Chapter 8
Performance Monitoring

8.1 Introduction

Performance monitoring of cover systems is necessary to both satisfy regulatory requirements and confirm the performance of a cover system. The feedback on the effectiveness of a cover system design can also improve future designs and performance predictions. As discussed by Kavazanjian (2000), development of performance monitoring data for geoenvironmental projects (such as cover systems) is often complicated by a number of factors:

- long time periods of interest;
- imperfect knowledge of phenomena and impacts, which is sometimes addressed by multi-parameter modeling, periodic review and updating of monitoring plans, and sensitivity studies;
- measurement of very small quantities or changes in a physical system, a factor that has resulted in the development of improved monitoring techniques and methods of statistical analysis and in the monitoring of surrogates; and
- difficulty in measuring parameters of interest, which is sometimes addressed by making indirect measurements (e.g., monitoring soil moisture rather than percolation through the cover system) or monitoring surrogates.

For MSW landfills and HW facilities, post-closure monitoring is required to assure that post-closure care needs are identified and addressed. Regulations for MSW landfills presented in 40 CFR 258.61(c) and regulations for HW facilities presented in 40 CFR 264.118 require facility owners or operators to prepare a written post-closure plan that includes a description of the performance monitoring activities and the frequency of such activities. The post-closure care period of 30 years given in RCRA regulations has generally been considered by EPA to be the minimum timeframe for performance monitoring and maintenance. EPA has the authority to designate a longer post-closure period under 258.61(b) if necessary for the continuing protection of human health and the environment. Requirements analogous to those given above for MSW landfills exist for HW disposal facilities in 40 CFR 264.117(a)(2)(ii). Also, the post-closure monitoring requirements for MSW and/or HW landfills will likely also be ARARs for any cover system that forms part of a CERCLA remediation.

While performance monitoring is important for all facilities with a cover system, it is particularly such for closed facilities, such as old dumps and remediation sites, not underlain by engineered liner systems or leachate collection systems which themselves can be monitored. For these sites, percolation monitoring via a lysimeter (see Section 8.2.4) or soil moisture monitoring (see Section 8.3) is recommended. Such monitoring is also recommended for alternative cover systems, including those with ET or capillary barriers (see Sections 3.2 and 3.3, respectively).

Prior to implementing a monitoring program, it is important to establish the criteria (i.e., action levels) for acceptable performance. These criteria are typically developed on a project-specific basis and may consider the characteristics of the material being contained, human health and environmental risk, properties of the cover system components, hydrogeologic setting, and other factors. For example, as discussed in Section 1.2.3, EPA requires that a landfill cover system have a maximum percolation rate over the considered monitoring period to prevent the "bathtub" effect. Exceedance of site specific percolation criteria could trigger additional requirements for the landfill owner or operator. For example, the facility owner could perform an investigation of the higher than anticipated percolation rates, with the study including an assessment of the monitoring instrument accuracy and drift, condition of the in-place cover system components, anticipated performance based on modeling (maybe there was a significant weather event), and other tasks.

In a project-specific context, monitoring will provide the facility owner/operator, design engineer, regulators, and other stakeholders with the data necessary to evaluate whether project design criteria are being achieved. For the entire industry, additional data on the hydraulic and geotechnical performance of cover systems would be very beneficial to the development of improved materials, designs, construction procedures, and monitoring/maintenance procedures for these types of facilities. As previously noted in this guidance document, few data currently exist on the field hydraulic performance of cover systems and on their long-term structural integrity when subjected to total and differential settlements.

The types of monitoring systems addressed in this chapter are:

- infiltration monitoring systems (Section 8.2);
- soil moisture monitoring systems (Section 8.3);
- gas emissions monitoring systems (Section 8.4); and
- settlement monitoring systems (Section 8.5).

Other types of post-closure monitoring activities typically associated with waste containment facilities are not addressed herein. These include groundwater monitoring systems, landfill gas monitoring systems, and monitoring for physical conditions at the site, such as the condition of vegetative cover, erosion control structures, sediment control structures, leachate collection and removal system, landfill gas extraction system, etc. The condition of all of these latter systems and structures must be monitored during the post-closure period to assure adequate performance of the site in the long term and to comply with various regulatory requirements. These systems all require regular inspection and maintenance, topics which are addressed in Chapter 9.

8.2 Infiltration Monitoring

8.2.1 Overview

Infiltration monitoring can be performed indirectly, by monitoring leachate collection system flows for landfills containing such systems, or more directly, by monitoring the cover system internal drainage layer when one exists or by monitoring a lysimeter installed beneath the hydraulic barrier layer. Each of these techniques is described below.

8.2.2 Leachate Collection System Monitoring

Data on the quantity and composition of leachate generated within a landfill can provide significant insight into the performance of a cover system. In facilities underlain by a leachate collection system and composite liner, leachate flow data can be used as an indicator of cover system performance.

If a cover system is properly designed and installed, the rate of leachate flow into the leachate collection system will decrease with time, with the possible exception of cases where leachate recirculation is practiced. This trend is clearly seen in Figures 1-8 and 1-9. For a cover system designed and installed to prevent infiltration, the long-term leachate collection system flow rate would be expected to approach zero. If the cover system does not act as an effective hydraulic barrier, higher than anticipated long-term leachate flow rates might be observed.

The decrease in leachate collection system flow rate with time after closure can occur relatively rapidly (e.g., within a few months) in some cases or more slowly (e.g., over several years), depending on the type and thickness of waste, the waste's moisture content relative to its field capacity at the time of closure, and, to a lesser extent, the rate of waste degradation (for MSW). Evaluation of cover system performance during this transition period requires some judgment. Techniques that can be used to help in the evaluation include: (i) plotting leachate flow rates in the manner shown in Figures 1-8 and 1-9 to observe the time trend in flow rates; (ii) estimating the timeframe for residual drainage from the waste using Darcy's equation, the known thickness of the waste, an estimate of the unsaturated hydraulic conductivities of the waste and daily/interim cover materials, and an assumed hydraulic gradient equal to one; and (iii) looking for anomalies in the trend of leachate flow rate with time.

