

MULTISCANTM – IN-SITU, REAL-TIME, AUTOMATED DETECTION AND MONITORING OF SUBSURFACE VOLATILE ORGANIC COMPOUNDS

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ABSTRACT

As more sites in the vadose zone enter the active remediation and post-remediation stages, the need and costs of long-term monitoring of volatile organic compounds (VOCs) are increasing. Recognizing this need, Science and Engineering Associates (SEA), jointly with the DOE, developed a cost-effective system for long-term monitoring of VOCs and soil gas pressure fields. This monitoring system, called MultiScanTM, is capable of in-situ, real-time, autonomous monitoring to:

- Assess the effectiveness of both active or passive remediation operations such as soil vapor extraction or bioremediation
- Assess the dynamic response or rebound of VOC plumes when a site leaves the active remediation stage and remediation systems are shut down
- Assess the influence of natural processes, such as changes in barometric pressure, on the VOC plume during active and post-remediation stages
- Ensure regulatory compliance

Up to 64 sample lines from either single or multi-point wells can be monitored. The sample lines are extended from the monitoring well to the scanning unit with small diameter (1/16" i.d.) tubing. Location of the sampling points depends on the lateral extent and depth of the contaminant plume, area of influence of an active or passive remediation operation, and/or the desired spatial resolution of the sampled soil gas data. Sampling points can be emplaced with either conventional drilling or direct-push emplacement tools.

The system is very rugged and can function unattended for extended periods of time (months). Soil gas is analyzed using a photoacoustic gas analyzer capable of a dynamic range of detection (such as 100ppm to 10ppb) for up to five different compounds or contaminants. Additionally, there are dedicated sensors to monitor soil gas CO₂ and O₂ levels, soil gas pressure, and barometric pressure and temperature. The system hardware and software is modular in design, allowing maximum flexibility. Additional monitoring ports may be added in banks of 16. Additional soil property measurements (such as matric potential or temperature) can be added at all or some of the ports. An analysis of all 64 ports can be completed in as little as five hours, allowing suites of data to be collected as frequently as two to four times per day.

The MultiScanTM system has been demonstrated for both soil gas contaminant analysis and tracer testing. Most notably, the system was used to monitor a pilot vapor extraction system in volcanic tuffs. This system has operated for several month-long intervals over the past three

years. The data recorded has allowed the users to clearly see where a TCA vapor plume was affected by an extraction well, as well as the vapor recovery after the extraction system was turned off.

This technology offers significant benefit to users in terms of reduced cost, time, and secondary waste generation. Cost analysis show that the system can reduce the cost of long-term monitoring by two-thirds or more over conventional manual sampling/analysis, while providing significantly more time series data, O₂ and CO₂ analysis, and soil gas pressure data. The measurement system features, results of field applications, and cost comparisons are discussed in more detail below.

INTRODUCTION

As more sites enter the active remediation and post-remediation stages, the need and costs of long-term monitoring of volatile organic compounds (VOCs) are increasing. Typically, long-term monitoring of VOCs requires expensive laboratory analysis of gas samples. Secondary waste generation is an expensive byproduct. More costly is the time to collect, package, ship, and analyze samples. Obtaining results of the analysis often takes months. Such time-consuming analysis is detrimental to real-time monitoring, decision making, and regulatory compliance. In response to the need for an improved long-term monitoring system, SEA developed MultiScanTM. The system is mature, cost effective, and capable of long-term monitoring of VOCs and soil gas pressure fields. It provides in-situ, real-time, autonomous monitoring, even under adverse field conditions.

MultiScanTM can assess the effectiveness of both active and passive remediation operations such as soil vapor extraction or bioremediation. Real-time monitoring of the soil gas composition, and subsequent data reduction and visualization characterizes the distribution and extent of the VOC plume. The extent to which the plume is shrinking (or growing) helps to assess the effectiveness of the remedial activity. Soil gas pressure measurements are crucial to understand the flow field for remediation processes requiring or inducing air flow through the soil. The unit can effectively measure resulting pressure fields in the soil.

