APPENDIX O

Calculation for SVE ROI Based On Oxygen Utilisation

United States
Environmental Protection
Agency

Office of Research and
Development
Washington, DC 20460

EPA/625/XXX/00
September 1995

EPA

Manual

Bioventing Principles and Practice

Volume II: Bioventing Design

EPA/540/R-95/534a
September 1995

US EPA
Extract from ^ Standard Manual

Manual

Principles and Practices of Bioventing
Volume II: Bioventing Design

U.S. Air Force Environics
Directorate of the
Armstrong Laboratory
Tyndall AFB, FL

U.S. Air Force Center for
Environmental Excellence
Technology Transfer Division
Brooks AFB, TX

U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Center for Environmental Research Information
Cincinnati, Ohio

have shown that rates can vary by as much as an order of magnitude between peak periods. For design of oxygen delivery systems, respiration rates should be measure during the peak season, typically during late summer.

If oxygen utilization rates were determined during periods of low activity, it is necessary to adjust the rates to the maximum level before making size calculations. The van't Hoff-Arrhenius equation can be used to predict oxygen utilization rates given an initial rate and temperature.[8] The activation energy, E_a, must be known for the site. Alternatively, E_a found from another site can be used, recognizing the temperature-adjusted rate is only a rough estimate. The following example illustrates a typical adjustment.

Example 1-9. Temperature Adjustment of Oxygen Utilization Rate: The oxygen utilization rate was measured in January at a site in Cheyenne, Wyoming. The rate was determined to be 0.75 percent/day (0.031 percent/hour). The temperature in the soil was measured at 4°C. Previous temperature measurements at the site have indicated that soil temperatures in August average approximately 24°C (i.e., 20°C higher than the temperature measured during January). The temperature adjustment to the rate for sizing calculations is as follows:

Using the van't Hoff-Arrhenius equation (Metcalf & Eddy, 1979):

$$\frac{dk}{dT} = \frac{E_a}{RT^2}$$

Integration of this equation between the limits T_1 (277°K) and T_2 (297°K) gives:

$$\ln \frac{k_T}{k_o} = \frac{E_a (T_2 - T_1)}{RT_1T_2}$$

where:

k_T = temperature-corrected oxygen utilization rate (% O2/day)

k_o = baseline reaction rate = 0.75%/day

E_a = activation energy[9] = 13.4 kcal/mole

R = gas constant = 1.987 cal/°K-mole

T_1 = absolute temperature for k_o = 277°K

T_2 = absolute temperature for k_T = 297°K

$$k_T = \left(0.75 \; \frac{\%}{day}\right) e^{\left[\frac{(13,400 \text{ cal/mole})(297°K - 277°K)}{\left(1.987 \frac{cal}{°K-mole}\right)(297°K)(277°K)}\right]}$$

$$k_T = 3.9 \; \frac{\%}{day}$$

As seen in this calculation, the site would require approximately five times greater oxygen delivery rate in the summer.

1.5 Soil Gas Permeability and Radius of Influence

In situ respiration rates may be used to calculate the required air flow rate to satisfy oxygen demand at a given site;[10] however, determining the distance air can physically be moved also is necessary. An estimate of the soil's permeability to fluid flow (k) and the radius of influence (R_I) of venting wells are both important elements of a full-scale bioventing design. Onsite testing provides the most accurate estimate of soil gas permeability. Onsite testing also can be used to determine the radius of influence that can be achieved for a given well configuration and flow rate. These data are used to design full-scale systems, specifically to space venting wells, to size blower equipment, and to ensure that the entire site receives a supply of oxygen-rich air to sustain in situ biodegradation.

Soil gas permeability, or intrinsic permeability, can be defined as a soil's capacity for fluid flow and varies according to grain size, soil uniformity, porosity, and moisture content. The value of k is a physical property of the soil; k does not change with different extraction/injection rates or different pressure levels.

Soil gas permeability is generally expressed in the units cm^2 or darcy (1 darcy = 1 x 10^{-8} cm^2). Like hydraulic conductivity, soil gas permeability may vary by more than an order of magnitude on the same site because of soil variability. Table 1-12 illustrates the range of typical k values to be expected with different uniform soil types. Actual soils contain a mixture of grain sizes, which generally increases the observed darcy values based on pilot testing.