With respect to item (ii) above, timeframes for residual drainage calculated using Darcy's equation should be considered at best order-of magnitude estimates because of the difficulty in estimating an appropriate value for the unsaturated hydraulic conductivity of waste, the fact that the unsaturated hydraulic conductivity of waste is not constant but rather varies with matric potential, and the difficulty in accounting for such factors as channelized flow along preferential pathways in the waste and lateral flow at interfaces between waste and daily/interim cover layers. Based on experience, it appears that the use of Darcy's equation, coupled with published estimates for MSW waste permeability, will typically provide a conservative, overestimate for the timeframe for residual drainage of MSW. For example, for a 25-m thick MSW landfill with an assumed average unsaturated hydraulic conductivity of 1 x 10^{-7} m/s, the timeframe for residual drainage from the waste by gravity is 7.9 years.

With respect to item (iii) above, several different types of anomalies in flow rates can occur. If periodic increased leachate collection system flow rates are observed, the timing of the increases should be compared to the timing of precipitation events at the project site. A correlation between the two is potentially indicative of a breach in the cover system. The most common potential breach locations are around gas well penetrations through the cover system and at the edge of the cover system around the perimeter of the facility. If the increased flow rates were due to a breach and associated influx of precipitation, the concentrations of leachate constituents in the leachate collection system flow would also be expected to lower (i.e., the flow is more dilute) during the period of increased flow than during other periods. If the increased flow rates do not correlate with precipitation, other sources need to be investigated. Another potential source involves the release of a slug of leachate from the waste to the leachate collection system. If the source of the flow anomalies is slug flow along preferential pathways in the waste (as opposed to uniform, porous media-type flow), leachate constituents would be expected to be similar to those at earlier times. However, the constituent concentrations may potentially be lower during the anomaly than at earlier times if a significant amount of the leachable constituents have already been transported from the pathways. Another potential source of long-term leachate flow for some older landfills is groundwater infiltration, either from perched water zones or from a continuous zone of saturation that rises above the bottom of the facility. Indicators of groundwater infiltration include relatively dilute leachate chemistry, changes in leachate predominant ion chemistry, and correlation between leachate collection system flow rates and changes in groundwater levels at the site.

It should be noted that the observation of a reduction in leachate collection system flow rate with time after closure does not by itself prove that a cover system is functioning as designed. The observed reduction in flow rate after closure may be due to decreasing residual drainage from the waste, with percolation into the waste reduced from the pre-closure value, but still at a rate above the intended design value. A slow rate of percolation into the waste may not be reflected in leachate collection system flow rates for some period of time, due to available moisture absorption capacity of some or all of the solid waste mass.

In summary, monitoring of flow from the leachate collection system is extremely valuable from the standpoint of evaluating the performance of the entire waste containment facility. This type of performance monitoring also provides a valuable indication that the cover system is (or is not) functioning as designed. However, if the actual performance of the cover system must be quantified or definitively demonstrated, more direct monitoring methods will need to be used.

8.2.3 Drainage Layer Monitoring

As previously discussed in Section 1.5.3, conventional RCRA-type cover systems may require a drainage layer installed between an overlying protection layer and underlying hydraulic barrier (Figure 1-12), particularly on sideslopes. Drainage from this layer can be monitored: (i) as confirmation that the layer is functioning as intended; and (ii) to generate data on the water balance for those components of the cover system above the drainage layer. Flow from the drainage layer can only be quantified if the layer is designed to convey flow to not more than a few discrete discharge points. At the discharge points, the flow rate can be monitored using a flowmeter, tipping bucket, pore pressure transducer, or other means. If the drainage layer simply daylights at the edge of the cover system and discharges as sheet flow to the surrounding area or surface-water drainage structure, such as shown in Figure 2-5(a), quantitative monitoring will not be possible. The need for monitorable discharge points results in a trade-off because, while it is beneficial to collect monitoring data, construction of the discharge points may complicate the design for some projects where simply daylighting the drainage layer would otherwise suffice.

Currently, drainage layer monitoring is not routinely performed; it is usually only conducted for a cover system test plot as part of a water balance assessment.

8.2.4 Lysimeter Monitoring

Lysimeters have long been used for agricultural and hydrologic studies to collect deep drainage or percolation data or to estimate recharge. Lysimeters have been used to monitor percolation through cover systems with hydraulic, ET, and capillary barriers. The most common approach is to use a collection lysimeter, also called a pan lysimeter or drainage lysimeter. Other types of lysimeters, including monolithic lysimeters, weighing lysimeters, and suction lysimeters, have been used for various types of research studies, but not specifically for evaluation of installed cover systems. The principal advantage of collection lysimeters is that, when properly designed, they provide a direct measure of soil-water flux. Lysimeters perform best when they are installed during cover system construction. When installed after the fact, great care is needed to assure that the boundary conditions (e.g., vegetation and soil properties) above and adjacent to the lysimeter are similar to the characteristics found elsewhere in the cover system.

The use of a collection lysimeter for percolation monitoring of a cover system is illustrated in Figure 8-1. A lysimeter of the type shown in Figure 8-1 is constructed with hydraulic barrier (typically GM) beneath or within the soil profile to be monitored. The liner is shaped to contain percolation and is typically backfilled with a granular (sand or gravel) or geosynthetic drainage layer. A geosynthetic drainage material may be preferred to a granular drainage material because it has lower storage capacity and faster response time than most granular drainage materials. Also, when a granular drainage material is used, it can impact the boundary conditions of the cover systems and create the capillary barrier effect described in Chapter 1. Liquid collected in the lined lysimeter drains by gravity to a monitoring point, where the flow is collected and periodically measured with a pore pressure transducer, float and a pulse generator, tipping bucket, or other means. To date, few lysimeters have been installed beneath full-scale cover systems; instead, they have been installed beneath cover system test plots. However, this statistic

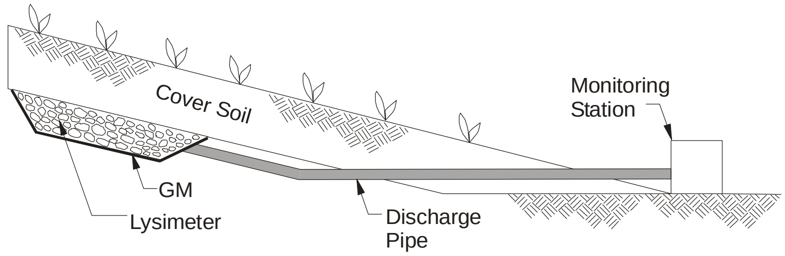

Figure 8-1. Example of a Collection Lysimeter Used to Monitor Percolation.

is changing since collection lysimeters are being installed beneath full-scale cover systems as part of the ACAP program, which was discussed previously in Section 3.4.3. Generally, the larger
the lysimeter, the more representative the monitoring results of the performance of the cover system as a whole.