The scanning system is also capable of monitoring the degradation history of organic contaminant vapor such as TCE, and the production of degraded byproducts such as vinyl chloride, methane, and CO₂. Based on these concentration histories, the effectiveness of a bioremediation activity may be assessed. In addition, the system can monitor soil gas O₂ levels to assess the effectiveness of aerobically enhancing bioremediation. When a site leaves the active remediation stage, and these types of remedial activities are stopped, the unit can continue real-time monitoring to measure the dynamic response or rebound of the VOC plume. Again, the extent to which the VOC plume shrinks (or grows) during the post-remediation stage, helps assess the effectiveness of the remedial activity.

TECHNOLOGY DESCRIPTION

MultiScanTM is a stand-alone, autonomous, soil gas sampling system. The system reliably monitors soil gas composition in real time by sampling up to 64 soil gas lines. Soil gas lines, which are typically small diameter polyethylene or teflon tubing, run from the system to porous filters that have been installed into the subsurface using conventional drilling or direct-push emplacement tools. Location of the sampling points depends on the lateral extent and depth of the contaminant plume, area of influence of an active or passive remediation operation, and/or

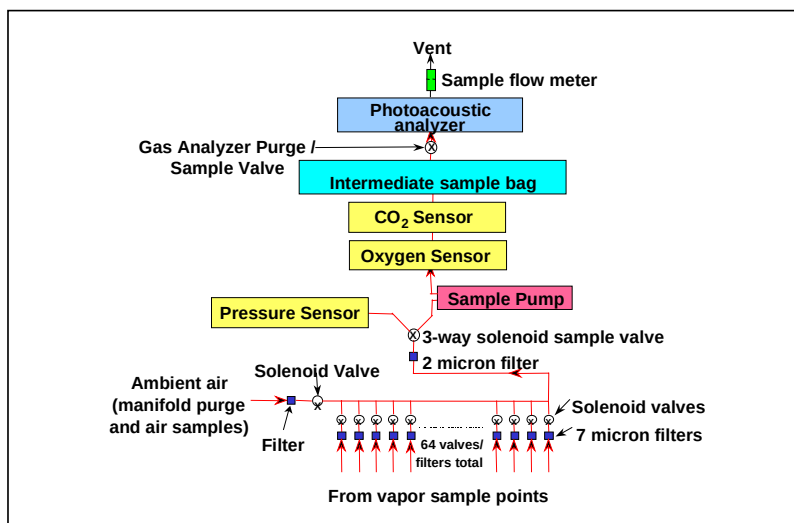
the desired spatial resolution of the sampled soil gas data. Soil gas is analyzed using a photoacoustic gas analyzer. The analyzer operates on photoacoustic principles where an intense infrared light is shined on the gas collected in a sample chamber and very sensitive microphones “listen” to the response of the gas to the light. The analyzer can read concentrations up to five orders of magnitude from the lower detection limit of the gas, to within 10 percent accuracy. Up to five different compounds or contaminants, including but not limited to TCE, TCA, vinyl chloride, benzene, toluene, or xylene, can be measured. The unit also measures water vapor. The analyzer has an operating temperature range of 5 to 40°C with a temperature influence of ± 10 percent of the detection threshold per °C. Performance reliability of the analyzer is ensured by a series of self tests.

In addition to the compounds or contaminants measured with the photoacoustic gas analyzer, dedicated sensors can be added to the system to monitor soil gas CO₂ and O₂ levels, soil gas pressure, barometric pressure, and temperature. Depending on the number and length of soil gas lines between the sample points and the system, and the number of compounds being analyzed, 3 to 7 minutes is required for each gas sample. Typically, 12 to 24 hour scanning intervals are used.

