



Bioventing Principles, Applications and Potential

Diane Hellekson

Introduction

In-situ or on-site bioremediation is among the most attractive options for reducing or eliminating contaminants in soil and water. With benefits that include minimal site disturbance and lower cost compared to other remediation technologies, in-situ bioremediation continues to be researched and applied with the goal of helping 'close out' specific sites, that is, reducing toxins to safe and/or legally acceptable levels (U.S. EPA 1995a; Page, 1997; Gibbs et al., 1999).

Among the most promising of these technologies is soil bioventing, the process of supplying oxygen to contaminated soil in hopes of stimulating microbial degradation of contaminants. A typical bioventing setup is appealingly simple: a blower or compressor connected to one or more air-supply wells and a series of soil-gas monitoring wells (Sellers, 1999). The technology of choice for remediating many petroleum wastes, bioventing may eventually be used to treat a wider variety of more recalcitrant toxins (McCauley, 1999a).

Bioventing has noteworthy remediation relatives, with distinct principles, goals and applications. *Air sparging* forces compressed air into saturated soil in hopes of promoting biodegradation. Unlike sparging, bioventing uses low-pressure air and is generally focused on the vadose, or unsaturated, zone of soil. *Bioslurping* combines bioventing and direct vacuum extraction of contaminants. *Soil vapor extraction* or soil vacuum extraction (SVE) maximizes volatilization of contaminants and sucks them out of the soil.

The idea of supplying oxygen to underground contaminants has been explored for several decades, but early research focused on using water as the oxygen carrier (for example, injecting hydrogen peroxide into soil). However, water is less effective than gases in penetrating soil and thus increasing oxygen available to the microorganisms that break down contaminants.

Bioventing began to mature as a technology after 1988, when researchers on a SVE operation at Hill Air Force Base, Utah, concluded that a significant proportion of contaminant decrease was not due to volatilization, but biodegradation (U.S. EPA, 1995a; Litchfield, 1993). Subsequent research, at the Hill site and elsewhere, explored remediation that would *reduce* volatilization and *maximize* biodegradation. One of the main attractions of this approach is that minimizing volatilization eliminates the need for treating off-gases, a significant part of SVE costs (Leahy, 1995). At Hill, switching to bioventing saved approximately \$13,000 per month by allowing removal of rented catalytic incinerators and thus eliminated propane costs (U.S. EPA, 1995a).

Among the more 'gentle' of remediation technologies, bioventing can be viewed as a stepped-up version of natural attenuation, which happens without intervention when native microbes degrade wastes over time. The advantage of bioventing is that it speeds the process, since oxygen is most often the factor that limits the efficiency of microbial degradation. However, for some

toxins in some geologic conditions (for example, when a hazardous contaminant is threatening ground water) it may not be fast enough, or may not work at all (Leahy 1995; U.S. EPA 1995a).

Common Applications

Hydrocarbons, organic compounds containing only carbon and hydrogen, are the main constituents in petroleum. Due to the prevalence of crude and refined oils being transported (and spilled) around the globe, hydrocarbons have become a significant substrate (life-support base) for microbial oxidation (Rosenberg, 1996). Ironically, perhaps, one reason why biodegradation of petroleum works so well is the prevalence of microbes that these spills have helped engender (Van Eyk, 1997). Bioventing, with its goal of maximizing biodegradation, has become an excellent option for treating petrochemical contamination.

When a petroleum product is spilled, it volatilizes and disperses into the atmosphere and/or sink into the ground, depending on its volatility and site conditions. In order for microbes to have sufficient time to degrade the hydrocarbon, bioventing works best with petroleum hydrocarbons of relatively low volatility. Put another way, the contaminant's rate of volatilization should not exceed its rate of biodegradation. Low volatility also reduces the probability that air injection will push toxic vapors into surrounding property or structures.

Bioventing is used to reduce a wide range of petrochemical compounds, including gasoline, fuel oil and bitumen. The constituents of these compounds are measured together as total petroleum hydrocarbons (TPH). Of even more interest, bioventing has been shown to dramatically reduce a subset of those compounds known as BTEX (benzene, toluene, ethylbenzene and xylenes), often to below-detection levels within one year. This is good news, for among petroleum hydrocarbons, BTEX compounds are among the most soluble, mobile and toxic (benzene is considered a human carcinogen) (U.S. EPA 1995a). A laboratory test comparing bioventing and SVE found bioventing superior in reducing toluene and decane, another petroleum hydrocarbon (Malina, 1998).