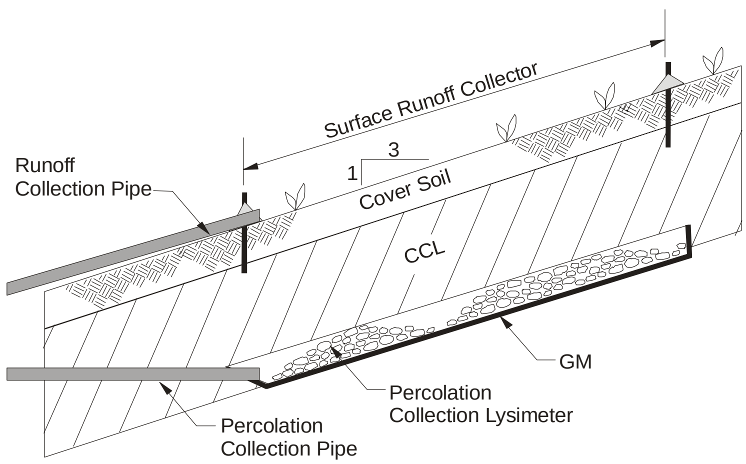

Figure 8-2. Collection Lysimeter and Runoff Collection Pipe Used to Monitor Percolation and Runoff at the Omega Hills, Wisconsin Test Plots Described in Section 7.2.1.

As described by Bonaparte et al. (2002), it appears that the best way to document the field performance of CCLs in cover systems is with the use of lysimeters installed at the base of the cover system. Five case studies reporting on the use of lysimeters to monitor percolation through cover systems (e.g., Dwyer, 1997, 1998, 2001; Melchior, 1997a,b and Melchior et al., 1994; Montgomery and Parsons, 1989, 1990; Nyhan et al., 1997; Paige et al., 1996) were described previously in Section 7.2. A sixth case study using a similar technique was described in Section 4.3.4 (Lane, 1992; Khire, 1995; Khire et al., 1997, 1999). The test plot and lysimeter set-up for the third and sixth case studies are illustrated in Figures 8-2 and 8-3, respectively. These figures also illustrate how surface runoff was monitored for the test plots. Other examples of the use of lysimeters in test plots are given by Webb et al. (1997) and Gee et al. (1997).

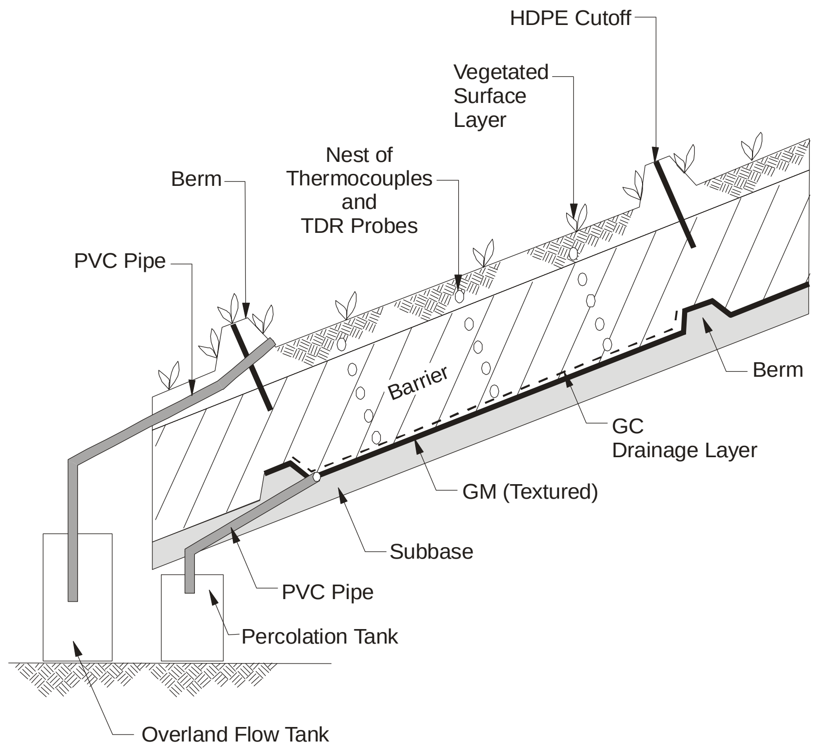

Figure 8-3. Collection Lysimeter and Runoff Collection Pipe Used to Monitor Percolation and Runoff at the Live Oak, Georgia and Wenatchee, Washington Test Plots Described in Section 7.2.4.

8.3 Soil Moisture and Matric Potential Monitoring

8.3.1 Overview

Soil moisture and matric potential measurements can be used to assess soil moisture or matric potential content at discrete locations, changes in cover system water storage, and vertical gradients in cover system soils. With careful calibration, the measured moisture contents can be converted to matric potentials, and vice-versa, through the use of an acceptable soil-moisture characteristic curve. Currently available techniques of assessing soil moisture content in cover systems include neutron probes, time domain reflectrometry (TDR) probes, and frequency domain reflectometry (FDR) probes. Methods of measuring soil matric potential include tensiometers, electrical resistance sensors, thermocouple psychrometers, and heat dissipation sensors. TDR and FDR probes have also been used to measure matric potential when they have been combined with a matrix material whose water retention function has previously been determined. With these modified sensors, the matrix material around the TDR or FDR probes comes into equilibrium with the surrounding soil, and the water content (and indirectly the matric potential) of the matrix material is measured with the probes. These modified probes will not be discussed further.

All of the soil moisture and matric potential monitoring methods listed above are non-destructive, in-direct techniques. With the exception of thermocouple psychrometers, good contact between the sensor and the soil (or borehole casing for neutron and FDR probes) is required to obtain accurate measurements. This is especially critical for sensors that measure matric potential and rely on good hydraulic contact with the soil to establish thermodynamic equilibrium. Good hydraulic contact may be hard to attain in very coarse soils, such as gravel, and in shrink-swell clays. Except for the neutron probe, all of the sensors can be fully automated.

