of  $\epsilon_b$  measured by time domain reflectometry. Many have used  $\beta = 0.5$ , which is shown by Roth, et al. (1990) to produce a calibration curve very similar to the third-order polynomial proposed by Topp, et al. (1980) over the water content range of  $0 < \theta_v < 0.5$ . If common values are assumed for the various constituents such as  $\beta = 0.5$ ,  $\epsilon_w = 81$ ,  $\epsilon_s = 4$ , and  $\epsilon_a = 1$  into Eq. (3-6), the resulting form is

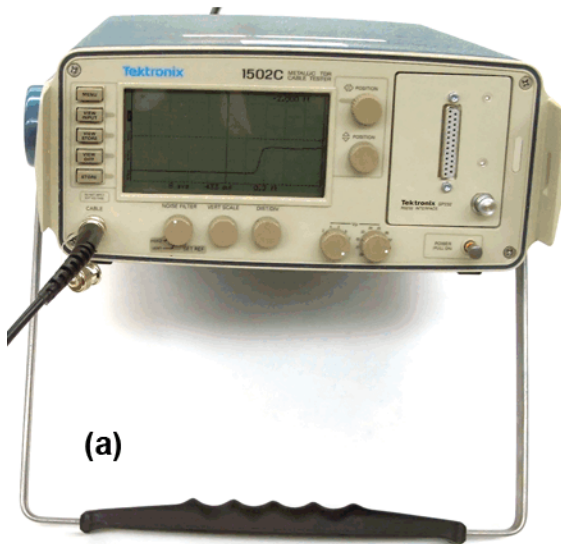
$$\theta_v = \frac{\sqrt{\epsilon_b} - (2-n)}{8} \quad (3-7)$$

Note that the porosity of the material must be known or estimated when using the mixing model approach. A comparison between the Topp, et al. (1980) expression [Eq.(3-4)] and a calibration

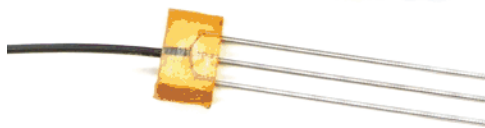
curve based on Eq. (3-7) with  $n = 0.5$  is depicted in Figure 3-6b. In summary, Eq. (3-4) establishes an empirical relationship between bulk soil dielectric and volumetric water content, whereas Eq. (3-6) is based on physical and geometrical considerations and Eq. (3-7) is a simplified version of Eq. (3-6).

Several commonly used time domain reflectometry systems are shown in Figure 3-7. Limitations or disadvantages of the time domain reflectometry method include relatively high equipment expense, potentially limited applicability under saline conditions due to signal attenuation, and the need for media-specific calibration for media having large amounts of bound water or high organic matter contents. Characteristics of the method relevant to performance confirmation are summarized in Summary Box 2.

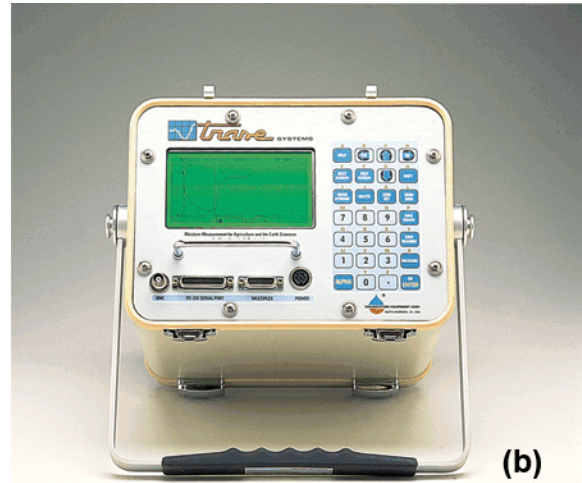
Summary Box 2. The Time Domain Reflectometry Method	
<b><u>Measurement Range</u></b>	
<ul style="list-style-type: none"> <li>Entire range of water contents</li> </ul>	
<b><u>Accuracy</u></b>	
<ul style="list-style-type: none"> <li><math>\pm 1</math> to 2 percent volumetric water content</li> </ul>	
<b><u>Advantages</u></b>	
<ul style="list-style-type: none"> <li>Superior accuracy to within 1 to 2 percent of the actual volumetric water content</li> <li>Minimal calibration requirements (usually no medium-specific calibration necessary)</li> <li>No radiation hazard</li> <li>Excellent spatial and temporal resolution</li> <li>Continuous measurements through automation and multiplexing</li> </ul>	
<b><u>Limitations</u></b>	
<ul style="list-style-type: none"> <li>Expensive—typical system costs approximately \$4,000</li> <li>Limited performance in saline porous media (for bulk electrical conductivity values in excess of 0.02 to 0.03 S/m)</li> <li>Potential temperature effects</li> <li>Specialized—no “off-the-shelf” systems; requires training</li> </ul>	
<b><u>Applicability for the Performance Confirmation Program</u></b>	
<ul style="list-style-type: none"> <li>Monitoring near field and in-drift variations in water content (using large probes for fracture integration)</li> <li>May be used to independently quantify percolation flux in the shallow subsurface [paired with deep (advanced) tensiometers]</li> <li>Confirmation of drift shadow below the repository</li> </ul>	



(a)



(c)



(b)

**Figure 3-7. Commonly Used Time Domain Reflectometry Systems: (a) Tektronix 1502c General Purpose Cable Tester, (b) Trase System (Soilmoisture Equipment Corp.), and (c) TDR100 (Campbell Scientific, Inc.) by Itself (Left) and TDR100 Installed in Enclosure (Right). [Photograph in (a) by M. Tuller, Image in (b) Courtesy Soilmoisture Equipment Corp., and Images in (c) Courtesy of Campbell Scientific, Inc.]**

### 3.1.3 Capacitance and Frequency Domain Methods

Two electrodes (parallel plates or rods) inserted into a porous medium form a capacitor (the porous medium is the dielectric). Capacitance is strongly dependent on the dielectric constant, which is dominated by the amount of water in the porous medium. The relationship between dielectric constant and electrical capacitance between two parallel plates of area  $A$  and spacing  $d$  is

$$C = \frac{A \epsilon^* \epsilon_0}{d} \quad (3-8)$$

where

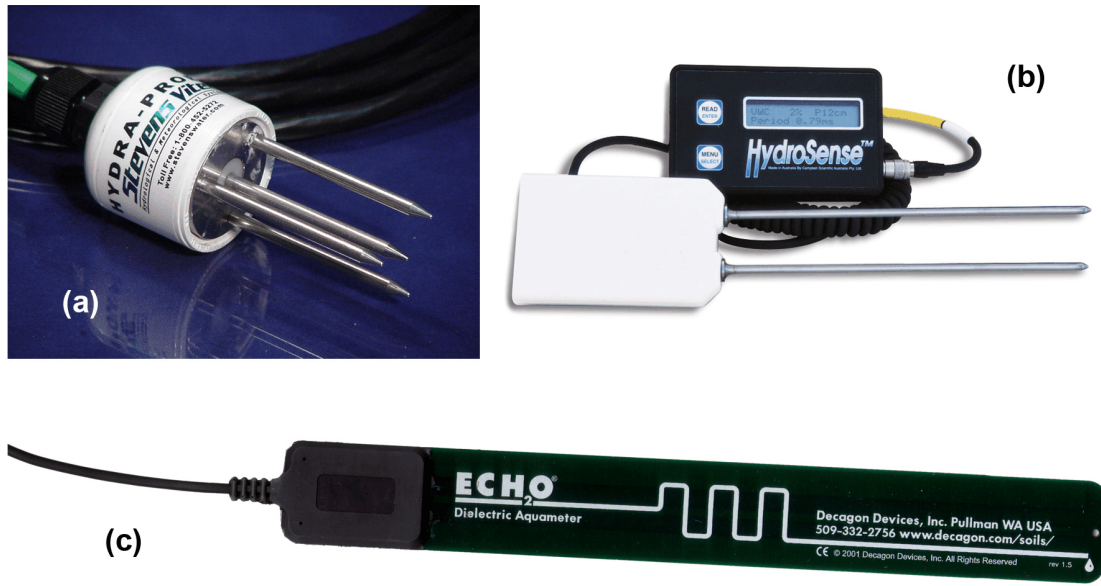
$\epsilon^*$	—	complex dielectric constant of the soil or rock
$\epsilon_0$	—	free space permittivity
$C$	—	capacitance

The complex dielectric constant contains both real ( $\epsilon'$ ) and imaginary ( $\epsilon''$ ) components, with  $\epsilon^* = \epsilon' - i \epsilon''$  and  $i = \sqrt{-1}$ . In most applications only the real part of the dielectric constant is considered.

When the capacitor is connected to an oscillator to form a tuned electrical circuit, changes in soil moisture can be detected through changes in operating frequency. This basic frequency domain theory is applied in capacitance and frequency domain reflectometry sensors. In capacitance sensors the dielectric permittivity of a medium is determined by measuring the charge time of a capacitor. In frequency domain reflectometry sensors the oscillator frequency is modulated within a certain range to find the resonant frequency (greatest amplitude), which is related to the medium's water content.

A material-specific calibration is typically necessary because the operating frequency of these devices is generally below 100 MHz, and at these low frequencies the bulk permittivity may be affected by minerals. Furthermore, effects of temperature, salinity, bulk density, and clay content are more pronounced than for high frequency techniques such as time domain reflectometry. Commercially available capacitance sensors include HYDRA probes (Stevens Water Monitoring Systems, Inc.), ECH<sub>2</sub>O probes (Decagon Devices, Inc.), CS616-L Water Content Reflectometers and CS620 HydroSense<sup>®</sup> probes (Campbell Scientific, Inc.). Commercially available frequency domain reflectometry sensors include the Sentry 200-AP probe (Troxler, North Carolina, USA) and the EnviroScan<sup>®</sup> sensor (Sentek Sensor Technologies, 2001). Representative capacitance sensors are shown in Figure 3-8, with the EnviroScan<sup>®</sup> sensor illustrated in Figure 3-9.

The measurement range and accuracy vary considerably among this family of sensors (Evelt and Steiner, 1995; Paltineanu and Starr, 1997). For example, Evelt and Steiner (1995) found measurement errors with the Sentry 200AP to be three times larger than comparable measurement errors using a neutron probe.



