

VERIFICATION OF SUBSURFACE BARRIER INSTALLATIONS WITH THE SEATRACETM GASEOUS TRACER SYSTEM

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ABSTRACT

In-situ barrier emplacement techniques and materials are being developed for the containment of high-risk contaminants in soils. Because of their relatively high cost, they are used in cases where the risk is too great to remove the contaminants, the contaminants are too difficult to remove with current technologies, or the potential movement of the contaminants to the water table is so high that immediate action needs to be taken to reduce health risks. Assessing the integrity of the barrier once it is emplaced, and during its anticipated life, is a difficult but necessary requirement.

Science and Engineering Associates, Inc. (SEA) has developed and demonstrated an integrated tracer-based monitoring/verification system. This system, called SEATRACETM, locates and sizes leaks in subsurface barriers emplaced in unsaturated media. It uses gaseous tracer injection, in field real-time monitoring, and real-time data analysis to evaluate barrier integrity.

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 (typically sulfur hexafluoride) is injected into the barrier, creating a large source volume of the tracer. 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 are transmitted (along with the sample port locations, medium properties, and the source concentration) to a global optimization code operating on the control computer. The code iterates to find a best-fit solution given the input parameters.

The data acquisition and analysis system is a stand-alone field unit. The system monitors up to 64 soil gas vapor lines and provides compositional analysis of up to five analytes in real time using a photoacoustic gas analyzer. The photoacoustic analyzer is well suited to measure the tracers typically used with SEATRACETM. The system is capable of unattended operation for long periods (weeks to several months). A full 64-port scan requires 5 to 6 hours. Inversion of the data to characterize leak location and size typically requires less than 30 minutes. The sequence repeats at predefined intervals, and analysis results can be obtained by the user either at the monitoring system, or remotely through a cellular modem data link.

The SEATRACETM system was used to evaluate three test barriers: a field-scale barrier mockup with engineered leaks, 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 faster and with greater spatial resolution than the other barrier verification technologies that were tested.

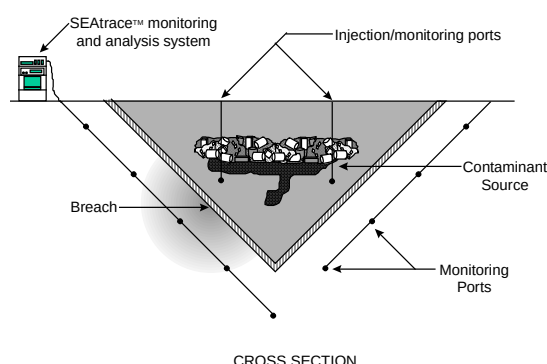
PROBLEM

In-situ barrier emplacement techniques and materials are being developed for the containment of high-risk contaminants in soils. These techniques include slurry walls, grout barriers, cryogenic barriers, and other forms of impermeable barriers. Because of their relatively high cost, they are used in cases where the risk is too great to remove the contaminants, the contaminants are too difficult to remove with current technologies, or the potential movement of the contaminants to the water table is so high that immediate action needs to be taken to reduce health risks. Consequently, 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. While surface-based geophysical techniques such as cross borehole electromagnetic surveys, ground penetrating radar, and electrical resistance tomography can detect the presence of emplaced barrier materials, their resolution is typically inadequate for leak detection purposes. Nuclear borehole logging is capable of greater resolution, but because of its limited penetration, would require an excessive number of boreholes, rendering it impractical for barrier assessment. Hydraulic testing in the vadose zone is not likely, as introducing water to the contained volume would mobilize contaminants otherwise in an immobile state. Only gaseous tracer testing of barrier installation shows the promise of resolving large and small flaws in barrier walls, so is an attractive approach for conservative verification of barrier integrity (1).

APPROACH

SEAttraceTM is predicated on the very simple and predictable transport process of binary gaseous diffusion in porous media. Diffusion is an attractive process to utilize for leak detection because the tracer concentration histories measured at locations distant from the source are highly sensitive to both the size of the breach and the distance from the leak source. This sensitivity allows a global optimization modeling methodology to iterate to a leak geometry and location by minimizing errors in the transport calculations.

A schematic of the system is shown in fig. 1, along with a photo of the monitoring unit. 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 (typically sulfur hexafluoride) is injected into the barrier, creating a large source volume of the tracer. 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 sample locations with respect to the barrier, medium properties, and the source concentration) into the global optimization code. The code iterates to find a best-fit solution given the input parameters. Solution is very rapid, typically requiring less than 30 minutes to characterize multiple leaks after completion of gas analysis. Thus, SEAttraceTM is made up of two distinct functional components: a monitoring system and an optimization code.



(a)



(b)

Fig 1(a) Schematic of the SEAttrace™ system. (b) Photo of the integrated SEAttrace™ field system.

The Monitoring System

Installation of the sampling ports can be accomplished by direct-push emplacement tools. If the barrier is shallow (3 to 6 m deep), a manually operated system would suffice (such as portable vaporpoint systems). As the emplacement depth increases or the geology becomes more resistive to vapor point emplacements a truck-mounted system (such as a Geoprobe unit) would be required. Such direct-push emplacements are less costly and more rapidly performed than drilling. Secondary waste generation is also minimized. The spacing and configuration of the sampling points are critical to the effectiveness and cost of the monitoring system. Site-specific parameters (geology, anticipated source concentration, barrier construction and geometry, properties of the tracer gas, etc.) will determine the optimum port locations. Calculations and field tests have shown that for typical vadose zone conditions, ports spaced on a 2-5 m grid placed 1 m from the barrier would adequately detect a breach anywhere on the barrier.