The monitoring system utilizes a solenoid valve system to sequentially connect each sampling port first to a pressure sensor, and then to the photoacoustic gas analyzer. Less than half a liter of soil gas is required for each analysis. The scanning system is managed by an on-board computer that controls the solenoid valves, the gas analyzer, stores pressure, temperature, and soil gas composition data, and performs self-diagnostic tests to assure the accuracy of the sampled data. Data may be downloaded remotely using a cellular data modem. The unit stores data in a standard, readily usable format that allows analysis and graphic presentation using standard spreadsheets (such as Microsoft Excel) and data visualization software (such as AVS/Express). The system may be powered by solar energy, a generator, or site power. The system is capable of unattended operation for weeks to months at a time. Fig. 1 shows both a photograph and a schematic of the MultiScanTM system.



(a)



(b)

Fig. 1. The MultiScan monitoring system (a) photograph (b) schematic of the system.

FIELD DEMONSTRATIONS

The MultiScanTM system is relatively mature, having been demonstrated for both soil gas contaminant analysis and tracer testing. The first application of the system was to evaluate the diffusivity of soils, using a crude system that integrated a datalogger and gas analyzer so that synchronized pressure and gas concentration measurements could be obtained (1). Following that work, numerous other demonstrations were completed. Upgrades to the system were made with each successive demonstration. A brief synopsis of three case studies follows.

Case Study #1: Los Alamos National Laboratory Vapor Extraction System

A MultiScanTM system was developed for Los Alamos National Laboratory to monitor a pilot vapor extraction system in volcanic tuffs (Fig. 2a shows a plan view of the wells in the experimental area). The vapor monitoring points are embedded in a borehole using the SEAMISTTM instrumentation system, and are located 20 feet from the extraction well. This system used a palmtop computer to control analog/digital hardware, a 16 port sampling manifold, and a photoacoustic gas analyzer. The analyzer measured TCA, TCE, Freon, CCL₄, CO₂, and water vapor. The system also measured pressures at all of the monitoring ports, and barometric pressure and temperature. The scanning system operated unattended for 2 to 3 months at a time, over a three-year period. During that time, a tremendous amount of data was collected. Fig. 2b shows a data record obtained during a vapor extraction test. Four sampling elevations are depicted in the plot, clearly indicating where the TCA vapor plume was affected by the extraction well, as well as the vapor recovery after the extraction system was turned off. Fig. 2c shows several contours / plots of subsurface pressure histories collected with the system. The collected data showed a clear response between the measured concentration of contaminants in the soil gas with barometric pressure changes. Results of the system were used in understanding the initial test results, and predicting future results in the area.

Case Study #2: Monitoring of a Passive Vadose Zone Remediation System at INEEL

A low-cost, simple solution has been developed as an in-situ containment and extraction methodology for sites where the contamination resides in the shallow vadose zone soil. Called BERTTM (Barometrically Enhanced Remediation Technology) the approach capitalizes on the vertical soil gas movement resulting from natural barometric pressure oscillations, and harnesses this mechanism to ensure a net vertical upward soil gas flux in the contaminated soil. The design requires no boreholes or site power, resulting in a low cost, low-maintenance remediation system.

Fig. 3a shows a schematic of the BERTTM system. Naturally occurring variations in barometric pressure are both diurnal, corresponding to daily heating and cooling of the atmosphere, and of a longer time period (several days), resulting from passage of weather fronts. As the barometric pressure rises, a gradient is imposed on the soil gas, which drives fresh air into the soil. As the barometric pressure drops, gas vents upward from the near-surface soil into the atmosphere. Displacement of soil gas can be controlled using surface features that impede the downward movement of vapor in the plume area, but allow upward movement. In operation, BERTTM ratchets the upward soil gas flow by allowing normal upward flow during barometric lows but restricting downward air flow during high-pressure cycles.

Over the last several years, BERTTM has been tested at a contaminated landfill site of the Idaho National Engineering Laboratory. A MultiScanTM system is being used to monitor changes in the subsurface and atmospheric pressures, wind speed, vent speed, and soil gas oxygen and carbon dioxide levels. The monitoring system was able to monitor the remediation project continuously, under very adverse conditions. Fig. 3b shows a sequence of in-situ soil gas pressure correlated with barometric pressure. There is a distinct change in contours when the barometric pressure starts rising, indicating the effect of the surface seal. Results from the monitoring system have shown how well BERTTM is working, and have been used to determine ways to boost the remediation system's performance.

