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SEAMIST™ In-Situ Instrumentation and Vapor Sampling System Applications in the Sandia Mixed Waste Landfill Integrated Demonstration Program

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ABSTRACT

The SEAMIST™ inverting membrane deployment system has been used successfully at the Mixed Waste Landfill Integrated Demonstration (MWLID) for multipoint vapor sampling/pressure measurement/permeability measurement/sensor integration demonstrations and borehole lining. Several instruments were deployed inside the SEAMIST™ lined boreholes to detect metals, radionuclides, moisture, and geologic variations. The liner protected the instruments from contamination, maintained support of the uncased borehole wall, and sealed the total borehole from air circulation.

The current activities have included the installation of three multipoint vapor sampling systems and sensor integration systems in 100-foot-deep vertical boreholes. A long term pressure monitoring program has recorded barometric pressure effects at depth with relatively high spatial resolution. The SEAMIST™ system has been integrated with a variety of hydrologic and chemical sensors for in-situ measurements, demonstrating its versatility as an instrument deployment system which allows easy emplacement and removal. Standard SEAMIST™ vapor sampling systems were also integrated with state-of-the-art VOC analysis technologies (automated GC, UV laser fluorometer). The results and status of these demonstration tests are presented.

INTRODUCTION

The MWLID is tasked with demonstrating innovative technologies for the clean-up of chemical and mixed waste landfills that are representative of many sites occurring throughout the DOE complex and the nation. Characterization and remediation at the MWLID emphasize in-situ technologies that promise to reduce the risk to the environment and personnel, save time, and produce more complete pictures of what is occurring underground.

The MWLID is focusing on two landfills located in Area III at Sandia National Laboratories on Kirtland Air Force Base in Albuquerque, New Mexico. The 1.9-acre Chemical Waste Landfill (CWL) was operated from 1962 to 1985, during which time a wide variety of organic and inorganic chemicals were disposed of at the site. There is believed to be about 450,000 cubic feet of contaminated material in the CWL including oxidizers, reducers, solvents and other organics, acids and alkali, and heavy metals. The 1.6-acre Mixed Waste Landfill (MWL) received hazardous and radioactive waste from 1959 to 1962, after which it received only radioactive waste, including classified radioactive waste, until its closing in 1988. Soil borings taken in 1989 indicate elevated tritium concentrations up to 100 feet beneath the MWL. The MWLID also has successfully demonstrated some characterization technologies at a DOD site on Kirtland Air Force Base, RB-11-a mixed waste landfill.

The three landfills (CWL, MWL, and RB-11) are situated in alluvial deposits approximately 12,000 feet thick consisting of alternating clays, sands, and gravels. A complex fault system controls ground water flow and, in some cases, the hydraulic connection across the faults is unknown. The aquifer below the landfills is believed to be over 10,000 feet thick, with the top of the aquifer lying approximately 500 feet below the surface. The arid Albuquerque climate, on average, receives less than eight inches precipitation annually, resulting in a very high potential evapotranspiration rate and a natural recharge rate that is only a few percent of the precipitation rate.

The SEAMIST™ system was developed by Science and Engineering, Associates, Inc. (SEA) with DOE (Argonne National laboratory) support explicitly to address DOE unsaturated zone characterization and monitoring needs. Since 1992, SEAMIST™ systems have been used in characterization and monitoring demonstrations in the CWL. The current activities include laboratory-scale and field evaluation of in-situ vadose zone sensors and samplers integrated with the SEAMIST™ deployment system. These include thermocouple psychrometers, gypsum blocks, pressure transducers, temperature sensors, colorimetric indicators, and hydrocarbon-sensitive adsorbing resistors. These sensors were successfully emplaced and operated in the CWL unlined chromic acid pit (UCAP) boreholes using SEAMIST™. These tests have demonstrated the capability of detailed pressure gradients and high resolution temperature and matric potential parameters. Standard SEAMIST™ vapor sampling systems were also integrated with state-of-the-art VOC analysis techniques (automated/unattended GC and UV imaging fluorometer)

INTEGRATING SENSORS WITH SEAMIST™

The SEAMIST™ system utilizes an inverting membrane to deploy sensors and sampling devices in boreholes (Figure 1). Depending on the sensor requirements, they can be mounted on the interior or exterior of the membrane. Signal cables or tubes are typically run to the surface on the inside of the membrane. Pressure-tight feed throughs pass the cable or tubing through the membranes and basepipe without damaging the system's pressure integrity.