The data acquisition and analysis system is a stand-alone field unit based on the SEA MultiScan™ autonomous soil gas analysis system. The system reliably monitors up to 64 soil gas vapor lines and provides compositional analysis of up to 5 analytes in real time using a photoacoustic gas analyzer. The photoacoustic analyzer is well-suited to measure the tracers typically used for barrier validation. Less than half a liter of soil gas is required for each analysis, and a dynamic range of orders of magnitude is maintained for most compounds. The system is capable of unattended operation for long periods (weeks to several months). Three to seven minutes is required for each sample, depending on the length and size of tubing between the monitoring system and the port, and the number of compounds being analyzed. Twelve or twenty-four hour scanning intervals are typically used. MultiScan™ records all pertinent data, and performs self-diagnostic-tests to assure the accuracy of the measured concentrations.

The Optimization Code: Leak Locating and Sizing Methodology

Once concentration history data has been collected, it must be analyzed if any tracer gas was detected outside the barrier. Often this type of post-test analysis is performed by manually trying to match field results to results from forward diffusion models through an iterative process. This is a time consuming, artful process as the leak geometry, dimensions, and location

are variable, the medium properties are often not well characterized, and the source concentration is variable. To overcome the difficulties of standard post analysis, SEAttrace™ uses a global optimization technique to effectively search multi-dimensional “space” to simultaneously find the best fit solution based on all of the input parameters.

The general methodology of this approach rigorously searches for a set of parameters that will best characterize the leak. It requires a diffusion model that calculates concentration histories from the multi-parameter “space”. These calculated concentrations are compared to the measured concentrations using an objective function. For SEAttrace™, the objective function is defined as the sum of the squares of the differences between the predicted and measured tracer concentrations. A stochastic method is then employed to minimize the objective function, thus finding a best fit to the data given a range of defined parameters. The stochastic method used is called Simulated Annealing. The technique selects points from the given input ranges for each parameter at random. Using these values, the objective function is evaluated. The process is repeated, the two values for the objective functions are compared, and the code chooses which is more accurate. This point is remembered and the process repeated with a new set of parameter values. The parameter values are chosen using a probability distribution that relies on the objective function of previous points in a complex way. The accuracy of the results is dependent on how well the chosen leakage model matches reality, and the number and ranges of the unknown input parameters.

Presently, the code developed to analyze the measured data uses a single one-dimensional spherical diffusion model. The model is constrained by assuming that a constant source concentration is maintained inside the barrier, and that the medium outside the barrier is homogenous (e.g., that the diffusivity of the tracer gas through the soil pores is constant). While this diffusion model is simplistic, to a first order it is realistic. If the area of the barrier wall is much greater than the area of the leak, at some distance from the leak the gas will approach spherical diffusion regardless of the true geometry of the leak. Additionally, the barrier wall will act as a flat no-flow boundary and the medium that the tracer gas is diffusing into can be assumed to be semi-infinite. Thus, the partial differential equation describing this transient process is:

$$\frac{\partial c}{\partial t} = \frac{D}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial c}{\partial r} \right) \quad (\text{Eq. 1})$$

where c is the concentration at radial position r and time t . The controlling parameter in this process is the diffusivity of the tracer in the soil gas, D , which is inclusive of the effects of porosity and soil tortuosity. If the barrier is well constructed (e.g., there are only a limited number of breaches in the barrier walls), the mass of tracer gas that can be injected into the internal pore volume of the barrier will be very large when compared to the mass of tracer gas that can diffuse through the leak area(s). Thus, the barrier will serve as an infinitely large reservoir of tracer gas at a fixed concentration (once the injected tracer gas has been completely injected and equilibrated). So boundary conditions can be set as:

$$c(r_0, t) = c_0 \text{ at } t \geq 0 \text{ and } c(r, t) = 0 \text{ at } t \geq 0 \quad (\text{Eq. 2})$$

Solving the differential equation results in a straightforward expression of:

$$c(r, t) = \frac{r_0}{r} c_0 \operatorname{erfc} \left(\sqrt{\frac{(r - r_0)^2}{4 D (t - t_0)}} \right), \quad r > r_0, t > t_0$$

(Eq. 3)

where:

- $r^2 = (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2$,
- $y_0 = a + b x_0$ (the barrier surface is a plane described by $y = ax + b$),
- (x_0, y_0, z_0) is the location of the leak,
- (x, y, z) is the location of the sampling point,
- t_0 is the time that the leak began, and
- r_0 is the constant radius of the leak after time t_0

The size and location of the leak and the time the leak began are treated as unknowns; the source concentration and diffusivity can be treated as either variables or constants; and the location of the sampling ports with respect to the barrier are assumed to be known. A range of values must be input for each variable.

In application, the system collects soil gas data and analyzes it for tracer gas concentration. A full 64-port system requires approximately 5 hours to complete a scan. Inversion of the data to characterize leak location and size typically requires less than 30 minutes for multiple leaks. The sequence repeats at predefined intervals, and analysis results can be obtained by the user either at the monitoring system or remotely through a cellular modem data link.

TESTING THE SEATRACE™ SYSTEM

Initial proof-of-concept tests of the system were conducted at an uncontaminated site at Sandia National Laboratory (Sandia). Results were very promising, with SEATRACE™ consistently able to detect and locate leaks, even under very adverse conditions (3). This program, supported by the Department of Energy (DOE) Subsurface Contaminants Focus Area, demonstrated that it was possible to monitor gaseous tracer distribution with adequate temporal and spacial resolution to detect leaks. The proof-of-concept tests also showed that a spherical diffusion model could reasonably characterize the leaks using simulated annealing to optimize the data inversion.

