A bioventing feasibility test to aid remediation strategy

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Abstract

A case study is presented where the feasibility of bioventing was assessed for the remediation of a petroleum-contaminated site. This was achieved through the determination of the radius of influence of a single vent well, the soil gas permeability of the site and the oxygen utilisation rate of the *in situ* micro-organisms.

The on-site test used one vent well and three monitoring wells. A radius of influence of 9.5 m was determined. A soil gas permeability of 3.8 Darcy was measured. The oxygen utilisation rate of 1.32% (v/v) O_2/h indicated that an active microbial population existed *in situ*. The theoretical biodegradation rate was calculated to be 752 mg hydrocarbon (based on hexane)/kg soil·month. Based on these results, bioventing was found to be a feasible bioremediation option for cleanup of the site, provided that other soil conditions were suitable for biological activity.

Introduction

Mason et al. (1992) have defined bioremediation as a biological process involving degradation of polluting organic compounds as a result of biochemical activity of micro-organisms. Each contaminated site requires a technique suited to the site-specific conditions. The choice of the correct remediation technique applicable to a specific site can impact both on the economic feasibility and the success of the treatment. One *in situ* bioremediation technique which is finding increasing application (Hinchee et al., 1992; Hoeppel et al., 1991) is bioventing. It obviates the cost to excavate and transport the soil to an alternative treatment site, as well as the need to backfill the excavated area with clean soil. Furthermore, this technique is effective and imposes minimum disruption to normal business activities on the site. Once installed, the system requires little maintenance.

In situ bioventing involves the continuous or pulsed introduction of air into the subsurface to stimulate the activity of the indigenous micro-organisms and hence to promote bioremediation. The air is introduced into the site either by blowing, or drawing a vacuum, through strategically placed injection or vent wells. The rate of introduction is such that volatilisation of the contaminant is minimised and *in situ* degradation is maximised. The required air flow rate is determined during an on-site feasibility test which measures the oxygen utilisation rate. The number of wells needed to cover the entire contaminated area is determined from the radius of influence of a single well, which is a measurement taken during the feasibility test.

Bioventing is not suitable for application at all contaminated sites (Pearce, 1996), and hence it is important to undertake an assessment of the site and test the feasibility of this remediation technique prior to application at full scale.

Bioventing feasibility test

The specific aims of the bioventing feasibility test (Hinchee et al., 1992) are to determine certain site-specific parameters whose values will indicate the feasibility of bioventing, and also aid in the design of the full-scale treatment system. These are:

- Radius of influence of a single vent well. This influences the number of wells needed to cover the contaminated area.
- Soil gas permeability.
- Oxygen utilisation rate.
- The soil gas permeability, together with the oxygen utilisation rate influences the pump size needed.
- An estimation of biodegradation rate, which gives an indication of the length of time needed to remediate the site.

The objective of this study was to measure and assess the above site-specific factors at a petroleum-contaminated service station with the view to determining an appropriate remediation strategy.

Methodology

System set-up

A vent well was established in the area where the spill had originated. Three wells were drilled at distances of 3 m, 8 m and 12 m respectively from the vent well. These were equipped as monitoring wells, and were named M1, M2 and M3 respectively.

The configuration of the bioventing test system is shown in Fig. 1.

The lower 0.6 m of the vent and monitoring wells was perforated to allow air flow into the vent well, and to allow free interchange with the resident soil vapour in the monitoring wells. The perforated portion of the wells consisted of 0.006 m diameter holes, covered by a geotextile to prevent soil entering the wells. Gravel packing was used in the outer annular around the screens, whilst bentonite was used as a sealant above this to prevent short-circuiting. A cement capping was put in place together with a meter box at ground level. The vent well was connected to a rotary vane blower.

A schematic diagram of a vent and a monitoring well is given in Fig. 2.

The monitoring wells were used to sample gas in short vertical sections of the soil. Monitoring Wells 1 and 2 were equipped with oxygen sensors which were connected to a

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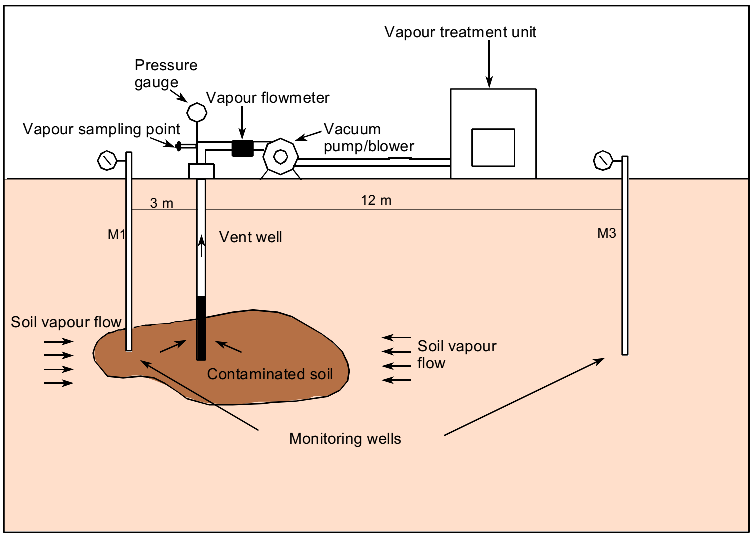