The basic requirement for any sensor emplaced with SEAMIST™ is that the sensor and its data cable not be damaged by the membrane emplacement process, nor can the membrane be damaged by the sensor hardware. Consequently, the cable (electrical or fiber optic) must be flexible and strong enough to withstand the membrane's inversion process, which will subject it to a bend radius, in the worst case, of one quarter of the borehole diameter. For maximum ease of emplacement, the detector or sampler should be no longer, in its dimension oriented with the borehole axis, than half the borehole diameter. However, if a sensor's cabling is very flexible and if the sensor itself is fairly rugged, it is possible to deploy a sensor who's longitudinal dimension is just less than the borehole diameter. About two thirds of the SEAMIST™ installations to date have been in 8 to 12-inch diameter boreholes, with the balance in roughly 4-inch-diameter casings or directionally drilled holes. All of the instruments tested for the MWLID easily satisfy the physical emplacement requirements.

[FIGURE 1 HERE]

IN-SITU SENSOR AND SAMPLER FIELD DEMONSTRATIONS

To demonstrate the utility of the SEAMIST™ system as a vehicle for in-situ sensors, this effort researched available sensors which could be integrated with the system, conducted laboratory tests on selected sensors to determine their feasibility of integration, and finally, deployed sensors using SEAMIST™ at the CWL.

The basic objective of these tests was to prove the sensors could be successfully deployed with the SEAMIST™ system, and once deployed, could function as designed. Thus an integrated package, including the SEAMIST™ system, the sensors, and methods of data acquisition was tested as a whole. Several readily available sensors capable of characterizing the downhole environment were incorporated in the field tests. These included small absolute pressure transducers and pressure ports, high precision platinum resistance thermometers to measure in-situ temperatures, and several devices (thermocouple psychrometers, gypsum blocks, and relative humidity sensors) to measure the matric potential. All of the sensors were connected to a Campbell Scientific CR7 datalogger. The CR7 controlled the frequency of data collection, converted raw output values to engineering units, and recorded and stored all data.

Soil gas pressure was measured using two approaches: (1) a single precision transducer, located on the surface, sequentially scanning the various tubes connected to ports downhole (Vaisala #PTA427A), and 2) locating small, inexpensive (and less accurate) absolute pressure transducers at each measurement location (Motorola MPX 5100). Using a high precision pressure transducer at the surface to measure in-situ pressures transmitted through tubes to the desired sampling elevation had positive features of: (1) being able to measure multiple sampling elevations with a single transducer; (2) the ability of easily using the same instrumentation with multiple SEAMIST™ systems; and (3) being able to easily access the instrumentation for calibration or repair. The main drawback with this approach was its sensitivity to temperature fluctuations. This problem can be minimized by insulating the transducer or by choosing a transducer which is compensated over a wide temperature range. Using individual pressure transducers located at each sampling elevation is useful under circumstances where very rapid measurements are desired. Because downhole temperatures are very stable, temperature sensitivity is not a major concern with this method. The sensors must be calibrated before emplacement if comparison of relative pressures at different sampling locations are desired. An offset drift observed in the gauges tested would render them unusable for long term monitoring, but higher precision transducers are available.

Downhole temperatures (even at shallow depths) were observed to be steady. The platinum resistance thermometers proved to be more stable and precise than thermocouples, being able to measure temperatures to ± .01°C. The ability to precisely measure borehole temperature is necessary, for example, in performing near surface soil moisture flux measurements.

Two sampling elevations, 6 and 51 feet deep, were chosen for physical sensor installation. Each elevation corresponds with depths where previous characterization data (permeability and soil pressure history measurements) were available. All sensors were included at each of the two elevations, staggered over a 1 foot interval along the membrane's diameter. A coarse weave mesh covered the sensors (except the gypsum block) to assure the sensors would be in contact with the soil gas . Air pressure in the membrane was maintained at 1.0 psi.

The systems were emplaced on September 2, 1993. Data was collected in one-half hour increments through mid morning of September 7, 1993, at which time it was removed to allow other experimenters access to the borehole. On September 15, 1993 the system was reinstalled to record more matric potential data. Before installation, simple checks were performed on all sensors and the datalogger system to assure they were functioning as designed.

The three sensors tested to measure the hydrologic matric potential included a resistive relative humidity sensor (Ohmic Instruments MHS Series, 80-99% rh), a thermocouple psychrometer (WESCOR PST-55), and a soil moisture block (Delmhorst Model 227 gypsum block). The data record shows a hydrologic potential of -0.2 to -0.3 bars at the 6-foot sampling elevation, and -0.9 to -1.0 bars at the 51-foot elevation. These potentials were out of range (too wet) of the relative humidity sensors, but were consistently measured by both the thermocouple psychrometers and gypsum blocks. The response at the 51-foot measurement location, after membrane installation, is shown in Figure 2 for both the psychrometer and gypsum block. The time required to reach an equilibrium state was up to 72 hours or longer for all of the sensors. The equilibration time of the gypsum blocks was found to be highly dependent on the state of the block (saturated versus unsaturated) when deployed.