Because of the promising results, the DOE chose to continue support of the system through the Federal Energy Technology Center, FETC (4). SEA was tasked to capitalize on the proof-of-concept work performed for Sandia. The soil gas scanning system and data inversion methodology were integrated in a field rugged enclosure for remote operation. The data acquisition/control software and hardware were developed and tested, the inversion methodology was programmed for real-time use, and a prototype system constructed for field testing. A mockup barrier, of a scale large enough to represent a typical installation, was constructed with engineered leaks at known locations. Results showed that the system was capable of locating and sizing multiple leaks in barrier installations. Leaks as small as 1.1 cm in diameter (0.95 cm² in area) could be detected. The positional accuracy was typically within 0.5 m.

While the initial phase of the FETC work was being completed, the DOE Subsurface Contaminants Focus Area chose to use the system on several test barriers installed during the summer of 1997. Two barriers were chosen, the Viscous Liquid (Colloidal Silica) Barrier at Brookhaven National Laboratory and a jet-grouted barrier at the Dover Air Force Base, and work on the project was continued in conjunction with Sandia National Laboratories. The SEAtTM approach and hardware systems successfully detected flaws (both intentional and unintentional) in both 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, and SEAtTM was able to locate these leaks very accurately (within 0.3 m of their actual location). Results of the system were corroborated by a combination of the construction records of the barrier, independent tracer tests, or geophysical verification methods. Complete summaries of the two case studies follow.

CASE STUDY: SEATRACE™ SYSTEM EVALUATION OF THE VISCOUS LIQUID BARRIER AT BROOKHAVEN NATIONAL LABORATORY (SUMMER 1997)

The SEATRACE™ gaseous tracer verification system was used to evaluate the viscous liquid barrier that was emplaced at Brookhaven National Laboratory. A subsurface barrier of colloidal silica was constructed at the Brookhaven using permeation grouting. The original design of the barrier was a V-shaped trough roughly 18 m wide, 10 m long and 9 m deep with vertical end walls. Construction difficulties resulted in the barrier being essentially cut in half, with one of the slant side walls being replaced with a vertical wall. Fig. 2a shows plan and side views of the barrier. The barrier walls began roughly 1 m below the surface of the ground. Each wall was formed of overlapping columns (primary and secondary injections); each column was formed by stacking “bulbs” of the viscous liquid on top of each other. The area between the grout columns was filled by tertiary injections. The completed wall was approximately 3' thick.

Before the test was initiated, a temporary surface seal was added and subsurface monitoring and injection ports were installed. A surface seal is needed to prevent excessive loss of the tracer gas to the atmosphere. To be effective, the surface seal was keyed into the barrier walls. Because the walls of the VLB do not extend to the ground surface, a shallow trench (nominally 3 - 3 ½' deep and 12" wide) was dug around the perimeter of the barrier to form the key. The seal material (several layers of a thin (6 mil) polyethylene membrane) was draped into the trenches and across the barrier. The trenches were then refilled to firmly hold the membrane in place, and the membrane was covered with several inches of soil for protection.

Installation of the ports was accomplished using a truck-mounted Geoprobe unit to auger monitoring wells at set locations around the barrier, lowering sampling ports into the holes (1 to 5 ports per well, depending on the well location), and backfilling around the ports with a silica flour/sand mixture. There were a total of 18 exterior monitoring wells (54 monitoring ports) and 3 interior injection wells (1 port per well) emplaced. Five of the exterior wells were directionally drilled (45° slant from vertical) to match the slope of the slant wall of the barrier. All of the monitoring wells were placed 2-to 3-feet from the anticipated location of the barrier wall. Fig. 2a shows the monitoring well locations.

The monitoring system used was capable of automatically collecting and analyzing up to 64 samples. If tracer gas was detected in any two adjacent ports, the system performed an inversion of the data to deduce where the source of the tracer gas was located. The system was completely autonomous, using solar energy with a backup generator for power. Results from the system, as well as the raw data, were collected daily via a modem.

Prior to injecting the tracer, several sequences of background data were measured. On the evening of September 15th, a total of 5 lb, 3 oz of the tracer (sulfur hexafluoride) was injected over a period of several hours to achieve a target source concentration near 10,000 ppm inside the barrier. The system detected its first leak within 12 hours of injection. On September 18th, the source concentration was boosted to achieve an average of approximately 20,000 ppm by adding another 5 lb, 4 oz of tracer. Two scans per day were successfully completed.

Summary of the VLB Barrier Verification Demonstration

SEATRACE™ located 10 leaks in the VLB. Of these, three were the result of the barrier not extending as near to the surface as specified in the design document, and one appeared to be caused by an end-wall column not being well keyed into the slant wall. There were at least two leaks on each of the four panels, with the largest leak being on the slant wall, and the second

largest on the vertical side wall. The north end-wall panel appeared to be the best constructed. Fig. 2b shows contour plots for each panel of the barrier, along with the predicted leak locations for data taken one week into the test. Table 1 summarizes the leak locations and radii as calculated automatically by the SEAttrace™ system (using the datum shown in fig. 2a).

The system calculated leak coordinates and radii after every scanning sequence was completed. It is important to note that there are two factors that contribute to the magnitude of the standard deviation. First, there is the inherent deviation associated with trying to fit measured data with an ideal model. This deviation can be found by inverting the same data numerous times and comparing the results. For the data collected, a common deviation for the calculated coordinates is less than 0.2m. Second, it is possible for the leak to “change” with time. As defined by SEAttrace™, leaks are spherical and there can only be one leak near any given port. If, in reality, there are two leaks very close together, the code will combine them based on the measured concentration histories at nearby ports. If the leaks are of different sizes, the amount each leak contributes to the total measured concentrations will vary with time until steady state conditions are reached. Thus, the greater the number of leaks near a port, the greater the standard deviation with time. Multiple leaks near a port are difficult to detect, however, if the leaks are similar in size and data is collected frequently enough, contour plots combined with simple modeling can give some insight as to their existence. Fig. 2c shows how the contours, and thus, the leak characteristics as determined by the inversion code, can change with time as a result of multiple leaks. The SEAttrace™ system determined the leak at virtually the identical location in the second data set, although tracer concentrations were much higher.