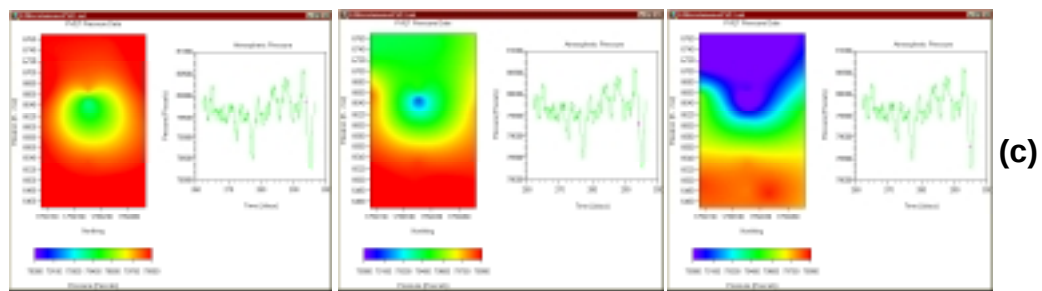
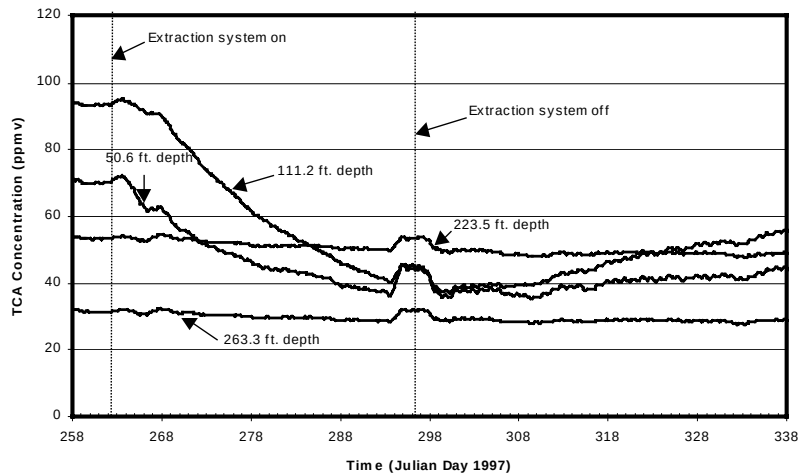
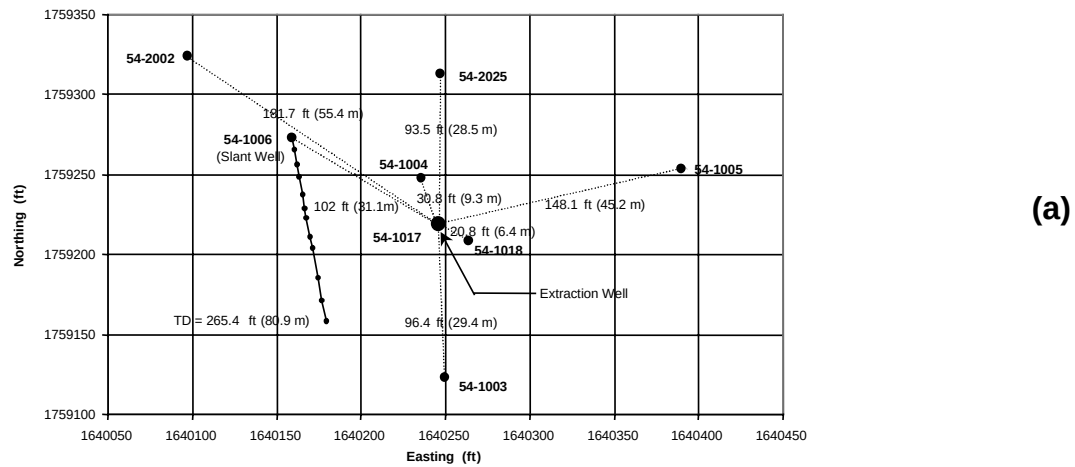
