

where

ρ_b — bulk density of the solid constituents
 C_s — specific heat capacity of the solid constituents
 $(\rho C)_w$ — volumetric heat capacity of water.

Equation (3-35) assumes that bulk density and solid specific heat capacity remain constant.

Ren, et al. (2000) introduced an application of the heat pulse method for estimating water flux density in a porous medium. The operational expression developed by Wang, et al. (2002) relates steady-state temperature differences between locations upstream and downstream of a heat source to the steady water flux density, J_w

$$J_w = \frac{2(\rho C)\alpha}{(\rho C)_w (r_d + r_u)} \ln\left(\frac{T_d}{T_u}\right) \quad (3-36)$$

where

α — porous medium thermal diffusivity (m^2/s)
 r_u, r_d — upstream and downstream distances from the heat source
 T_u, T_d — upstream and downstream measured temperatures

In theory, the expression is suitable for fluxes in the range of 0.1 to 5.0 m/day. Thermal dispersion should be considered for high water fluxes. Current methods can reliably determine temperature differences of approximately 0.01 °C, implying that this method cannot observe water fluxes less than 0.06 m/day (Mori, et al., 2003). Mori, et al. (2003) performed a series of tests using the method, with results that suggest the method may not be reliable for unsaturated conditions but may perform better for saturated conditions, perhaps in part because higher fluxes were tested under saturated conditions.

3.8 *In Situ* Gas Flux Measurement

The primary methods for gaseous measurements within porous media include direct pore air sampling at different depths (Buyanowski and Wagner, 1983) and laboratory analysis of core samples (Cortassa, et al., 2001). Measurements of surface CO_2 flux are typically based on the “closed-chamber method,” whereby surface flux is determined from changes in gas concentration within an enclosed volume on the ground surface (de Jong, et al., 1979; Cropper, et al., 1985; Drewitt, et al., 2002). Portable devices such as the Li-6400 systems by Li-COR Biosciences (shown in Figure 3-40) are capable of measuring soil CO_2 fluxes using high accuracy research-grade instrumentation (Dugas, 1993).

Among the primary limitations of soil chamber measurements are the lack of continuous observations, manual setup, and impact on surface boundary conditions that could alter the nature of the diffusive flux (Davidson, et al., 1998). Attempts to improve temporal coverage (de Jong, et al., 1979; Cropper, et al., 1985; Freijer and Bouten, 1991) by continuous air pumping from the enclosure to a gas analyzer resulted in significant alteration of the ground surface boundary conditions due to variations in air pressures within the chamber (Lund, et al., 1999) and perturbation of natural conditions at the surface (e.g., gas concentration gradients, precipitation, radiation).

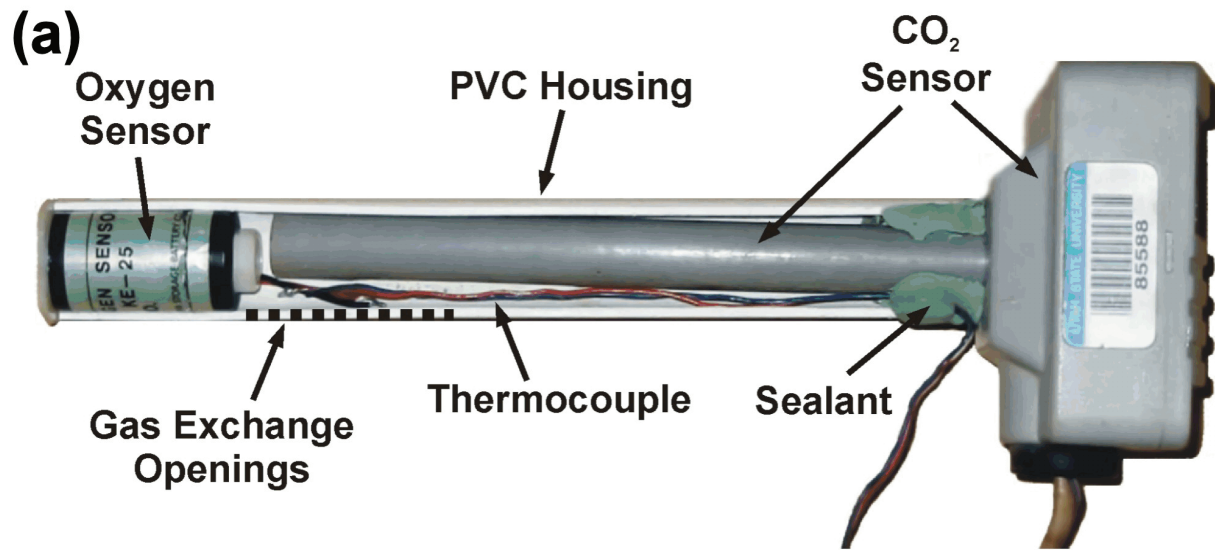


Figure 3-40. Gas-Flux Sensors: (a) Detailed View of Gas-Flux Sensor Arrangement With CO₂ and O₂ Sensors [Turcu, et al. (2005)], (b) Gas Flux Measurement System Li-8100 With Special Surface Chamber (See www.licor.com/env/ for System Description) [(a) Reproduced From Turcu, et al. (2005) With Permission; Photographs in (b) by D. Or]

Recently, automated surface chamber designs have been proposed for capturing short-term changes in soil respiration. Such systems were developed for customized experiments (Ambus and Robertson, 1998) or by specialized companies (i.e., the LI-8100 system by Li-COR Biosciences, Lincoln, Nebraska). However, these quasi-continuous systems still present short-time surface boundary-condition changes and biases due to air pumping and short-time pressure differences between soil and the chamber, and are difficult to calibrate. Moreover, surface chamber measurements only consider surface CO₂ fluxes without measuring subsurface CO₂ fluxes. The need for accurate determination of soil CO₂ flux and associated concentration profiles for extended periods is widely recognized as key to reliable integration of total CO₂ exchange between soil and the atmosphere (Ouyang and Boersma, 1992).

3.9 Sensor Pairing for *In Situ* Characterization and Monitoring

Certain characterization and monitoring activities rely on multiple sensor measurements within the same volume of medium. This is particularly important for *in situ* determination of various transport properties, such as hydraulic conductivity and liquid retention characteristics, and for continuous monitoring of fluxes.