[FIGURE 2 HERE]

The four chemical sensors integrated and tested with the SEAMIST™ system include Adsistors™, Gore-Sorbers, Dräger tubes, and litmus paper. Adsistors™ detect hydrocarbon contaminants by sensing a resistance change as the contaminants sorb onto the sensor (Portnoff, et. al., 1991). All hydrocarbons will adsorb (some changing the resistance more than others), making the Adsistor™ a gross contaminant monitoring technique. They have been developed for large hydrocarbon concentration measurements (i.e., percentages) for underground storage tank leak detection. The sensors were evaluated in laboratory tests to determine their potential for low concentration measurements . The detector's response to a 150 ppm concentration of TCE in air is shown in Figure 3, demonstrating the sensor's reversibility. One set of transient measurements in UCAP3 is plotted in Figure 4. The change in the sensors' output is significant. Further testing of the sensors' response to individual contaminants is needed before results from the Adsistors™ can be fully understood. Positive features of this sensor are that it is sensitive to less than 100 ppm hydrocarbon concentration variations, is reversible at these low concentrations, is very easy to monitor with a standard field data logger, and is presently available for use. Adsistors™ are seen as a potentially very simple and inexpensive method of contaminant monitoring.

[FIGURES 3 & 4 HERE]

Gore-Sorbers are passive absorbent charcoal modules (Stutman, 1993). The modules sense the integrated amount of contaminants absorbed over the time the modules are exposed to the contaminants. They are especially useful in detecting very small concentrations. Gore-Sorbers were emplaced at nine sampling elevations in UCAP3 for 12 days. Results showed that the contaminant concentrations in general increased with depth (Figure 5).

[FIGURE 5 HERE]

INTEGRATING VOC-ANALYSIS FIELD INSTRUMENTS WITH SEAMIST™

The SEAMIST™ vapor sampling system was integrated with a modified, commercially available gas chromatograph and with a R & D ultraviolet imaging fluorometer in order to demonstrate its versatility and ease of use with a variety of instrument. Field tests of each integrated system were conducted at the CWL using the UCAP boreholes.

SEAMIST™-Automated/Unattended Gas Chromatograph

A commercially available gas chromatograph has been modified by Sandia engineers for completely automated and unattended operation. The hardware modifications included: 1) the attachment of three vapor port sampling lines from the SEAMIST™ vapor sampling system to the multiport sampling valve on the GC and 2) adjusting the flow controller to a lower mass flow rate. The software modifications consisted of 1) changing the scheduling control file to four run types instead of two run types and 2) changing the main GC software control files to accommodate the altered timing necessary to accommodate the lower mass flow rate. The modified GC has been used on several other projects to detect VOCs. The GC has been calibrated to detect and quantify pentane; freon 113; 1,1,1-trichloroethane; trichloroethylene; toluene; tetrachloroethylene; ethyl benzene; o-xylene; and 1,2-dichlorobenzene. A number of other compounds, including m-xylene and p-xylene, can be detected but not quantified.

A combined SEAMIST™/Automated Gas Chromatograph test was conducted at the SNL Chemical Waste Landfill site in Technical Area III. The goals were to detect, quantify, and monitor VOCs from three vapor ports at different depths (Port A @ 6 ft., Port B @ 11 ft., and Port C @ 51 ft.) in the UCAP3

SEAMIST™ vapor sampling system. Data was collected on three separate occasions for approximately three days. The concrntration leves of the detected contsminsnts are given in Table 1. Generally, the contaminants concentrations are constant with time at a particular depth, the concentrations increase with depth, and not all contaminants are present in all depths. Typical concentrations profiles with time of three contaminats are shown in Figure 6.

Table 1. Summary (Average) Concentration Results

Compound	Port A (ppm)	Port B (ppm)	Port C (ppm)	Run
pentane	---	11	11	1
	---	---	13	2
	---	---	18	3
freon 113	4	7	14	1
	5	7	15	2
	6	6	22	3
1,1,1-trichloroethane	4	6	22	1
(TCE)	5	7	25	2
	10	10	39	3
trichloroethylene	8	25	120	1
	10	22	115	2
	40	40	230	3
tetrachloroethylene	3	---	5	1
(TetCe)	---	4	6	2
	---	5	11	3
1,2-dichlorobenzene	---	4	---	1
	---	1	---	2
	---	2	---	3

[FIGURE 6 HERE]