Table 1-12. Soil Gas Permeability Values (JOB

Soil Type	k in Darcy
Coarse sand	100 to 1,000
Medium sand	1 to 100
Fine sand	0.1 to 1.0
Silts/clay	<0.1

---

[8] See Volume I for a discussion of the effect of temperature on microbial activity.

[9] Calculated from a different field site. See Example 3-2 in Volume I for a description of the calculation of the activation energy.

[10] See Section 2.2 for a presentation of the calculation of required air flow rates.

Several field methods have been developed for determining soil gas permeability (EPA, 1991b). The most favored field test method probably is the modified field drawdown method developed by Paul Johnson at Arizona State University and former associates at the Shell Development Company. This method involves the injection or extraction of air at a constant rate from a single venting well while measuring the pressure/vacuum changes over time at several monitoring points in the soil away from the venting well.[11]

The field drawdown method is based on Darcy's law and equations for steady-state radial flow to or from a vent well. A full mathematical development of this method and supporting calculations are provided by Johnson et al. (1990). Johnson developed the HyperVentilate computer program to store field data and to compute soil gas permeability. This or other commercially available programs can be used to speed the calculation and data presentation process.

Two solution methods may be used for soil gas permeability as described in Johnson et al. (1990). The first solution is based on carefully measuring the dynamic response of the soil to a constant injection or extraction rate. The second solution for soil gas permeability is based on steady-state conditions and the measurement or estimation of the radius of influence at steady state. Whenever possible, field data should be collected to support both solution methods because one or both of the solution methods may be appropriate, depending on site-specific conditions. An example procedure for conducting a soil gas permeability test is provided in Appendix C.

1.5.1 *Radius of Influence Determination Based on Pressure Measurements*

At a bioventing site, the radius of influence is defined in two ways, as the oxygen radius of influence or the pressure radius of influence. The oxygen radius of influence is defined as the maximum distance from the air extraction or injection well where a sufficient supply of oxygen for microbial respiration can be delivered. The pressure radius of influence is the maximum distance from the air extraction or injection well where vacuum or pressure (soil gas movement) occurs. Under heterogeneous conditions, the pressure radius of influence is theoretically infinite; for practical purposes, however, it usually is considered to be the maximum extent to which pressure changes can be measured.

The oxygen and pressure radius of influence is a function of soil properties but also is dependent on the configuration of the venting well and extraction or injection flow rates and is altered by soil stratification. The oxygen radius of influence also is dependent on microbial oxygen utilization rates. On sites with shallow contamination, the oxygen and pressure radius of influence also may be increased by impermeable surface barriers such as asphalt or concrete. These paved surfaces may or may not act as vapor barriers. Without a tight seal to the native soil surface,[12] the pavement will not significantly affect soil gas flow.

At a bioventing site, the oxygen radius of influence is the true radius of influence for system design. A connection exists between the pressure radius of influence and the oxygen radius of influence; however, many variables exist that are not fully understood. Empirically, during a soil gas permeability test, an increase in oxygen concentration has been found at contaminated sites wherever pressure changes are measured. Also, the pressure radius of influence has been found to be a conservative measure of the oxygen radius of influence. The oxygen radius of influence may be directly determined by measuring the distance from the vent well at which a change in oxygen concentration can be detected. Several days or weeks may pass, however, before equilibrium is reached and an accurate oxygen radius of influence is measured.

In addition, if microbial acclimation occurs, microbial activity may increase, effectively reducing the oxygen radius of influence because of increased oxygen consumption. Therefore, the best approach is to measure the oxygen radius of influence at times of peak microbial activity. Alternatively, the pressure radius of influence may be determined very quickly, generally within 2 hours to 4 hours. Therefore, the pressure radius of influence typically is used to design bioventing systems.

The pressure radius of influence should be determined at three different flow rates, with a 1-hour to 2-hour test per flow rate during the permeability test. Determining the radius of influence at different flow rates allows for more accurate blower sizing.[13] Recommended flow rates for the permeability test are 0.5 cfm, 1.5 cfm, and 3 cfm (14 L/min, 42 L/min, and 85 L/min) per ft (0.3 m) of well screen.