Sensor pairs, such as time domain reflectometry probes and tensiometers, may be used for simultaneously determining water content and matric potential within the same volume. The limitations of most sensor pairing techniques stem from (i) differences in the volumes sampled by each sensor (e.g., large volume averaging by a neutron probe versus small volume averaging by a heat dissipation sensor or psychrometer); (ii) different equilibration times for each sensor (e.g., many *in situ* water content measurement methods are instantaneous but matric potential sensors require time for equilibrium, so that the two measurements may not be indicative of the same conditions); (iii) limited parameter ranges; and (iv) deteriorating sensor accuracy, often resulting in limited overlap in retention information and interpretation difficulty due to measurement errors within the range of overlap (Or and Wraith, 1999).

A visual summary of the methods available for matric potential measurement and their range of application is presented in Figure 3-41. The figure illustrates that most available techniques have a limited range and many ranges do not overlap. Some of the methods shown in Figure 3-41 are laboratory methods unsuitable for *in situ* field applications. In addition, various methods and combinations of sensor pairs have widely variable accuracy, adding to the complexity of data interpretation.

The Performance Confirmation Plan suggests that DOE will rely on highly variable and strongly nonlinear transport properties to estimate some quantities of interest. For example, the Plan suggests that deep percolation flux and gaseous fluxes will be estimated using unsaturated hydraulic conductivity and the unsaturated gaseous diffusion coefficient, respectively. The use of such parameters may lead to highly unreliable estimates. For example, Hubbell, et al. (2004) estimated downward liquid flux in the deep vadose zone {30 to 70 m [98 to 230 ft]} using the Darcian approach, combining *in situ* water potential measurements with laboratory estimates for unsaturated hydraulic conductivity, but the estimates were hindered by large uncertainty in the values of unsaturated hydraulic conductivity. Even though the existence of a unit hydraulic gradient in the formation was confirmed by remarkably stable tensiometer data over nearly 30 months, flux estimates (shown in Figure 3-42) ranged over four orders of magnitude. The highest flux value was approximately 500 times the mean precipitation of 22 cm/yr [8.7 in/yr]. It is anticipated that

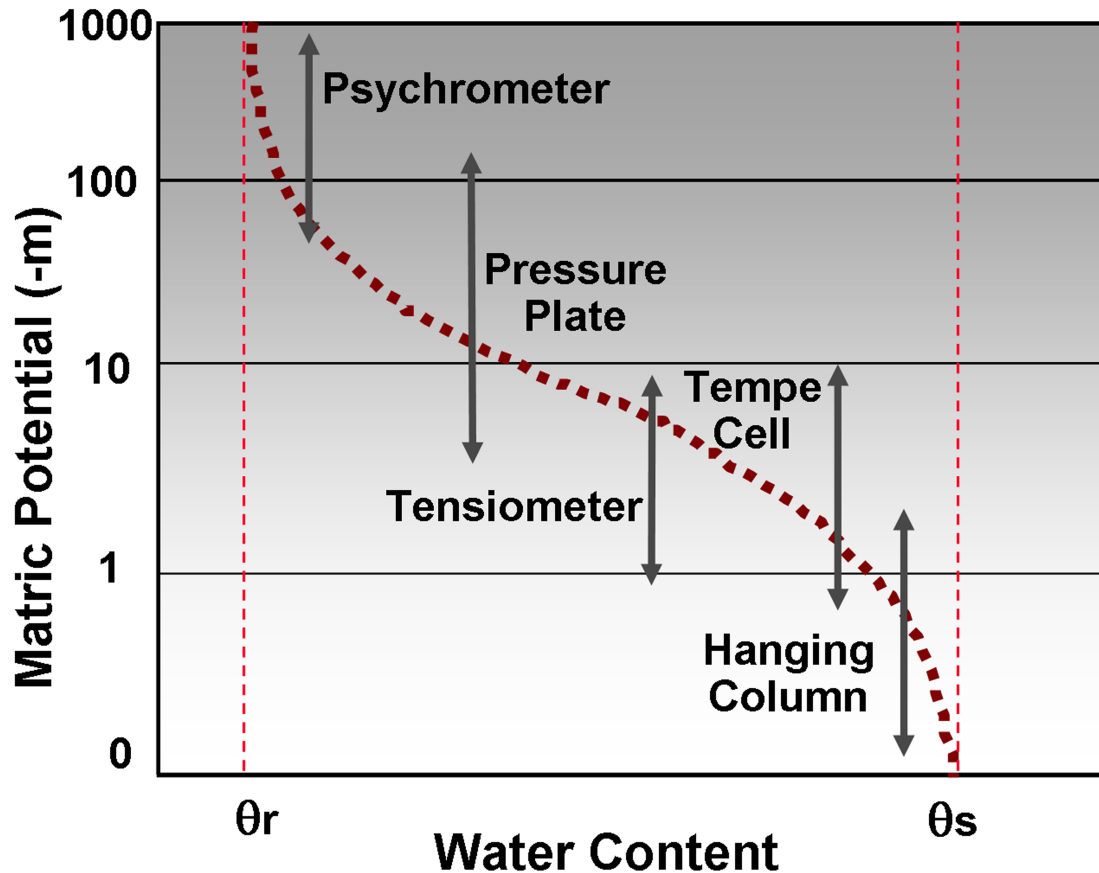


Figure 3-41. The Effective Measurement Range of Commonly Used Matric Potential Measurement Methods

techniques based on transport properties may feature improved flux estimates using *in situ* characterization of the transport properties. *In situ* characterization of transport properties invariably relies on use of sensor pairs for repetitive and non-destructive measurements of properties and dynamics within the same volumes of a porous medium. The following are typical examples:

- Figure 3-43 shows an experimental set-up using time domain reflectometry probes in close proximity to tensiometers for concurrent measurement of water content and matric potential dynamics (with plant root uptake in this experiment). The information is used to delineate an important region of the water characteristic curve *in situ* {albeit in the narrow range of matric potentials from 0 to -10 m [0 to -33 ft]}.
- Similar sensor pairing methodology may also be used for monitoring percolation fluxes and *in situ* determination of unsaturated hydraulic conductivity using the so-called instantaneous profile method. Figure 3-44 illustrates typical spatial and temporal data obtained from sensor pairs (neutron probe and tensiometers) that is subsequently