Site Assessment, Design, and Monitoring

Assessing Feasibility

While bioventing has been proven effective at numerous sites, including military bases with jet fuel spills and an abandoned asphalt plant, it is not universally appropriate. Aspects that influence bioventing feasibility include site geology, soil moisture and microbial activity, and the nature of the contamination. These factors are assessed via three primary physical parameters: 1. Soil gas permeability. A function of (1) soil structure, (2) particle size (clay versus sand) and (3) moisture content, this factor relates to oxygen's ability to move freely through the soil and thus be available to hungry bacteria. One might be tempted to assume a positive correlation between tight, fine-textured soils (e.g., clays) and poor potential for bioventing. But according to results of a large-scale testing by the United States Environmental Protection Agency, excessive soil moisture proved a more limiting factor than soil texture (U.S. EPA 1995a; Sellers, 1999). The aggregation of the three soil gas permeability factors is measured in Darcy units; ratings higher than 0.1 darcy are generally sufficient for bioventing (U.S. EPA, 1995a). Bioventing may

be possible in soils with lower ratings, if fractures or higher-permeability strata (e.g., sand lenses in a clay soil) are present to allow alternate pathways for gas flow.

2. Contaminant distribution. Contaminants have highly individual behaviors underground, depending on both site geology and contaminant chemistry. Because bioventing is focused on the vadose, or unsaturated zone, it works best for contaminants that spread downward but then laterally once they reach the capillary fringe, the area immediately above the water table. A large group of immiscible contaminants that behave this way are less dense nonaqueous phase liquids (LNAPLs), which include most petroleum hydrocarbons (U.S. EPA, 1995a).

Due to shifting water tables, however, even LNAPLs can accumulate in the capillary fringe or move below the water table. In these cases, dewatering or using a combination of air-sparging and bioventing may be appropriate.

The best way to thoroughly assess both the vertical and lateral extent of contamination is a series of soil tests, based on a review of existing site data (such as the amount and date of a spill) and previous soil-gas studies (U.S. EPA, 1995b). Very high contaminant concentrations can be toxic to microorganisms and thus may preclude bioventing.

3. Oxygen radius of influence. This complex parameter is defined as the radius to which oxygen must be supplied in order to sustain maximal biodegradation (U.S. EPA, 1995b). Essentially an estimate of how well a single venting well will function, it is dependent on soil properties, well design (proposed) and, especially, microbial populations. (U.S. EPA, 1995a).

Biodegradation Rates

Bioventing's key players, aerobic microorganisms (primarily bacteria and fungi), depend on several factors to function effectively. These include sufficient moisture, soil pH (between 5 and 9, ideally just above 7), adequate nutrient supply and appropriate temperature. Temperatures are organism- and site-specific, but in general, degradation doubles for every 10 degrees C. of temperature increase (U.S. EPA, 1995b).

Typically, an in-situ respiration test is conducted to assess the intrinsic biodegradation rates at a given site. This test consists of placing three to four soil gas monitoring points into contaminated areas, first measuring concentrations of carbon dioxide and oxygen in soil gas. Then the points are used to vent the soils with air containing an inert 'tracer' gas (typically helium) for about 24 hours, with measurements taken at frequent intervals. The air provides oxygen to the soil, where it is either used by microbial populations, or leaks out of the test area. The relative measurements of carbon dioxide, oxygen and helium help indicate whether oxygen utilization rates are caused by microbial utilization or diffusion, thus indicating ambient biodegradation rates and whether a system is operating efficiently or losing oxygen to uncontaminated soils. If bioventing proceeds on the site, in-situ respiration tests may be used later to yield a progress report.