Soil moisture and matric potential measurements may also be made directly on soil samples excavated from the cover system. While this latter method is reliable for determining soil moisture content or matric potential, it involves destructive sampling (i.e., damage) of the cover system soil and the inherent problem of sample variability associated with the destructive sampling protocol.

8.3.2 Neutron Probes

The neutron probe, when calibrated, can yield very good indirect measurement of soil moisture content. The probe is inserted into a cased access borehole, orientated in any direction, where readings are taken at various locations (Figure 8-4). The casing material is generally aluminum or PVC piping. The principle of operation is based upon the neutron thermalization process, wherein a radioactive source emits high-energy neutrons, with an energy of about 5 MeV, into the soil. These neutrons are then reduced to a lower energy state upon colliding with hydrogen atoms associated with soil water (Gardner, 1987). After an average of 19 collisions, the neutrons cease to lose further energy and are said to be “thermal” neutrons with an energy of approximately 0.025 MeV. Higher molecular weight elements, such as oxygen, also slow the neutrons, but far fewer collisions are required with hydrogen to slow the reaction to thermal energy levels. The source of the high-energy neutrons in most commercially available neutron probes is a radioactive americium and beryllium mix. The americium emits an alpha particle that bombards the beryllium atoms, which, in turn, emit a neutron. The fast neutrons are emitted approximately radially from the source and form a sphere around the source within which the neutrons are attenuated. The size of this spherical influence varies inversely with the moisture content. The sphere is about 0.7 m for dry soil and about 0.16 m for saturated soil; sphere diameter is unaffected by the strength of the radioactive source (Gardner, 1987). The number of pulses counted by the probe detector is proportional to the number of thermal neutrons encountered. A calibration curve can be developed to correlate count rate with soil moisture content.

While the probe's manufacturer usually supplies calibration curves, calibration for each application is recommended. A calibration involves taking multiple readings in a given soil against a range of gravimetrically-determined moisture contents. Soil heterogeneity and organic matter can have adverse affects on accuracy of neutron probe readings. Also, extraneous

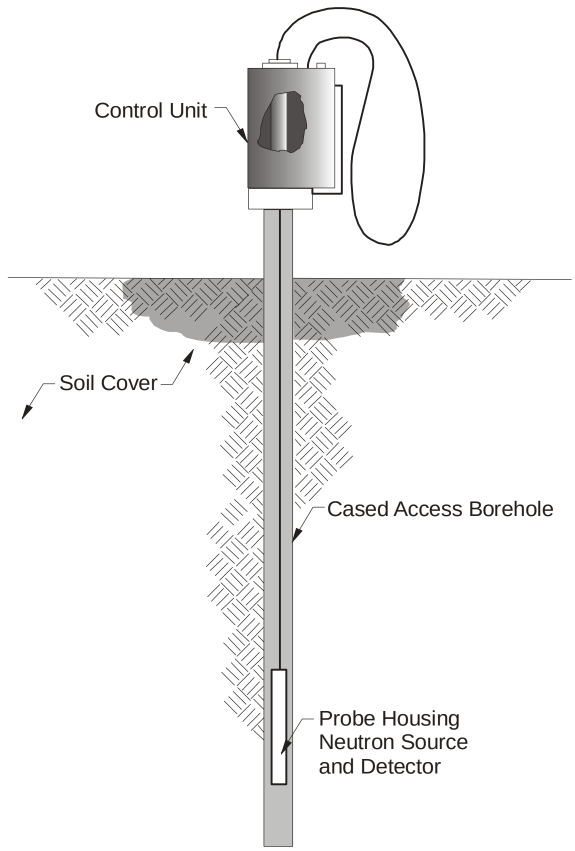

Figure 8-4. Neutron Probe Installed in a Vertical Cased Borehole.

hydrogen atoms not associated with water can also impact probe accuracy. Potential sources of the extraneous hydrogen atoms include hydrocarbons, methane gas, hydrous minerals (e.g., gypsum), hydrogen-bearing minerals (e.g., kaolinite, illite, and montmorillonite), and organic matter in the soil. Irregularities in the borehole casing or contact with the soil around the perimeter of the borehole can also produce error in moisture content values obtained. A disadvantage to the use of a neutron probe is the fact that a radioactive source is present, thereby posing a potential hazard for the operator as well as imposing difficulty in its use and maintenance (i.e., regulatory constrains). In addition, because of the regulatory constraints for using the radioactive source, this method cannot be automated.

In cover system monitoring applications, neutron probes are typically placed into access tubes in the cover system, and water content measurements are made at discrete locations at discrete time intervals. Neutron probes have been used to monitor soil moisture content in cover systems at a number of sites (e.g., Montgomery and Parsons, 1989, 1990; Nyhan et al., 1990; Fayer et al., 1992; Anderson et al., 1993; Schultz et al., 1995; Paige et al., 1996).

8.3.3 Time Domain Reflectometry

The process of sending electromagnetic pulses through a conductor and observing the reflected waveform is called time domain reflectometry (TDR). When monitoring soil moisture, TDR equipment generally consists of a cable tester or a specially designed commercial TDR unit, coaxial cable, and a stainless steel probe (Figure 8-5). The type of material surrounding the conductor (i.e, cable and probe) influences the waveform traveling down the conductor. The waveform is reflected differently when it reaches the start of the probe and the end of the probe.

Figure 8-5. TDR Probe and Coaxial Cable.

The time-of-travel along the conductor is dependent on the dielectric constant of the surrounding medium (e.g., the sheath around the cable or the soil around the probe). If the dielectric constant of the medium surrounding the conductor is high, the electronic signal propagates more slowly. Because the dielectric constant of water is much higher than most materials, a signal within a wet or moist medium propagates slower than in the same medium when dry. The dielectric constant of water is about 80, whereas the dielectric constant of dry soil is typically in the range of about 3 to 5. Ionic conductivity affects the amplitude of the signal but not the propagation time. Thus, soil moisture content around the probe can be assessed by a pre-determined correlation between time-of-travel along the probe (obtained from analysis of the reflected waveform) and soil moisture content. A generic calibration equation developed by Topp et al. (1980) is sometimes used. However, the probes should be calibrated for their specific application (e.g., soil texture and density and cable length) to yield accurate soil moisture measurements (Lopez and Dwyer, 1997).

