

BIOVENTING

History

When SVE was implemented, progress of remediation was monitored by measuring the concentrations of contaminants in the extracted gas (Ca) and the depletion of contaminant mass in the subsurface. There should have been a mass balance:

contaminant mass removed in SVE gas = contaminant mass depleted in soil

However, it was found that the contaminant mass in the soil was decreasing faster than was accounted for by the mass extracted. This was most common at gasoline spill sites undergoing SVE remediation.

Where was the mass of contaminant going?

The answer: Bacterial degradation!

Natural bacteria present in the soil were degrading the contaminants. The activity of the bacteria pre-SVE was limited by oxygen availability. Usually, oxygen got into the soil pore space simply by diffusion from the above-ground atmosphere. This is slow, and in contaminated areas bacteria quickly removed all of this oxygen as they biodegraded the contaminants (in the background soil, the carbon is usually at low concentrations and is poorly degradable; therefore, oxygen in uncontaminated vadose zone soil is usually ok at 5-18%). After SVE was started, air containing oxygen from uncontaminated regions or the atmosphere was pulled into the contaminated zone, and now the bacteria had oxygen to respire so they could grow by eating the available food source (the contaminant).

Thus, the idea for “Bioventing” was born....

Aerobic Biodegradation of Contaminants

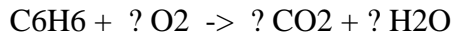
For bioventing to work, natural bacteria in the soil must have the capability to degrade the contaminants in the presence of oxygen. Luckily, aerobic bacteria (those that “breathe” oxygen for survival) able to degrade fuel spill compounds (BTEX, alkanes, etc.) are common in almost ALL soils.

Bacteria are made primarily of COHNSP elements, plus trace amounts of many other elements such as Fe, Mn, Mg, Ca, etc. To survive, aerobic bacteria must have oxygen. To grow and reproduce, aerobic bacteria must additionally have a source of carbon (the food). The generalized reaction representing this bacterial activity is:

Bacteria + Organic compound + O₂ --> CO₂ + H₂O + more bacteria

For organic contaminants, this has the potential to transform them from a harmful state into benign carbon dioxide, water, and more bacteria (don't worry, these bacteria are not the kind that cause illness in people!).

How much oxygen is needed to degrade contaminants? You can get an idea by writing the stoichiometry of the “mineralization” reaction (ignore the new bacteria growth). Ane sample for benzene is:



Just balance the # of C from benzene with CO₂.... therefore, 6 CO₂ formed

then balance the H from benzene with H₂O.... therefore, 3 H₂O formed

Lastly, determine how much O₂ is required to supply the O in CO₂ and H₂O

...therefore, (6*2) + (3*1) = 15 O needed...7.5 O₂ molecules

With this balanced stoichiometry, we have the approximate number of moles of oxygen needed per mole of benzene we want to biodegrade. This can be converted to a mass of oxygen per mass of benzene (benz) using molecular weights:

$$1 \text{ g benz} * (1 \text{ mol benz}/78 \text{ g benz}) * (7.5 \text{ mol O}_2/\text{mol benz}) * (32 \text{ g O}_2/\text{mol O}_2) = 3.1 \text{ g O}_2$$

Therefore, 3.1 g oxygen will be consumed for every g of benzene biodegraded.

Of course, other factors will influence the survival of the bacteria and the RATE at which they degrade the contaminants. Temperature, moisture, nutrients (mostly N,P), pH, absence of toxic conditions (such as high metals or contaminant concentrations) all influence bacterial survival.

Bioventing Basics

The general concept of bioventing is to supply oxygen to bacteria in contaminated vadose zone soil so that they can degrade the contaminants. This is generally accomplished by INJECTING AIR (20-21% oxygen) into the contaminated soil using vertical or horizontal wells (just like those used for SVE).

If this method is going to enhance the clean-up of the contaminated site, 2 conditions must be met:

1) the contaminant MUST be biodegradable by aerobic bacteria in the soil

if not, adding oxygen will have no effect

2) oxygen must currently be limited in the contaminated area

if plenty of oxygen is already there, adding more won't help

The primary advantages of bioventing compared to SVE:

1) under proper operation and site conditions, no off-gas treatment is needed
(this saves money!)

2) some contaminants that are not very volatile and cannot be efficiently removed by SVE are aerobically biodegradable and can potentially be removed by biodegradation

When air is injected into the subsurface, spreading the contamination into clean soil by moving the soil pore gas or forcing this contaminated soil gas to above the ground are concerns. Therefore, bioventing is not recommended if the contaminant is highly volatile.

Rule of thumb: Vapor pressure >1 atm then use SVE not bioventing
(unless the solubility is greater than 10 μ Molar, then can go up to 10 atm)

Intermediate volatility compounds can be remediated efficiently by bioventing (assuming biodegradability) OR SVE; vapor pressure between 1 and 0.001 atm. At less than~ 0.001 atm, the compounds are not volatile enough to be efficiently removed by SVE... but if they are aerobically biodegradable, bioventing can be used.