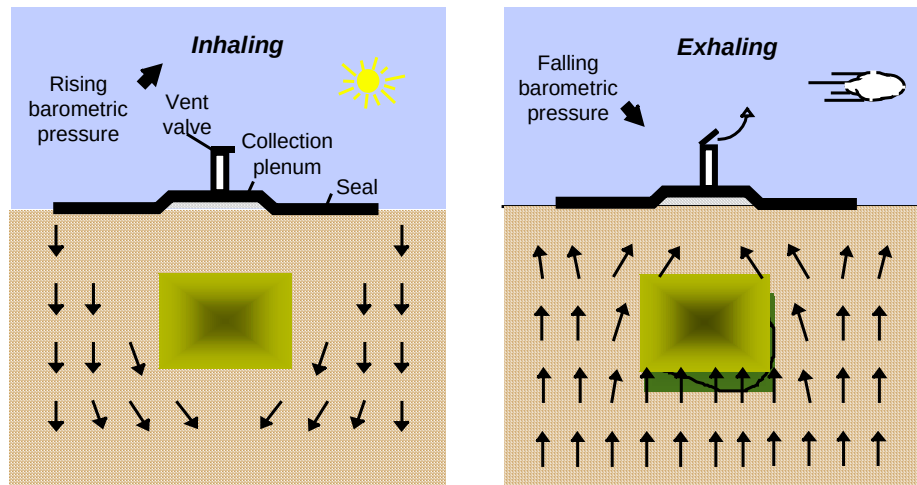
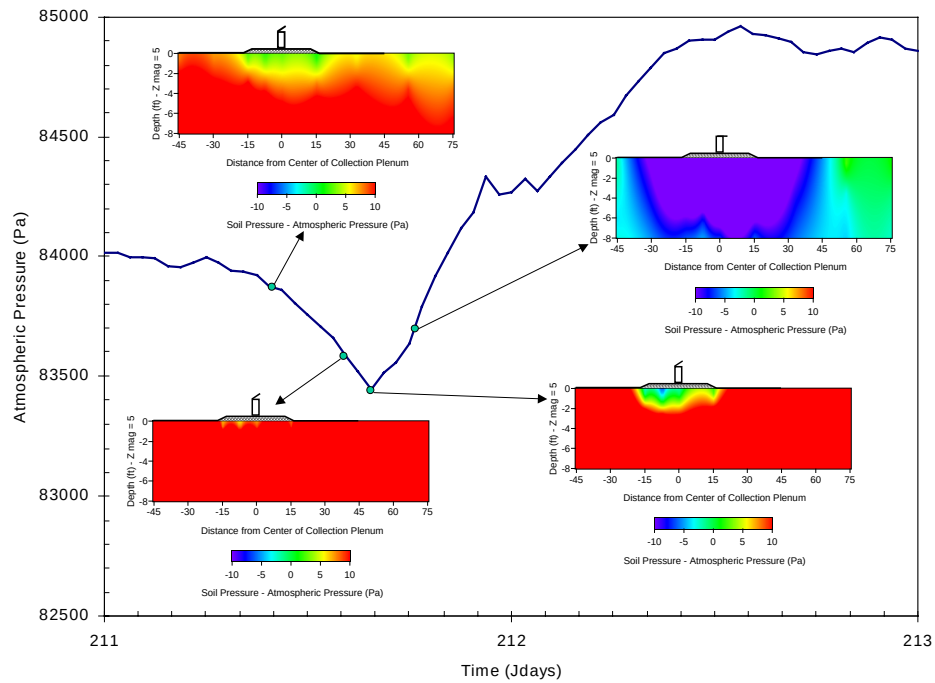