The accuracy of TDR for soil moisture measurements is relatively good for many soil types and, according to Schofield et al. (1994), about the same as that for neutron attenuation. A disadvantage of TDR is the fact that accuracy decreases with increased cable length between the probe and the cable tester; generally a maximum range of about 60 m is recommended. In addition, soils with a high moisture content and a high electrical conductivity rapidly attenuate the electrical pulse before it is reflected back. If the attenuation is great enough there will be no return signal and the probe cannot be used. However, probes can be coated to reduce signal attenuation.

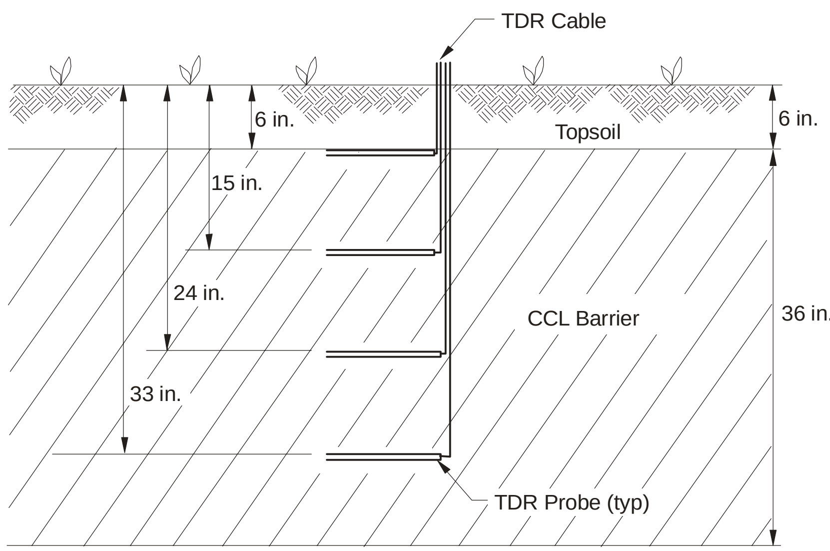

Figure 8-6. Example of Horizontally Orientated TDR Probes in a Cover System.

Probes may be installed during or after construction. They can be installed in any direction; however, when installed after construction, they are usually inserted vertically. When installed in this fashion, care should be taken to minimize the soil disturbance around the probe such that the probe fits snuggly in the soil. There have been cases where a space formed between the probe and soil during installation such that water was able to infiltrate into the space and short-circuit the cover system during heavy rainfall events. Consequently, the water content measurements at the probe were not representative of the surrounding cover system soils. Recent developments have attempted to minimize the cable length problem and reduce the cost of the TDR system. The latest development is a probe that does not require a cable tester or TDR unit but rather connects directly to a data logger. Calibration similar to the traditional TDR system is required for best results. The probe consists of two stainless steel rods connected to a printed circuit board. A five-conductor cable is connected to the circuit board to supply power, activate the probe, and monitor pulse output. The circuit board is potted in an epoxy block.

TDR has been used to monitor soil moisture content in cover systems at a number of sites (e.g., Dwyer, 1997, 1998, 2001; Kavazanjian, 2000; Khire, 1995; Khire et al., 1997,1999; Lane et al. 1992; Montgomery and Parsons, 1989, 1990; Nyhan et al., 1997). The use of TDR for soil moisture content monitoring is illustrated in Figure 8-6.

8.3.4 Frequency Domain Reflectometry

Frequency domain reflectometry (FDR) methods of soil moisture content measurements are also known as radio frequency (RF) capacitance techniques. These techniques actually measure soil capacitance. The probe contains a pair of electrodes and the soil serves as the dielectric medium completing a capacitance circuit comprising part of a feedback loop of a high frequency transistor oscillator. As high frequency radio waves (about 150 MHz) are pulsed through the capacitance circuitry, a natural resonant frequency dependent upon the soil capacitance is established. The soil capacitance is related to the dielectric constant by the geometry of the electric field established around the electrodes. Either the natural resonant frequency or the frequency shift between the emitted and received frequencies is recorded.

The FDR probe is often used in an access tube (cased borehole) similar to the neutron probe for measuring soil moisture content at various depths. In this application, it is important that the access tube be sized to provide a snug fit around the probe, thereby minimizing annular air gaps that greatly affect the travel of the electronic signal into the soil. Installation of the access tube also requires special attention to ensure complete soil contact with the casing since annular air gaps or soil cracks around the outside of the tube also produce erroneously-low readings.

Though the FDR probe manufacturer may provide calibration curves, it is important that the probe be calibrated with the site-specific soil. With proper calibration and use, the accuracy of the FDR method for measuring soil moisture content is good.

8.3.5 Tensiometers

A tensiometer measures soil matric potential values between 0 and approximately -90 kPa. The range of measurement is limited by the cavitation of water, which occurs at matric potentials less than -100 kPa. A tensiometer commonly consists of a high air entry, porous ceramic cup connected to a pressure measuring device through a rigid plastic tube (Figure 8-7). Plastic is the preferred material for the tube because of its non-corrosive nature and lower heat conduction properties. The tube is sealed at the top with a removable cap allowing the tensiometer to be filled with deaired water and accumulated air to be purged. A Bourdon gauge, manometer, or

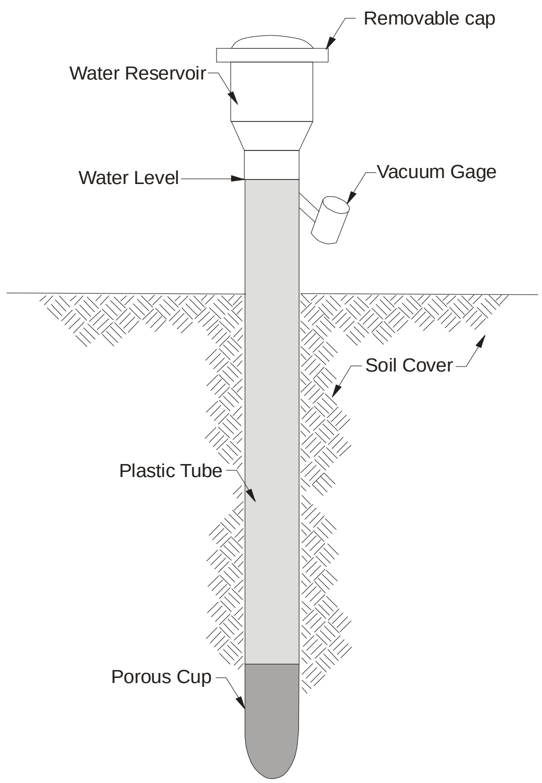

Figure 8-7. Tensiometer.

pressure transducer is attached to the upper portion of the water-filled tube to measure the negative pressure of the water in the tensiometer. The matric potential of the soil is equal to this negative pressure plus a pressure correction that accounts for the elevation potential of the water column in the tensiometer.