Calculated radii of the leaks are not as accurate as calculated positions. This is an artifact of the forward model used in the inversion code. In general, the code was capable of determining relative sizes of the leaks.

Combining contour plots, simple modeling, and the information calculated by the SEAttrace™ system, the integrity of the barrier can be summarized by panel as:

- Slant side wall: There are two large leaks very close to each other (probably within a meter) on the north side and approximately midway down the panel. There is at least one smaller leak on the southern side and closer to the top of the panel.
- Southern end wall: This panel appears to have numerous breaches. There are two areas along the wall where the surface seal did not meet the top of the panel, indicating that the panel probably does not extend to within 3' of the surface. There is a clearly defined breach near the bottom of the wall, and there appears to be a breach near the panels intersection with the vertical side wall, approximately halfway down the panel.
- Vertical side wall: There are two clearly defined breaches on this panel. Both are in the top half of the panel, one closer to the north end panel and the other to the south end panel. The breach closest to the southern end panel is the larger of the two.
- Northern end wall: This panel showed the lowest measured concentrations with time. The main leak found on this panel was near the top of the wall, most likely caused by a column not extending to within 3' of the surface. The only other leak found by the inversion code is near the intersection of this panel and the vertical side wall, about halfway down the panel.

Table 1: Leak positions and radii as calculated automatically by the SEAttrace™ system. Values have been averaged over time.

Leak	Description	x (ft)	StdDev	y (ft)	StdDev	z (ft)	StdDev	r (ft)	StdDev
1	north side of slant wall	-17.78	2.33	11.32	1.15	-16.04	1.84	1.54	1.12
2	south side of slant wall	-29.36	0.22	14.96	0.31	-9.38	0.46	1.77	1.41
3	surface of south end wall	-39.86	1.25	4.99	2.49	-6.63	2.89	0.43	0.66
4	bottom of south end wall	-39.90	1.54	-1.57	0.85	-16.77	1.67	0.82	0.89
5	surface of south end wall	-41.41	1.64	-1.71	0.72	-4.72	2.32	0.27	0.31
6	corner of south end wall and vertical side panel	-40.38	2.43	-4.88	2.39	-13.18	1.59	0.69	0.73
7	south side of vertical wall	-33.78	1.11	-5.41	1.12	-13.57	0.88	1.11	0.79
8	north side of vertical wall	-19.07	0.57	-4.83	1.30	-14.64	0.01	1.11	0.34
9	corner of vertical wall and north end wall	-1.82	1.47	-4.41	3.86	-13.82	1.96	0.13	0.09
10	surface of north end wall	-2.21	1.06	3.22	1.54	-5.79	3.76	0.48	0.57