**Figure 3-8. Commercially Available Capacitance Sensors: (a) HYDRA Probe (Stevens Water Monitoring Systems, Inc.), (b) CS620 HydroSense® Probe (Campbell Scientific, Inc.), and (c) ECHO (Decagon Devices Inc.). [Image (a) Courtesy of Stevens Water Monitoring Systems, Inc.; Image (b) Courtesy of Campbell Scientific, Inc.; and Image (c) Courtesy of Decagon Devices. Photocredit: photobay.biz; Reproduced With Permission From Decagon Devices Inc.]**

### 3.1.4 Impedance Sensors (Amplitude Domain Reflectometry)

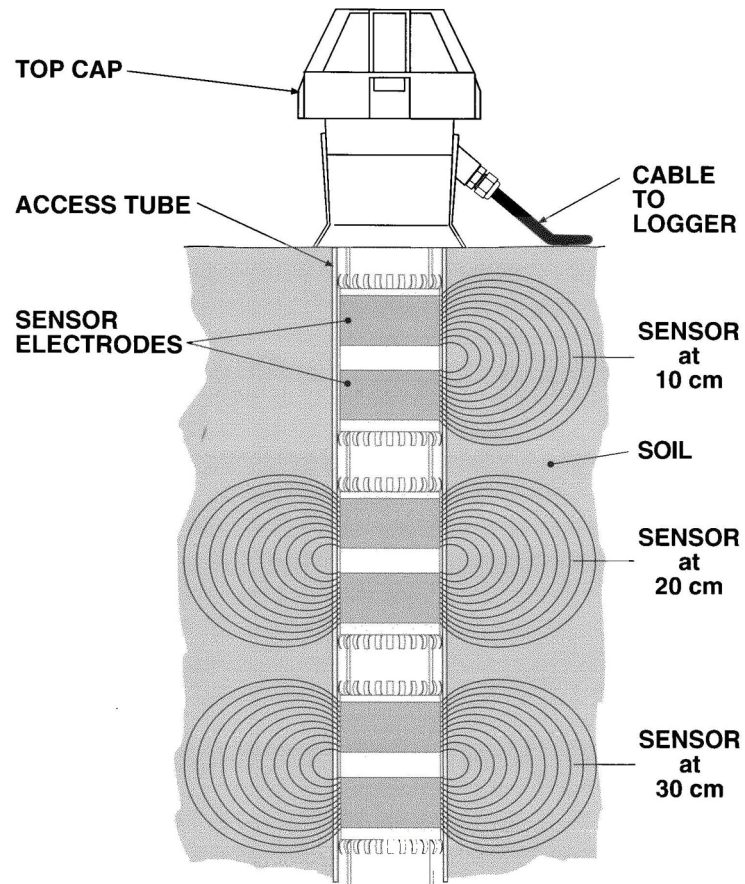
Electrical impedance represents the total opposition of a system to an alternating current at a given frequency. Impedance is a complex quantity with the real component called resistance and the imaginary component called inductive or capacitive reactance. When an electromagnetic wave traveling along a transmission line reaches a section of the line with a different impedance, part of the transmitted energy is reflected back toward the source. The reflected wave interacts with the incident wave, producing a voltage standing wave along the transmission line (i.e., change of wave amplitude along the length of the transmission line).

The impedance change due to a combination of a probe and porous medium can be estimated by measuring the change in amplitude (Gaskin and Miller, 1996; Nakashima, et al., 1998). These sensors improve the estimates of water content in the surrounding medium by using a measurement frequency that reduces the influence of the electrical conductivity in the surrounding medium. Impedance sensors use an oscillator to generate a sinusoidal signal at a fixed frequency (e.g., 100 MHz), which is applied to a coaxial transmission line that extends into the porous medium through an array of parallel metal rods; the outer rod forms an electrical shield around the central signal rod. This rod arrangement acts as an additional section of the transmission line, having impedance that depends on the dielectric constant of the soil between the rods. An example of an impedance sensor is shown in Figure 3-10.





## EnviroSCAN PROBE DESIGN



**Figure 3-9. Commercially Available Frequency Domain Sensor: Sentek EnviroSCAN® Sensor for Profiling Water Content Along an Access Tube [Images Reproduced With Permission From Sentek Pty Ltd. Copyright Sentek Pty Ltd 2001. EnviroSCAN® Is a Registered Trademark of Sentek Pty Ltd]**



**Figure 3-10. Commercially Available Impedance Sensor: (a) ThetaProbe ML2x Soil Moisture Sensor and HH2 Moisture Meter (Photograph Courtesy Delta-T Devices, Ltd.—[www.delta-t.co.uk](http://www.delta-t.co.uk)), and (b) Field Application of a Bank of Soil Moisture Sensors. [Photograph Reproduced From Calder, et al. (2002) With Permission]**

### 3.1.5 Phase Transmission Sensors

A sinusoidal electromagnetic wave shifts phase as it moves away from the source. This phase shift depends on travel distance, wave frequency, and propagation velocity. Given the wave frequency and travel distance, the water content can be determined based on the magnitude of phase shift because propagation velocity is related to the water content of the medium. The probe uses a particular waveguide design (two concentric metal, opened rings) so that phase shift is measured at the beginning and end of the waveguides. An example of a phase transmission sensor is shown in Figure 3-11.

### 3.1.6 Ground-Penetrating Radar

Ground-penetrating radar is a geophysical technique used in reflection mode to non-invasively image the shallow subsurface (Davis and Annan, 1989). An example of how the technique may be applied in the field using a mobile unit is shown in Figure 3-12a. Ground-penetrating radar is an antenna-based tool that transmits short electromagnetic waves into the ground, and in return, receives backscattered radar echoes from subsurface interfaces, as indicated by Figure 3-12b. The reflection strength of each echo and the two-way travel time needed to send the pulse and receive each echo are recorded. Common mid-point soundings are used to estimate the average velocity of electromagnetic waves in a given subsurface environment, thus providing a conversion factor for associating each subsurface reflection with a particular depth [recall Eq. (3-3)]. A cross section of subsurface reflectors as a function of lateral and vertical



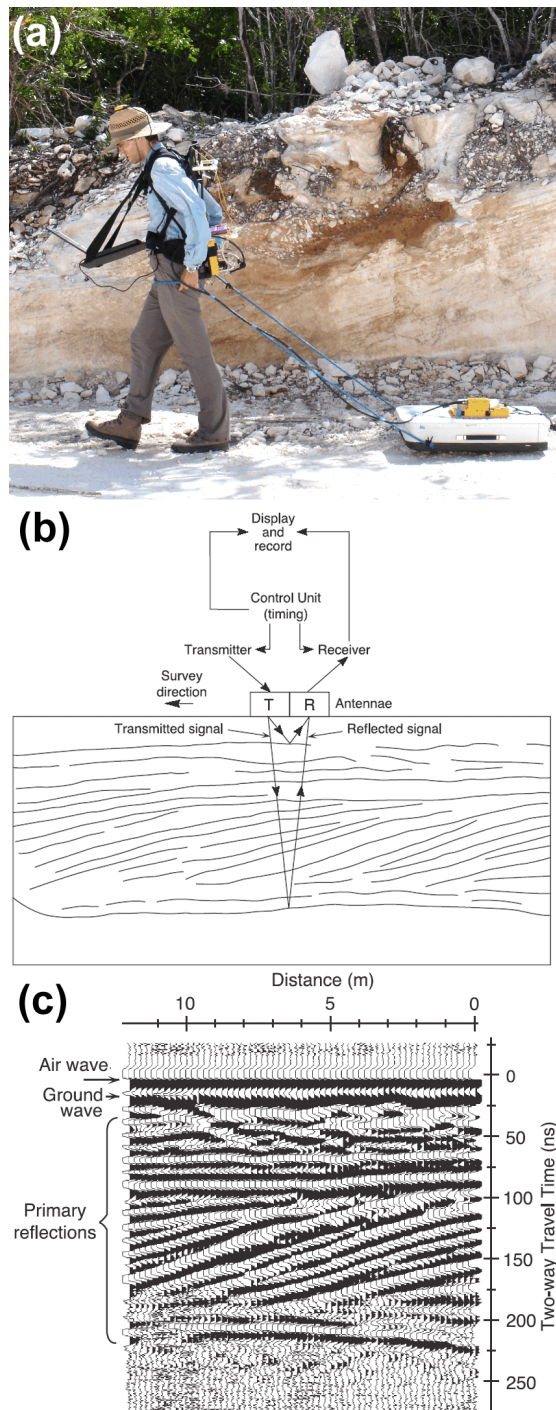
**Figure 3-11. Commercially Available Phase Transmission Sensor: VIRRIB® Soil Moisture Sensor. [Reproduced From Muñoz-Carpena (2004) With Permission]**

distance is then built using common offset profiling, which consists of repeatedly pulsing the transmitter and receiving the echoes at incremental positions along a transect. Figure 3-12c shows a typical tracegram with distinct reflectors.

Radar reflections originate primarily at discontinuities of relative dielectric constant where the electromagnetic wave undergoes an abrupt change in velocity. The relative dielectric constant of a given geologic unit determines the velocity of radar waves in that unit. The relative dielectric constant of a material is a measure of its capacity to store electrical charge. Good dielectric materials store electrical charge (e.g.,  $\epsilon^* = 1$ ); thus, water ( $\epsilon^* = 81$ ) is a poor dielectric, given that it easily conducts charge when subject to an electric field. On this basis, ground-penetrating radar is potentially useful for estimating the water content of the subsurface, because the velocity of electromagnetic waves is very fast in dry material, solid ice, and air, and is slow in water-saturated material. Empirical models and mixing models may be used to estimate water content, just as with Time Domain Reflectometry, as discussed in detail in Section 3.1.2.

Two important aspects of ground-penetrating radar are resolution and penetration depth. Ground-penetrating radar resolution is determined by the period of the emitted pulse, which is controlled by the frequency bandwidth of the system. Because impulse radar systems are designed with bandwidths that are approximately equal to the center frequency, the resolution of ground-penetrating radar increases with increasing center frequency (Davis and Annan, 1989).





**Figure 3-12. Ground-Penetrating Radar Operation: (a) Field Application of a Mobile Unit, (b) Illustration of Operational Setup, and (c) a Typical Radar Cross-Section of a Subsurface Formation. [(a) Photograph Courtesy of M. Grasmueck, Rosentiel School of Marine and Atmospheric Science, University of Miami; (b) and (c) Reprinted From Earth-Science Reviews, 66, A. Neal, Ground-Penetrating Radar and Its Use in Sedimentology: Principles, Problems and Progress, Page 266, Copyright (2004), With Permission From Elsevier]**

Ground-penetrating radar penetration depth is dependent on the center frequency of the system, the electrical conductivity of the subsurface environment, and on the scattering properties of the geology.