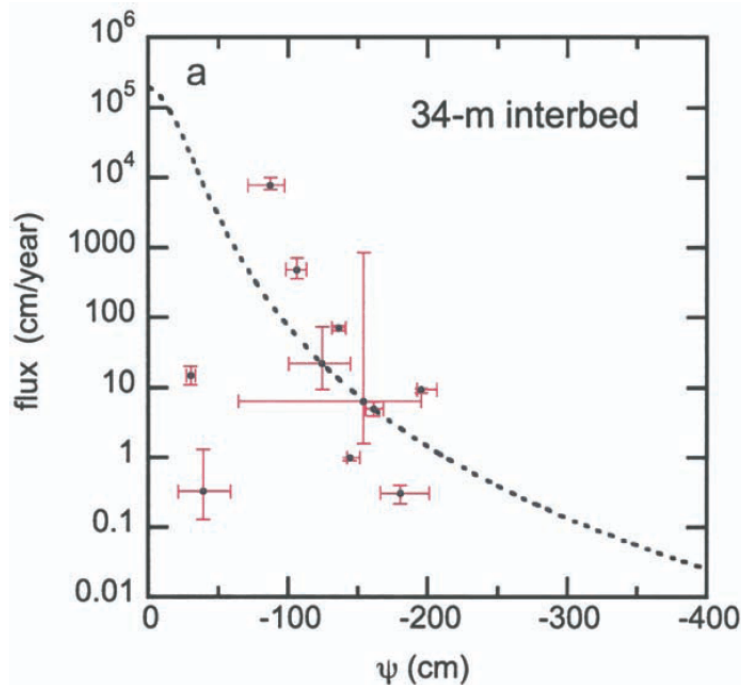


Figure 3-42. Vertical Flux Estimates from a Site in Idaho Exhibiting a Unit Gradient. Horizontal Bars Represent the Range of Water Potentials Measured at a Location, With the Solid Dot Placed at the Mean. Vertical Bars Represent the Range of Hydraulic Conductivity $K(\psi)$ Estimated From Those Values. The Dashed Lines Represent the Generic Curves Developed in Earlier Studies (Hubbell, et al., 2004). [Reproduced From Hubbell, et al. (2004) With Permission]

used to deduce the unsaturated hydraulic conductivity from a transient water flow experiment by the instantaneous profile method.

Figure 3-42 illustrates the inherent noise associated with field data, and the resultant need for averaging and integration to obtain quantities sufficiently reliable for flow parameter estimation. In addition to limited and non-overlapping measurement ranges of different sensors (e.g., Figure 3-41), experimentalists often encounter data with nonuniform error structure such as obtained from psychrometer measurements (where errors vary with water potential range). Differences in automation potential and in sampling intervals required for different sensors (rapid tensiometer sampling versus slow neutron probe measurements) complicate matters. These issues of range, error, and sampling interval compatibility become particularly important for extended monitoring periods.

In summary, each of the issues related to single-sensor accuracy are present when using multiple sensors. The use of multiple sensors to determine a quantity creates additional issues about the accuracy and representativeness of the desired quantity, because (i) the sensors typically have significantly different characteristics that may strongly affect data interpretation, and (ii) the likelihood of sensor deterioration is proportional to the number of sensors used.

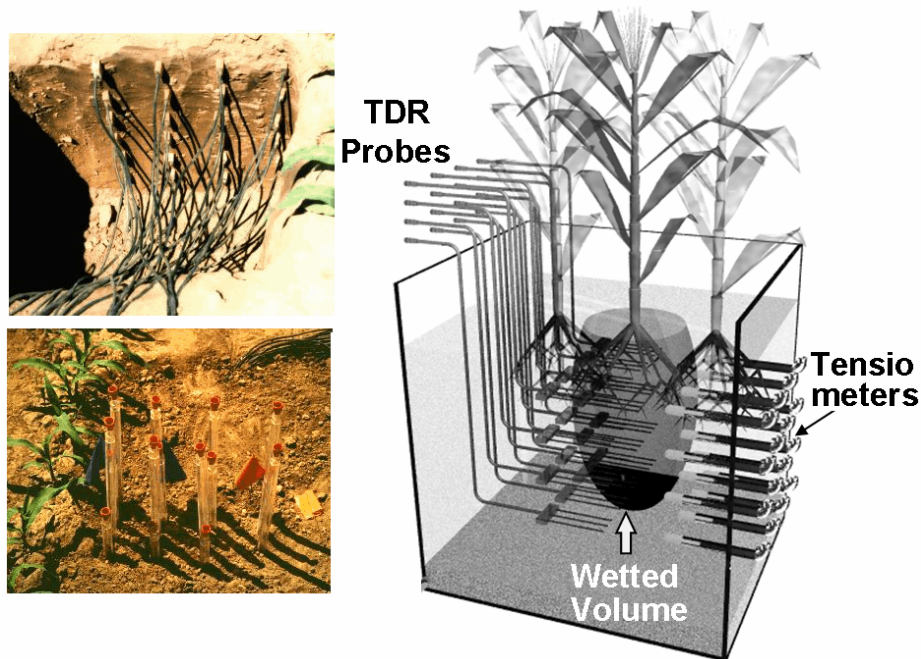


Figure 3-43. Time Domain Reflectometry Probes and Tensiometers Combined to Continuously Monitor Soil Water Dynamics in the Plant Root Zone [Photographs by D. Or]