When the tensiometer is inserted into the soil, the soil absorbs water from the tensiometer and as this occurs the water pressure in the tensiometer decreases until the tensiometer fluid pressure is in equilibrium with soil water matric potential outside the cup. Tensiometers are limited to moist soils.

8.3.6 Electrical Resistance Sensors

Electrical resistance sensors have been used for over 60 years in agricultural applications (Bouyoucos and Mick, 1940). They consist of electrodes embedded in a gypsum, nylon, or fiberglass porous material that equilibrates with the surrounding soil. During equilibrium, water and solutes exchange between the sensor and the soil; therefore, the matric potential of the sensor is the same as that of the soil after equilibrium. Although electrical resistance varies primarily with water content, the equilibrium between the sensor and the soil is a matric potential rather than a water content equilibrium. These dual relationships result in a hysteretic relationship between the sensor's electrical resistance and matric potential. In practice, the sensors are more often calibrated to soil water content than to matric potential.

The electrodes in electrical resistance sensors have leads connected to a Wheatstone bridge to measure resistance. When the sensor is placed in firm contact with the soil, water flows into or out of the sensor until equilibrium is established. As the moisture content of the resistance block decreases, the electrical conductivity of the block decreases and the electrical resistivity of the block increases. Ohmmeters are used to measure resistance. The upper measurement range of the sensors is controlled by the air entry pressure of the sensor matrix material, and the lower limit depends on the range in smaller pore sizes of the sensor matrix. For gypsum blocks, the upper limit is approximately –30 kPa (Bourget et al., 1958) and the lower limit is approximately –1000 kPa (Tanner et al., 1952; Bourget et al., 1958). Additional discussion of gypsum blocks and fiberglass moisture sensors are given below.

Daniel et al. (1992) described gypsum blocks as prismatic or cylindrical blocks of gypsum that change electrical resistance when they change moisture content. The gypsum block is placed in the soil and the gypsum either takes in water from or gives up water to the surrounding soil until thermodynamic equilibrium is established. The electrical resistance of gypsum varies with moisture content: the higher the moisture content, the higher the electrical conductivity and, hence, the lower the electrical resistance. Because gypsum is partly soluble in water, it gives the sensor a buffering capacity that makes it insensitive to soil electrolyte concentrations less than about 300 ppm (2 mmhos/cm). However, for salt concentrations greater than 5,000 ppm in the surrounding soil, the electrolyte concentration in, and electrical resistance of, gypsum blocks can be affected. As a result of their solubility, gypsum blocks placed in wet soils tend to disintegrate. However, resins may be added to gypsum to improve their longevity. It has been reported that gypsum blocks may function for more than 5 years in dry soils but as little as 3 months in wet soils.

Daniel et al. (1992) report that fiberglass sensors work in much the same way as gypsum blocks; however, they don't have the buffering capacity that is provided by the dissolving gypsum. A porous fiberglass cloth is placed in the soil; the fiberglass gains or loses water until thermodynamic equilibrium is reached. A temperature-measuring probe may be a part of the unit.

Both gypsum blocks and fiberglass sensors were used to monitor the performance of the GCL test plots described previously in Section 7.4.5. The shapes and dimensions of the sensors used in the test plots are shown in Figure 8-8, and a typical placement of the sensors within a test plot cover system cross section is indicated in Figure 8-9. As indicated by Figure 8-9, the gypsum blocks were placed in the subgrade beneath the cover system geosynthetics. The fiberglass sensors were placed at the subgrade/GCL and GCL/GM interfaces.

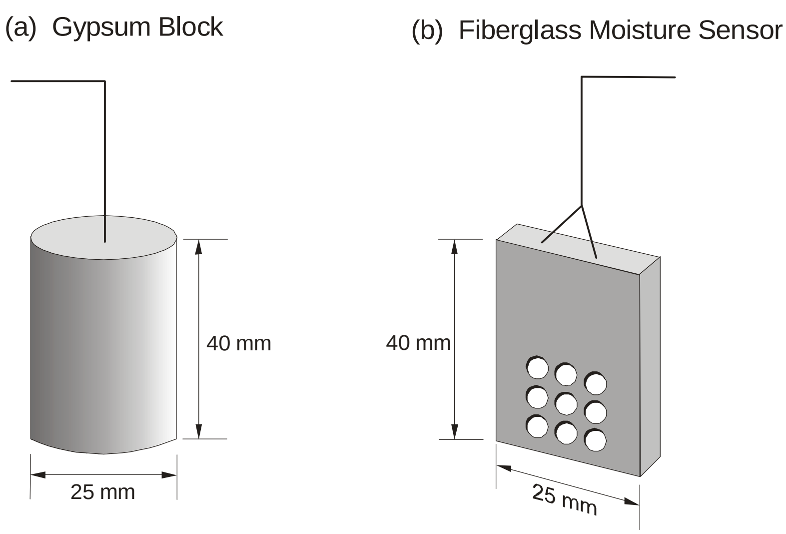

Figure 8-8. Dimensions of Electrical Resistivity Sensors Used in GCL Test Plot Described in Section 7.4.5.

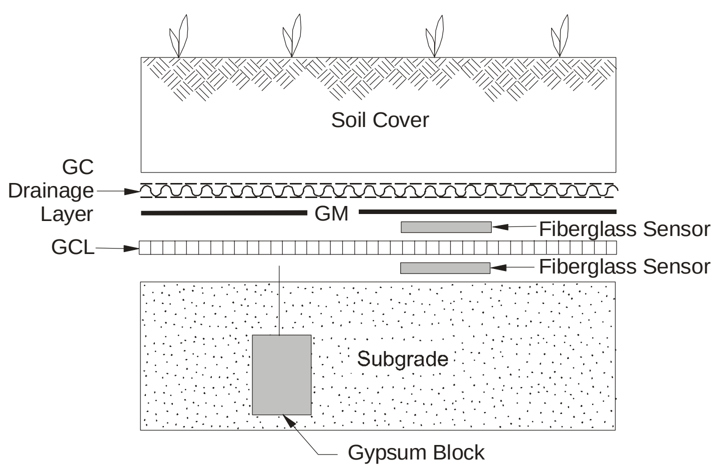

Figure 8-9. Layout of Electrical Resistivity Sensors Used in GCL Test Plot Described in Section 7.4.5.