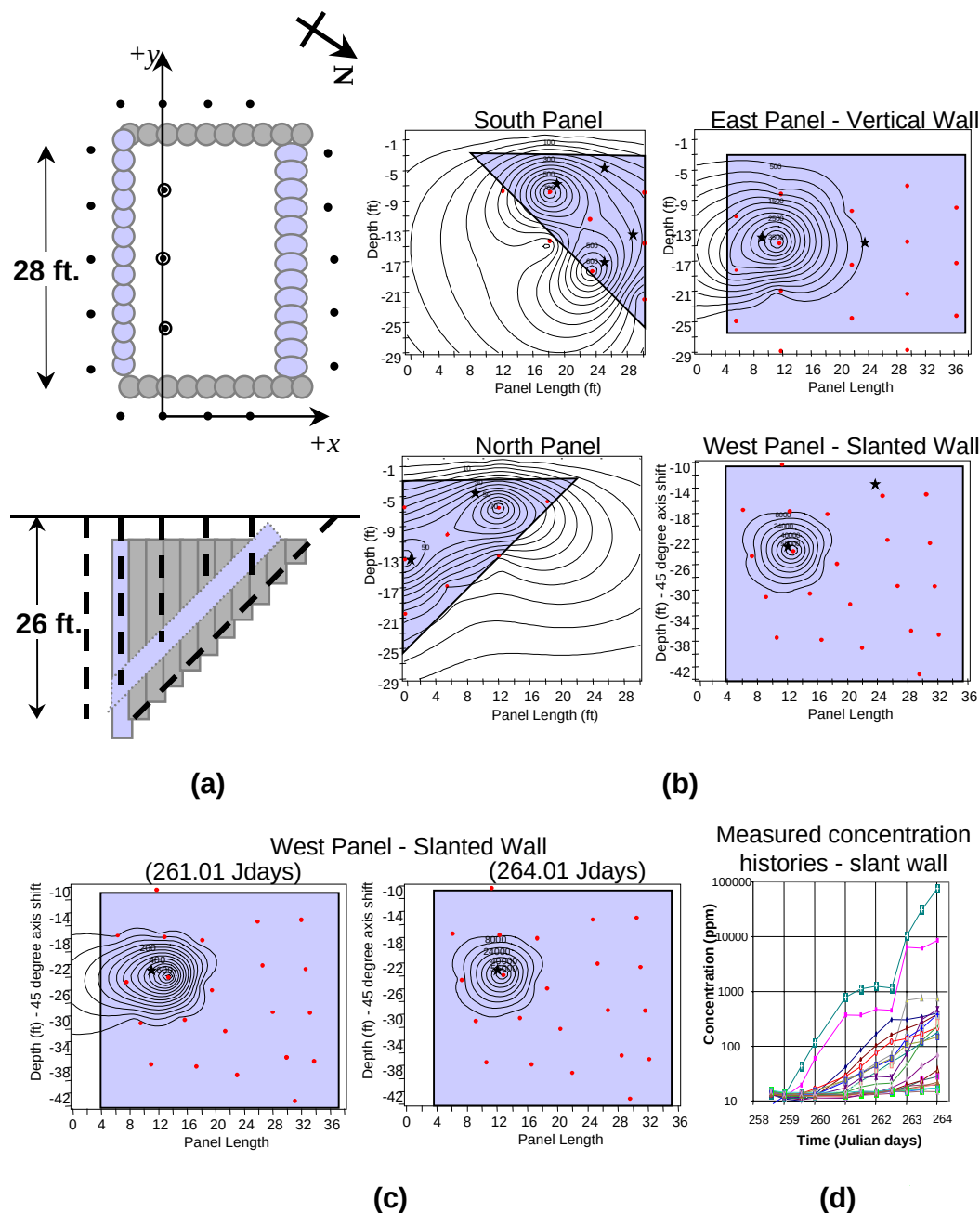


Fig. 2: Viscous Liquid Barrier at Brookhaven National Laboratory. (a) Plan and side view of the barrier, showing monitoring well locations. (b) Contour plots from data collected one week after injection (Julian day 264.01). Shaded area depicts the barrier panels. Dots show monitoring port locations, stars depict SEATRACETM calculated leak locations. (c) Contour plots of the slant wall for two different times, Julian day 261.01 and 264.01. (d) Measured concentration histories for ports near the slant wall.

CASE STUDY: TRACER VERIFICATION AND MONITORING SYSTEM EVALUATION OF THE JET-GROUTED DIAPHRAGM WALL TEST BARRIERS AT DOVER AIR FORCE BASE (SUMMER 1997)

The system was applied at the Dover Air Force Base Groundwater Remediation Field Laboratory to evaluate two diaphragm wall jet-grouted barrier test emplacement boxes. During the course of this testing program, the system evaluated the west cell of the Shallow Active test box, the south cell of the Deep Active test box (in its emplaced form and later with a hole of known size drilled into one of its panels after construction), and an emplaced leak anomaly container.

Tests were conducted by covering the barrier test cell with a temporary surface seal to prevent loss of tracer gas to the atmosphere using a polyethylene tarp. The tarp material was keyed into the barrier by hand digging down to the top of the barrier grout, then setting the tarp in place, and refilling the trench. Soil vapor monitoring points were emplaced outside of the barriers using a small diameter auger rig to form 4" diameter holes, lowering sample tubing bundles in the holes (up to three sample lines per hole), and then backfilling the boreholes with a mixture of silica flour and sand. The sample lines were routed to an automated monitoring system housed inside a shed. The monitoring system is a 32-port sampling and analysis system, which automatically collects and analyzes the soil gas with a photoacoustic analyzer. This was a first-generation monitoring system that does not automatically perform the data inversion for leak locating and sizing. Consequently, data were downloaded from the monitoring system and transmitted back to the SEA office by e-mail for inversion.

To initiate a test, the monitoring system gathered ambient background soil gas data for one or two days, then sulfur hexafluoride tracer gas was injected into the barrier volume slowly over several hours. Soil gas samples were collected every 12 hours, until sufficient sample sets were obtained to identify leaks. The data were first plotted with contour plotting software, then inverted using the inversion software to estimate discrete leak location in space as well as the size of the leak. This system characterizes a leak as a circular opening in an otherwise impermeable barrier wall, even though the flaw may be noncircular in form.

The test results indicated that the inversion code's ability to locate flaws in the barrier is good, locating the two engineered flaws within 1 to 2 ft. from their actual location in space. The code predicted the size of the flaws within a factor of 2 to 3 for these two known leaks.

The summary results of the inversion operation on the test panels are presented below, followed by detailed descriptions.

- The SEAtaceTM operation located three discrete flaws in the west test cell (cell SA-C1) of the Shallow Active box: 1) a long, distributed flaw running along the bottom of the north panel where the panel intersects the water table, 2) a discrete leak located on the west panel in its lower central area (at 5.9 ft. depth), and 3) a flaw on the south panel at the 7.6 ft. depth, on the joint between the south and west panels.
- The leak anomaly was constructed using a buried box with a 3" diameter gate valve located at the 5.5 ft. depth. The inversion code located this leak within 0.9 ft., and indicated a leak diameter of 6".
- The Deep Active box tests indicated 3 leaks in the initial tests of the south test cell (cell DA-C1): 1) one located at 11.9 ft. depth where the west panel joins the panel to the north, 2) a shallow leak at 7.3 ft. depth, located on the seam of the south panel and west

panel (0.1 in. dia.), and 3) another joint flaw (0.1 in. dia.) at 11.0 ft. depth just south of the panel's northern most vapor monitoring port.

- After the initial Deep Active box testing was completed, a 12" diameter auger was run in at a shallow angle to form a leak on the south panel. Also, tracer gas concentrations were increased inside the cell after the intentional flaw was formed. Inversion of resulting data centered the new flaw at the 11.6 ft. depth, indicating a 4.5 in. diameter hole on the right center of the south panel (which was the anticipated target of the auger operation).