The pressure radius of influence may be estimated by determining pressure change versus distance from the vent well. The log of the pressure is plotted versus the distance from the vent well. The radius of influence is that distance at which the curve intersects a pressure of 0.1 "H_2O (25 Pa). This value was determined empirically from Bioventing Initiative sites. Example 1-10 illustrates calculating the radius of influence in this manner.

[11] See Appendix B for recommended specifications and manufacturers for the soil gas permeability testing equipment.

[12] In the authors' experience, this seal does not occur at most sites.

[13] See Section 2.4 for a discussion of blower sizing.

Example 1-10. Calculation of the Radius of Influence Based on Pressure Measurements: Soil gas permeability results from the Saddle Tank Farm Site at Galena AFS, Alaska, are shown in Figure 1-11 with the log of the steady-state pressure response at each monitoring point plotted versus the distance from the vent well. The radius of influence is taken to be the intersection of the resulting slope of the curve at a pressure of 0.1" H_2O (25 Pa). Therefore, in this instance, the pressure radius of influence would be estimated at 92 ft (28 m).

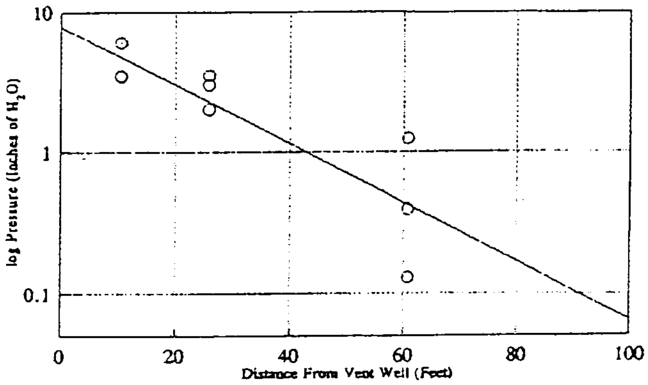

Figure 1-11. Determination of radius of influence at the Saddle Tank Farm, Galena AFS, Alaska.

The estimated radius of influence actually is an estimate of the radius in which measurable soil gas pressures are affected and does not always equate to gas flow. In highly permeable gravel, for example, significant gas flow can occur well beyond the measurable radius of influence.

On the other hand, in a low-permeability clay, a small pressure gradient may not result in significant gas flow.

1.5.2 Interpretation of Soil Gas Permeability Testing Results

The technology of bioventing has not advanced far enough to provide firm quantitative criteria for determining the applicability of bioventing based solely on values of soil permeability or the radius of influence. In general, the soil permeability must be sufficiently high to allow movement of oxygen in a reasonable timeframe (1 to 10 days) from either the vent well, in the case of injection, or the atmosphere or uncontaminated soils, in the case of extraction. If such a flow rate cannot be achieved, oxygen cannot be supplied at a rate to match its demand. Closer vent well spacing or high injection/extraction rates may be required.

If either the soil gas permeability or the radius of influence is high (greater than 0.01 darcy or a R | greater than the screened interval of the vent well), this is a good indicator that bioventing may be feasible at the site and proceeding to soil sampling and full-scale design is appropriate. If either the soil gas permeability or the radius of influence is low (less than 0.01 darcy or a R less than the screened interval of the vent well), this may indicate that bioventing is not feasible. This situation necessitates an evaluation of the cost-effectiveness of bioventing over other alternative technologies for site remediation. The cost involved in installing a bioventing system at a low-permeability site is driven primarily by the necessity of installing more vent wells, using a blower with a higher delivery pressure, or installing horizontal wells.

