INSTRUMENTED MEMBRANE TECHNOLOGY: CURRENT USES AT LAWRENCE LIVERMORE NATIONAL LABORATORY (LLNL)

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Introduction:

Instrumented Membrane Technology (IMT) uses a flexible, removable, plastic-coated membrane-tube to deploy various types of instruments and at least two different kinds of sampling systems in uncased boreholes. The IMT membrane-tube is “blown” down the borehole from a spool within a pressurized canister by compressed air. Once in place, the membrane-tube is held against the sides of the borehole by filling the tube with compressed air, sand, water or with a foam packer.

Sorbent-pads affixed to the outside of these membrane-tubes are used to collect and retrieve soil pore-water samples for laboratory analysis. Measuring the electronic resistance across two electrodes mounted on these pads can be used to make estimates of soil moisture tension.

Small diameter tubes installed on these membranes are used to collect soil-vapor or liquid-water from known depths in the borehole and to transport these materials to the surface where they can be sampled. These tubes can also be connected to pressure transducers that log soil-pressures when these tubes are not needed for sampling.

A wide variety of electronic and mechanical sensors can be incorporated into the IMT systems when they are manufactured. An example of this approach would be the soil moisture tension measurements made with the sorbant-pads, described above. The disadvantage of this approach is it 1) increases the cost of the IMT device and 2) makes the replacement or relocation of these devices difficult.

A more flexible and economic approach to the deployment of these kinds of sensors is the Beavertail Strap. These straps are foam-filled membrane-tubes that look like a beavertail in cross section (tapering from a thicker center to minimal thickens on either side). When the Beavertail Strap is constructed, wires and/or tubes are run from the end that is to be attached to the surface, through the center of the Beaver-tail strap to the desired position in the borehole. Prior to deployment, sensors are attached to these wires and/or at each level. When deployed, the strap is attached at the surface and hung down the annulus of the borehole. Once the strap is in place, the IMT membrane-tube is deployed in the same borehole and is used to press the Beavertail Strap and its instruments against the soil. The IMT devices used with Beavertail Straps may be fitted with their own set of sampling and/or measurement instruments.

Applications:

IMT systems are currently being used at five different sites in thirteen different boreholes at LLNL. One of these sites was constructed as a vadose zone observatory in pristine soil. Two of the other sites are contaminated with tritium, while three of the five sites contain VOCs.

The Sites

Building 292

The vadose zone under the Building 292 area at LLNL was contaminated by tritium from a leaking underground tank some time between 1986 and 1989. Two IMT systems were installed near this tank during May of 1992 in two uncased four-inch boreholes that were drilled to a depth of about 40 feet. At the time these systems were installed, there was as much as 1×10^8 pCi of tritium per liter of condensed soil moisture. A soil-gas sampling IMT system was deployed in one these boreholes while a sorbant-pad IMT system was deployed in the other.

Once the soil-gas system was in place, it was filled with sand to keep the vapor ports sealed against the soil. Because this resulted in a semi-permanent installation, the membrane was never removed during the course of the study. Periodically, soil-gas samples were taken from these ports and analyzed for tritium. On one occasion, soil-gas samples were analyzed by mass-spectrometry to get the ratio of carbon dioxide to oxygen. It was thought that an increase in this ratio would indicate soil-microbial activity.

Because the IMT membrane-tube must be removed from the borehole to recover the sorbant-pads, this installation was pressurized by compressed air while the membrane was in place. Eight levels of thermistors were subsequently added to the sorbant-pad system so that soil temperatures could be monitored. This was accomplished by hanging two strings of four thermistors each in the annulus of the borehole prior to deploying the IMT sorbant-pad or blank-membrane system. When sorbant pads were not deployed in this borehole, a blank-membrane was deployed to keep the borehole open. On several occasions when the blank-membrane was in place, a neutron-logging tool was passed through the annulus of the IMT membrane-tube, which allowed us to estimate changes in soil-moisture content.

Building 5475

Soils under the Building 5475 area contain both tritium and VOCs. VOCs were introduced into these soils during the Second World War as a result of aircraft engine maintenance in the area. Later on, tritiated-water evaporation ponds were constructed in the area. These ponds eventually formed leaks and tritium escaped into these soils by infiltration.