Shallow Active Box

The Shallow Active box test configuration is shown in plan view in fig. 3a. Due to limitations of the number of the sampling ports available with the monitoring system, only the west cell (SA-C1) of the box was selected for testing. Initial tracer injection occurred the evening of July 3, to a target concentration of 15,000 ppm sulfur hexafluoride in the soil gas inside the test cell. On the following day (July 4), the tracer concentration was boosted to a higher level, expected to be about 100,000 ppm. Sampling system data showed that extremely high concentrations of SF₆ were present at the sampling points near the surface, indicating that the primary tarp cover formed a leaky seal with the top of the barrier wall. The resulting accumulation of tracer near the surface prevented/masked delineation of leaks further down the barrier wall, and the tarp secondary extension outward from the barrier wall was retaining the tracer at the high concentrations outside the wall and below the tarp extension. Consequently, the tarp extensions were removed on Saturday, July 5, to allow the high, near-surface tracer concentrations to vent to the atmosphere. This alleviated the problem and on July 20 the final data set was obtained. Contours of this data are plotted by panel in fig. 3b, with the monitoring points indicated by solid black circles and the inferred leak locations by stars. While the code predicts a discrete flaw, it may in reality be a crack, open seam, or very thin section of the barrier. Three discrete flaws were identified:

1. A long, distributed flaw runs along the bottom of the north panel where the panel intersects the water table at a depth of 8 to 10 ft. The location of this leak is determined by the contour plots and the assumption that the tracer gas could not transmit through the water at such a rate to produce these results, hence, the leak must be above the water table. The inversion code, because it assumes a circular leak shape, could not resolve this leak realistically and estimated that the leak may extend well below the water table.
2. A discrete leak is located on the west panel, located 5.9 feet deep, just north of the central vapor monitoring port outside the panel.
3. A flaw on the south panel is located at the 7.6 ft. depth, on the joint between the south and west panels.

Because the concentrations measured by the photoacoustic analyzer exceeded its calibration range, the inversion code was not able to reasonably estimate the sizes of the leaks (always indicating unrealistically high leak diameters for this barrier). The analyzer is calibrated for a maximum concentration of 5000 ppm, and its response above that range is nonlinear likely indicating artificially high concentrations above 5000 ppm. However, repeated monitoring system scans were consistent and sufficient to estimate locations of leaks. For subsequent tests the source tracer gas concentrations were maintained at much lower values to prevent exceeding the range of the analyzer.

Engineered Leak

A large sealed plastic cooler with a 3" gate valve was buried in the soil near the shallow passive box with the valve located at the 5.5 ft. depth. The area was instrumented with three vapor sampling wells (see fig. 3c). The cooler was filled with tracer gas to a desired concentration and the gate valve opened. The monitoring system was reconfigured to sample these ports, and the test run from July 21 to July 23. The resulting contour plot is also shown in fig. 3d, with the leak location as determined by the inversion code overlaid on the plot. The code determined the leak to be 6" in diameter, and located within 10.8 inches of its surveyed position.

Deep Active Box

The monitoring system was reconfigured to sample the vapor points around the south test cell (DA-C1) of the Deep Active box as shown in fig. 4a. This box was also covered with a temporary surface seal in a similar fashion as the Shallow Active box, but without the tarp extension along land surface. Initial tracer injection started July 23. By July 29 sufficient data were obtained to produce inversion results, and the contours are shown in fig. 4c (also with the discrete leaks overlain). Leaks were located at three positions:

1. On the west panel, at the 11.9 ft. depth, along the joint with the adjacent panel to the north. The equivalent diameter of this leak was estimated to be 1.5 inches.
2. On the south panel at the 7.3 ft. depth, along the joint between the south and west panels.
3. At the 11.0 ft. depth on the east panel, 1.0 ft. south of northernmost vapor monitoring port on the east panel, estimated 0.1" diameter (see fig. 4a for monitoring port locations).

On August 1, a 12-in. diameter auger was moved to the site for the purpose of forming a known leak in the south panel of the Deep Active box. The tracer gas concentration inside the cell was boosted prior to drilling the leak. Monitoring continued for several days, and on August 17 sufficient data were collected to determine the leak location with the inversion code. The contour plot and estimated leak location is depicted on fig. 4b. The inversion code estimated the leak to be 4.5 in. in diameter, centered at the 11.6 ft. depth and about 0.5 ft. east of the center monitoring well on the south panel.