Radar energy is significantly attenuated in materials having elevated electrical conductivity, such as silts, clays, and low to moderate water content material with high concentrations of total dissolved solids or salts (from evaporative losses in desert environments, for example). In low conductivity media, such as porous dry sands and sandstone, gravel or ice, low-frequency antennas (<100 MHz) can achieve signal penetration to depths exceeding several tens of meters, and mid- to high-frequency antennas (>100 MHz) can achieve signal penetration up to several meters.

The Tumalo Tuff (Oregon) and the Bishop Tuff (California) have both been demonstrated to scatter radar waves (Rust and Russell, 2006; Grimm, et al., 2006); the Bandelier Tuff (New Mexico) is known to be opaque to radar waves.<sup>1</sup> In sum, radar techniques are sensitive to changes in physical and mineral properties, including permittivity, magnetic permeability, electrical conductivity, porosity and density. This sensitivity does reduce the range of subsurface environments in which the ground-penetrating radar method can be successfully applied.

In addition to surface application, ground-penetrating radar may also be used in boreholes by, for example, lowering a transmitter into a borehole and recording signal strength at a receiver at the ground surface or in another borehole. An example of this procedure is shown in Figure 3-13, in which the cross-borehole application of ground-penetrating radar is compared to neutron-probe observations. Cross borehole radar tomography (ground-penetrating radar used in transmission mode) was used at Yucca Mountain during Site Characterization. These data are only now undergoing analysis (Kowalsky, et al., 2005).

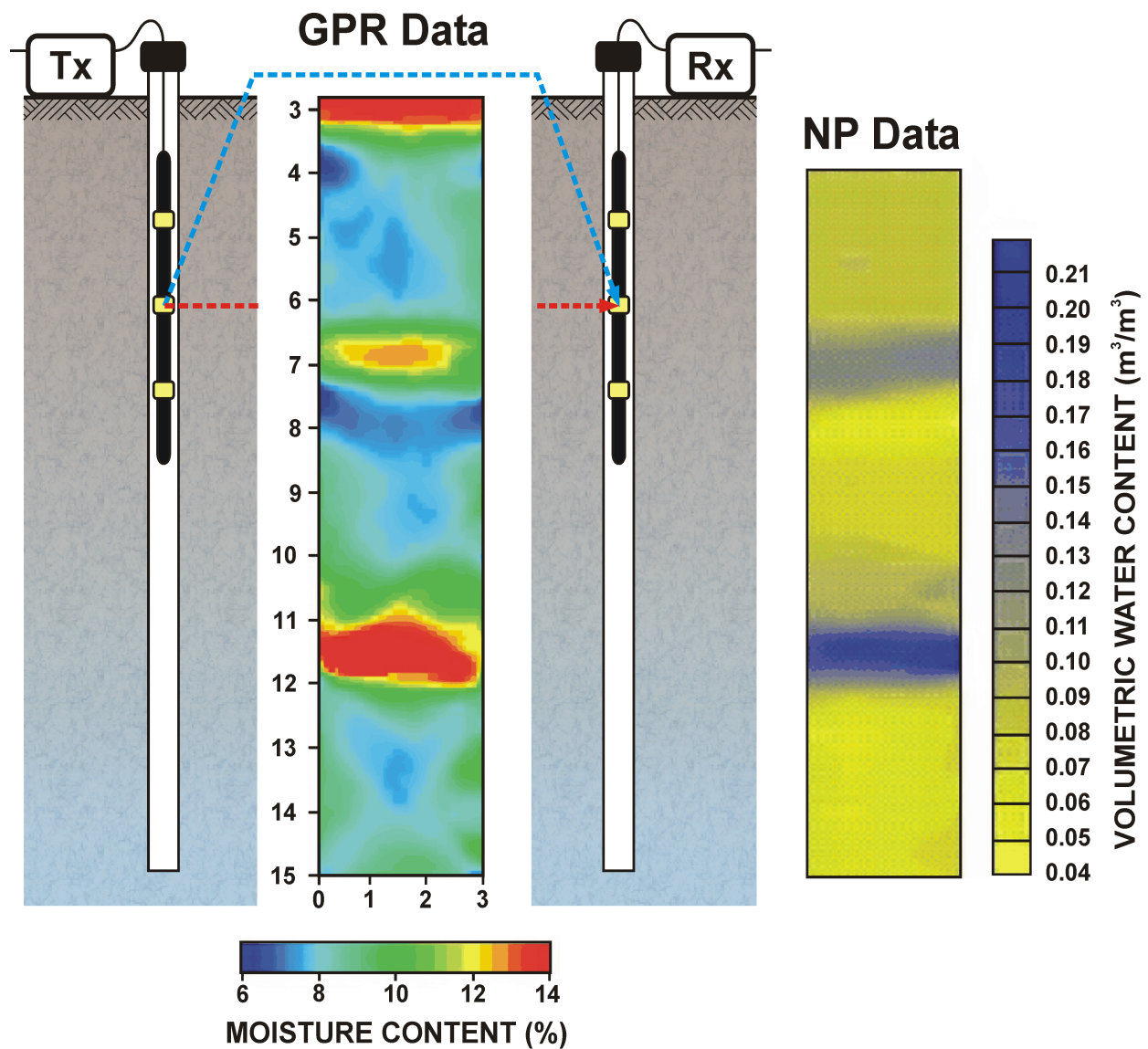
## **3.2 Matric Potential Measurement**

### **3.2.1 Background**

Water held in the pore space of a porous medium is subjected to several force fields. The combined effects of these forces result in a deviation in potential energy relative to the reference state, called the total water potential,  $\psi_T$ , defined as the amount of work that an infinitesimal unit quantity of water at equilibrium is capable of doing when it moves (isothermally and reversibly) to a pool of water at similar standard (reference) state (i.e., similar pressure, elevation, temperature, and chemical composition). There are alternative definitions of water potential using concepts of chemical potential or specific free energy of the chemical species. The water chemical species is just one component of the solution called the water phase; the methods documented in this report typically consider the water phase, not the water species. Some of the arguments concerning the definitions and their scales of application are presented by Corey and Klute (1985), Iwata, et al. (1988), and Nitao and Bear (1996). Because these fundamental concepts are subject to ongoing debate, simple and widely accepted definitions

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<sup>1</sup>P. Annan. Personal communication to C. Dinwiddie, Geosciences and Engineering Division, Southwest Research Institute. Mississauga, Ontario, Canada: Sensors & Software, Inc. 2005.



**Figure 3-13. Cross Borehole Ground-Penetrating Radar Measurement Layout and Comparison Between Ground Penetrating Radar and Neutron Probe Measurements From the Same Domain [Modified From Majer, et al. (2002) and Ferré, et al. (2003) With Permission]**

are presented that are applicable at macroscopic scales and yield an appropriate framework for practical applications.

The primary forces acting on water held within a rigid porous matrix under isothermal conditions can be conveniently grouped (Day, et al., 1967) as (i) matric forces resulting from interactions of the solid phase with the liquid and gaseous phases; (ii) osmotic forces owing to differences in the chemical composition of the water solution across a semi-permeable membrane, which will be neglected in this report; and (iii) body forces induced by gravitational and other (e.g., centrifugal) inertial force fields.

The thermodynamic approach, whereby potential energy is considered rather than forces, is particularly useful for equilibrium and flow considerations. Forces are extremely difficult to measure, and vector balances are computationally difficult to work with. Potential energy is a scalar quantity, defined as the negative integral of the force over the path taken by an infinitesimal amount of water when it moves from a reference location to the point under consideration. Consequently, the hydraulic potential ( $\psi_h$ , or the total potential neglecting the osmotic component) can be expressed as the algebraic sum of the component potentials corresponding to the different fields acting on soil water, or

$$\psi_h = \psi_m + \psi_p + \psi_z \quad (3-9)$$

where

$\psi_m$  — is the matric potential  
 $\psi_p$  — is the pressure potential  
 $\psi_z$  — is the gravitational potential

The matric potential,  $\psi_m$ , results from the combined effects of capillarity and adsorptive forces within the porous matrix. The primary mechanisms for these effects include (i) capillarity caused by liquid-gas interfaces forming and interacting within the irregular soil pore geometry, (ii) adhesion of water molecules to solid surfaces due to short-range London-van der Waals forces and extension of these effects by cohesion through hydrogen bonds formed in the liquid, and (iii) ion hydration and water participating in diffuse double layers (particularly near clay surfaces). There is some disagreement regarding the practical definition of this component of the total potential. Some researchers consider all contributions other than gravity and solute interactions (at a reference atmospheric pressure). Others use a device known as a tensiometer (discussed in Section 3.2.3) to provide a practical definition of the matric potential for water in contact with its porous cup (Hanks, 1992). The value of  $\psi_m$  ranges from zero, when the soil is saturated, to increasingly negative values as the soil becomes drier {note that  $\psi_m = 0$  mm [0 in] is greater than  $\psi_m = -1,000$  mm [-39.4 in]}.

The pressure potential,  $\psi_p$ , is defined as the hydrostatic pressure exerted by the column of unsupported water above a point of interest divided by the density of water. Using units of energy per unit weight provides a simple and practical definition of  $\psi_p$ , which is the vertical distance from the point of interest to the free water surface (unconfined water table elevation). The convention used here is that  $\psi_p$  is always positive below a water table and zero at or above the water table. With this convention, nonzero magnitudes of  $\psi_p$  and  $\psi_m$  are mutually exclusive: either  $\psi_p$  is positive and  $\psi_m$  is zero (saturated conditions), or  $\psi_m$  is negative and  $\psi_p$  is zero

(unsaturated conditions), or  $\psi_p = \psi_m = 0$  at the free water table elevation. Note that some researchers prefer to combine the pressure and matric components into a single term, which assumes positive values under saturated conditions and negative values under unsaturated conditions. Based on operational and explanatory considerations, the more commonly used separate-components convention is adopted here.

The gravitational potential,  $\psi_z$ , is determined solely by the elevation of a point relative to some arbitrary reference datum, and is equal to the work needed to raise a body against the earth's gravitational pull from the reference datum to its present position. When expressed as energy per unit weight, the gravitational potential is simply the vertical distance from the reference datum to the point of interest. The numerical value of  $\psi_z$  itself is not important (it is defined with respect to an arbitrary reference datum)—what is important is the difference (or gradient) in  $\psi_z$  between any two points of interest. This difference is independent of the reference datum.