Four IMT systems were eventually deployed in the Building 5475 area in three different eight-inch boreholes that were drilled as deep as 110 feet. A sorbant-pad system was used in the first borehole for about eight months. During this time sorbant-pads were deployed and retrieved several times. These pads provided data on both the tritium and the VOC content of these soils, as well as seasonal soil moisture variations. Attempts to use a neutron-logging tool in this borehole resulted in ambiguous data.

After the last of the sorbant-pads were retrieved, a soil-gas system equipped with thermocouples was deployed in this borehole. Soil-vapor samples were collected from the soil-gas ports and analyzed for both VOCs and tritium. Soil temperatures have been logged from this borehole since December of 1993.

The two new IMT systems were deployed towards the end of 1996. These units were equipped with gas-port sampling systems and Beavertail Straps. The Beavertail Straps were instrumented each with eight levels of thermistors to measure soil temperature and gypsum blocks to measure soil moisture. Tritium and VOCs were sampled periodically from the gas-ports in each system. At all other times, soil-gas pressures were logged automatically with pressure transducers connected to each of these ports. These soil-pressure measurements were used to characterize soil-pressure gradients produced by soil-gas extraction and re-injection during a vapor-extraction feasibility test. When vapor extraction was not underway, these pressure data were logged to evaluate natural diurnal changes caused by changes in barometric pressure. Five-minute averages of these data were logged each hour since 1996 (Berg et al., 1998).

Building 518

Soils in the Building 518 area contain VOCs as a result of unplanned releases from an adjacent solvent storage yard. This resulted in high concentrations of these compounds in the vadose zone. Two IMT systems were installed in the area in late 1995 to characterize this area and to monitor the effects of soil-vapor extraction planned to commence later on that year.

Both IMT systems were equipped with soil-gas ports and Beavertail Straps. Both Beavertail straps were equipped with thermistors to measure soil temperature and with gypsum blocks to measure soil-moisture tension.

Soil-pressure measurements made at the IMT soil-gas ports, and adjacent grouted wells provide information on the pressure fields generated by the vapor-extraction system as well as diurnal soil-pressure changes cause by daily fluctuations of barometric pressure. A continuous record of all of these parameters has been kept since October of 1995 (Berg et al., 1994).

Building 875

Soils in the Building 875 area contain VOCs that had been undergoing remediation for a number of years by soil-vapor extraction. Two IMT systems were installed in the area in late 1996 to characterize this area and to monitor the effects of remediation efforts.

Both IMT systems were equipped with soil-gas ports and Beavertail Straps. Both Beavertail straps were equipped with thermistors to measure soil temperature and with gypsum blocks to measure soil-moisture tension. In addition, one of the IMT systems was equipped with a second IMT membrane equipped with sorbant-pads. This double membrane system is called a “Duet” system by the manufacture, FLUTe of Santa Fe, NM. The advantage of this system is that it allows uninterrupted measurements to be made from the soil-gas port systems and Beavertail-Strap systems and the ability to deploy and retrieve soil-moisture samples with the sorbant-pads.

Vadose Zone Observatory

The vadose zone observatory was constructed in 1997 over uncontaminated soils and was designed to study the fate of substances injected into soils as gas or in the aqueous phase. Four IMT systems were installed around a central injection well. Three IMT systems fitted with gas-ports were deployed during the first year of these studies. A Beavertail Strap with thermistors and gypsum was deployed along with one of these membranes. During the second year, a sorbant-pad system was installed in the fourth borehole along with a Beavertail Strap equipped with tensiometers. The soil-gas membrane from one of the three original boreholes was replaced with a second sorbant-pad system. The pads on both of the sorbant-pad membranes were equipped with electrodes in order to make soil-moisture tension estimates.

Soil pressure measurements were made from each of the gas-port membranes and from three other wells that were completed with grout. Surface barometric pressures were measured at this site so that changes in soil pressures could be related to diurnal changes in barometric pressures. Vapor samples were also taken from each of these sample ports (Carrigan et al., 1999; Carrigan et al., 1998).

Measurements

Tritium vapor sampling: Tritium in the form of water vapor was sampled from IMT gas-port systems by pumping soil-gas from each port through a cold trap. Water vapor from the gas-stream out of each port was condensed and frozen in individual vials. When vapor collection was complete, the samples were thawed into liquid water and were analyzed for tritium in a scintillation counter (Martins, 1992a).