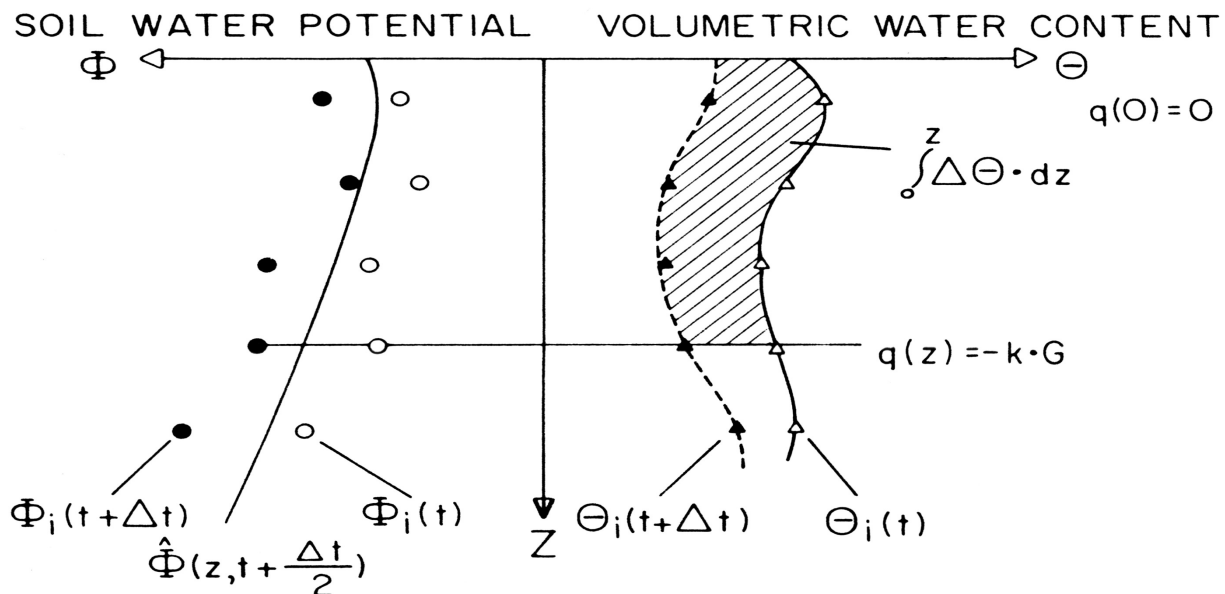


Figure 3-44. The Instantaneous Profile Method for Measurement of Hydraulic Conductivity *In Situ* Using Concurrent Measurements of Water Content and Matric Potential From Sensor Pairs [Reproduced From Flühler, et al. (1976) With Permission]

3.10 Characterization and Monitoring in the Vadose Zone

The measurement and characterization methods reviewed in this section use diverse operating principles and have widely varying sensitivities and accuracies. Vadose zone measurement methods are most commonly used for applications such as water management (agricultural), estimating recharge (hydrology and water resources), pollution mitigation and remediation (environmental), and infrastructure monitoring (geotechnical). These applications usually consider shallow vadose zone processes in unconsolidated material. Each of these applications feature (i) a relatively short duration for continuous use (days to months), (ii) ready accessibility for data retrieval and servicing, and (iii) relatively simple replacement and upgrading. The current generation of technology reflects these application fields, thus the most mature technology is designed for relatively short-term use in near-surface soils or sediments. Hard and fractured rock is inherently more difficult to access and instrument than unconsolidated material; however, technology applied in hard and fractured rock is usually modified from methods first proven in shallow unconsolidated materials.

Characterization activities typically require intensive sampling and observations for a relatively short period of time, using equipment that is highly sensitive to the measured quantities. Ongoing characterization of the potential repository at Yucca Mountain has used current technology, and in principle more of the reviewed techniques may be modified for characterization studies in hard and fractured rock. Specific examples where current technology could be adapted for characterization in fractured rock are discussed in Section 4. It is reasonable to expect that the normal pace of technological development will produce enhanced sensors and methodology for the shallow subsurface that may be adapted to hard and fractured rock, even if such applications are not the primary driver for sensor development.

Monitoring activities may have different objectives than characterization activities. Monitoring activities may require reliable, robust sampling over many years with little or no maintenance, but these attributes were not a priority in developing the current generation of characterization technology. Indeed, sensitivity and robustness are often conflicting design parameters. Reliability and robustness become even more important when monitoring the near field of a hot repository, because the equipment would be placed in a harsh environment with little or no opportunity for maintenance and upgrading. Market forces have produced relatively reliable and robust sensors in areas that are important to industry, such as temperature and humidity sensors, and these market forces would presumably continue to operate. However, it is not clear that most current technology used to measure properties of porous media can be easily adapted to achieve monitoring goals, even in relatively benign environments far from the near field of a hot repository. It is doubtful that market forces will emphasize development of reliable, robust monitoring technology that can withstand the harsh conditions typical of the near field of a hot repository.

It appears fair to conclude that relatively short-term characterization activities under ambient conditions in both unconsolidated media and fractured rock are supported by current technology or straightforward modifications of current technology, and it is likely that commercial sensor development will continue to improve sensors for characterization activities. It is also fair to conclude that long-term monitoring activities are not well supported by commercially available technology. It is clear that sensor choices are far more restricted under harsh near-boiling conditions, even for short-term studies. Furthermore, it is not clear that market forces are acting to dramatically improve sensor longevity and robustness, nor is it clear that market forces will provide sensors that can withstand near-field conditions.

4 EXAMPLE APPLICATIONS USING CURRENT TECHNOLOGY

There are a wide variety of vadose zone processes that occur at a geologic repository that may require characterization and monitoring, but the deep percolation flux passing through the repository horizon is one of the most fundamental hydrologic quantities affecting repository performance. Several representative approaches to estimating deep percolation flux are discussed in Section 4, demonstrating how currently available technology might be used for characterization or monitoring activities at a hypothetical geologic repository. The first example illustrates how applied tracers might be used to quantify fluxes, lateral diversion, and fast pathways within the vadose zone. The second example illustrates how current technology might be used to quantify water fluxes in the shallow subsurface.

4.1 Tracers and Fractured Rock

The period of atmospheric atomic testing provided an unexpected benefit to environmental science. As a result of atomic testing, radioactive materials entered the subsurface during precipitation, providing an unmistakable bomb-pulse signature that has helped (i) differentiate pre-bomb-pulse waters from post-bomb-pulse waters and (ii) fingerprint fast pathways through the subsurface. However, the bomb-pulse signature was derived from application over an extended period of time, and background levels of cosmogenically produced radionuclides make it difficult at times to interpret observations.