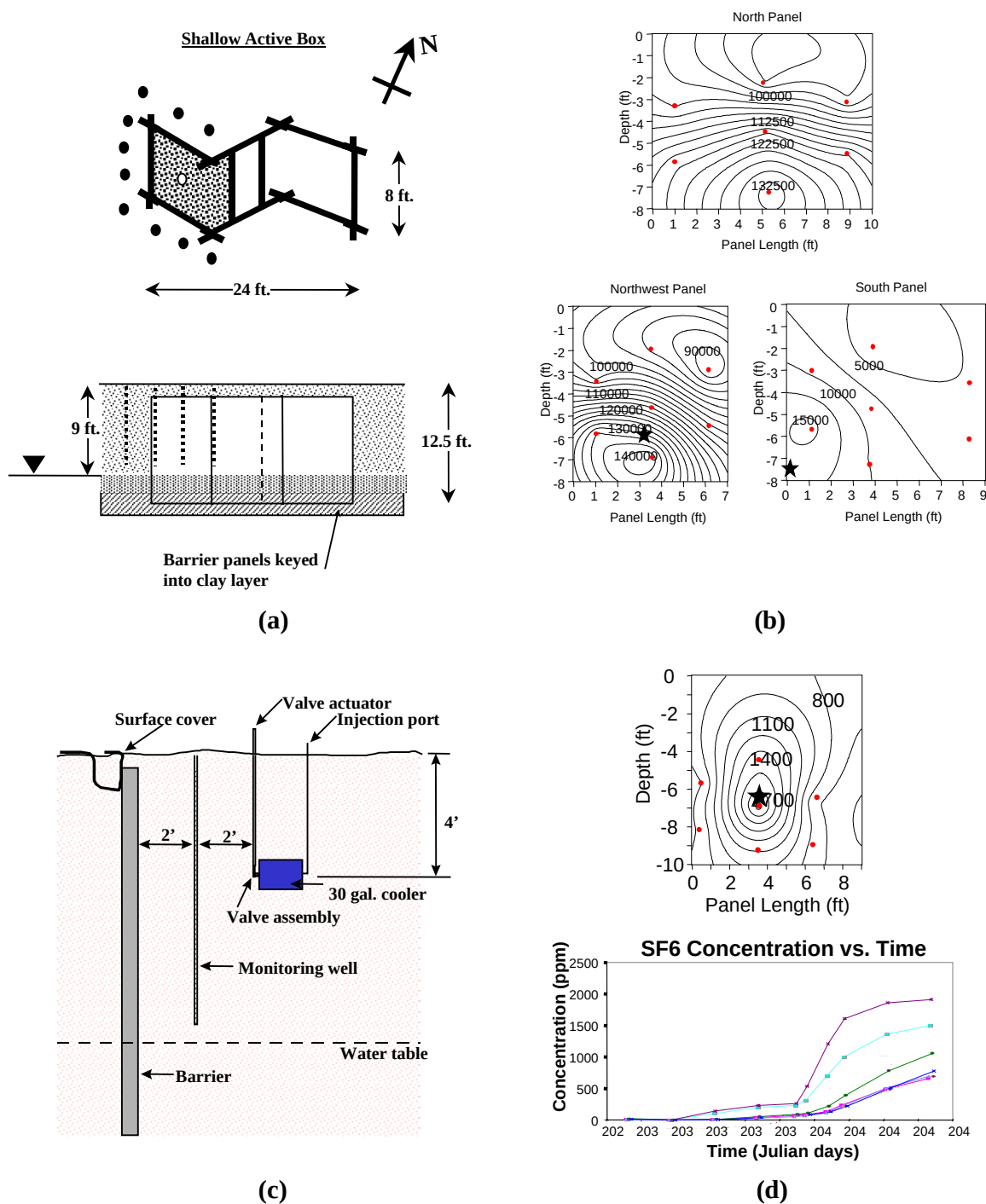


Fig. 3. Jet-grouted barrier at the Dover Air Force base. (a) Plan and side view of the shallow active box showing the site geology and monitoring well placement. (b) Contour plots of resulting data. Dots depict monitoring ports, stars show SEAttrace™ calculated location of the breaches. (c) Side view of the engineered leak tested at the site. (d) Contour plot of the resulting data from the engineered leak, along with the measured tracer gas concentration histories for ports near the engineered leak.