8.3.7 Thermocouple Psychrometers

A psychrometer infers the matric potential of the liquid phase of a soil from measurements within the vapor phase that is in equilibrium with the sample. It measures the relative humidity within a soil system as the difference between a dry bulb (non-evaporating) temperature and a wet bulb (evaporating) temperature. The primary difficultly with this technique is that the relative humidity in the soil gas phase changes only a small amount within the typical range of interest. For example, at 25 °C, a water potential of –1.5 MPa (wilting point) corresponds with a relative humidity of about 0.99, and a water potential of –8 MPa (lower limit of extraction for many desert plants) corresponds with a relative humidity of 0.94. Thus, practically all measurements of interest to most cover system studies lie in a narrow relative humidity range between 0.94 and 1.0. Thermocouple psychrometers are typically used to monitor matric potentials in the range of –8MPa to –30 kPa.

The majority of psychrometers used in the field utilize the Spanner design. This design is composed of a thermocouple, a reference electrode, a heat sink, a protective porous ceramic bulb or wire mesh screen, and a recorder. The technique is based on measuring the temperature of a water droplet or wet surface using thermocouple junctions. Calibration curves are developed by immersing the unit in a series of sodium or potassium chloride solutions of known concentration (generally 0.1, 0.3, 0.5, 0.8, and 1.0 molar (Morrison, 1983)) at specified temperatures. The calibration curves are used to compute the in-situ soil-water potential from the measured field output voltage. Problems sometimes encountered with psychrometers are that their calibration can change over time due to corrosion (Daniel et al., 1981) and/or microbial growth on the thermocouple wires (Merrill and Rawlins, 1972).

8.3.8 Heat Dissipation Sensors

Heat dissipation sensors, also called thermal conductivity sensors (Fredlund, 1992) or matric potential sensors, rely on the relationship between the heat dissipation of a ceramic matrix in contact with soil and the matric potential of the soil. These sensors also have a relatively long history of use in agricultural studies. The sensor consists of a heater and a temperature sensor in a ceramic matrix (Figure 8-10). A current is applied to the heater and the temperature of the sensor is measured at certain time intervals, typically at 1 and 20 s after the initiation of heating. The change in temperature (i.e., the heat dissipation) is controlled by the water content of the ceramic matrix because water conducts heat much more readily than air (i.e., thermal conductivity increases with water content). The measured temperature increase represents the heat that is not dissipated. The temperature increase is calibrated to sensor matric potential.

The upper measurement range of the sensor is controlled by the air entry pressure of the sensor matrix material, which is generally about –10kPa. The lower limit is generally considered to be about –1 MPa (Reece, 1996). The sensitivity of the heat dissipation sensors decreases as soils dry below –1 MPa.

Heat dissipation sensors have been used to monitor soil matric potential in cover systems at a number of sites, including the ACAP test sites.

Figure 8-10. Heat Dissipation Sensor.

8.4   Gas Emissions Monitoring

Gas emissions measurements can be used to assess the performance of cover systems and gas control systems. Gas emissions are a common concern for MSW landfills or CERCLA sites that contain MSW. Landfill methane emissions measured at MSW landfill sites and reported in the literature have ranged from about 0.003 to 3,000 $g/m^2/d$ (Bogner and Scott, 1997). In general, the higher rates were associated with landfills that did not have gas recovery and that were covered with dry soils without a GM barrier. For example, at the Olinda MSW Landfill in Southern California, which is covered by a sandy silt soil layer, measured emission rates were greater than 1,000 $g/m^2/d$ prior to installation of a gas collection system. After a gas collection system was installed, measured gas flux rates were less than 10 $g/m^2/d$. The flux rates were still lower (less than 0.01 $g/m^2/d$) in the area of the landfill with a gas recovery system and covered with a clayey silt layer. Given this wide range of emissions, it is appropriate at many MSW sites and CERCLA sites that contain MSW to divide the sites into areas with different surface characteristics, moisture regimes, and gas control strategies and obtain order-of-magnitude estimates of fluxes from these areas for the purposes of assessing emissions. For HW landfills or waste piles that began operation after EPA passed its Land Disposal Restrictions, emissions are generally at much lower rates than recently filled MSW landfills and it may be possible to install a passive venting system.

Landfill gas emission rates can be measured indirectly or directly. Subsurface vertical methane gradients calculated using Fick's First Law (i.e., assuming diffusive transport only) and measured concentrations at gas probes at various depths have been used to estimate gas emissions. This indirect method typically results in higher estimated fluxes than those measured using a direct chamber technique (e.g. a flux chamber) (Rolston, 1986). However, the indirect method is often useful as an independent check on emission values obtained using a flux chamber (Bogner and Scott, 1997). The most common direct methods for monitoring landfill gas emissions are vent sampling and the flux chamber techniques. The most common means of evaluating gas emissions is by using indirect methods (i.e., back-calculating emissions from the source based on a measured concentration). One method of indirect monitoring (described in EPA, 1992) involves concentration profile sampling. The sampling device is placed at the cover system with sampling probes spaced at different intervals. The concentration, wind speed, and temperature are measured at each of the probe heights to generate profiles for each. This technique does not work when quiescent or unstable wind conditions exist, such as shifting of direction. The site must be relatively homogeneous; the technique will not work if emissions or waste composition vary with respect to locations. In all cases, gas sampling must be conducted over a period of time, since gas emission rates are not constants.

The transect technique, performed with a device that used both a vertical and horizontal array of sampling probes placed downwind of the source in the plume centerline, has also been used. Background measurements are also made upwind of the source to correct for the contribution from other sources. The device also has instruments to measure wind speed, wind direction, and temperature. The measured concentrations are spatially integrated and a Gaussian dispersion model is used to back-calculate the emission rate from the source that would be needed to give the measured concentration.