An improved signature can be obtained by marking surface water with periodic applications of environmentally benign tracers with negligible background concentrations. Controlled tracer application is a relatively simple and inexpensive procedure that allows the age of waters to be precisely dated deep in the geologic profile. A sampling network installed at depth may be used to identify tracer pulses via pore water extraction methods, allowing deep percolation rates to be quantified and the presence of preferential flow paths to be identified. Fiber optic methods may be an alternative to pore water extraction in the near future.

Applied tracers can also be used to identify and quantify lateral flow in the natural environment. Long-term tracer studies can identify lateral flow if several zones along a transect receive different tracers. The presence of a tracer outside of the application zone would strongly suggest that lateral diversion is occurring. The distance between an observation of the tracer and the application zone gives a minimum estimate for diversion distance. A better estimate could be derived by using several observation locations, or by applying different tracers at different distances from an observation location.

In general, tracer solutions for vadose zone hydrological studies can be applied to the soil surface or directly injected into the soil or rock, depending on the specific purpose of the tracer experiment.

4.1.1 Tracers

Long-term monitoring of deep percolation would be enhanced if a suite of tracers of different chemical composition were applied to the ground surface. A series of clearly distinguishable pulses would result from well-separated tracer applications (e.g., at intervals of 5 to 10 years), and each individual application would be clearly differentiated if a different tracer was used for

each application. Systematic marking of shallow subsurface water provides an excellent way of dating deep water, which is extremely useful in identifying water velocity.

Desirable characteristics for tracers include:

- Conservative and nonreactive movement (e.g., similar to water)
- Minimal background concentrations, so that signals may be clearly distinguished
- Insensitivity to changes in pH, alkalinity, or ionic strength of the aqueous solution
- Detectability by chemical analysis or visual observation (e.g., dyes)
- Minimal biological and chemical impact, so that the study environment is not damaged

Comprehensive reviews compiled by Drew (1968), Knutsson (1968), Käss (1998), and Flury and Wai (2003) suggest, in light of the desirable characteristics listed above, that stable isotopes (^2H , ^{13}C , ^{15}N , ^{18}O , and ^{34}S), ethanol, benzoate, and fluorobenzoates are useful tracers.

Deuterium ($^2\text{H}_2\text{O}$) at low concentrations is considered an ideal aqueous tracer; however, like most other stable isotopes, sophisticated instrumentation is required for chemical analysis and quantification.

Malcolm, et al. (1980) conducted a series of recharge and injection experiments using ethanol and benzoate as tracers; they found that both tracers mimicked the conservative, non-sorbing character of bromide. Malcolm, et al. (1980) recommended benzoate as a groundwater tracer due to its high sensitivity to spectrophotometry. Benzoate and benzenesulfonic acids have been used as geothermal groundwater tracers (Adams, et al., 1989). A variety of fluorinated benzoate compounds proposed as tracers (Stetzenbach, et al., 1982; Bowman, 1984; Bowman and Gibbens, 1992) are shown in Figure 4-1. Bowman (1984) and Bowman and Gibbens (1992) compared the performance of the benzoate tracers (using bromide as a reference tracer), finding that each benzoate tracer exhibited negligible sorption to the soil and aquifer materials in laboratory column tests, and the mobility of the benzoates mimicked that of bromide. However, some of the benzoate tracers appeared to degrade under field conditions. On the basis of their resistance to degradation, Bowman and Gibbens (1992) ranked the fluorobenzoates shown in Figure 4-1 in the following order, with PFBA being the best tracer:

- PFBA
- 2,6-DFBA
- 2,3-DFBA, 2,5-DFBA, 3,4-DFBA, and 3,5-DFBA
- o-TFMBA
- m-TFMBA

Sorption and transport of the benzoate tracers depends on pH, because these tracers contain a carboxylic acid group. The $\text{p}K_a$ values for these tracers are relatively low ($\text{p}K_a$ is $-\log K_a$, where K_a is the equilibrium constant for acid dissociation), so that under most environmental conditions the tracers should be predominantly negatively charged. Results from sorption and