Figure 1 (left)
Configuration of a bioventing system

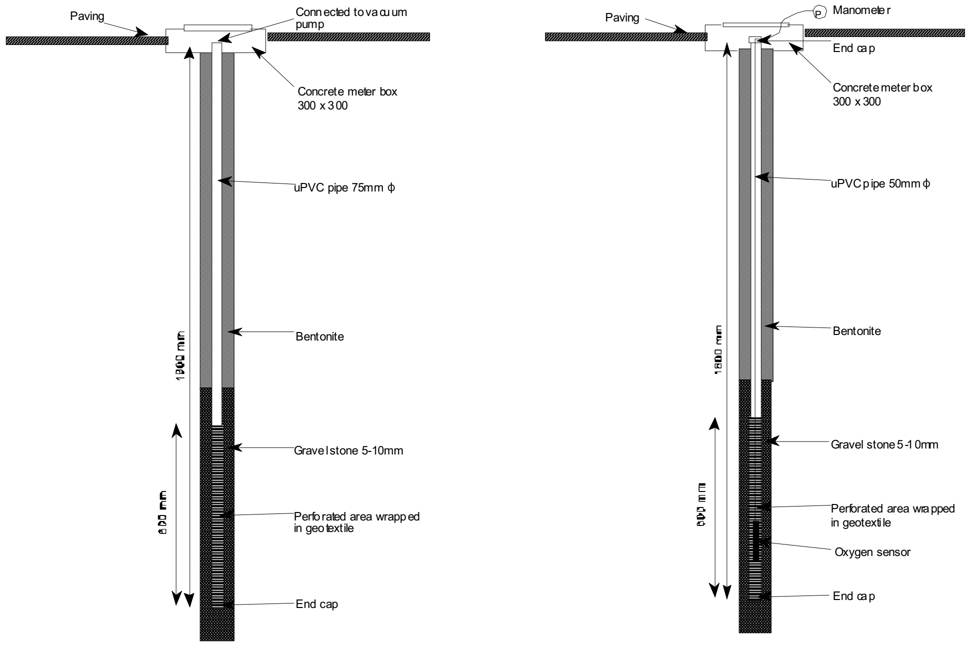


Figure 2 (bottom)
Schematic diagram of a vent (left) and a monitoring (right) well

micrologger (Datawrite Research Company Part # XT252-25). The monitoring wells were sealed to the atmosphere, but had an outlet which was connected to a manometer for the measurement of vacuum.

A vent well and one monitoring well (BV and BM) were established in a nearby uncontaminated area, so that a background oxygen respiration rate could be obtained.

Radius of influence

Air was drawn from the subsurface at a constant rate of 24 m^3/h at a vacuum of 400 cm H_2O. Pressure readings (cm H_2O) were recorded at monitoring Wells 1 to 3 over a 3-h period. The temperature, flow rate of the air from the vent well and the vacuum were monitored at 30 min intervals.

The starting time was recorded as the time that the blower was switched on. The pressure was recorded at each monitoring point at 1 min intervals. After 10 min, the interval was extended to 2 min. After 20 min, the interval was lengthened to 3 min. This was continued until the pressure change over a 3 min interval was less than 0.25 cm H_2O. Once this occurred, the recording interval was lengthened to 10 min. The monitoring continued until the pressure in monitoring Well 2 did not change by more than 10% in an hour.

The value of the radius of influence of a single vent well, R_I, was determined by plotting the vacuum at each monitoring point as a function of the log of the radial distance of the monitoring well from the vent well. The plot is extrapolated to determine the distance where the vacuum is 2.54 cm H_2O. This distance is the radius of influence (Johnson and Ettinger, 1994).