Total water potential and its components may be expressed in several ways depending on the definition of a “unit quantity of water.” Potential may be expressed as (i) energy per unit of mass, (ii) energy per unit of volume, or (iii) energy per unit of weight. A summary of the resulting dimensions, common symbols, and units are presented in Table 3-1. The various expressions of soil water energy status are equivalent, with

$$\mu = \frac{\psi}{\rho_w} = gh \quad (3-10)$$

where

$\rho_w$  — density of water  
 $g$  — gravitational acceleration

Only  $\mu$  has actual units of potential;  $\psi$  has units of pressure and  $h$  has units of length (representing the height of water over a datum). However, each of these expressions is widely used in earth sciences in a generic sense to refer to potential.

### 3.2.2 Overview

Four techniques are commonly used to measure matric potential, each with different ranges of applicability. Tensiometers rely on a direct hydraulic connection between an engineered porous medium and the surrounding medium, thus are appropriate for relatively wet conditions but are

Table 3-1. Units, Dimensions and Common Symbols for Potential Energy of Soil Water				
Units	Symbol	Name	Dimensions*	SI Units
Energy/Mass	$\mu$	Chemical Potential	$L^2/T^2$	J/kg
Energy/Volume	$\psi$	Soil water potential, suction, or tension	$M/(LT^2)$	N/m <sup>2</sup> (Pa)
Energy/Weight	$h$	Pressure head	L	m
*L is length, M is mass, and T is time.				



subject to failure under dry conditions. Heat dissipation sensors also rely on a direct hydraulic connection between an engineered porous medium and the surrounding medium; however, compared to tensiometers, heat dissipation sensors are slower to equilibrate, may not be as accurate in the range of potentials where tensiometers are valid, but are less prone to fail and can consider drier conditions. Electrical resistivity sensors are akin to heat dissipation sensors, except matric potential is inferred from electrical resistivity within the engineered medium and the sensor may be affected by the ionic composition of the surrounding medium.

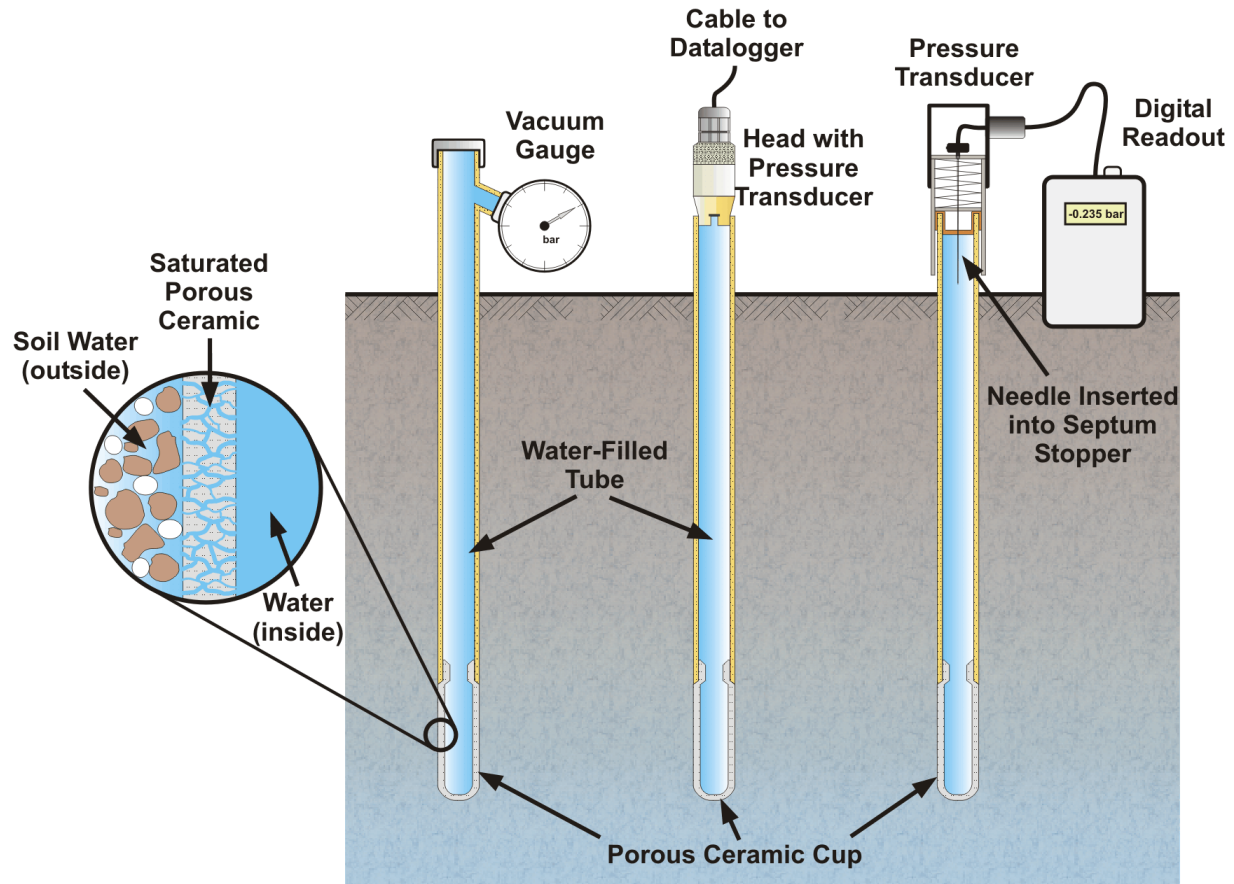
Psychrometers work with water vapor rather than liquid water, unlike the other matric-potential sensor types, obviating the need for liquid-phase connectivity between the bulk medium and sensor. Psychrometers measure relative humidity, estimating matric potential using the known equilibrium between water vapor and liquid water. Psychrometers are appropriate for dry conditions, but are inaccurate under wet conditions. There is little overlap between tensiometer and psychrometer measurement ranges.

### **3.2.3 Tensiometers**

Tensiometers directly measure the water potential in the surrounding porous medium. A tensiometer consists of a porous cup, usually made of ceramic (or sintered metal) with very fine pores, connected to a vacuum gauge through a water-filled tube, as shown in Figure 3-14. The porous cup is placed in intimate contact with the bulk porous medium at the desired measurement location. When the matric potential of the surrounding medium is lower (more negative) than the potential inside the tensiometer, water moves from the tensiometer to the surrounding medium through the saturated porous cup in response to the difference in potential, thereby creating suction measured by the gauge. Water flow continues until the suction inside the tensiometer equals the bulk matric potential. Flow may occur in either direction. The volume of exchanged water is typically very small because water is essentially incompressible and air is excluded from the tensiometer. Because the tensiometer actually measures the pressure difference between the atmosphere and the water inside the tensiometer, it is straightforward to consider both matric potential and pressure potential (i.e., saturated conditions) with the same device.

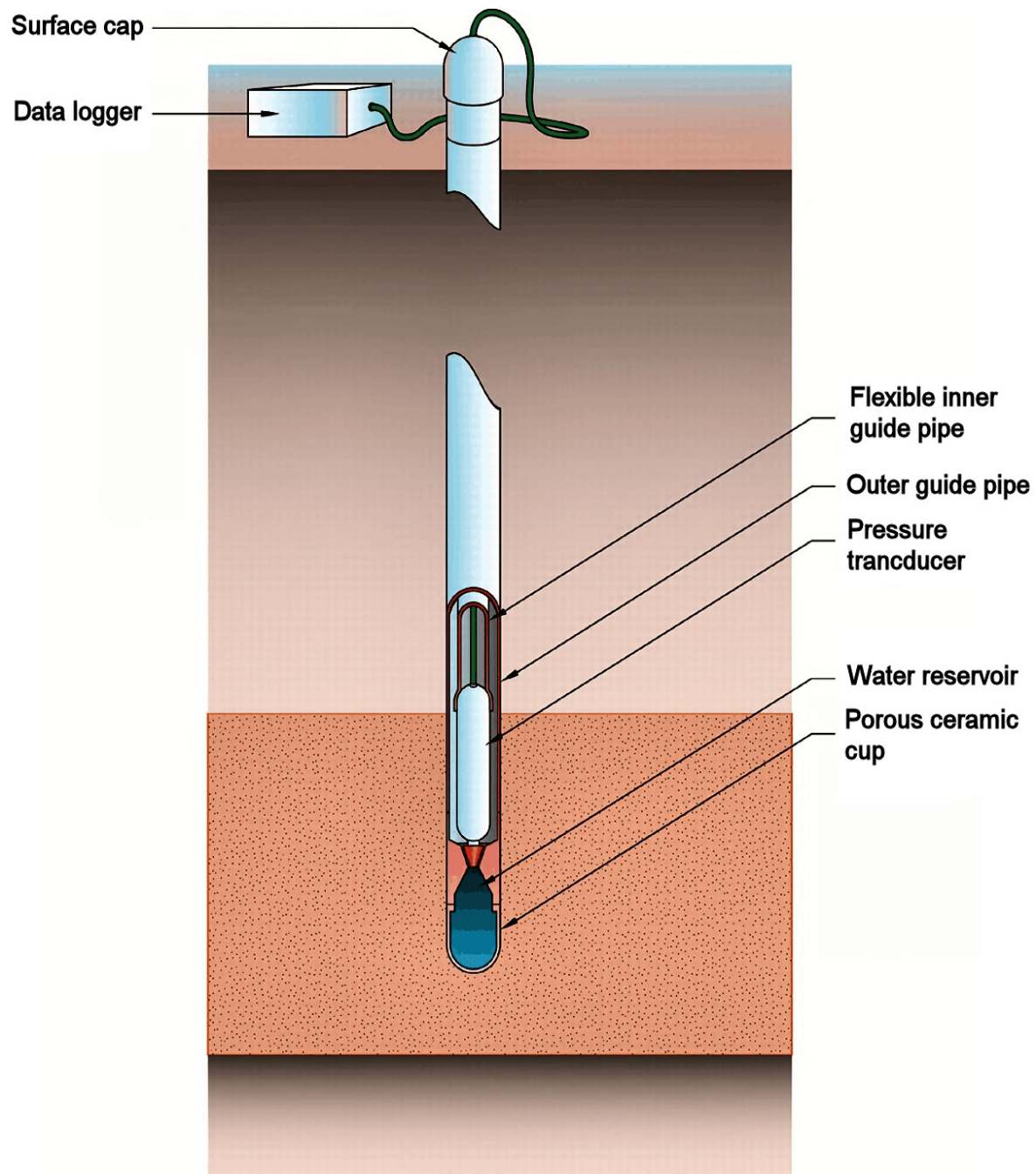
A tensiometer fails if a gas bubble forms inside the device, because the connection with the bulk soil is no longer almost incompressible. Spontaneous cavitation of water occurs as the water tension nears 8 to 10 m [26.2 to 32.8 ft] under typical pressure and temperature conditions, with impurities and small entrapped gas bubbles serving as nuclei for cavitation. Porous cups for tensiometers are usually designed with sufficiently small pores that cavitation occurs before air penetrates the porous cup. Despite efforts to extend the range of tensiometric measurements by delaying onset of cavitation, the practical range for these devices remains limited to suction (negative matric potential) less than 100 kPa [1 bar] {i.e., 10 m [32.8 ft] head of water}, and other techniques must be used for matric potential measurement under drier conditions.