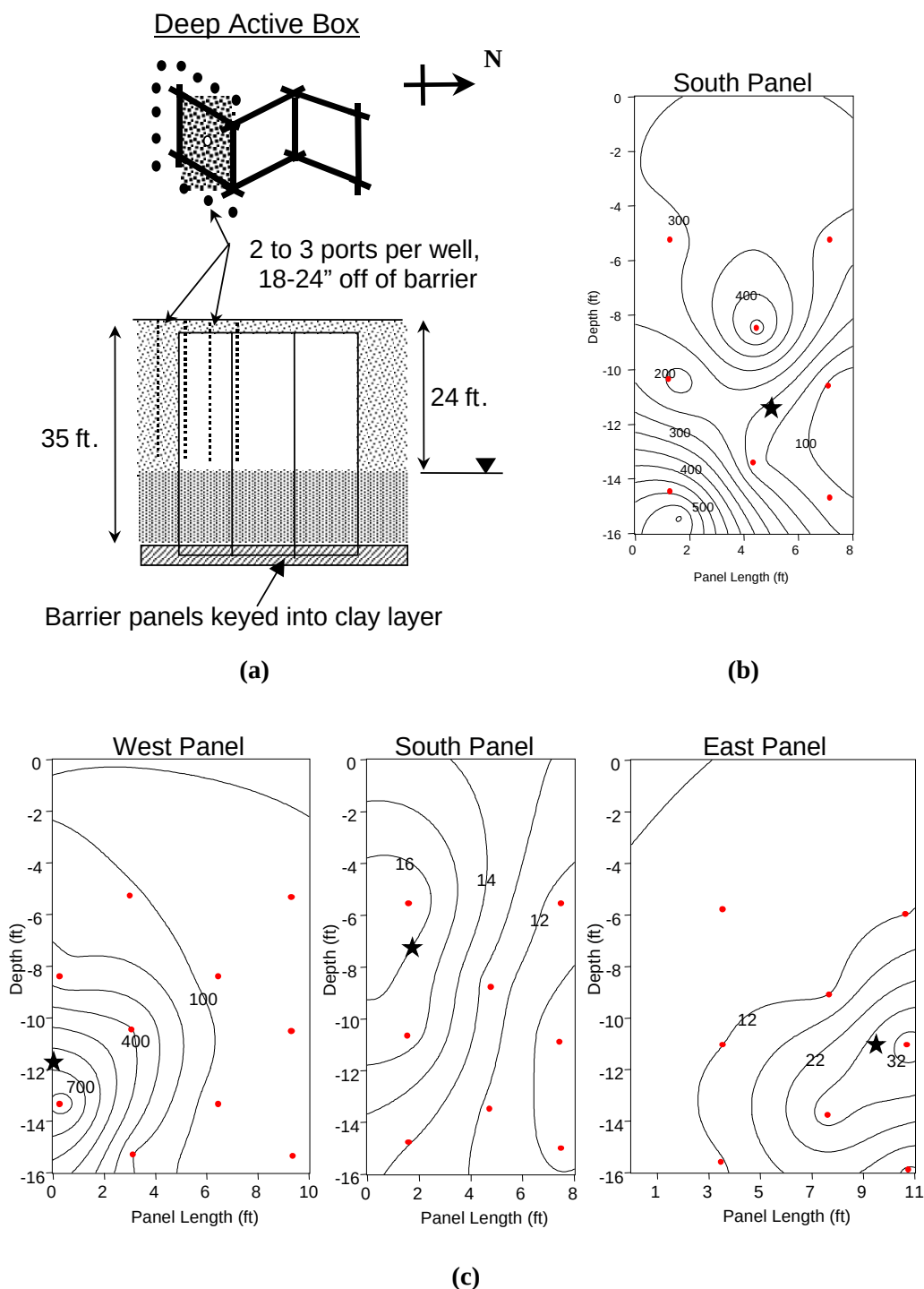


Fig. 4. Jet-grouted barrier at the Dover Air Force base. (a) Plan and side view of the deep active box showing the site geology and monitoring well placement. (b) Results of the SEAttrace™ test after a hole was augered through the south panel. Dots depict monitoring ports, stars show calculated location of the breach. (c) Results of the verification operation prior to augering a known leak on the south panel.

Corroborative Results

The test results of the flaws in the Shallow Active box test cell corroborate with the initial results of the hydraulic, saturated tracer, and electrical resistance tomography field tests. Each of these techniques showed detectable flaws in the area of the north panel of the SA-C1 test cell, and the barrier construction records indicate an operational event which may have caused an incomplete joining of sections (this was the first barrier to be injected in this program). Hydraulic tests in the Deep Active box test cell DA-C3 showed extensive flaws in the barrier, which would be consistent with the flaws detected in DA-C1 with the tracer system. It is noteworthy that, even though the SEAttrace™ system is constrained to measurements above the water table, it can detect features such as flawed vertical joints which may extend below the water table.

REGULATORY ISSUES

Barriers, in the most common form of slurry walls, historically have been applied to control groundwater movement. The classic validation technique used for these applications is to draw down the water level inside of the volume contained by the wall and observe its recovery, or draw it down to a constant level and measure the pump rate. Consequently, it is possible to calculate a bulk hydraulic conductivity of the barrier with relatively straightforward measurements. Containment applications in the unsaturated zone, however, are relatively new and pose different constraints upon validation techniques. New validation techniques are being developed and tested because drawdown measurements cannot be safely applied to contaminated sites above the water table. The SEAttrace™ technology, for example, has been developed to indicate the location and size of breaches in a barrier wall, based on diffusive transport processes. These are not directly correlable to advective flow properties, which is the case with saturated hydraulic conductivity measurements.

The current regulatory climate is driven by the historical practice of either laboratory testing on backfill samples or drawdown measurements for barrier sections below the water table. Performance specifications will typically be dictated as equivalent hydraulic conductivity (even though in the unsaturated zone). These criteria are not readily applicable to unsaturated zone barriers. None of the validation techniques under development (gaseous tracers, electromagnetic, electrical resistance tomography, neutron logging, ground penetrating radar, etc.) directly provide data that quantitatively relates to saturated hydraulic conductivity.

As in other characterization and monitoring technologies, regulations will probably develop as the measurement technologies mature. Also, as barrier emplacements become common for unsaturated zone applications, relevant specifications need to evolve that can be verified by the new characterization technologies.

CONCLUSIONS

The SEAttrace™ system was developed specifically for subsurface barrier validation in the unsaturated zone. It is capable of locating and estimating the relative size of breaches in the barrier, based on the vapor diffusion process. It uses gaseous tracer injection, in-field real time monitoring, and real time data analysis to characterize barrier flaws. The initial system proof-of-concept testing, conducted at Sandia National Laboratories, showed that a data inversion methodology could back-calculate reasonably well to determine leakage characteristics. Subsequent engineering development of a fully automated SEAttrace™ unit and tests in a test

barrier with known flaws demonstrated the viability of the field system. Two demonstrations at actual test barriers, one on a viscous liquid barrier and the other on jet-grouted barriers, evaluated the system under actual barrier field conditions. For each of these test barrier installations, the system identified leaks with a degree of resolution unattainable by other validation technologies under evaluation.

Limitations in the SEAttrace™ technology relate to its basic premise, ie, that it can only test for flaws as evidenced by vapor phase diffusion. The system cannot operate below the water table. Highly variable water saturation will impact the diffusive properties of the soil. Furthermore, soil heterogeneities will impact the accuracy of the measurement. However, the results from the field demonstrations indicate that the system can resolve flaws, even with these real world conditions, to an accuracy sufficient for barrier repair in a timely fashion.

The SEAttrace™ barrier monitoring system is an enabling technology that provides quantitative barrier verification for installations above the water table where no capability currently exists:

- The approach is conservative in that it measures vapor leaks in a containment system where the greatest risks are posed by liquid leaks.
- SEAttrace™ provides a degree of resolution in both leak size and location that is unattainable with geophysical techniques. Field demonstrations on known leaks showed that the system could resolve leak size within 0.15-meter diameter, and leak locations within 0.5-meters.
- Leak assessments are completed within 30 minutes of sample analysis.
- It is applicable to any impermeable barrier emplacement technology in the unsaturated zone.
- The approach uses readily available non-hazardous gaseous tracers.
- Direct-push vapor point emplacement techniques avoid excessive drilling costs and secondary waste generation.
- In addition to assessing initial barrier integrity, the system can also provide long-term monitoring of contaminant soil gases for surveillance of the containment system's performance over time.

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