Instantaneous Surface Monitoring (ISM), Integrated Surface Sampling (ISS), and flux chamber techniques (Cooper and Bier, 1997; Lu and Kunz, 1981). Each of these methods is described below. For all of these methods, monitoring is generally not conducted within 72 hours following a precipitation event to allow the cover soil to drain (the trapped water in the soil impedes emissions). Gas emissions can also be measured by vent sampling, which requires the volumetric rate of flow be measured.

With ISM, a portable flame ionization detector (FID) is used to measure the instantaneous concentration of total organic compounds (TOCs) (as methane) along transects or grids established at the landfill surface. This method does not measure flux, but can be used to divide the site into areas with different emission rates. The specific emission rates of these areas can then be evaluated using a flux chamber.

ISS uses a grid-based method to collect samples of the surface gases. Within each grid square, a 8 to 10 L sample of gas is continuously collected from about 50 to 75 mm above the soil cover surface over 25 minutes. Thus, the method provides an average constituent concentration, but not flux, in a grid square. The gas samples can be analyzed in the field or laboratory.

Flux chamber methods have been used at landfill sites since at least the late 1970's (e.g., at the Fresh Kills Landfill, New York (Lu and Kunz, 1981). They involve enclosing a known volume of atmosphere above a known soil surface area and obtaining a direct, though spatially limited, measurement of emission rate. Flux chambers represent a compromise as they may influence flow fields, temperature, and concentrations at the soil/atmosphere interface. However, they have significant advantages if they are operated over short time periods and minimize disturbance. Also, unlike the ISM and ISS methods, the flux chamber method can be used to monitor emissions in high winds; the ISM and ISS methods should generally not be performed when the average wind speed exceeds 16 kph to avoid dilution of the emitted gas by air (Cooper and Bier, 1997). The sensitivity of the flux chamber method can be adjusted by varying the flux chamber volume. They are good for measurement over a 1 to 10 m^2 scale, but are typically less than 1 m^2 with a volume less than 20 L.

8.5 Settlement Monitoring

Post-closure settlement monitoring should consider both total and differential landfill settlements. In general, differential settlements are of most concern because they may induce unacceptable tensile stress and strain in one or more cover system components and they may cause cover system slopes to change or reverse grade. As previously discussed in Section 6.4, cover system settlement can be considered to have one of three sources: (i) settlement of foundation soil; (ii) settlement due to overall waste mass compressibility; and (iii) settlement due to localized mechanisms in the waste. When monitoring cover system settlements, the sources of the settlements are not differentiated; rather, the total settlement at any point due to all of these sources is measured. The measured settlements are then evaluated to assess the effect of the settlements on the cover system components and slopes. For example, most compacted clays exhibit failure at extensional strains of 0.5% or less, as discussed in Section 6.4.5.

Procedures for monitoring total settlements of the cover system surface include:

- aerial surveys, which are generally limited to a vertical accuracy of about 100 to 200 mm with good ground control, and are often more expensive than ground surveys depending on the size of the survey area; the accuracy of aerial surveys may be impacted by a number of things including time of day, angle of sun, and cloud and ground cover; they also require a certain amount of field surveying for ground-truthing and targeting;
- conventional instrumental ground surveys of settlement monuments installed on the cover system, which can achieve high precision (vertical accuracy to within less than 1 mm); and
- global positioning system (GPS) surveys performed using hand operated equipment; the precision and cost of GPS surveys are a function of the specific equipment used; if

significant vegetation is present, GPS may be less reliable since it may be difficult to receive satellite signals.

In addition to total settlements of the cover system surface, settlement of the components within the cover system are sometimes monitored. For example, the settlements of the cover system components for a low-level radioactive waste landfill are being monitored by settlement plates and ground penetrating radar (GPR). The settlement plates were installed above the drainage layer during cover system construction to verify that sufficient drainage layer slope is being maintained. The GPR targets were installed at different locations within the protection layer (Figure 8-11). Both the settlement plates and the GPR targets are periodically surveyed.

Figure 8-11. Placement of GPR Target on Top of Drainage Layer (and at the Bottom of the Protection Layer) During Cover System Construction.

Settlement monuments can be installed on cover system slopes to monitor for downslope creep or instability. This type of monitoring may not be necessary for cover systems designed to conventional factors of safety (as defined in Chapter 6 of this document). However, for situations where lower factors of safety are utilized, slope monitoring is advisable. Slope monitoring should also be considered for final cover systems in seismic impact zones where the cover system is designed to yield (undergo permanent seismic displacement) during the design earthquake event. Slope inclinometers can also be used to monitor for slope movements.

Differential settlement monitoring may be identified through aerial or ground survey techniques if the differential settlement feature is large enough to be captured by the resolution of the survey technique used. Area-wide surface depressions less than 300 to 600 mm in depth are unlikely to be identified through aerial survey. Likewise, highly localized raveling (fines moving into larger voids) or sinkhole features are likely to go undetected in aerial surveys. These same features would be missed in ground surveys where it would be unusual, for example, to install settlement monuments on a survey grid with a grid dimension smaller than about 30 m. The most reliable means for identifying localized differential settlements is to perform periodic visual surveys across the entire landfill surface. This type of survey should ideally be performed immediately after a rainstorm when puddles and ponded water would provide evidence of surface depressions. At the same time, the cover system can be inspected for evidence of other types of differential settlement features such as sinkholes, gullies, or raveling conditions. Also, experience indicates that contrasts develop in surface vegetation in and around depressions, since the cover soil in the depression tends to stay wetter than elsewhere. Thus, contrasts in cover vegetation color and health can be used to identify locations where surface depressions might exist.

As pointed out in EPA (1991), subsidence depressions should be remediated below the level of the hydraulic barrier to avoid long-term acceleration of the subsidence due to a “roof ponding” mechanism. Roof ponding refers to the common structural problem in flat roof systems where ponding water causes the roof rafters to deflect, thus allowing more water to pond, causing more deflection, and so on. This mechanism continues until the roof collapses. In addition, ponding above a portion of the hydraulic barrier increases the potential for percolation through the barrier within the ponded area. Remediation requires removing the cover system in the region of subsidence, backfilling the depression with fill, and then reconstructing the cover system in the repaired area. To minimize the potential for continuing settlement, the use of engineering measures such as geosynthetic reinforcement or separation layers, lightweight fill, vibratory compaction of backfill (to help fill ravel features and voids), etc. should be considered.