Tensiometer maintenance demands for deep monitoring are reduced with the suggested tensiometer proposed by McElroy and Hubbell (2004), as shown in Figure 3-15. The advanced tensiometer has a relatively small water reservoir adjacent to the porous cup, reducing the need for refilling, and instrument accuracy is enhanced by placing the pressure transducer adjacent to the reservoir where temperatures are relatively stable.



**Figure 3-14. Illustration of Typical Tensiometers for Matric Potential Measurement Using Vacuum Gauges and Electronic Pressure Transducers. [Illustration Copyright 2005 From “Field Methods for Monitoring Solute Transport” by Tuller and Islam, 2005. Reproduced by Permission of Routledge/Taylor & Francis Group, LLC.]**

Tensiometers must maintain direct hydraulic connection between the vacuum gauge and the surrounding bulk medium or the device fails, so proper tensiometer installation is critical to sensor performance. Prior to installation, porous cups should be soaked for 24 to 48 hours, followed by thorough testing of the tensiometers under controlled laboratory conditions, to ensure that the device is free of bubbles. The orientation of the installation borehole is not important, but it should be only slightly larger than the tensiometer to better maintain hydraulic connection between tensiometer and the bulk medium. A tight hydraulic connection is formed by pressing the tensiometer into a slurry emplaced at the measurement location. The slurry is preferably formed of the native granular material cored from the measurement location during borehole installation, but silica flour may replace the native material for installation in rock. In expansive soils, a bentonite collar should be poured and compacted around the top portion of the sampler to prevent water from seeping through gaps between the sampler and installation borehole.



**Figure 3-15. An Advanced Tensiometer for Large Depths Installed in a PVC Guide Pipe [Reproduced From McElroy and Hubbell (2004) With Permission]**

Macropores or highly structured and coarse porous media may limit the application of tensiometric measurements.

Characteristics of the tensiometer method are summarized in Summary Box 3.

Summary Box 3. Tensiometers	
<b><u>Measurement Range</u></b>	
<ul style="list-style-type: none"> <li>Typically from 0 to –10 m [0 to –32.8 ft] of pressure head (some can measure positive pressure)</li> </ul>	
<b><u>Accuracy</u></b>	
<ul style="list-style-type: none"> <li>Dependent on pressure gauge and response time, typically within <math>\pm 10</math> mm [<math>\pm 0.4</math> in]</li> </ul>	
<b><u>Limitations</u></b>	
<ul style="list-style-type: none"> <li>Frequent maintenance (newly designed advanced tensiometers depicted in Figure 3-15 reduce maintenance)</li> <li>Limited measurement range</li> <li>Small measurement volume</li> </ul>	
<b><u>Advantages</u></b>	
<ul style="list-style-type: none"> <li>Repetitive and nondestructive measurements at a location</li> <li>Most direct measurement of capillary/matric potential (at appropriate range)</li> <li>Automation and remote monitoring and service (advanced design)</li> <li>Low cost</li> </ul>	
<b><u>Applicability for the Performance Confirmation Program</u></b>	
<ul style="list-style-type: none"> <li>May be used to independent quantify percolation flux in the shallow subsurface (combined with neutron probes or time domain reflectometry)</li> <li>Perhaps the most sensitive sensor for <i>in situ</i> assessment of local hydraulic gradients associated with capillary diversion around drifts</li> </ul>	

### 3.2.4 Heat Dissipation Sensors

Heat dissipation sensors are akin to electrical resistivity sensors (Section 3.2.5), in that the technique relies on measurements within a medium with known characteristics emplaced within the bulk medium. As with electrical resistivity methods, it may take a long time for the emplaced medium to come to complete equilibration with the surrounding bulk medium, particularly under dry conditions.

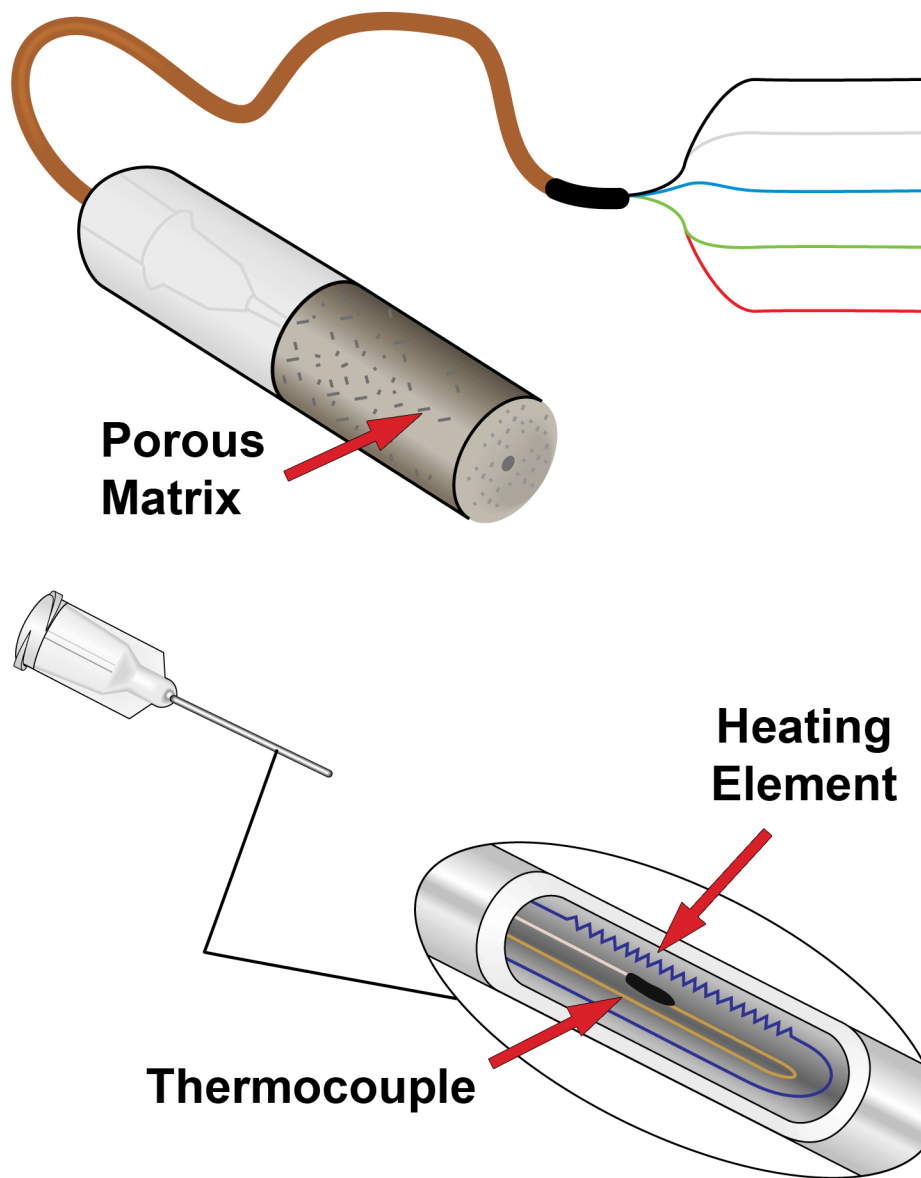
Heat dissipation sensors characterize matric potential by analyzing the thermal response of the emplaced rigid porous medium. Heat dissipation sensors contain heating elements in line source or point source configurations embedded in a rigid porous matrix with fixed pore space. A heat pulse is created by applying a constant current through the heating element for a specified time period, with the thermal response measured by a thermocouple placed at a certain distance from the heating source (Phene, et al., 1971; Bristow, et al., 1993). The rate of heat dissipation in a porous medium is dependent on the specific heat capacity, thermal conductivity, and density of the medium. All three quantities increase with increasing water content, which in turn increases with increasing matric potential. These relationships are

determined before sensor emplacement. The thermocouple response following a pulse allows the thermal properties of the emplaced medium to be estimated, which in turn allows determination of matric potential. Often the magnitude of temperature increase following a pulse is linearly related to the natural logarithm of matric potential, with a larger temperature increase occurring under drier conditions.