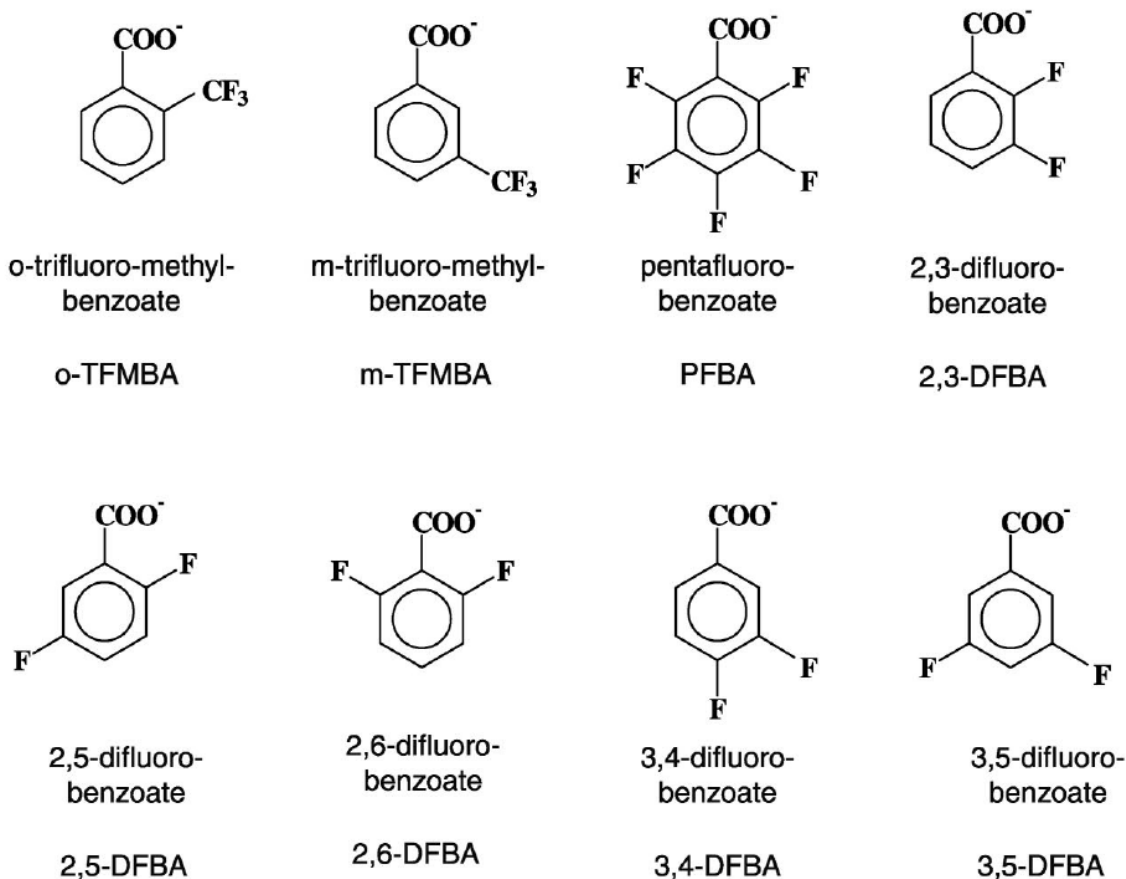


Figure 4-1. Fluorobenzoate Tracers [Reproduced From Flury and Wai (2003) With Permission]

transport experiments indicate that benzoate tracers behave conservatively as long as the pH of the pore solution remains about two pH units above the pK_a of the tracer (McCarthy, et al., 2000). Flury and Wai (2003) found that benzoate and fluorobenzoates migrate similarly to bromide under most pH conditions found in soils and aquifers, but mobility usually decreases under low pH conditions. Because sorption and transport of fluorobenzoates can be affected by organic carbon, clay, and Fe-oxide content, it is useful to evaluate the tracer behavior with sorption or column tests before running field experiments where these compounds may occur.

4.1.2 Measurement and Sampling in Fractured Rock

Tracer sampling is particularly difficult within unsaturated fractured rock masses. Usually sampling occurs within small-diameter boreholes drilled into the host rock. Two issues must be considered: One, how is the tracer extracted from unsaturated rock, given that water does not enter a cavity under unsaturated conditions? Two, is a sample location more representative of matrix conditions or fracture conditions?

Absorber methods are the most reliable current technology for obtaining tracer samples. As described in Section 3.3.5, it is important to ensure that absorber elements maintain contact

with the borehole wall to avoid evaporative concentration of the tracer, which leads to erroneous concentration estimates. Contact is assured by pressing the absorbers to the borehole wall using inflatable packers, as illustrated in Figure 4-2. Continuous monitoring of gas pressure in the packers and absorbers allows detection of gas leakage. The absorbers are removed after a pre-determined time interval, and analyzed for the tracer. Other absorber placement techniques, such as those outlined in Section 3.3.5, could be modified and applied. The next generation of sampling technology may replace absorbers with procedures for directly measuring tracer concentrations. For example, fiber optic spectrometry (see Section 3.4.3) offers the potential to enable direct measurement of tracer concentrations at the borehole walls.

Sections of the borehole that contain fractures can be determined from core analysis or video imagery, but these methods cannot distinguish between fractures that are connected to a larger network and fractures that dead-end. Gas permeameter testing provides a straightforward method for finding sections of a borehole with fractures connecting to a larger fracture network. A small section of the borehole can be isolated with inflatable packers and pressurized with a gas such as N_2 , as shown in Figure 4-3. Gas permeability can be calculated from measured gas flux and the pressure history in the test section. Zones with

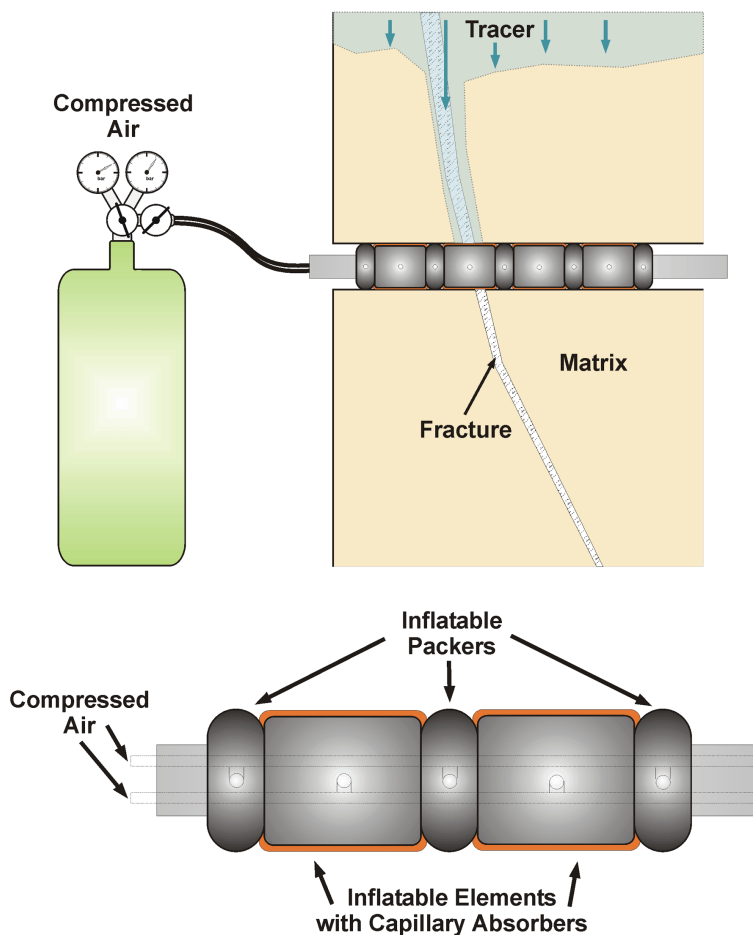


Figure 4-2. Potential Design and Placement of Capillary Absorbers for Solution Sampling From Boreholes