Tritium pore-water sampling: Tritium from soil pore-water is sampled with IMT sorbant-pad systems. Dry pads are deployed in these boreholes and left in place for at least 24 hours so that the pads can soak up soil-pore water, and come to equilibrium with the soil around it. The pads that have been exposed to the soils in this way are carefully removed from the membrane and placed in sealed containers. Prior to analysis, the wet pads are weighed. After all liquid is extracted from the pads by lyophilization, the pads are re-weighed so that their moisture content can be determined. Liquid water recovered from the pads by lyophilization is analyzed for tritium in a scintillation counter (Mallon et al., 1992).

VOC vapor sampling: VOCs were sampled from IMT gas-port systems in several ways. With all methods, the void-volume of the sample lines between the gas-port and soil were purged by pumping at least 3 line-volumes of soil-gas before sampling. The most straightforward approach uses a PID Organic Vapor Analyzer (OVA) to make direct measurements of total VOC concentration. Soil-gas is pumped from the gas-port to the OVA. The OVA then analyses the gas stream and displays concentration as ppmv.

Other methods involve collecting the soil VOCs into some type of container followed by laboratory analysis. We have used at least three different methods. They are sorbant-cartridge (such as Tenax), Tedlar Bags and Summa Canisters.

VOC pore-water sampling: Soil pore-water is sampled with pads from the IMT sorbant-pad systems. Dry pads are deployed in these boreholes and left in place for at least 24 hours so that the pads could soak up soil-pore water, and come to equilibrium with the soil around it. The pads that have been exposed to the soils in this way are carefully removed from the membrane and placed in soil-VOAs. Prior to analysis, the VOAs containing the wet pads were weighed. After the VOC fraction of the pore-water was removed by a purge-and-trap system, the VOCs containing the extracted pads were dried and re-weighed so that the moisture content of the pads could be determined. When the volume of pore-water on the pads and the total mass of VOCs extracted from the pads are known the concentration of VOCs in pore-water can be expressed as ppm (Martins, 1992b).

Soil-gas pressure measurements: Because the overall rate of change of soil-gas pressures is fairly slow, and there are usually a large number of soil gas-ports to monitor for pressure, a system was developed to multiplex up to eight different ports through a single pressure transducer. This arrangement allowed us to observe each port once or twice each hour and to reduce the cost and size of the system by limiting the number of sensors and data loggers used.

Each of the gas-ports on an IMT system can be switched to the same pressure transducer with solenoid valves that are controlled by a data logger. The data logger acquires and averages the soil pressure data from each port over a period of time (usually five minutes) and then logs the pressure data along with the gas-port ID and a time/date stamp. Because pressures measured from several gas-ports are made by the same pressure transducer, these values can be compared one to another without regard to differences caused by individual pressure transducer calibration.

Soil temperature measurements: A thermistor is an electronic device that changes its resistance in a predictable way with temperature. When placed in soils and connected to a suitable data logger, thermistors can be used to measure and log soil temperature data. We have spent some effort acquiring these kinds of data from the vadose zone because annual cooling of our soils causes liquid water to flow through the soil column due to reflux-condensation. This can effect the migration of contaminants in these soils as much as, or more than, water infiltration from seasonal rains.

Soil moisture measurements: Soil moisture measurements are made in several ways. One of the first devices we used for these measurements was the agricultural gypsum block. These blocks are actually cylinders of gypsum with two concentric stainless steal cylinders embedded within. When placed in soil, the moisture content of the gypsum will eventually come to equilibrium with that of the soil. Wires connected to each of the cylinders are attached to a data logger where the electronic resistance between the cylinders is measured and logged. Water entering the gypsum block causes the resistance of the block to drop. Conversely, dry blocks have a higher resistance. A standard formula is used to convert the resistance measurements to soil-suction expressed as bar of soil moisture tension.

We are currently experimenting with sorbant-pad electrical resistance measurements. The theory here is the same as used with the gypsum blocks. Wet pads have low resistance and dry pads have high resistance. While no data are currently available that relate these measurements to soil-moisture tension, we believe that these data can indicate an infiltration front passing the sorbant-pad. With a little additional work, it may be possible to develop the same kind of mathematical relationship between sorbant-pad resistance and soil-moisture tension that is used with gypsum blocks.

We currently have plans to deploy remote-controlled tensiometers with a Beavertail Strap at one of our installations. Tensiometers measure soil-suction directly through a pressure transducer and have the added advantage of allowing the investigator to sample soil-pore moisture as liquid water. If the pressure transducer is connected to a data logger, soil moisture tension may be logged more-or-less continuously.

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