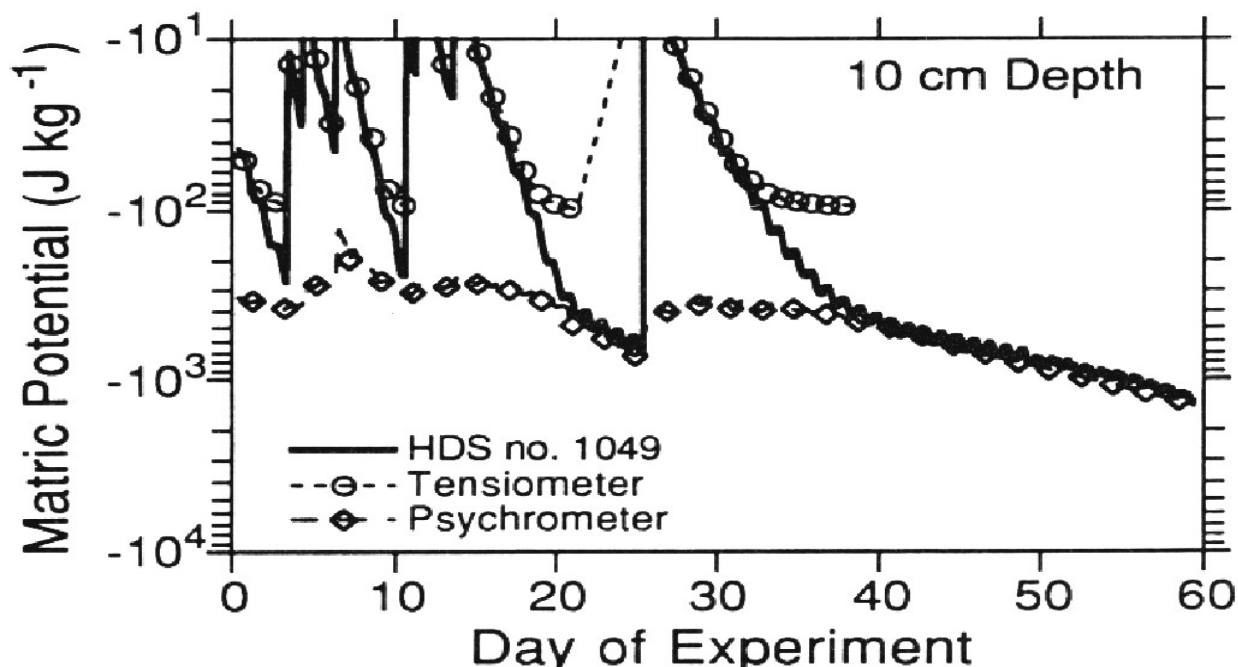
A line source sensor is shown in Figure 3-16. This sensor has a fine-wire heating element axially centered in a cylindrical ceramic matrix, with a matrix radius of 1.5 cm [0.59 in] and a matrix length of 3.2 cm [1.26 in]. A thermocouple is located adjacent to the heating element at mid-length. Both the heating wire and the thermocouple are contained in the shaft portion of a hypodermic needle. A comparison between heat dissipation, tensiometer, and psychrometer measurements of matric potential within the same soil volume in a laboratory experiment (Reece, 1996) is shown in Figure 3-17. The heat dissipation measurements follow the tensiometer measurements in the wet range and the psychrometer measurements in the dry range, suggesting that the heat dissipation approach may be appropriate in the intermediate range where neither of the other two methods are accurate.

Characteristics of heat dissipation sensors are summarized in Summary Box 4.

Summary Box 4. Heat Dissipation Sensors	
<b><u>Measurement Range</u></b>	
<ul style="list-style-type: none"> <li>Typical matric potential range from <math>-0.01</math> to <math>-1</math> MPa [<math>-0.1</math> to <math>-10</math> bar] {Flint, et al. (2002) claim an upper range of <math>-100</math> MPa [<math>-1000</math> bar], which seems highly unlikely for many soils}</li> </ul>	
<b><u>Accuracy</u></b>	
<ul style="list-style-type: none"> <li>Measurement sensitivity is proportional to matric potential value. The data of Flint, et al. (2002) suggest 20 percent absolute in the range of <math>-0.01</math> and <math>-35</math> MPa [<math>-0.1</math> and <math>-350</math> bar], while the data considered by Reece (1996) place the value at approximately <math>\pm 7</math> percent</li> </ul>	
<b><u>Limitations</u></b>	
<ul style="list-style-type: none"> <li>Limited accuracy</li> <li>Slow response time</li> <li>Hydraulic decoupling with surrounding porous media under dry conditions</li> <li>Indirect measurement of matric potential</li> <li>Requires calibration</li> </ul>	
<b><u>Advantages</u></b>	
<ul style="list-style-type: none"> <li>Simple installation</li> <li>Low maintenance</li> <li>Remote monitoring</li> <li>Automation</li> <li>Low cost</li> </ul>	
<b><u>Applicability for the Performance Confirmation Program</u></b>	
<ul style="list-style-type: none"> <li>A potential backup sensor for tensiometers under dry conditions</li> </ul>	



**Figure 3-16. A Schematic of the CSI 229 Heat Dissipation Sensor (Campbell Scientific, Inc.) [Illustration Courtesy of Campbell Scientific, Inc.]**



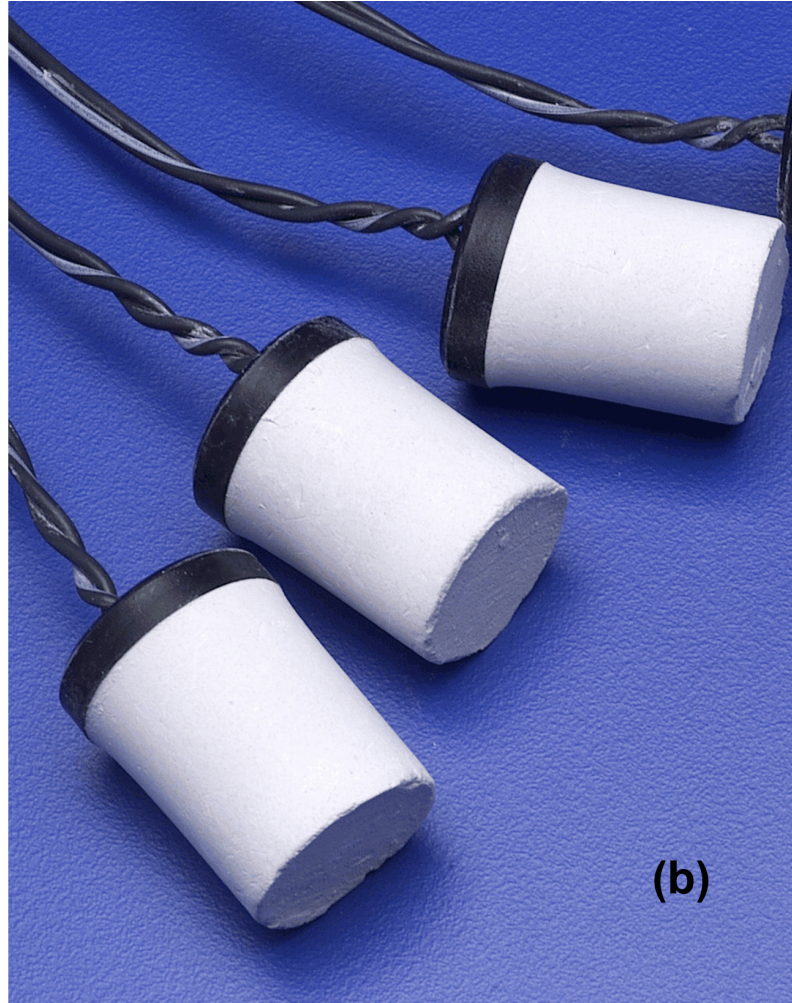
**Figure 3-17. Water Potential Dynamics Measured by Heat Dissipation Sensor, Tensiometer, and Psychrometer During a Laboratory Experiment. The Tensiometer and Psychrometer Ranges do not Overlap, but the Heat Dissipation Sensor Bridges the Gap. [Reproduced From Reece (1996) With Permission]**

### 3.2.5 Electrical Resistivity Sensors

The electrical resistivity of a porous medium depends on the water content and soluble ionic constituents. Simple and inexpensive sensors, such as the sensor shown in Figure 3-18, have been developed to infer water status using the dependence of resistivity on water content. These sensors usually consist of concentric cylindrical or flat parallel electrodes embedded in an engineered porous matrix and connected to lead wires. Resistance is measured within the engineered porous matrix, and the relationship between resistance and water potential obtained from calibration prior to installation is used to determine water potential. The commonly used term 'gypsum block' arises from early models, which were made of gypsum to buffer ionic effects from the surrounding medium (Buoyoucos and Mick, 1940), and from the practice of using gypsum as a buffer for many sensors using some other material for the porous matrix. As with tensiometers and heat dissipation sensors, the sensor is embedded in the surrounding medium and allowed to equilibrate.

Under equilibrium conditions, the sensor matric potential is equal to the surrounding water matric potential, but the sensor water content may be different than water content of the surrounding medium. Electrical resistivity measurements are often used to estimate soil water content, either by using a known relationship between soil matric potential and soil water content (Gardner, 1986) or by inferring soil water content directly with proper calibration for a particular soil (Kutilek and Nielsen, 1994).





**Figure 3-18. Commercially Available Electrical Resistance Sensors: (a) 253-L Watermark Soil Matric Potential Block (Irrometer Company, Inc.), and (b) Gypsum Blocks (Delmhorst Instrument Co.). [Image (a) Watermark Sensors, Irrometer Company, Riverside, California, Reproduced With Permission; Image (b) Courtesy of Delmhorst Instrument Co.]**

The primary advantages of electrical resistance sensors are their low cost and simple measurement requirements. Measurements may be obtained using a simple resistance meter, or more conveniently acquired automatically using a data logger. However, each electrical resistance sensor must be calibrated before use, which can be a significant effort, because the sensors can be affected by the ionic composition of the surrounding solution. Moreover, the method is inaccurate under wet conditions, thus this measurement method is appropriate mostly as a qualitative indicator of water status (Spaans and Baker, 1992).



### 3.2.6 Psychrometers

Psychrometric measurements are based on equilibrium between liquid water and water vapor in the ambient pore space. Water potential in the gaseous phase is related to relative humidity, through the Kelvin equation (Or and Wraith, 2002)

$$RH = \frac{e}{e_0} = \exp \left( \frac{M_w g h}{RT} \right) \quad (3-11)$$

where

RH	—	relative humidity
$e$	—	water vapor pressure
$e_0$	—	saturated vapor pressure at the same temperature
$M_w$	—	molecular weight of water (0.018 kg mol <sup>-1</sup> )
$g$	—	gravitational acceleration (9.81 m s <sup>-2</sup> at sea level)
$h$	—	water potential (m)
$R$	—	ideal gas constant (8.31 J K <sup>-1</sup> mol <sup>-1</sup> )
$T$	—	absolute temperature (K)

Note that  $h$  includes both the matric potential and the osmotic potential because air is an effective diffusion barrier for most solutes. Rearranging Eq. (3-11) and taking a log-transformation leads to

$$h = \frac{RT}{M_w g} \ln \left( \frac{e}{e_0} \right) \quad (3-12)$$

When  $e/e_0$  is close to 1, which is usually the case in the vadose zone in humid climates or at large depths in arid areas, the logarithm in Eq. (3-12) can be linearized with little loss of accuracy, resulting in

$$h = \frac{RT}{M_w g} \left( \frac{e}{e_0} - 1 \right) = 471 T \left( \frac{e}{e_0} - 1 \right) \quad (3-13)$$

for  $h$  in meters. Accuracy deteriorates approximately linearly with  $h$ ; the linearized relationship has an error of approximately 7.5 percent for  $h = -150$  m, which is roughly the wilting point for many plant species.