SEAMIST™-UV Imaging Fluorometer

An ultraviolet (UV) imaging fluorometer was previously developed by Sandia National Laboratories to detect volatile organic compounds in the atmosphere. The imaging fluorometer was modified to mount on a transportable system for field integration with the SEAMIST™ vapor sampling system in the UCAP boreholes at the CWL. The sensitivity of the fluorometer was improved by an order-of magnitude to detect aromatic compounds in this field demonstration. The improved sensitivity was gained by developing a system to selectively trap the aromatic compounds and performing the fluorescence measurements at reduced pressure in the fluorometer chamber. This reduces the effects of oxygen and water vapor quenching on the fluorescence signal. Calibration of the modified fluorometer indicate a sensitivity of approximately 1 ppm. Fluorescence measurements were conducted on the same boreholes previously used for the automated/unattended GC field studies. The results are being evaluated. The automated/unattended GC was able to identify a number of aromatics, but could not quantify all these compounds. The UV imaging fluorometer should resolve this problem.

ASSESSMENT OF SOIL VAPOR MOVEMENT DUE TO BAROMETRIC PUMPING

To understand the vapor transport mechanisms in the vadose zone, both the advective movement of the bulk vapor, and the diffusive movement of the vapor's constituents, must be understood. This effort is an initial evaluation of advective movement due to barometric pumping.

Barometric pumping of soil gas results from the cyclic variations in the atmospheric pressure caused by daily heating/cooling cycles (typically 5 to 8 millibars in amplitude) and occasional weather fronts (up to 60 millibars). The oscillatory pressure at the surface causes a piston-like vertical gas displacement, with an impermeable boundary provided by the water table. In a homogeneous medium with steady state conditions, the total amplitude of this displacement is:

$$\Delta \ell = \frac{\Delta p}{P_{atm}} \times L$$

where Dp is the cyclic pressure variation, P_{atm} is the nominal absolute (barometric) pressure, and L is the distance to an impermeable boundary such as the water table. Given that the depth to the water table at the CWL is approximately 485 feet, daily 5 mbar barometric pressure variations would result in total vertical displacement of a gas molecule at the 20-foot depth of 2.8 feet (830 mbar is the average barometric pressure at the site). For the larger pressure variations (60 mbar) associated with weather fronts the maximum displacement would be 34 feet. Two features of the real soil environment cause significant departures from this simple model, one potentially increasing and the other decreasing the total displacement. If the soil is homogeneous and isotropic, the net vertical movement of the vapor molecule at depth will be zero over time, since the barometric pressure always returns to a mean value. However, lab tests have shown that the vertical movement can be amplified and result in a net displacement if soil heterogeneities are present (Peterson, et. al., 1987). This ratcheting occurs because as soil gas flows upward in its regular cycle, it travels farther in some areas than others (because of heterogeneities in the soil properties). Contaminants diffuse laterally from these leading fronts, but do not diffuse back into the plume on the reverse cycle because of inadequate concentration gradients. An extreme case of ratcheting occurs when the contaminant is sufficiently close to the surface to release to the air during its maximum vertical displacement. The second effect will decrease the displacement. The simple oscillatory flow model is an absolute maximum case, assuming a steady state condition. The resistance to gas flow caused by the soil's permeability dampens the soil gas pressure response, preventing the attainment of a true steady state condition. The soil gas at depth never quite has enough time to fully equilibrate with the surface pressure because the surface pressure is constantly changing .

To evaluate the vapor displacement due to barometric pressure variations, three SEAMIST™-instrumented boreholes were studied, each with 11 measurement ports down to 95 feet deep (UCAP1, 2, and 3). Gas pressure measurements were taken with a precision barometric pressure transducer, which sequentially scanned the various pressure measurement points downhole with a solenoid valve manifold system.

The surface and in-situ gas pressures were recorded every 30 minutes for the 140 hour test duration. A ribbon plot of a typical multipoint pressure history is depicted in Figure 7. The gas at depth responds very quickly to surface perturbations, since very small gradients are measured (typically a maximum of 1.0 to 1.5 mbar over the full 95-foot depth).

[FIGURE 7 HERE]

The movement of soil gas can be estimated if the pressure gradient in the soil, and the soil's permeability, are known. Straddle packer measurements had been conducted in the UCAP boreholes, and those results are used to estimate the permeability distribution in the soil. The permeability is combined with the pressure gradients measured with the SEAMIST™ systems to estimate soil gas velocity histories at specific depths in the soil. For the very small pressure fluctuations caused by barometric changes (on the order of 5 millibars) air flow in soils can be considered incompressible. A simple Darcy flow model predicts steady state porous flow under these conditions:

$$Q = \left(\frac{kA}{\mu}\right)\left(\frac{\Delta p}{L}\right)$$

where Q = volumetric gas flow through soil
k = permeability of soil
A = cross sectional area
$\frac{\Delta p}{L}$ = $\frac{\text{pressure gradient in soil}}{\text{measurement point spacing}}$
μ = soil gas viscosity

The gas permeability over the interval is an average of the in-situ measurements. Even though pressure data was available at finer spacing, the calculations were done over roughly 20-foot intervals to determine pressure differences with sufficient accuracy.