Fig. 2. Los Alamos National Laboratory Vapor Extraction System (a) plan view of the wells in the experimental area (b) data record obtained from monitor well 54-1018 (20 ft. from the extraction well) during the vapor extraction test (c) several contours / plots of subsurface pressure histories collected with the system.



(a)



(b)

Fig. 3. Passive Vadose Zone Remediation System at INEEL: (a) schematic of the BERTTM passive remediation system (b) sequence of in-situ soil gas pressure correlated with barometric pressure.

Case Study #3: Subsurface Barrier Verification

In-situ barrier emplacement techniques for the containment of high-risk contaminants in the vadose zone are currently being developed by the DOE. These barriers are primarily intended for use in the high-risk sites where few viable alternatives exist to stop the movement of contaminants in the near term. Assessing the integrity of the barrier once it is emplaced, and during its anticipated life, is a very difficult but necessary requirement.

Science and Engineering Associates, Inc. (SEA) has developed a tracer-based monitoring/verification system. This system, called SEAttraceTM, is able to locate and size leaks with a high degree of accuracy in subsurface barriers that are in an unsaturated medium. It combines the MultiScanTM monitoring system with gaseous tracer injection and real time data analysis to evaluate barrier integrity.

A schematic of the system is shown in Fig. 4a. Multiple sample points are located outside the barrier, as well as one or more injection and sample ports inside the barrier. These ports are connected to a stand-alone data acquisition and analysis system. A tracer gas (sulfur hexafluoride) is injected into the barrier. If the barrier has a breach, the tracer will diffuse into the surrounding medium and the exterior sample ports will measure the amount of tracer in the soil gas with time. These concentration histories can then be input (along with the known sample locations, and ranges for the medium properties and the source concentration) into a global optimization code. The code iterates to find a best-fit solution given all the input parameters.

The SEAttraceTM system has been used to evaluate two barriers constructed by the DOE, a colloidal silica permeation-grouted barrier at Brookhaven National Laboratory and a thinwall jet grouted barrier at the Dover Air Force Base. The system was able to detect flaws in each of the barriers. Results from the system proved to be faster and have greater spatial resolution than other barrier technologies tested. At the Dover jet-grouted barrier, two engineered leaks were included in the study. The system was able to locate these leaks very accurately (within 0.3 m of their actual location). Fig. 4b and 4c show results of the MultiScanTM/SEAttraceTM system from the engineered leak at the Dover Air Force Base. Results of the system for the non-engineered leaks were corroborated by a combination of the construction records of the barrier, independent tracer tests, or geophysical verification methods.

In addition to measuring the tracer gas, the monitoring system can measure up to four other compounds or contaminants. Thus the system can be used not only to verify the integrity of the barrier after it has been emplaced, but can also be used to quantify the performance of the barrier over time by monitoring for the contaminants contained within the barrier.