Psychrometers typically measure the difference between a dry bulb, and wet bulb temperature. The dry bulb is at the temperature of the surrounding medium. An evaporating surface fixes the temperature of the wet bulb, with the difference in temperature between dry and wet bulbs dependent on evaporation rate, which is in turn dependent on the relative humidity of the gas phase. The difference in temperatures between the wet and dry bulb is related to the relative humidity by the psychrometric equation

$$\frac{e}{e_0} = 1 - \left( \frac{s + \gamma}{e_0} \right) \Delta T \quad (3-14)$$

where

$s$	—	slope of the saturation water vapor pressure curve ( $s = de_0/dT$ )
$\gamma$	—	psychrometric constant $\{\sim 0.067 \text{ kPa K}^{-1} \text{ at } 20^\circ\text{C} [68^\circ\text{F}]\}$
$\Delta T$	—	temperature difference ( $^\circ\text{C}$ ) between the dry and wet bulb

A thermocouple is a double junction of two dissimilar metals. A thermocouple psychrometer uses a fine-wire chromel-constantan or other bimetallic thermocouple. When the two junctions are subject to different temperatures, they generate a voltage difference (the Seebeck effect) (Seebeck, 1921). Conversely, when an electrical current is applied, the junction is heated or cooled, depending on the direction of the current (the Peltier effect). In typical use, one junction of the thermocouple is suspended in a thin-walled porous ceramic or stainless steel screen cup buried in the medium of interest, while another is embedded in an insulated plug to measure the ambient temperature at the same location (Figure 3-19). An electrical current cools the suspended thermocouple below the dew point until water condenses on the junction, whereupon the cooling current is stopped. The wet bulb temperature is achieved during subsequent evaporation from the junction.

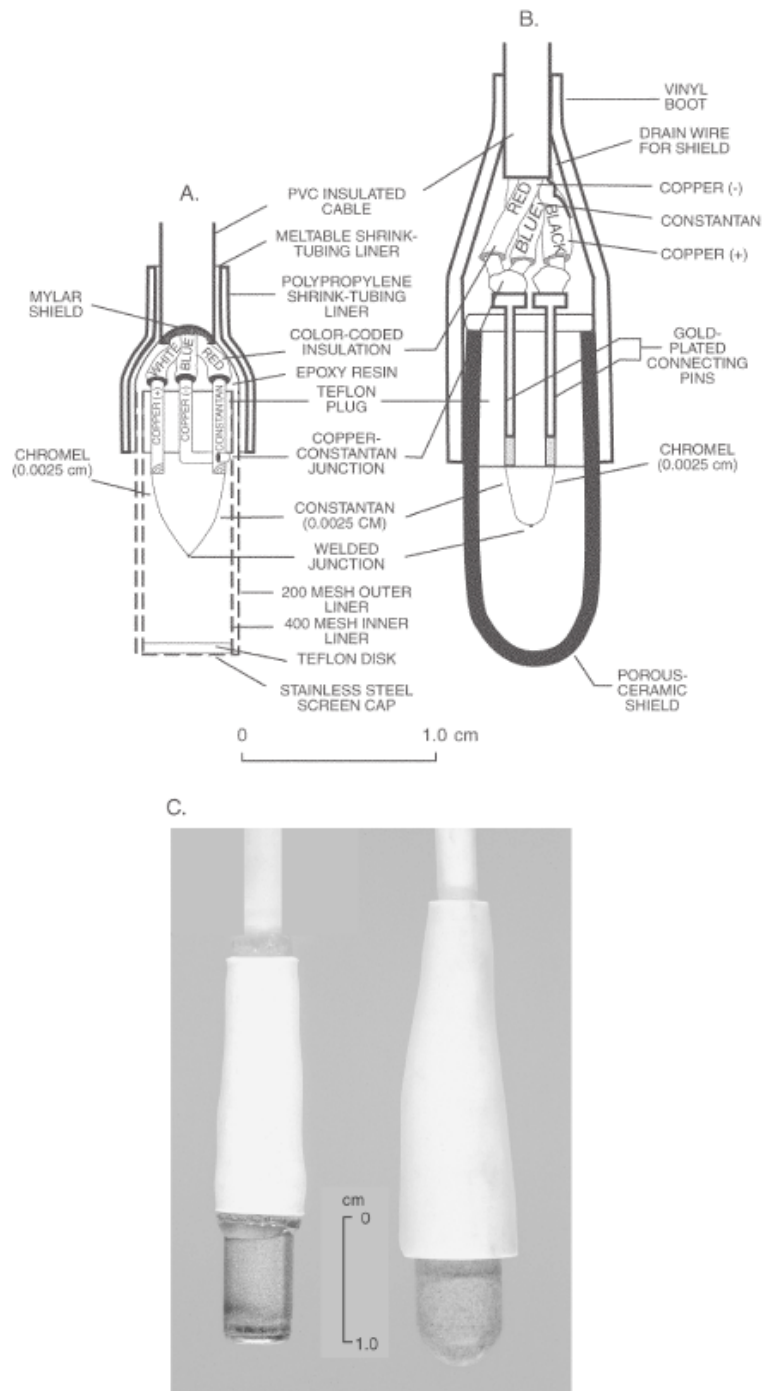
An accurate measurement of the temperature difference plays a critical role in psychrometric water potential determinations. For example, temperature-difference measurements must be accurate to  $0.005^\circ\text{C}$  [ $0.009^\circ\text{F}$ ] for water potential measurements to be accurate to  $\sim 10^4 \text{ m}$ . Psychrometers are, therefore, highly susceptible to thermal gradient effects and do not perform well when significantly affected by diurnal temperature variations. Psychrometers have a relatively slow response time, because the method requires that the vapor and liquid phase must come to equilibrium. Psychrometers may be buried and left for long periods, although corrosion is a problem in some environments.

Recently introduced water activity measurement devices (Decagon Devices, Inc., Pullman, Washington) rely on a *chilled mirror* sensor to measure water potential to as low as  $-300 \text{ MPa}$  [ $-3,000 \text{ bar}$ ] following equilibration of liquid and vapor phases of water in a sample within a closed chamber. A thermoelectric (Peltier) cooler controls the mirror temperature. An infrared light beam is directed onto the mirror and reflected to a photodetector, which detects the change in reflectance when condensation occurs on the mirror (wet bulb temperature). A thermocouple attached to the mirror accurately measures the dew-point temperature.

Characteristics of psychrometers are summarized in Summary Box 5.

### 3.3 Pore Water Extraction

The importance of collecting pore water solution for measuring the concentrations of dissolved constituents, and conducting environmental studies in general, was recognized by Joffe (1932), who described the soil water solution as the “blood circulating in the soil body.” Soil scientists, hydrologists, geochemists, ecologists, engineers, and health safety specialists have major interest in the chemical composition of the soil solution, as it provides crucial information regarding the distribution of plant nutrients and hazardous chemicals in the vadose zone. Water quality monitoring below waste disposal sites, for example, is important for detection of contaminant plumes migrating from leaking liners, and allows early initiation of remedial measures. A wide variety of extraction techniques and devices are available.



**Figure 3-19. Psychrometers: Schematics of (a) Screen-Caged Psychrometer Sensor (b) Ceramic-Cupped Psychrometer Sensor, and (c) Photograph of Commercially Available Sensors. [Reproduced From Andraski and Scanlon (2002) With Permission]**

### Summary Box 5. Psychrometers

#### **Measurement Range**

- Andraski and Scanlon (2002) state that the upper measurement limit of a psychrometer is approximately  $-0.03$  to  $-0.2$  MPa [ $-0.3$  to  $-2$  bar]. The lower limit of routine measurements made with Peltier sensors is approximately  $-8$  MPa [ $-80$  bar]. At lower water potentials, the dew-point temperature is more than  $0.6$  °C [ $33$  °F] below ambient temperature and Peltier cooling is too inefficient to condense sufficient water on the sensing junction for stable readings. The lower limit of water potential measurements with wet-loop sensors (where a large drop of water is placed on the sensing junction) is approximately  $-300$  MPa [ $-3,000$  bar] because water application produces readings that are more stable than achieved by Peltier cooling sensors. A typical range for field sensors is  $-0.1$  to  $-10$  MPa (e.g., Wescor PST-55).

#### **Accuracy**

- $\pm 2$  percent {at best,  $-0.01$  MPa [ $-0.1$  bar]}
- Dependent on relative humidity or matric potential

#### **Limitations**

- Limited measurement range
- Coarse resolution at the wet end

#### **Advantages**

- Good *in situ* measurement capability in the dry (low relative humidity) range

#### **Applicability for Performance Confirmation Program**

- Extends the range of *in situ* matric potential measurement in the dry range
- Supports water content measurement in drying regions

Six common techniques for extracting pore water are discussed in this section, including suction cups, combined tensiometers and suction cups, suction lysimeters, passive capillary samplers, capillary absorbers, and extraction from samples.

### 3.3.1 Suction Cups

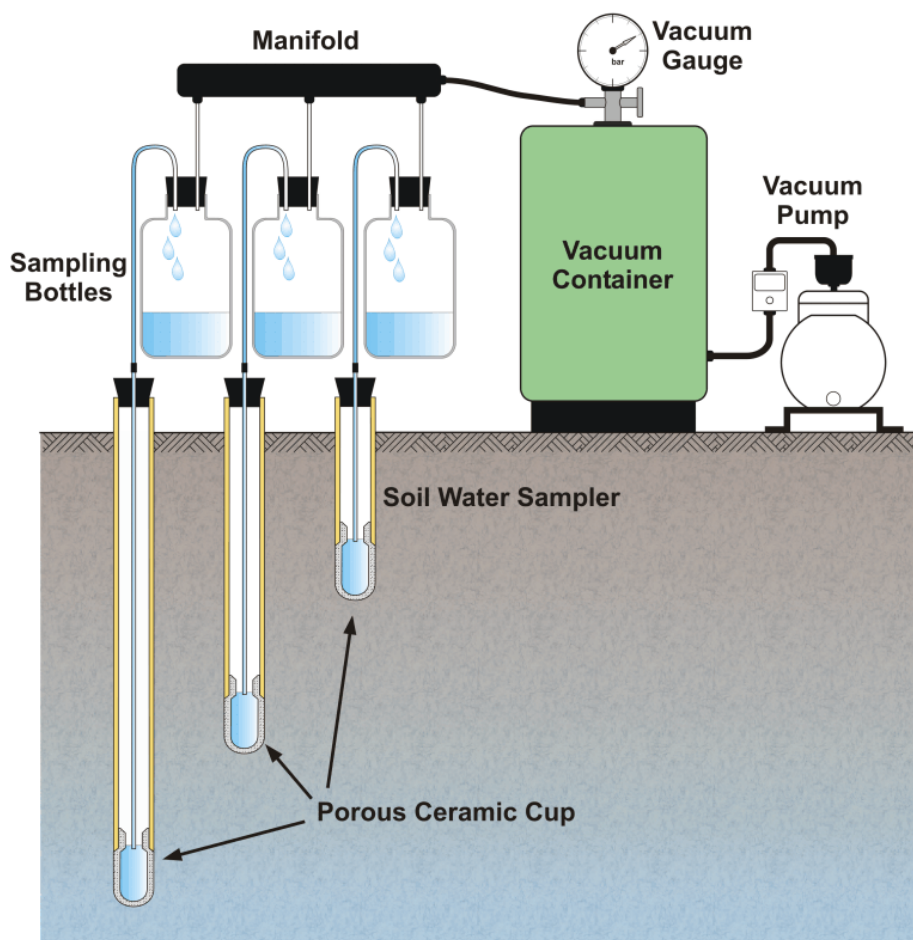
Briggs and McCall (1904) were among the first to introduce a method for extracting soil water through porous ceramic cups. Numerous modifications to the initial design of the suction cup have been made since its invention almost a century ago. Cole (1968) introduced automated soil solution samplers. Chow (1977) developed a vacuum sampler that automatically shuts down after collecting a specific volume of soil solution. Additional improvements were introduced by Parizek and Lane (1970) and Wood (1973). Stone and Robl (1996) designed a heavy duty device to withstand soil compaction due to farm equipment.

