CONF-9510108--33

DOE/MC/32109-96/C0613

Barometric Pumping with a Twist: VOC Containment and Remediation Without Boreholes

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Contract Number:

DE-AR21-95MC32109

Conference Title:

Environmental Technology Development Through Industry Partnership

Conference Location:

Morgantown, West Virginia

Conference Dates:

October 3-5, 1995

Conference Sponsor:

U.S. Department of Energy, Office of Environmental Management, Morgantown Energy Technology Center

PII.11 Barometric Pumping with a Twist: VOC Containment and Remediation Without Boreholes

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1. Abstract

A large national cost is incurred in remediating near-surface contamination such as surface spills, leaking buried pipelines, and underground storage tank sites. Many of these sites can be contained and remediated using enhanced natural venting, capitalizing on barometric pumping.

Barometric pumping is the cyclic movement experienced by soil gas due to oscillations in atmospheric pressure. Daily variations of 5 millibars are typical, while changes of 25 to 50 millibars can occur due to major weather front passage. The fluctuations can cause bulk vertical movement in soil gas ranging from centimeters to meters, depending on the amplitude of the pressure oscillation, soil gas permeability, and depth to an impermeable boundary such as the water table. Since the bulk gas movement is cyclic, under natural conditions no net advective vertical movement occurs over time.

Science and Engineering Associates, Inc., is developing an engineered system to capitalize on the oscillatory flow for soil contaminant remediation and containment. By design, the system allows normal upward movement of soil gas but restricts the downward movement during barometric highs. The earth's surface is modified with a sealant and vent valve such that the soil gas flow is literally "ratcheted" to cause a net upward flow over time. A key feature of the design is that it does not require boreholes, resulting in a very low cost remediation effort and reduced personnel exposure risk.

In the current phase (Phase I) the system's performance is being evaluated. Static and transient analysis results are presented which illustrate the relative magnitude of this advective movement compared to downward contaminant diffusion rates. Calculations also indicate the depth of influence for various surface and soil configurations. The system design will be presented, as well as a cost assessment compared to conventional techniques.

2. Environmental Restoration Technology Need

The majority of the planned remediation sites within the DOE complex are contaminated with volatile organic compounds (VOCs). In many instances the contamination has not

Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under Contract DE-AR21-95MC32109 with Science and Engineering Associates, Inc., 1570 Pacheco St., Suite D-1, Santa Fe, NM 87505; telefax: 505-983-5868.

reached the water table, does not pose an immediate threat, and is not considered a high priority problem. These sites will ultimately require remediation of some type, either by active vapor extraction, bioremediation, or excavation and ex-situ soil treatment. The cost of remediating these sites can range from $50 K to well more than $150 K, depending on site characteristics, contaminants, and remediation method. Additionally, for many remediated sites, residual contamination exists which could not practically be removed by the applied remediation technology. This contamination must be immobilized, contained, or controlled.

These circumstances result in modest sites with contamination of limited risk, but by regulation they must still be controlled. A remediation solution being developed by Science and Engineering Associates, Inc. (SEA) for the Department of Energy serves as an in-situ containment and extraction methodology for sites where most or all of the contamination resides in the vadose zone soil. The approach capitalizes on the advective soil gas movement resulting from barometric pressure oscillations.

3. Approach

Oscillations in barometric pressure are both diurnal, corresponding to daily heating and cooling of the atmosphere, and of longer time periods, resulting from the passage of weather fronts. Daily variations will average about 5 millibars (one millibar is roughly one thousandth of an atmosphere) while those due to weather front passage can be 25 or more millibars. As the barometric pressure rises, a gradient is imposed on the soil gas which drives fresh surface air into the soil. As it drops, gas vents upward from the soil into the atmosphere. The pressure changes and resulting gradient are depicted in Figure 1, which shows data records in Albuquerque, NM. The total movement of soil gas is dependent primarily on the magnitude of the pressure oscillations, the soil gas permeability, and the depth to an impermeable boundary. This boundary can be the water table, bedrock, or extensive layers of very low permeability , such as caliche or clay. Since the fractional change in atmospheric pressure is small (typically 0.5 percent) the overall soil gas displacement during the daily cycle is also small. Furthermore, the daily oscillations in atmospheric pressure always return to a mean value. Over time, no net soil gas displacement occurs due to advective forces alone.