The net velocity of gas in the soil is:

$$V = \frac{Q}{A \cdot \varphi}$$

where j is the porosity of the soil accessible to soil gas. To determine displacement of the soil gas, the velocity is integrated over time. The analyzed data set started on June 15, running for 140 hours. The resulting displacement histories for all points on the UCAP1 membrane are shown in Figure 8. The recording period centered about a barometric low, which is apparent in Figure 7. The daily cycles appear on the displacement histories but are less than 20 percent of the displacement due to the slower low pressure front. The displacements scale with the permeability, so the high estimated displacement (nearly 4 meters) at 10.5 feet in UCAP1 is attributed to a very high permeability of 450 Darcies measured at that location. At the other depths in the borehole the displacement is less than 15 cm. Similar results were calculated in the other two boreholes, with most of the displacements being less than 20 cm.

[FIGURE 8 HERE]

The advective component of the vapor movement is one factor in the transport of volatile contaminants in soil, and by itself will not result in a net vapor movement over time since it is cyclic in nature. Laboratory tests and analysis have shown that when lateral diffusion is coupled with the cyclic vertical motion in heterogeneous media, an irreversible displacement of contaminants in the soil vapor can occur. Tracer measurements are required to detect this effect, making the next step to understanding plume movement a coupling of these measurements with tracer injection and automated gas analysis at multiple points to evaluate movement of contaminant species within the soil vapor.

SUMMARY

The focus of the in situ instrument field tests was the demonstration of the SEAMIST™ system's deployment versatility. All the sensors and samplers were readily integrated with the SEAMIST™

system. Standard, available sensors in a variety of shapes and sizes were used. From the laboratory and field test results, the membrane deployment did not appear to degrade the performance of the sensors or samplers. The instrumented membranes were quickly emplaced and removed to allow other activities in the boreholes. This study clearly demonstrated the ease with which an array of sensors/samplers could be deployed with SEAMIST™.

Downhole pressure measurements were used to infer soil gas displacement due to barometric pressure oscillations. Net displacements of ten to several hundred centimeters were predicted, depending on local permeability. These results provided an insight into the advective component of vapor movement. The diffusion of contaminants in the soil vapor must also be understood to determine contaminant transport characteristics.

ACKNOWLEDGMENTS

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G. Laguna, Sandia National Laboratories Department 2337, engineered the modifications of the gas chromatograph and has interpreted the data collected with the integrated SEAMIST™-Automated/Unattended Gas Chromatograph.

P. Hargis, Sandia National Laboratories Department 1128, is the developer of the SNL UV Imaging Fluorometer and is working to integrate it with SEAMIST™.

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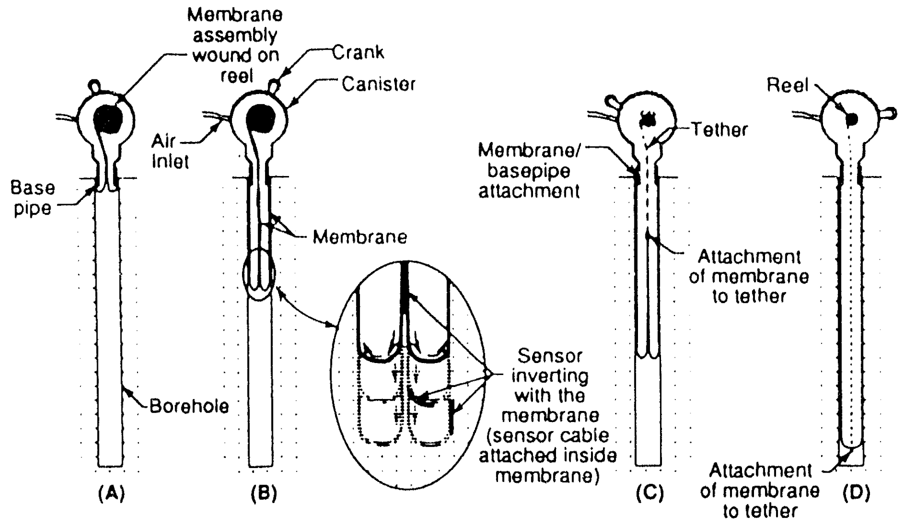

Fig. 1. Extension of the SEAMIST™ membrane: a) the packaged system is placed at the mouth of the borehole; b) an increased pressure "blows" the membrane (with the help of unwinding the crank) through the basepipe and into the borehole. Insert shows how an instrument inverts with the membrane going from being protected by the membrane to being fully exposed to the surrounding medium; c) once the membrane is unwound from the reel, the tether controls the rate of membrane emplacement; d) a fully extended membrane and tether.