The most commonly applied devices for collection of solution from unsaturated soils are vacuum soil water samplers (Rhoades and Oster, 1986), such as suction cups or suction lysimeters. These instruments operate under the same principle. A porous material (cup or plate) is brought into hydraulic contact with the surrounding soil, the sampler is evacuated to a pressure slightly below the matric potential in the surrounding medium to induce a pressure gradient, and pore water flows into the sampler and collection containers. It is important to adjust the applied vacuum (usually based on tensiometer measurements) to prevent high gradients and the development of preferential flow paths towards the cup. Accordingly, soil water samplers are

commonly installed in combination with tensiometers, or the sampler and tensiometer are combined in one instrument, as discussed in Section 3.3.2. The potential field developing around a suction cup was measured with tensiometers by Krone, et al. (1951).

The time required for solution collection depends on the volume necessary for chemical analysis, the hydraulic conductivity and water content (matric potential) of the medium, and the applied gradient (Rhoades and Oster, 1986). A sandy soil close to field capacity (i.e., shortly after gravity drainage ceases following saturation) will provide sufficient sample volume for most analyses within a few hours, while less permeable or drier media may require considerably more time to extract the same volume. Note that automated sampling stations (Cepuder and Tuller, 1996) enable continuous sampling.

A typical soil water collection system contains three main functional units: the suction cups or plates, sampling bottles, and a vacuum container connected to a vacuum pump, as illustrated in Figure 3-20. The applicable range of soil water samplers is limited to suction values (vacuum)



**Figure 3-20. Typical Setup of Soil Water Samplers (Suction Cups) [Illustration Copyright 2005 From “Field Methods for Monitoring Solute Transport” by Tuller and Islam, 2005. Reproduced by Permission of Routledge/Taylor & Francis Group, LLC.]**

of less than 10 m [32.8 ft] head of water due to onset of cavitation in the metastable solution at subatmospheric pressure and the propensity of air to enter porous materials. Installation of suction cups closely follows procedures discussed for tensiometers, because the two devices have similar operational characteristics.

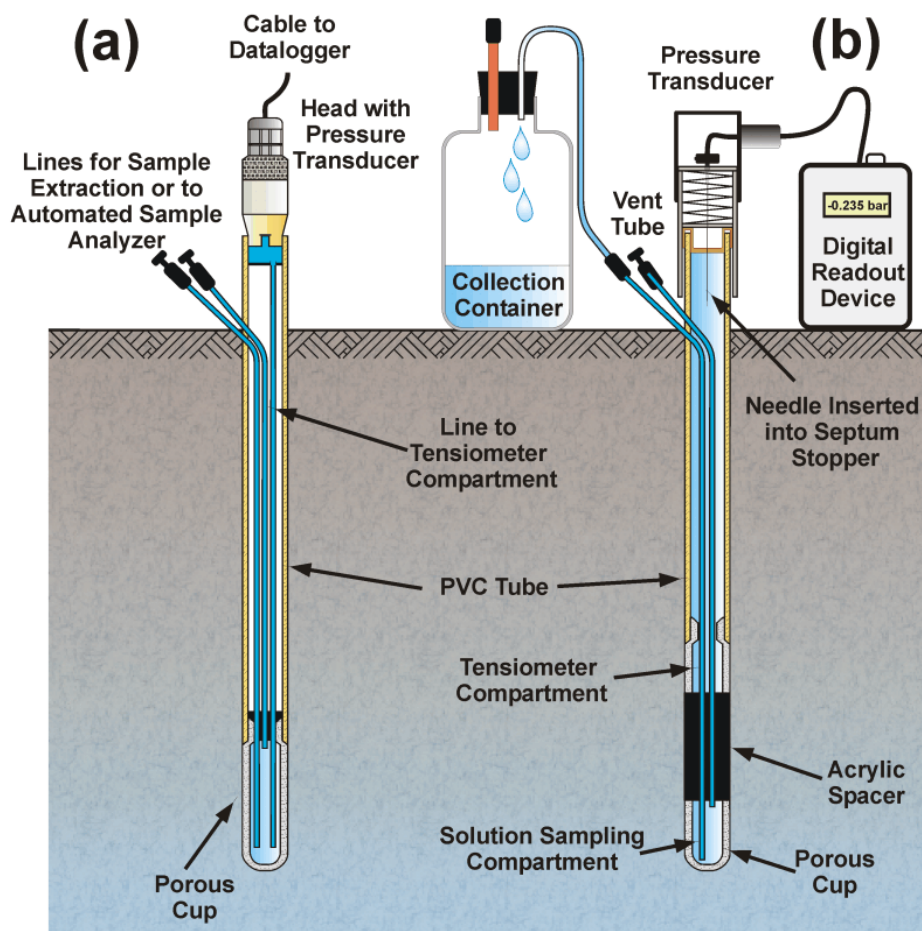
Suction samplers primarily differ in the shape and size of the devices, and in the chemical and physical properties of the porous materials used to establish hydraulic contact with the surrounding soil. A large number of porous materials such as ceramic (perhaps the most widely used), polytetrafluoroethylene, polyethylene, stainless steel, nylon, polyvinyl chloride, polypropylene, polyvinylidene fluoride, Teflon<sup>®</sup>, and glass may be used for suction cups or plates. The porous material is often selected based on cost, durability, and minimization of chemical interactions with components in pore water. There is conflicting evidence concerning the applicability of ceramic samplers for collecting pore water for chemical analyses, probably due to differences in chemical composition and physical properties of the ceramic materials used in the devices and differences in chemical composition of soil solution.

### **3.3.2 Combined Solution Sampling—Tensiometer Probes**

Characterization of solute transport in the vadose zone requires measurement of spatial and temporal changes in both solute concentration and water content (or matric potential). These observations are commonly made using suction samplers and tensiometers. It is convenient to combine these devices into one probe to take advantage of the similarities in the basic design of the two devices.

Moutonnet, et al. (1989) introduced a modified tensiometer they call the Tensionic probe (shown in Figure 3-21a) that allows concurrent measurement of matric potential and extraction of pore water. The Tensionic probe uses a porous ceramic cup to contact the surrounding medium, just like a standard tensiometer. The ceramic cup is placed at the tip of a polyvinyl chloride shaft. The shaft protects three tubes entering the cup, with one tube connected to a sealed compartment in the upper portion of the shaft that contains the tensiometer sensor, and two tubes forming a conduit to the surface for priming and sample extraction. The tensiometer is primed with de-aired and deionized water at the start of each sampling cycle. Once the Tensionic probe equilibrates matric potential with the surrounding medium, the Tensionic probe operates in tensiometer mode like any tensiometer. Ions present in the pore water continually diffuse through the porous cup while the Tensionic probe is in place, and ultimately the water inside the tensiometer attains chemical equilibrium with the surrounding pore water. Moutonnet, et al. (1993) report that 8 to 10 days were required for equilibrium to occur for  $\text{NO}_3^-$ . Once chemical equilibrium is reached, the sample is extracted and the tensiometer is flushed and refilled with de-aired and deionized water to start another sampling cycle. Moutonnet, et al. (1993) and Moutonnet and Fardeau (1997) used automated Tensionic probes to determine concentrations of  $\text{NO}_3^-$ -N,  $\text{NO}_2^-$ -N, and  $\text{NH}_4^+$ -N under maize. Similar devices were applied by Morrison, et al. (1983) and Rehm, et al. (1986) to characterize contaminant migration under waste disposal sites. Major drawbacks of the Tensionic probe are the lack of control over the sample volume, which is largely dependent on water content (Saragoni, et al., 1990), and uncertainty regarding the time required for chemical equilibration.

Essert and Hopmans (1998) took a different design approach when combining a tensiometer and pore water sampler. They separated the porous cup with an acrylic barrier into two compartments, as shown in Figure 3-21b. The bottom compartment is used for sample



**Figure 3-21. Combined Solution Sampling: (a) The Tensionic Probe (Moutonnet, et al., 1993), and (b) A Probe with Separated Sampling and Tensiometer Compartments (Essert and Hopmans, 1998). [Illustration Copyright 2005 From “Field Methods for Monitoring Solute Transport” by Tuller and Islam, 2005. Reproduced by Permission of Routledge/Taylor & Francis Group, LLC.]**

extraction, while the top compartment operates as a tensiometer. Interactions between the two compartments would interfere with the operational modes, and may occur due to (i) reduction of the matric potential in the surrounding medium as water is removed during solute extraction, and (ii) change of solute concentration due to exchange with the tensiometer compartment. Essert and Hopmans (1998) recommend separating the compartments with a 10 cm [3.9 in] spacer to overcome these biases. This distance is somewhat arbitrary, although it is supported by theoretical considerations (Warrick and Amoozegar-Fard, 1977).

### 3.3.3 Lysimeters

Lysimeter studies date back to the late 18th century when scientists investigated the fate of precipitation in soils (Joffe, 1932). The term “lysimeter” originated from the Greek words “luisis” (loosening) and “meter” (measuring), and is somewhat misused today. Lysimeters were originally developed to study complex soil-plant-atmospheric relationships, with solute transport