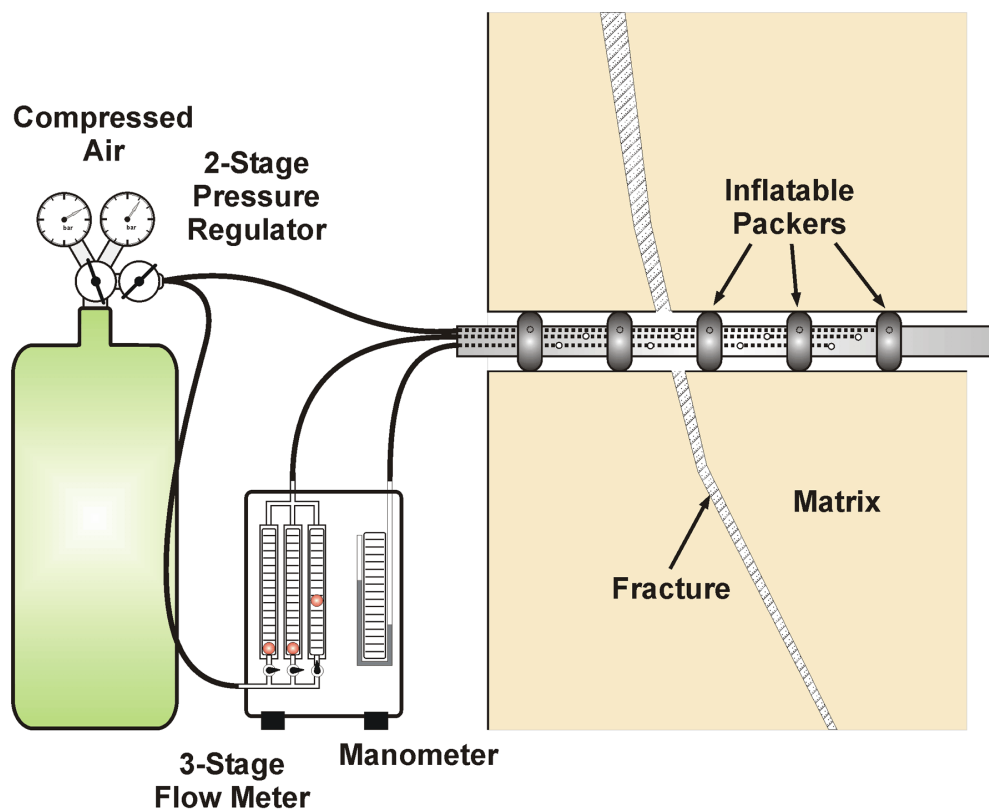


Figure 4-3. A Setup for Gas Permeability Mapping in a Borehole Using Inflatable Packers

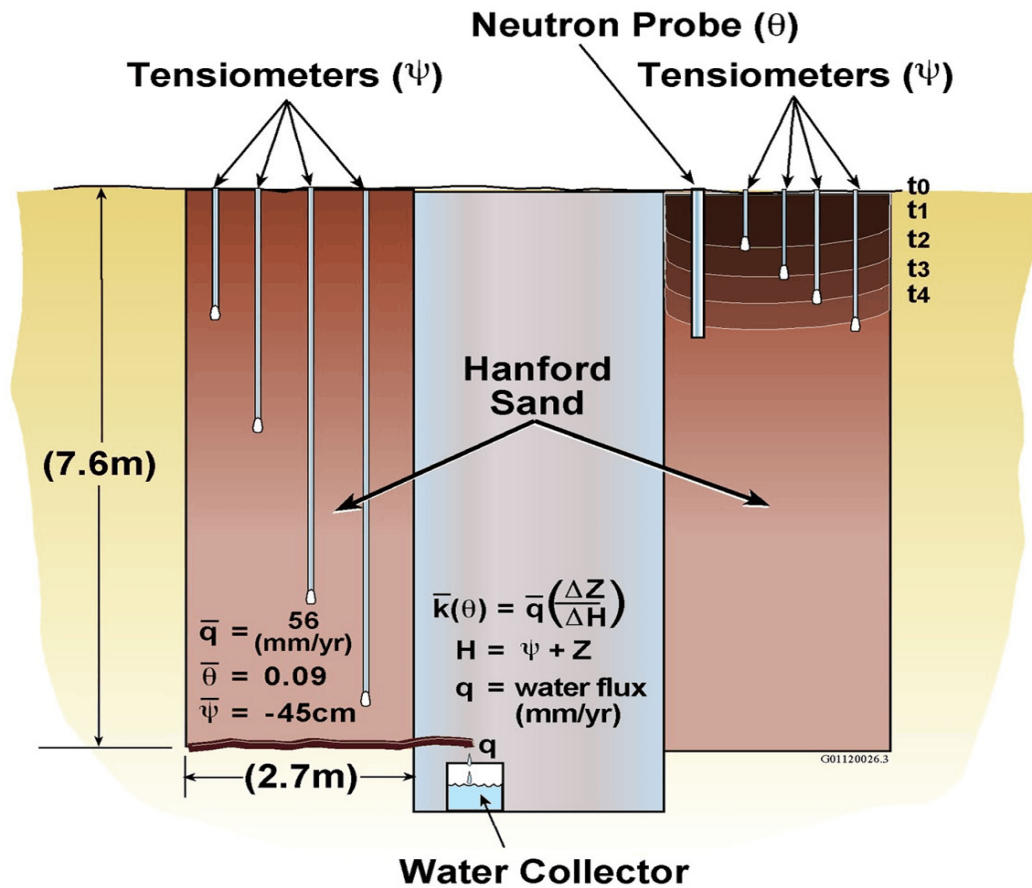
high gas permeability typically correspond to zones with connected fractures, although some care in interpretation is needed for zones near open cavities.

4.2 Near-Surface Water Fluxes

Vadose zone measurement technology may be most fully developed in the shallow subsurface (the realm of soil scientists), and several approaches may be taken to quantify net infiltration (the source of deep percolation fluxes in the vadose zone).

Atmospheric flux measurements, which are used as forcing functions in soil water-balance closure models, provide an indirect method for estimating deep percolation flux. The difference between annual precipitation and measured annual evapotranspiration provides an estimate for the annual deep percolation flux in the atmospheric-flux-based method. Direct measurements of actual evapotranspiration are made using a method such as the eddy covariance technique (Massman and Lee, 2002). The error in this estimation method is approximately 20 percent due to limitations in the eddy covariance technique for estimating evapotranspiration; however, the accuracy of this estimate may be increased with the aid of shallow soil water content measurements; for example, by using a neutron probe as illustrated on the right side of Figure 4-4. Errors in atmospheric-flux-based deep percolation estimates supplemented with soil moisture measurements are approximately 10 percent. Note that

Hydraulic-Property Field Test



evapotranspiration measurements are representative of a larger area than are soil-water measurements; soil-water measurements provide “point” values that may vary considerably with soil type and vegetation cover.