Note: some compounds are degraded faster by bacteria which function in the absence of oxygen. An example are fully chlorinated compounds....these CANNOT be degraded by aerobic bacteria (at least no one has discovered these bacteria YET...) but can be degraded by bacteria that function without oxygen (oxygen is actually toxic to these bacteria). So, in some cases it is better to let natural bacteria work under oxygen-depleted conditions... it is just typically a very slow process.

To help minimize “spreading” of the contaminants and exposing people by forcing the contaminants above-ground into the atmosphere, the top of the well should be screened no closer than 3 to 5 ft below the ground.

Design of Bioventing

1. Characterize the site to determine what kinds of contaminants present using records or existing data.

The contaminants present will allow you to determine if they have appropriate volatility and aerobic biodegradability. If ok, then proceed.

2. Soil gas survey.

Goal: to determine the distribution of contaminants and oxygen in the vadose zone soil, both areally and with depth.

Grid the site with monitoring “points”. Start in the middle of the contaminated area, and work out until uncontaminated soils are reached, allowing you to “bound” the contaminated region. Measure “Total Volatile Petroleum Hydrocarbons” (TVPH) using a field instrument. Also measure oxygen and carbon dioxide.

If oxygen levels at the contaminated locations are > 5% in the soil vapor, then oxygen is not limiting biodegradation. Therefore, bioventing is not recommended.

Generally, there will be higher oxygen concentrations in the soil vapor near the ground surface, and depletion with depth. Carbon dioxide should be elevated in areas with high bioactivity, but cannot be used as a quantitative indicator due to the effects of soil type (buffering and carbon dioxide involvement in carbonate cycle).

Oxygen and carbon dioxide should also be measured in uncontaminated “background” soil, and are generally >18% oxygen and <0.5% CO₂.

3. In Situ Respiration Test

Measure the oxygen uptake rate during a field “pilot” bioventing test, which will indicate contaminant biodegradation rate.

Procedure:

- a) select or drill a vadose zone well in the contaminated region
- b) inject AIR plus 1-3% unreactive tracer gas into the subsurface for about 24 hours
(goal: replace existing soil vapor with the “new” injected gas that is ~20% oxygen)
generally the tracer gas used is Helium
- c) stop injection of gas
- d) monitor the change in oxygen, carbon dioxide, and tracer gas in the soil vapor over time; can measure at monitoring well near injection point OR the injection point itself
 - measure about once per hour
 - should observe a linear decline in oxygen (plus increase in CO₂, hopefully stable level of tracer)
 - continue monitoring for 24 hours or until <5% oxygen in soil gas
- e) calculate the oxygen uptake rate (OUR); the linearized % oxygen depletion / time
$$\text{OUR} = \% \text{ O}_2 \text{ removed} / \text{d}$$
- f) IF the concentration of oxygen in the background soil was <18%
need to determine how much oxygen uptake observed in the contaminated region is attributable to biodegradation of natural soil organics. Therefore, repeat the above oxygen uptake rate procedure in uncontaminated soil. Calculate the “OUR-bkg” = % O₂/d

Then, correct the OUR calculated in part e for bkg
$$\text{OUR-contam} = \text{OUR}(e) - \text{OUR-bkg}$$

OR if background oxygen is >18%, assume OUR-bkg is negligible

RULE OF THUMB: If OUR-contam is >0.1%/d then bioventing is recommended

If OUR-contam <0.1%, look for factors limiting bioactivity such as moisture content or nutrient availability (these could be modified in addition with air injection for in-situ biodegradation of contaminants)

g) From the OUR-contam, estimate contaminant biodegradation rates

calculate stoichiometry of contaminant mineralization (as discussed in the “Aerobic Biodegradation of Contaminants” section above)

convert OUR into a mass O₂ consumed per mass of soil
$$\text{OUR}/100 = \text{mol O}_2/\text{mol air-d}$$

$\text{mol O}_2/\text{mol air-d} * \text{mol air}/22.4 \text{ L} * \text{MWO}_2 * n\text{-air} * p_b = \text{mass O}_2/\text{kg soil-d}$
 where MW O₂ = molecular weight of oxygen
 n-air = air-filled porosity of soil
 p_b = bulk density of soil, kg/L

$\text{g O}_2/\text{kg soil-d} * \text{g contam}/\text{g O}_2 = \text{g contam}/\text{kg soil-d}$

4. Conduct an InSitu Air Permeability Test

same test procedure as for SVE (can inject air instead of extract if preferred)
 want $k_a > 1 \text{ E-9 cm}^2$

estimate the radius of influence of the well....

But the PRESSURE radius of influence calculated from the SVE equations
 will be different from the distance at which enhanced oxygen levels are
 achieved....

For bioventing:

$$R_i = \frac{Q_a (21\% - 5\%)^{0.5}}{b \text{ OUR } n\text{-air}}$$

b = vadose zone thickness

If pressure $R_i <$ bioventing R_i (from above), use limiting case of SVE R_i for
 well spacing

RULES OF THUMB FOR BIOVENTING DESIGN:

Q_a-BV is approx. 0.1 Q_a-SVE

0.1 to 1 air exchanges of pore volume / d is generally sufficient