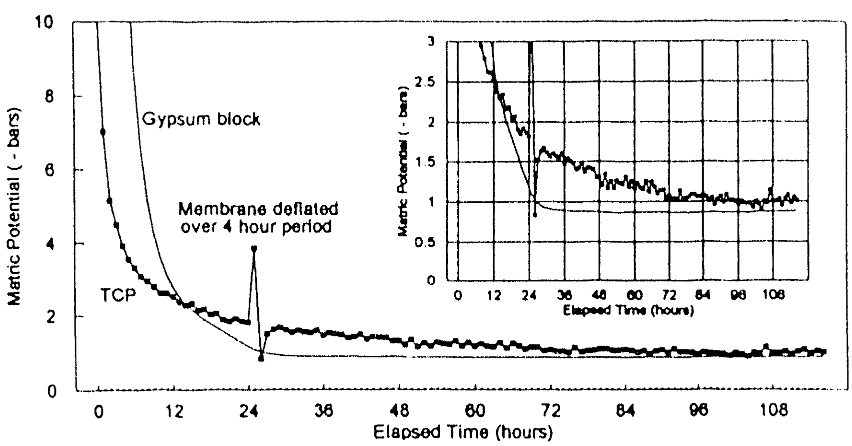

Fig. 2. Comparison of thermocouple psychrometer and gypsum block matric potential measurements at the 51-foot depth (UCAP2).

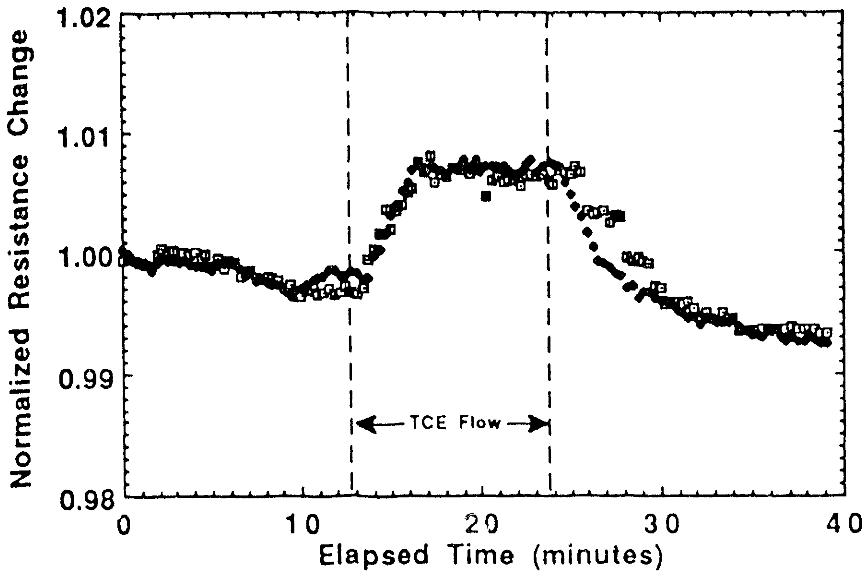

Fig. 3. Resistance response of two Adsistors™ momentarily exposed to 100 ppm TCE in air.

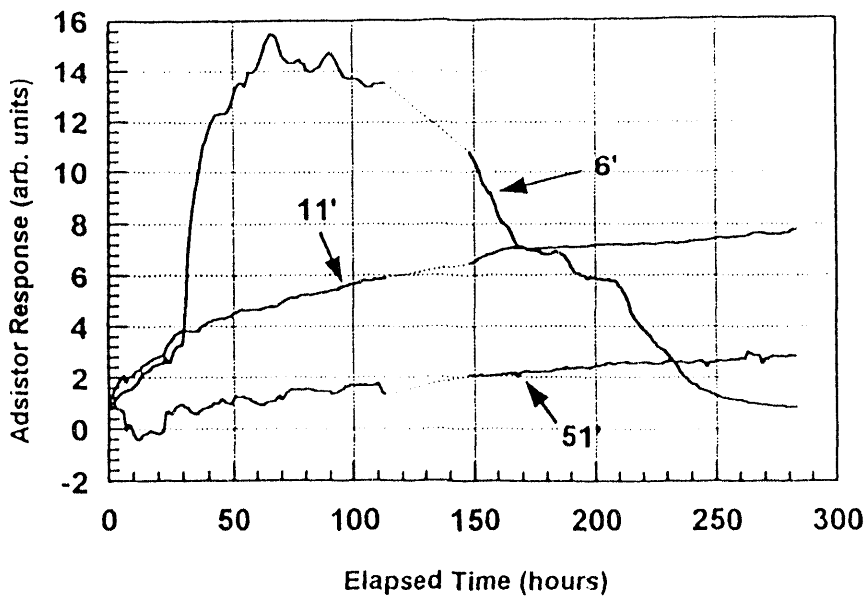

Fig. 4. Data record of three Adsistors™ emplaced in UCAP3.