Design

Bioventing can employ either of two methods of supplying air to the soil: injection or extraction. Injection systems (Figure 1) are generally simpler and less expensive to install and operate because they require no treatment of off-gases (contaminants that may be pulled to the surface with an extraction system). Injection systems are favored at sites with low-permeability soils and with contaminants of low vapor pressure, located relatively deep in the soil. Injection is safest when contamination is distant from structures or property boundaries, since injected air tends to push contaminant vapors outward from their initial location, even in less permeable, clay soils. When injection points are located away from structures, the outward air pressure is beneficial: it increases biodegradation efficiency, as it puts contaminants in contact with a larger area of soil and, consequently, more microbes (U.S. EPA, 1995b; Sellers, 1999).

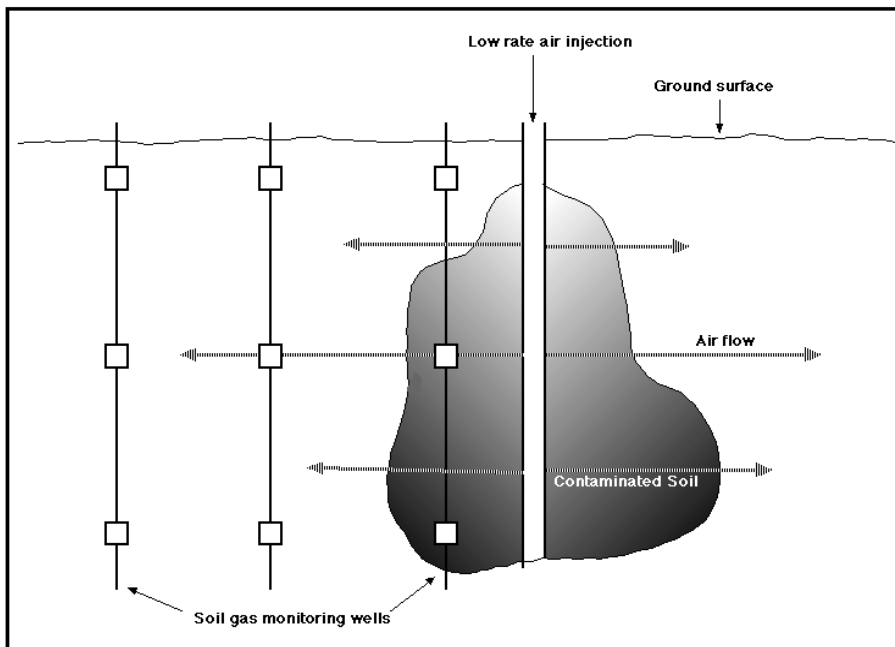


Figure 1. Schematic air-injection bioventing system (adapted from U.S. EPA bioventing design manual)

A beneficial side-effect of air injection is its potential to temporarily push down the water table, allowing for treatment of soil in the capillary fringe. Extraction, on the other hand, can cause the water table to rise slightly, decreasing the volume of contaminated soil that can be effectively treated (Sellers, 1999). Extraction systems (Figure 2) are generally chosen only for safety reasons, when there is no way to avoid pushing hazardous vapors into buildings or property boundaries near the contaminant area (U.S. EPA, 1995b).