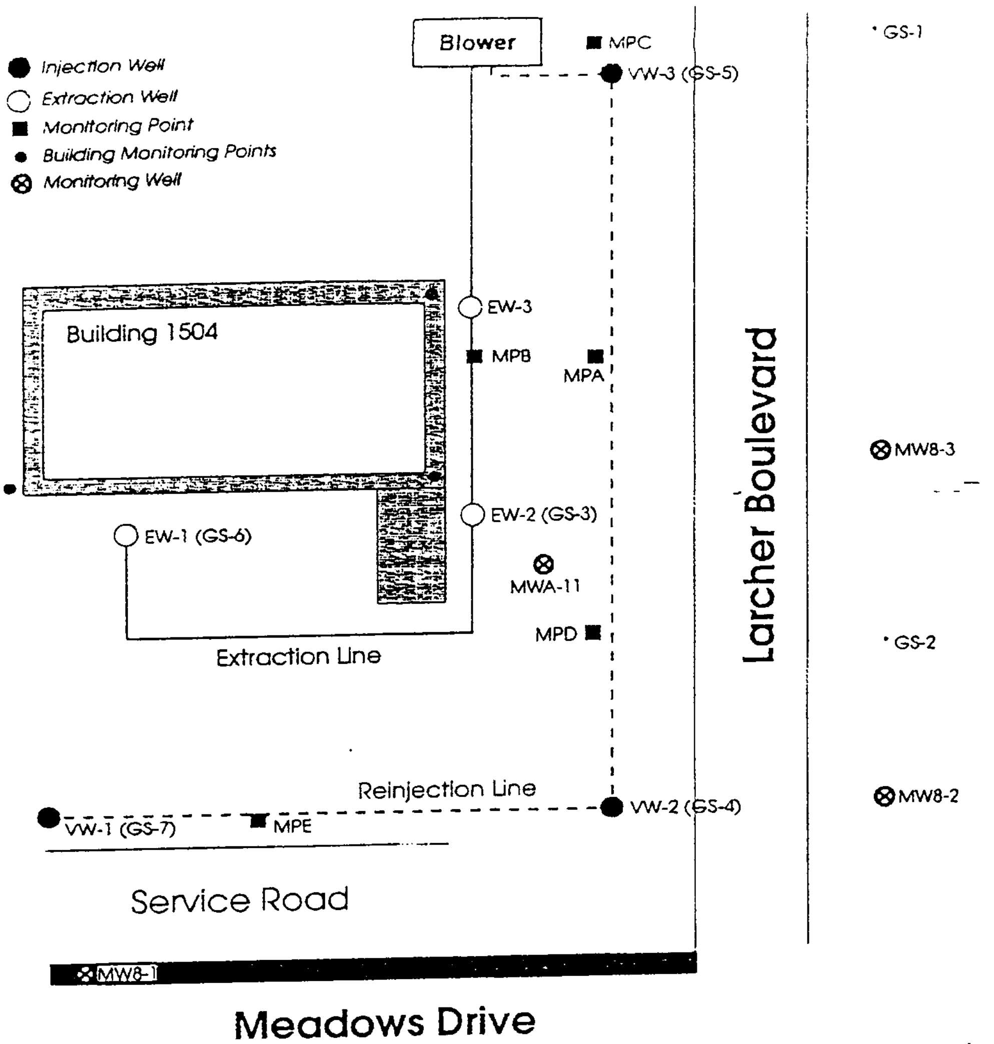

Figure 2-12. Schematic of the extraction with reinjection system at Aoc A, Keesler A

entire treatment cell, a minimum level of 5 percent should be maintained.

2.3 Well Spacing

To determine the required number of wells and appropriate spacing, an estimate of the radius of influence is necessary. Many approaches to obtaining this estimate are possible, but those normally in use are:

- Based upon measured pressure in monitoring points during a soil gas permeability test.
- Estimated from air flow and oxygen consumption.
- Measured empirically.

Estimating the radius of influence based on pressure measurements during an in situ permeability test is a common approach used in soil venting or soil vapor extraction and is probably the fastest method. This calculation is normally performed by plotting the log of pressure versus distance, as described in Section 1.5.1.

The limitation to this approach is that it only incorporates one of the three factors affecting the radius of influence. To determine more exactly the radius of oxygen influence, air flow rate and oxygen utilization need to be considered. In low-permeability soils, a pressure effect may be seen in a monitoring point, but air flow rates to that point may be too low to supply adequate oxygen. Conversely, in a high-permeability soil, air flow rates sufficient to supply oxygen may occur at pressure differentials that cannot be measured. In the authors' experience, if a pressure criterion of 0.1 " H_2O (25 Pa) is used the estimated radius of influence will be conservative for well spacing and site aeration.