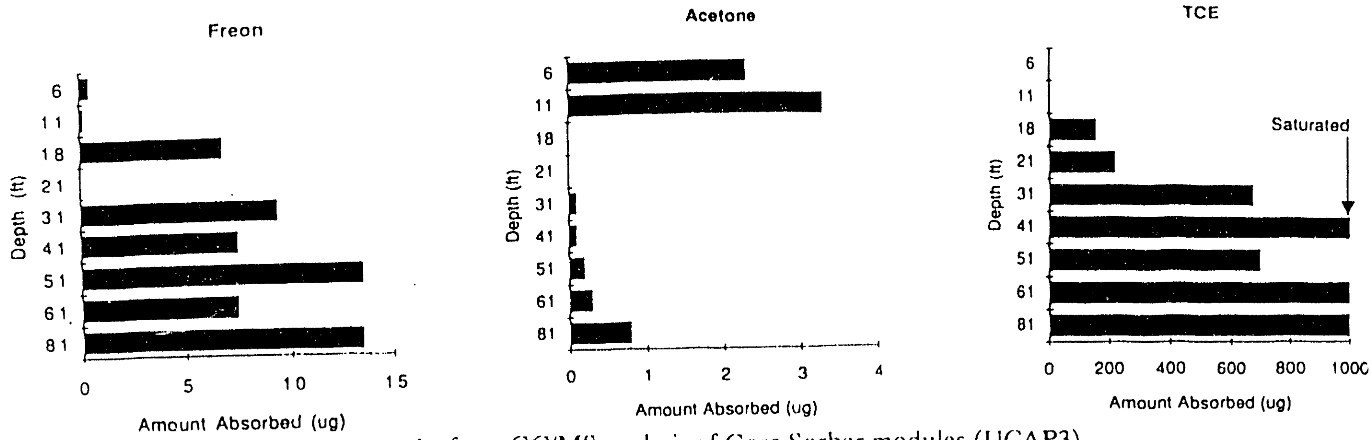

Fig. 5. Results from GC/MS analysis of Gore Sorber modules (UCAP3).