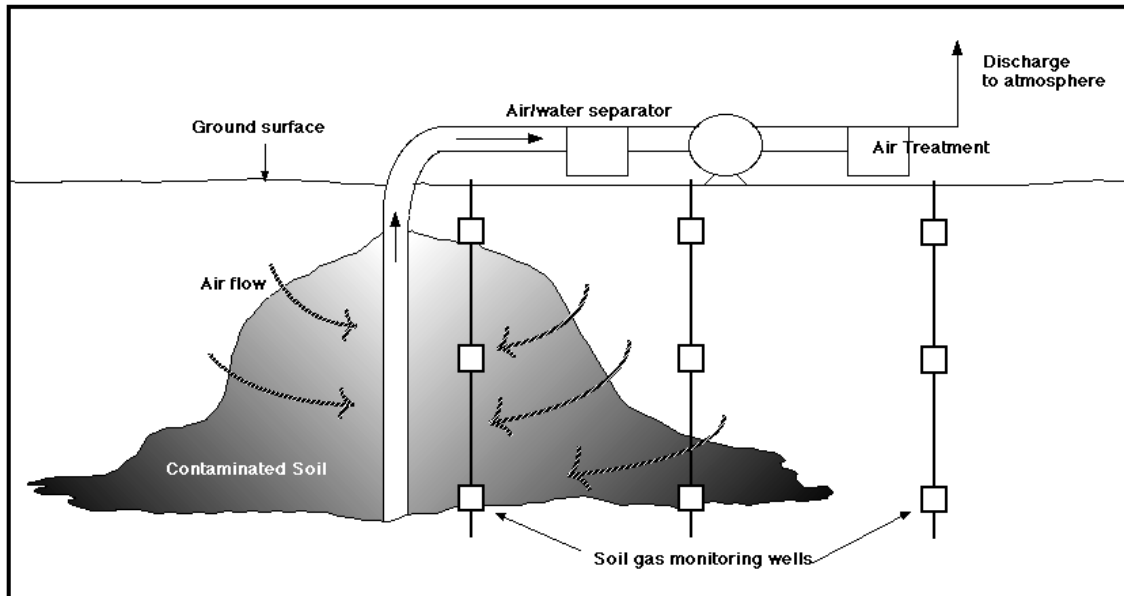


Figure 2. Schematic air-extraction bioventing system (adapted from U.S. EPA bioventing design manual)

With either air-supply system, optimal bioventing design means spacing wells and adjusting air flow to maximize microbial activity without promoting emissions to the atmosphere or using unnecessary resources. For example, at a 15-square-meter test plot on the former Reilly Tar plant, St. Louis Park, Minnesota, researchers found that even a one-horsepower blower was excessive; it aerated not only the test plot but the control site 150 feet away (McCauley, 1999a),

Monitoring.

Periodic monitoring is an integral part of bioventing, allowing supervisors to assess system performance, refine the aerobic environment (usually by adjusting air flow), determine when to conclude an operation, and evaluate final results. Keeping close tabs on degradation progress may result in reduced costs (due to reduced power needs) and data that may assist design of future cleanups.

In addition to the one or more venting wells, several monitoring wells are installed, at distances determined by the radius of influence explained above. Typically, levels of soil gas (hydrocarbon vapors, oxygen and carbon dioxide, the latter two indicating respiration) are measured weekly until the site become fully aerated. These same levels are measured semiannually for the first year, in the warmest and coldest months and, finally, once a year for the duration of treatment.

The levels are compared to atmospheric air and uncontaminated background soils to help measure the progress of biodegradation.

In-situ respiration tests, described earlier, may also be used to check progress. This test is also the primary indicator for site closure, which, for petroleum products, usually occurs after three to ten years (Leahy, 1995). When the respiration rate is similar to that of the uncontaminated soils, the site is likely remediated, and final soil samples can be taken to determine remaining contaminant concentrations, if any. Because of its expense, soil testing not used in process monitoring, except in some controlled research situations (U.S. EPA, 1995a; McCauley, 1999a).

Emerging Application

Polycyclic aromatic hydrocarbons (PAHs or PCAs), another particularly toxic fraction of petroleum, represent an important frontier in bioventing. Sixteen PAH compounds are identified as priority pollutants by the U.S. EPA, including known carcinogens benz(a)anthracene (C₁₈H₁₂) and benzo(a)pyrene (C₂₀H₁₂). While PAHs occur in nature, as part of the carbon cycle and as a byproduct of forest fires (thus accounting for the natural occurrence of bacteria that feed on the compounds), contamination of soils and water are a result of human-generated industrial wastes: creosote, coal tar, petroleum and industrial effluents and gases (Mueller et al., 1996). The building block of PAHs is the benzene ring (C₆H₆), which, particularly when clustered in groups of four or more, appears to be more slow to degrade than other equal-weight hydrocarbons (Van Eyk, 1997). High-molecular weight PAHs, sometimes defined as those with five or six rings, are Övery difficult to treat effectively by bioremediationÓ (Sellers, 1999).

However, recent research at Reilly Tar has indicated that even high-ring PAHs (including pyrene, fluoranthene and benzo(a)anthracene) are amenable to degradation via bioventing. According to preliminary results of a pilot study, which treated a 15.2 square meter area, 2-ring PAHs were reduced by 62 percent; 3-ring by 50 percent; 4-ring by 31 percent; 5-ring by 20 percent; and 6-ring PAHs by 24 percent.