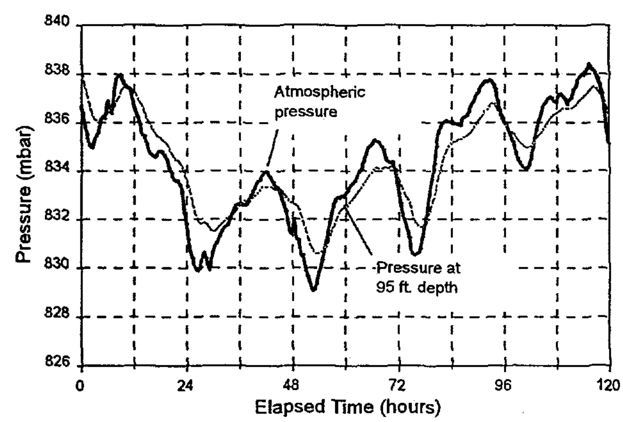


Figure 1. Barometric pressure, and soil gas pressure response at 95 ft. depth, recorded in Albuquerque, NM.

Displacement of soil gas can be controlled using surface features which impede the downward movement of vapors, but allow upward movement. The design incorporates a surface seal, a plenum, and an extraction vent valve. These components are depicted in Figure 2.

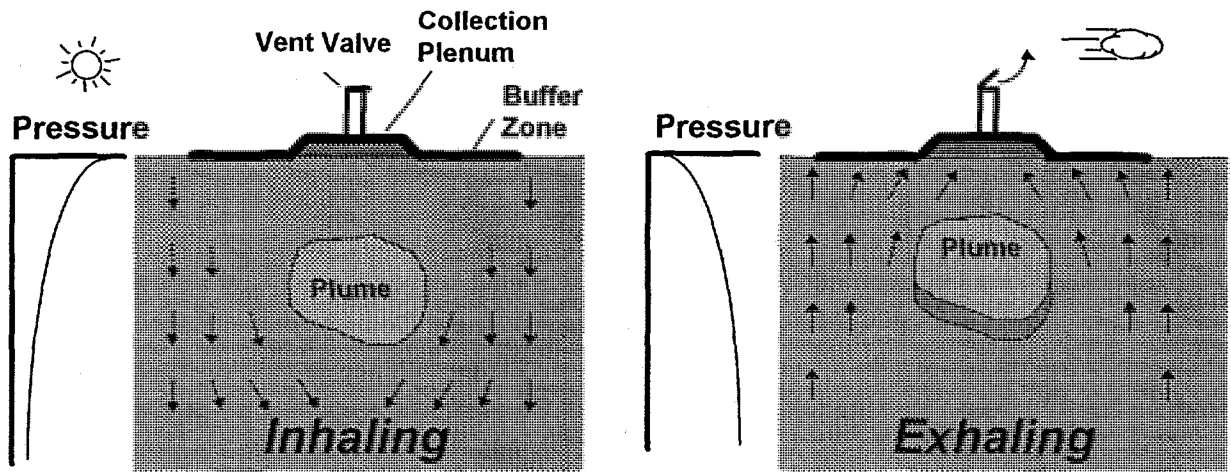


Figure 2. The surface treatment system controls the movement of soil gas due to barometric pressure changes

Directly above the contaminant plume is a layer of highly permeable material, such as pea gravel, which forms a collection plenum for the upward-moving soil gas. A surface seal is placed over and radially outward from the collection plenum directly on the soil surface to form a buffer zone, which controls the radial movement of air flowing into the soil during the high pressure periods. The surface seal is an impermeable, rugged material (such as a geotechnical membrane) which forms a no-flow boundary at the ground surface. The plenum is connected to atmospheric pressure with a high volume vent valve, open only when soil gas is moving upward (during a barometric low pressure cycle).