Radius of influence can be estimated for a given air flow rate based on oxygen utilization. Assuming the use of a vertical well so that air flow can be described in cylindrical coordinates and assuming that the radius of influence is much greater than the well radius, the following equation may be used:

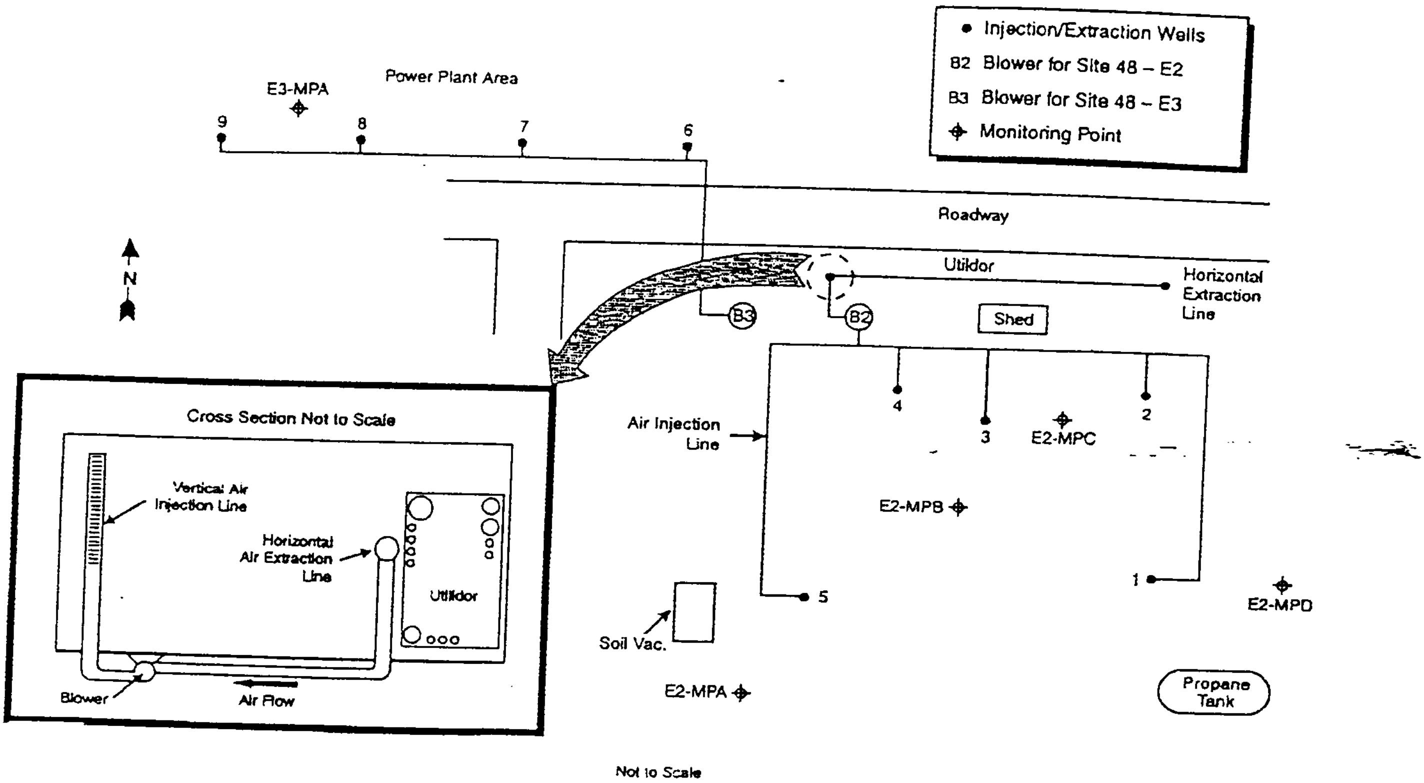

Figure 2-13. Soil gas extraction to isolate a subsurface structure at Site 48, Eielso

$$R_I = \sqrt{\frac{Q(20.9\% - 5\%)}{\pi h\ k_o\ \theta_a}} \quad \text{(Eq. 2-3)}$$

where:

R_I = radius of influence (ft)
Q = air flow rate (ft^3/day)
20.9% - 5% = oxygen %
h = aerated thickness (ft)
k_o = oxygen utilization rate (%/day)
θa = air filled porosity (cm^3_{air}/cm^3_{soil})

Example 2-3. Calculation of Radius of Influence To calculate the radius of influence at Dover AFB, Equation 2-3 is used with the following parameters:

Q = 20 cfm (570 L/min) = 28,800 ft^3/day (820,800 L/day); k_o = 4 %/day; θ_a = 0.25; h = 20 ft (6.1 m)

$$R_I = \sqrt{\frac{\left(28{,}800\ \frac{ft^3}{day}\right)(20.9\% - 5\%)}{\pi\,(20\ ft)(4\%/day)(0.25)}}$$

(Eq. 2-4)

Therefore, the radius of influence at this site is equal to approximately 85 ft (26 m).

In practice, the best approach is to estimate the radius of influence from both pressure measurements and oxygen utilization. This incorporates all three of the key factors: pressure connection, air flow, and oxygen utilization. The authors have never found in practice a site where this combined approach has overestimated the radius of influence.

The most conclusive determination of radius of influence is empirical measurement. The blower can be started and oxygen levels measured in monitoring points. The problem with this approach is that a minimum of several days is required to reach steady state. At some sites, more than 30 days are required.

Well spacing typically is 1 to 1.5 times the radius of influence. when multiple wells are installed, some consideration may be given to air flow patterns. In theory, air flow lines may develop that create "dead zones"; however, given vertical and horizontal flow paths and diffusion, these dead zones are unlikely to occur, so compensating for them is not routinely recommended.

2.4 Blowers and Blower Sizing

A blower provides the driving force to move air through the bioventing system. In selecting a blower size, important

Calculation of ROI for SVE

Based on Oxygen utilisation rate (USEPA, 1995 "Bioventing Principles and Practice, Vol. 2 Bioventing Design")

The oxygen utilisation rates were determined by calculating the slopes of the regression lines of the plots of oxygen versus time:

At VT4 (Long-term Combined SVE/AS test data)

	Equation of regression line	Oxygen utilisation rate ($\% h^{-1}$)
Shallow probes 1m	$y = -0.0701x + 8.5612$	0.0701
" " 5m	$y = -0.0666x + 6.2051$	0.0666
" " 10m	$y = -0.0701x + 8.6176$	0.0701
" " 20m	$y = -0.0605x + 6.7044$	0.0605
Deep probes 1m	$y = -0.0416x + 14.52$	0.0416
" " 5m	$y = -0.0772x + 14.889$	0.0772
" " 10m	$y = -0.0694x + 6.456$	0.0694
" " 20m	$y = -0.0735x + 6.5961$	0.0735
Shallow Radial probes E1	$y = 0.104x + 8.7257$	cannot be used since -ve
" " " F1	$y = 0.0661x + 12.041$	cannot be used since -ve
Deep Radial probes E2	$y = -0.0586x + 6.7776$	0.0586
F2	$y = 0.0576x + 11.767$	cannot be used since -ve

Arithmetic mean = 0.0653 ($\% h^{-1}$)

$$R = \sqrt{\frac{Q(20.9\% - 5\%)}{\pi h k_o \theta}}$$

where R = ROI in metre

Q = flow rate = 8 cfm = $0.227\ m^3 min^{-1}$ = $13.62\ m^3 h^{-1}$

$\pi = 3.1416$

h = aerated thickness = depth to top of AS well screen = 5.5m

k_o = oxygen utilisation rate = $0.0653\ \% h^{-1}$

θ = soil porosity = 0.395 (based on previous results)

$$= \sqrt{\frac{(13.62\ m^3 h^{-1})(15.9\%)}{(3.1416)(5.5m)(0.0653\% h^{-1})(0.395)}} \Rightarrow R = \underline{22m}$$