Further, the test confirmed earlier research regarding soil conditions suitable for degrading high-molecular-weight hydrocarbons: high carbon dioxide levels (>1 percent); low oxygen levels (< 5 percent); PAH contaminations high enough to support increased growth of native microorganisms; unsaturated, unconsolidated soil; and sufficient nitrogen and phosphorus to support new cell growth and development (Alleman et al., 1995; McCauley, 1999b).

Another group of contaminants beginning to be addressed by bioventing is chlorinated compounds, including 1,2-dichloroethane, and trichloroethylene (TCE), among others. A study conducted at a chemical disposal pit at Hill AFB showed promising results for several nonpetroleum hydrocarbons, particularly 1,2-, 1,3- and 1,4-dichlorobenzene (DCB), which "should be added to the list of candidate compounds for bioventing applications" (Gibbs et al., 1999).

The study also demonstrated a significant reduction in chlorinated solvents (1,2-dichloroethylene, 1,1,1-trichloroethane, TCE and tetrachloroethylene), but this appeared to be due to volatilization rather than biodegradation. It must be noted that most chlorinated solvents are dense nonaqueous phase liquids (DNAPLs), which tend to migrate more quickly to the capillary zone and below the water table (U.S. EPA, 1995a). This characteristic, of course, will complicate if not rule out bioventing.

Gibbs notes that the contamination at the Hill chemical pit occurred from the 1950s until 1973, and suggests that newer PAH spills might not be as amenable to biodegradation. The ability of bacteria to biodegrade DCB, for instance, is not a natural occurrence, so indigenous bacteria must reside in the presence of the contaminant for some time in order to exchange genetic material and "learn" to decompose the new compound.

Other research has indicated that very deep soils also may lack sufficient microbial populations (Frishmuth, 1995). This, along with Gibbs' observations, underscores the importance of considering the specifics of the site, including geology and the nature of the contamination, before bioventing is assumed to be the answer.

Conclusion

Clearly, there is a future for bioventing. The relative simplicity and low cost of the technology, along with public interest in more 'natural' methods of remediation will surely encourage continuing experimentation (Page, 1997). In addition to expanding the list of contaminants it can handle, bioventing research indicates numerous examples of both wider and more specialized applications:

¥ Cold-climate bioventing. Tests at Eilson AFB in Alaska suggest that, while expensive, soil warming during bioventing may be cost effective in cold-climate situations where bioremediation speed is critical (U.S. EPA, 1995a).

¥ Ex-situ bioventing. Sludge covered Oils lakes in Kuwait had to be excavated due to the high levels of raw petroleum there. But reclamation efforts were significantly aided by bioventing the resulting soil piles. The technique was more effective and less costly than either windrow composting piles or landfarming (Balba, 1998).

¥ Anaerobic bioventing. Research has suggested that anaerobic conditions may assist in degrading recalcitrant contaminants such as PAH and chlorinated solvents, opening possibilities of venting substrates other than oxygen for microbial growth (Litchfield, 1993; Gibbs, 1999; McCauley, 1999a).

¥ Cometabolic bioventing. In certain cases, one contaminant may actually assist in degradation process of another. Chlorinated compounds often degrade anaerobically, but some (such as PCE and TCE) can be degraded aerobically in the presence of cometabolites, including aromatic compounds such as toluene (Sellers, 1999; Gibbs, 1999).

¥ Combination systems. Due to the complexity of many contaminated sites and the specific strengths of various remediation technologies, bioventing may continue to find favor in combination with other technologies, such as air sparging and soil vapor extraction. Combining nutrient addition with bioventing is a little-explored option, though early research indicated that in sites amenable to bioventing, nutrients are rarely a limiting factor (U.S. EPA, 1995a; Leahy, 1995; Moller, 1996).

If enthusiasm for bioventing continues to build, however, caution will be essential, particularly in working with PAHs and chlorinated solvents. The breakdown of either one of these chemicals may result in other, perhaps even more hazardous toxins. Furthermore, microbial activity during degradation could spur mobilization of other potentially harmful materials, such as manganese or arsenic (U.E. EPA, 1999; Rosenberg, 1996).

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