In operation the system ratchets the upward soil gas air flow by allowing normal upward flow during barometric lows but restricting downward air flow during high pressure cycles. High pressure periods result in restricted downward gas movement because the vent valve is closed and soil gas tends to flow around the plume ("inhaling"). When the atmospheric pressure is lower than the soil gas pressure at depth, soil gas flows upward and the surface seal forces the contaminated gas into the plenum, where the opened vent valve exhausts it to the atmosphere ("exhaling").

4. Project Description

The objective of this project is to evaluate, design, and demonstrate a system which relies upon barometric pressure oscillations to remediate soils contaminated with volatile compounds in the unsaturated zone.

The major challenge associated with the development of this system is to demonstrate that the pressure-driven soil gas flow can be controlled such that its net upward vertical velocity (over time) is sufficient to overcome the downward diffusion of contaminants from the liquid source. If this feature can be demonstrated then the system can reliably protect the water table from diffusively transported contaminants.

Phase I of the project consists of four tasks.

In Task 1 SEA will assemble the information required for the DOE to prepare the appropriate level of NEPA documentation for the project. This will assume a demonstration test planned at a specific site in Phase II.

In Task 2, SEA will predict the flow of soil gas due to barometric processes. This will include the geometric configuration of the surface seal design, with plenum and buffer zone dimensions. The modeling will evaluate the sensitivity of the extraction rate to plenum areal extent, and buffer zone size, particularly in relation to the depth and size of the plume. The analysis will also compare the advective gas flow rate caused by barometric pumping to the estimated diffusion rate of typical contaminants. Thermal effects of the soil surface will be considered.

For Task 3, using the results of parametric evaluations of the previous task, we will develop general design guidelines for the implementation of the barometric pumping system. The guidelines will define the relationship between plenum size, buffer zone configuration, plume depth and geometry, and geologic setting (depth to impermeable zone). Monitoring requirements and general monitoring system design will also be developed. The cost of a prototypical installation will be estimated.

The results of the analysis and design efforts will be summarized in the topical report prepared in Task 4.

5. Accomplishments

Results to date have shown that the system can capitalize upon naturally occurring vertical air flow to sweep contaminated soil gas upward. Static analyses have been conducted to demonstrate that non-trivial displacements can occur. Transient simulations show the integrated effects of local setting and installation geometry.

In a homogeneous medium the movement of soil gas caused by fluctuations in the surface barometric pressure is analogous to the displacement of a piston in a cylinder (Figure 3). As the barometric pressure (P_1) rises, the piston is displaced downward a distance Δx until the barometric pressure (P_1) equilibrates with the soil gas pressure below (P_2). In the absence of diffusion or density-related forces a molecule of soil gas will undergo the same displacement as the piston. In soil, the displacement is:

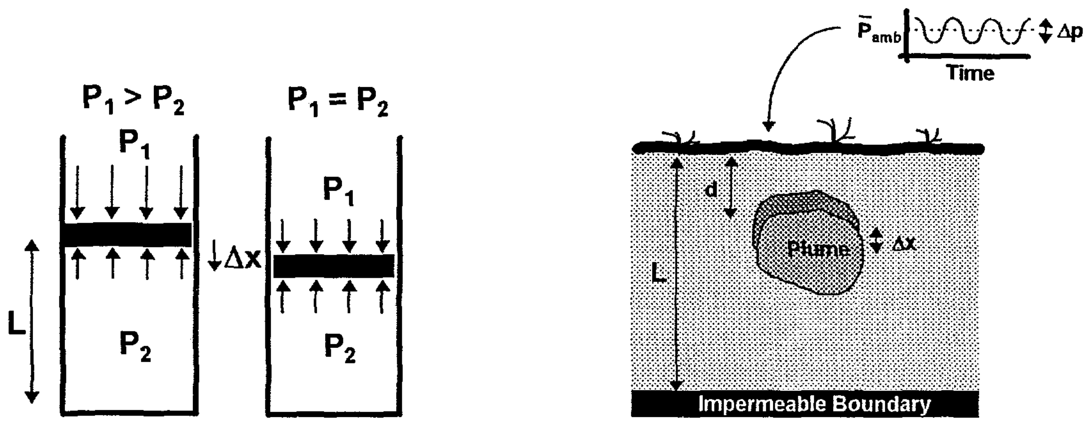
$$\Delta x = \frac{\Delta p}{P_{amb}}(L - d) \qquad \text{(Eq. 1)}$$

where ΔP is the amplitude of the cyclic variation in barometric pressure, P_{amb} is the average barometric pressure, d is the depth of the gas in the soil, and L is the depth below surface to the impermeable layer. This is a steady state relation, appropriate if the soil gas response is relatively rapid (i.e., L is not too large and the soil permeability is not too small). The measurements in alluvial deposits (Figure 1) showed the response at depth to be almost immediate.

Using Equation 1 it is possible to predict the gross movement near the surface. For example, given a 5 mbar pressure change and depth to the water table of 100 m., soil gas at 5 m will displace:

$$\Delta x = \frac{5\text{mbar}}{1000\text{mbar}} \bullet (100\text{m} - 5\text{m}) = 0.475\text{m}$$

For the same setting a 50 mbar change will result in 4.75 m total displacement. Since the barometric pressure always returns to its original value, this displacement is oscillatory



(a) (b)

Figure 3. Piston/cylinder analogy of soil gas movement due to barometric pressure changes (a), and the parameters affecting steady state soil gas displacement due to barometric pressure oscillations (b).

and results in no net vertical movement, except very near the surface where release directly to the atmosphere occurs on each upward cycle. Consequently, to incur bulk upward flow at depth the natural forces need to be harnessed through the use of engineered features to "ratchet" the flow upward.

The transient multidimensional process is being modeled with the Los Alamos National Laboratory FEHM (Finite Element Heat and Mass transfer) code. The oscillatory surface pressure, the surface treatment (plenum and buffer zone), and the one way valve can be modeled to determine the extent of impact of the surface features. This allows parametric variations of the plenum and surface seal geometry, soil gas permeability, and depth to the water table. A typical case includes these conditions:

- Soil gas permeability = 5 Darcies
- Soil gas porosity = 35%
- Plenum radius = 5 m
- Buffer zone extends additional 5 m radially outward from plenum
- Barometric pressure varies a total of 5 mbar with a 24 hour period.
- Depth to the impermeable zone = 100 m

The average vertical soil gas velocity which occurs along the vertical centerline (i.e., directly below the center of the plenum) over 24 hours is shown in Figure 4. Note that for the plotted depth it is always positive (upward). With no surface treatment the average velocity would everywhere be zero. While the numbers appear small, at the soil's surface the velocity results in almost 1 m of vertical displacement in a day.

This will happen every day, as long as the surface treatment is in place.