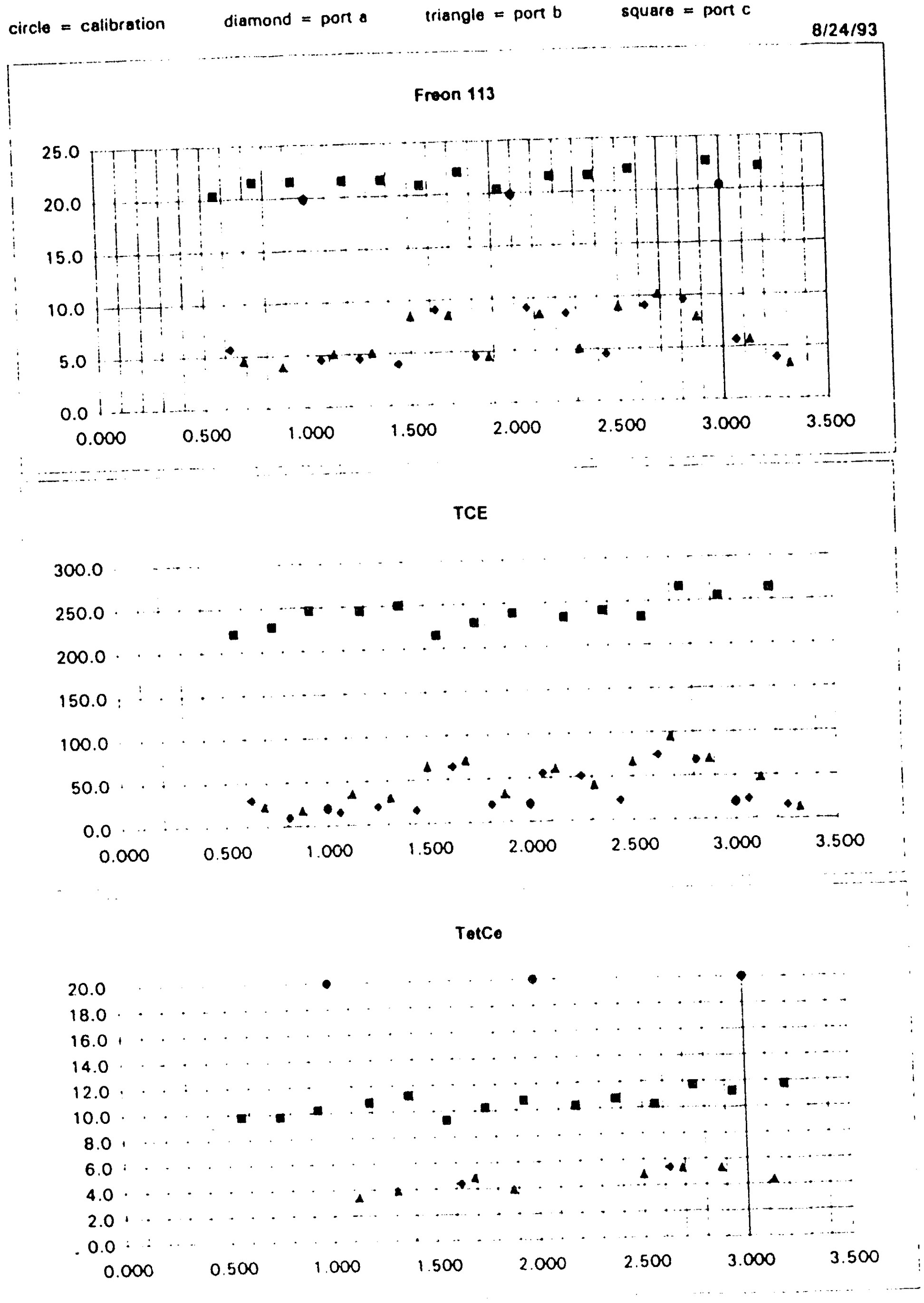

Fig. 6. Typical data acquired by automated/unattended GC; the time is in days and concentrations are given in ppm (Port A @ 6 ft., Port B @ 11 ft., and Port C @ 51 ft.).

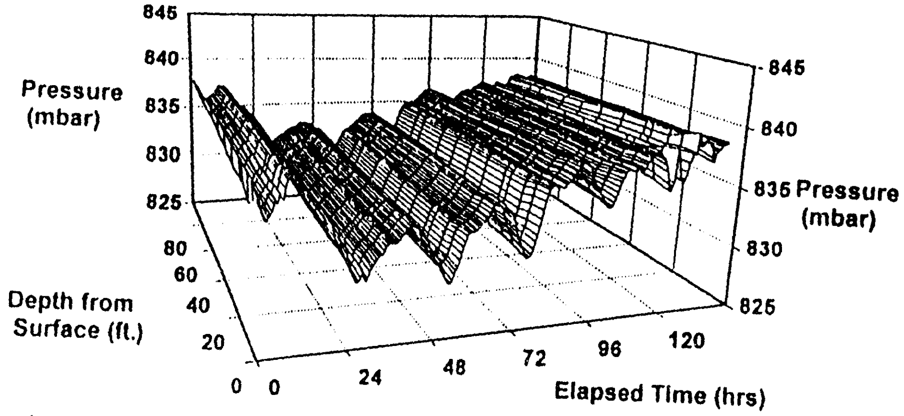

Fig. 7. Transient data record of the in-situ soil gas pressure recorded in UCAP1, starting June 15, 1993.

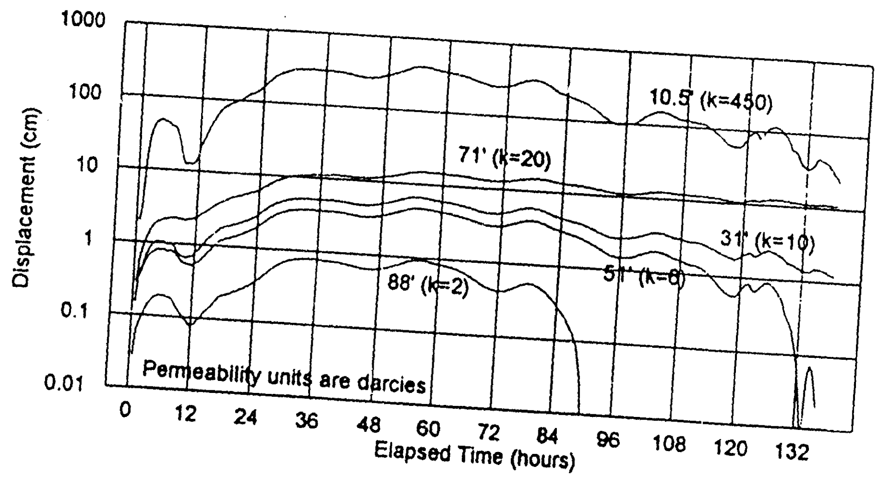

Fig. 8. Estimated soil vapor displacement due to barometric pressure oscillations for UCAP1. Permeabilities are indicated on the curve labels.

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