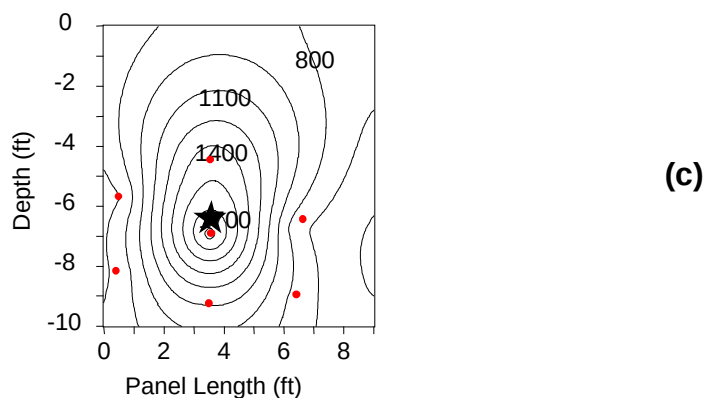
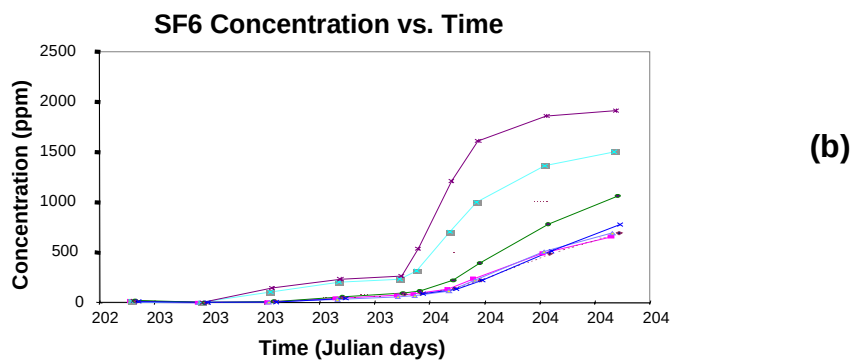
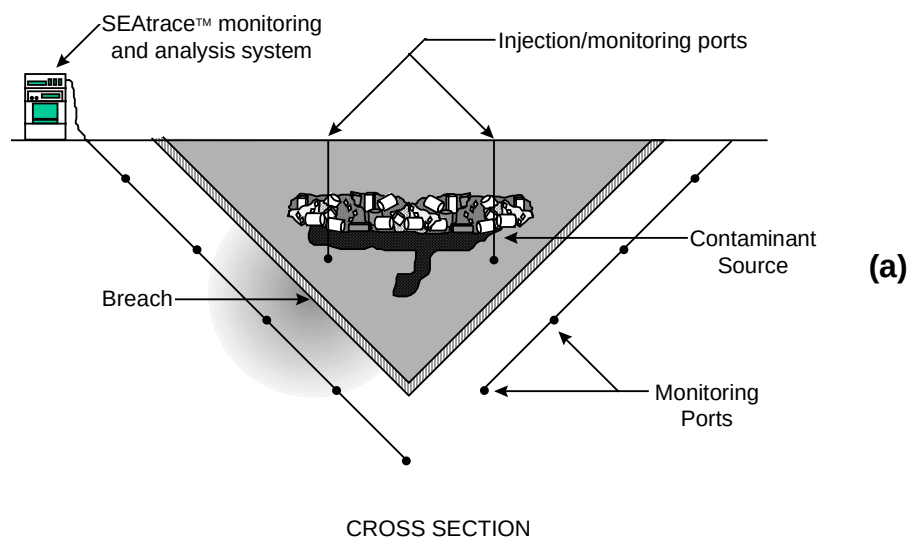


Fig. 4. SEAttrace™ barrier verification and monitoring system: (a) schematic of the SEAttrace™ system (b) measured concentration histories of the tracer gas at several monitoring ports (c) contour plot of the measured concentration data recorded on Julian day 204.6. The dots depict locations of the monitoring ports, the star shows where SEAttrace™ automatically determined the location of the leak. The true location of the leak was within 11" of the determined position.

BENEFITS

This monitoring technology offers significant benefits in terms of reduced cost, time, and secondary waste generation. The baseline against which MultiScanTM is best compared is the standard practice of soil gas samples taken by hand and submitted for laboratory analysis. This practice is susceptible to sampling errors, sample mislabeling, and sample alteration during the wait period prior to analysis. Analytical laboratory costs for a typical Method 8021 analysis (35 compounds ranging from BTEX to chlorinated hydrocarbons, but not including oxygen and carbon dioxide) are approximately \$175/sample, with three day turnaround.

An example remediation monitoring case can be analyzed with the following assumptions:

- Soil vapor sampling locations exist by a variety of standard emplacement methods (wells, Geoprobe, CPT emplacements, etc.)
- 20 sampling locations
- Weekly sampling for each of the 20 locations
- Total monitoring period duration of 24 weeks
- Laboratory method 8021 soil gas analysis

The cost of monitoring by manual sampling and lab analysis includes the labor to draw the samples (estimated at one day for a field technician to acquire and ship 20 samples) and the analysis cost, resulting in a total monitoring cost of \$96,000 (see table 1).