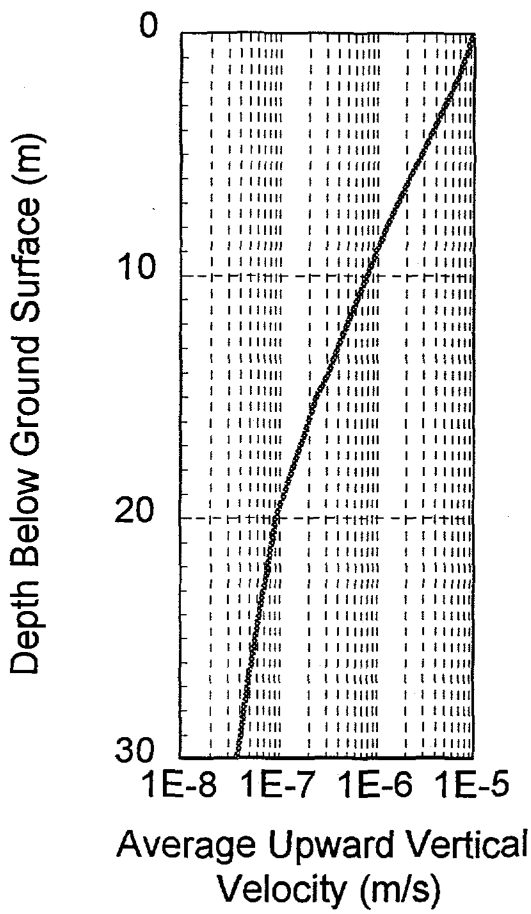


Figure 4. Average upward soil gas velocity over
a 24 hour period, for the case cited in the text.

6. Applications and Benefits

The proposed system is applicable to near surface VOC contamination in the vadose zone. In general, this will be an attractive approach if one or several of the following conditions are met:

- The plume is not posing a significant, immediate threat to water contamination.

- The site has already been actively remediated (by vapor extraction, for example) but residual contamination exists. Incorporating this system can assure no residual contamination reaches the water table.

- Usage of the site is not imminent. If the site became a desirable location for a parking lot, for example, the parking lot could perform the role of the surface seal.

- Typical applications may include underground storage tanks, leaking buried pipelines, surface spills, or shallow landfills.

The system serves as an in-situ containment and extraction methodology for contaminated sites where most or all of the contamination resides in the vadose zone soil. The approach capitalizes on the advective soil gas movement resulting from barometric pressure oscillations to result in a system which harnesses this mechanism to assure a net vertical upward soil gas flux in the contaminated soil. Its main benefits include:

- The design prevents soil vapor flow down to the water table by assuring a net upward movement of soil gas.

- No boreholes are required for the remediation/containment process.

- The vented air, since this is a slow process, is of sufficiently low volatile concentration that under most state regulations can be released to the air where it is naturally degraded by the sun's ultraviolet radiation.

- Fresh surface air is brought into the contaminated zone to replenish the air released at the surface, enhancing natural diffusion and biodegredation.
- The design allows simultaneous use of the area for other purposes.
- The system requires no site power.
- The design is very low cost (probably less than $30 K per installation) since it does not require boreholes or an active off-gas treatment system.

Remediation of VOC-contaminated soils is presently accomplished by excavation of soil and ex-situ treatment or disposal, soil vapor extraction (SVE), enhancement of microbial degradation with bioventing, and SVE processes enhanced with electrical heating. All of these processes require boreholes or soil excavation, resulting in waste generation and high construction costs (ranging from $50 K to well more than $150 K for typical sites).

7. Future Activities

The Phase I predictive analysis will be completed in September 1995. An initial field demonstration is planned to start in November (the tentative start date of Phase II if Phase I is successful). The first effort in Phase II is to select an appropriate demonstration site. The initial test will probably be conducted using a surrogate, inert tracer (such as sulfur hexafluoride) which can be injected into the soil under controlled conditions. The field test will last 12 months. Subsequent tests on contaminated sites will be conducted depending on the success of the initial demonstration.

8. Acknowledgments

The authors wish to acknowledge the support of the METC COR, Mr. Carl Roosmagi, and DOE/METC in general for supporting innovative technology development. The Los Alamos National Laboratory EES-5 Division is also acknowledged for their support of the FEHM simulations.

This contract's period of performance is from March through mid-November 1995 for Phase I. If funded, Phase II will run for 18 months as a demonstration test.