Another near-surface approach for quantifying deep percolation flux relies on monitoring of hydraulic gradients well below the influence of surface processes and plant roots. Monitoring is accomplished with tensiometers (or psychrometers for drier conditions), such as the bank of tensiometers on the right side of Figure 4-4 (Hubbell, et al., 2004). A reliable independent estimate of unsaturated hydraulic conductivity is required to estimate water fluxes using Darcy’s Law, which is a significant limitation to this approach.

Deep lysimeters (hydrologically isolated blocks of soil or rock) overcome the need for a reliable estimate of unsaturated hydraulic conductivity, especially for locations with deep alluvial cover. The left side of Figure 4-4 represents a lysimeter with tensiometers emplaced to monitor the actual hydraulic gradients within the soil or rock mass in the lysimeter. Psychrometers may be appropriate for drier conditions. Water flux is intercepted and directly measured as drainage from the lysimeter, thus it is not necessary to use unsaturated hydraulic conductivity to estimate fluxes. Installation and maintenance of a lysimeter is expensive, especially in fractured rock, and the accuracy of this method is strongly dependent on the extent of disturbance to the natural hydrological setting.

5 SUMMARY AND DISCUSSION

The 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 used to mimic postclosure conditions, where access for maintenance and upgrades may be severely restricted.

5.1 Summary of Measurement Technology

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 in order to provide baseline information on the suite of sensors that are available for characterization and monitoring activities in the vadose zone.

The widest variety of approaches are brought to bear on obtaining water content, taking advantage of the distinct physical, electrical, and thermal properties of liquid water compared to air and solid grains. Most of the techniques take advantage of the large dielectric constant of liquid water relative to air and solid grains, using an electromagnetic pulse or wave to estimate bulk dielectric constant, but the neutron-scattering and heat-pulse methods probe the system using a radioactive source and a heat source, respectively. Fiber optic sensors probe the system with light. Dielectric and electric measurement methods may be applied in a direct and an indirect way. The direct method makes measurements in a calibrated engineered porous medium that is in equilibrium with the natural medium, while sensors in the indirect method interrogate the natural medium without benefit of a direct calibrated relationship between water content and the sensed quantity.

Matric potential is also determined with a variety of methods. Tensiometers are the most direct method for obtaining matric potential, but only work under relatively wet conditions. Heat dissipation and electrical resistivity sensors probe water content in an engineered porous medium in equilibrium with the bulk medium, using a thermal or electrical signal; the relationship between the signal and matric potential is calibrated before sensor emplacement. Psychrometers measure relative humidity instead of water content, using an equilibrium relationship between matric potential and vapor density. No single method works over the entire range of potentials that may be observed in the field.

Pore water samples are difficult to obtain from the vadose zone, as water is held within the pore space by capillary forces. Sampling techniques induce a gradient in matric potential (e.g., through vacuum extraction, hanging wicks, or pressing a dry medium to the bulk

medium) to draw out the pore water. Solute concentrations can also be obtained by allowing a known quantity of distilled water to come to equilibrium with the bulk solution. Obtaining samples can be time-consuming, leaving laboratory extraction from samples as the alternative under dry conditions.

Temperature sensors infer temperature from the known response of an engineered component to temperature. Thermocouples measure temperature differences by generating voltage from dissimilar metals subjected to the same temperature difference. Resistance temperature detectors and thermistors relate the change in electrical resistance to temperature. Fiber optic sensors use the decay time of a phosphor after excitation from a light-emitting diode to estimate temperature.

Some relative humidity sensors (psychrometers and chilled mirror hygrometers) use the difference between ambient temperature (dry bulb temperature) and the temperature at which water vapor evaporates (wet bulb temperature) to estimate relative humidity. Capacitive and resistive humidity sensors relate changing electrical properties to relative humidity. Thermal conductivity sensors compare the thermal response of a reference gas and the ambient gas to estimate absolute humidity, from which relative humidity is obtained by comparison to the known response of saturated absolute humidity to temperature.

Direct *in situ* measurement of water flux is extremely difficult, especially in the vadose zone. A water flux meter can be used in an unconsolidated medium, using a hanging wick at the bottom of a funnel to induce a water potential unit gradient that pulls water through the funnel. Heat pulse sensors estimate water fluxes based on differential thermal responses at probes surrounding a heat source.

Direct *in situ* measurement of gas-species flux is even more difficult. Current practice within a porous medium infers fluxes from point concentration measurements and a diffusion coefficient that depends on water content. Fluxes across an interface between a medium and the atmosphere are quantified using the closed-chamber method, which quantifies flux by using the change in concentration within the chamber, but the presence of the measurement device has been found to significantly alter the flow fields being measured.

5.2 Discussion

The current state of the art in vadose-zone measurement methods is dominated by characterization applications from the shallow subsurface. Vadose-zone measurement methods are most commonly used for applications such as water management (agricultural), estimating recharge (hydrology and water resources), pollution mitigation and remediation (environmental), and infrastructure monitoring (geotechnical), all of which tend to consider shallow vadose-zone processes in unconsolidated material. These applications tend to feature (i) a relatively short duration for continuous use (days to months), (ii) ready accessibility for data retrieval and servicing, and (iii) relatively simple replacement and upgrading—current sensor technologies for characterization do not emphasize long-term maintenance-free operation. The current generation of technology reflects these fields of application, and is generally designed for relatively short-term use in near-surface unconsolidated porous media under ambient temperatures. Some of the technology is used in a wider context, such as temperature and relative humidity sensors that may be used for

long-term monitoring, and in these fields market forces have provided sensor technology that is more robust and requires less maintenance.

Hard and fractured rock is inherently more difficult to access and instrument than unconsolidated material, thus technology applied in hard and fractured rock to date is usually modified from methods first proven in shallow unconsolidated environments. Accordingly, the technology applied to hard and fractured rock tends to be less developed than technology intended for unconsolidated media.

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 methodologies for the shallow subsurface that may be adapted to hard and fractured rock, even if the rock applications themselves do not drive sensor development.

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 further 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.

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