Table 1: Monitoring costs for manual sampling/lab analysis

Cost Category	Description	Cost (6 mo.)
Sampling labor	\$500/sampling run (1 day), once per week, for 24 weeks	\$12,000
Analysis cost	\$175/sample x 20 samples/run x 24 weeks	\$84,000
	TOTAL	\$96,000

Monitoring the same scenario with MultiScanTM includes amortization of the system's capital cost, maintenance, setup, and calibration. Twenty sampling points are monitored as above (although the system is capable of monitoring up to 64), and the monitoring period is 24 weeks (data is acquired automatically several times per day). The projected cost using the monitoring system is \$32,988 (see table 2).

Table 2: Monitoring costs for MultiScan™

Cost Category	Description	Cost (6 mo.)
Amortization of system capital cost	MultiScan™ costs approximately \$100,000 to fabricate. If its amortization period is three years, at a 5% interest rate the monthly amortization cost is \$2998.	\$17,988
System setup and checkout	2 field technicians for 1 week.	\$5,000
Periodic maintenance	1 field technician for 1 week, every 12 weeks: \$2500 x 2 visits	\$5,000
Calibration	Factory calibration every 6 months (\$2500)	\$2,500
Abandonment	1 field technician for 1 week	\$2,500
	TOTAL	\$32,988

Consequently, the MultiScan™ monitoring data is produced at a cost of approximately one third that of the laboratory analysis method, while providing significantly more time series data, O₂ and CO₂ analysis, and soil gas pressure data. Since the system is capable of monitoring 64 ports in its current configuration, it can monitor three times the ports as that proposed for the lab analysis with virtually no additional cost.

LIMITATIONS OF THE SYSTEM

The primary limitation of MultiScan™ is that it can currently be implemented only above the water table. The system's soil gas analysis is limited to soils where the capillary tension holding water in the pore space is greater than the vacuum produced through the sampling line. Water traps and desiccant help prevent water from entering the photoacoustic gas analyzer in the event a small amount is pulled into the soil gas sampling line. However, a version of the system that uses an in-situ air-sparging/headspace technique to extract a gas sample from the groundwater is under investigation.

A second limitation is that the photoacoustic gas analyzer is only capable of analyzing 5 compounds, compared to a laboratory technique that will report on up to 35 compounds. For this reason, the implementation of the field portable GC/SAW gas analyzer is being investigated as a replacement analyzer for the photoacoustic analyzer.

SUMMARY

MultiScan™ provides a cost effective, reliable way to monitor long-term monitoring of volatile organic compounds. The systems key features include:

- Real-time data analysis and visualization
- Field soil gas analysis measurements
- Multipoint sampling
- Increased sampling frequency over current manual sampling practices
- Remote access
- Automatic calibration

- Data checking
- Cal gas
- Background measurements
- Manifold integrity checks
- Sample flow rate checks (determines if have failed lines)
- Pressure field scans
- Temperature field scans
- Discrete O₂ and CO₂ sensors for biologic processes

The system is a mature technology. It has been used for both soil gas contaminant analysis and monitoring site remediation. In addition, the monitoring unit has been adapted to monitor in real-time, gaseous tracers to validate subsurface barriers.

MultiScanTM offers significant benefit in terms of reduced cost, time, and secondary waste generation. The baseline against which the technology is best compared is the standard practice of soil gas samples taken by hand and submitted for laboratory analysis. This practice is susceptible to sampling errors, sample mislabeling, and sample alteration during the wait period prior to analysis. Analytical laboratory costs for a single sample range from \$150 to \$250. Costs associated with manually collecting the samples are typically \$300 - \$500/day. Because of the high costs, data is collected infrequently, often only monthly or quarterly. Cost analysis have shown that the costs associated with MultiScanTM are less than one quarter of the baseline, with the system providing significantly more time series data, O₂ and CO₂ analysis, and soil gas pressure data.

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