Soil gas permeability

The same data that had been collected for determining the radius of influence was used to calculate the soil gas permeability (k), using Eq. (1) (Hinchee et al., 1992).

$$k = \frac{Q\mu \ln \frac{R_W}{R_I}}{H\pi P_W[1-(P_{Atm}/P_W)^2]} \tag{1}$$

where:

Q = volumetric flow rate from the vent well (cm^3/s)
μ = viscosity of air (1.8×10^{-4} g/cm·s at 18°C)
P_{Atm} = ambient pressure (at sea level 1.013×10^6 $g/cm \cdot s^2$)
R_w = radius of a vent well (cm)
H = length of screen (cm)
R_I = the maximum radius of venting influence at steady state (cm)
P_w = the absolute pressure at the venting well ($g/cm \cdot s^2$)

Figure 3
Plot of pressure response at monitoring wells

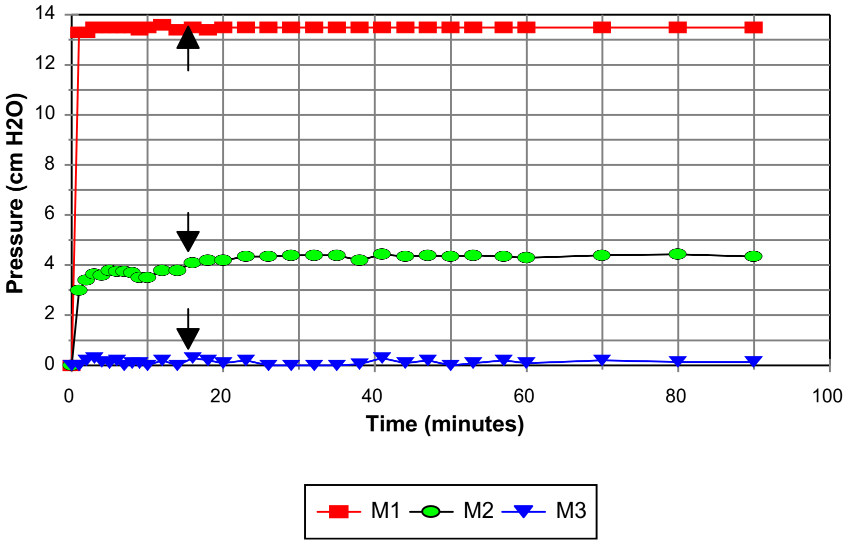
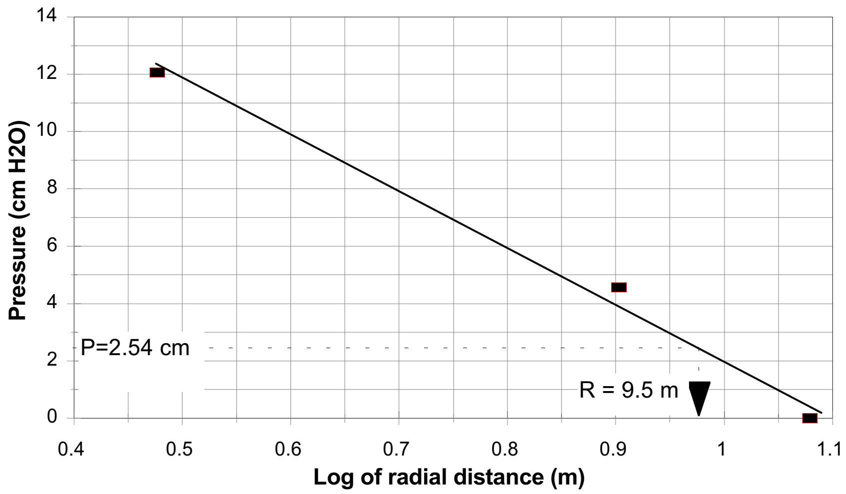


Figure 4
Determination of radius of influence



Oxygen utilisation rate (OUR)

Air was drawn from the vent well at a rate of 24 m^3/h, until the oxygen concentration in monitoring Well 2 had reached 19.4%, from an initial 2%. The pump was then stopped and the decreasing oxygen concentration in monitoring Well 2 was monitored at 30 min intervals. The test was terminated when the oxygen concentration was 1.6%. The OUR was calculated from the slope of the oxygen concentration, time curve.

This procedure was repeated at the background well.

Biodegradation rate

The stoichiometric relationship for the oxidation of hexane, which is taken as a representative hydrocarbon (Hinchee et al., 1992), is shown below:

$$C_6H_{14} + 9.5\ O_2 \rightarrow 6CO_2 + 7\ H_2O$$

This relationship can be used to estimate the biodegradation rate in terms of mg of hexane equivalent per kg of soil per day. It is recognised that the influence of biomass cell yield has not been taken into consideration. However, Hinchee et al. (1992) suggest that the following equation be used to estimate the biodegradation rate:

$$K_B = -K_o\ A\ D_o\ C/100 \qquad (2)$$

where:

K_B = biodegradation rate (mg/kg·d)
K_o = OUR (%/d)
A = volume of air/kg of soil (ℓ/kg)
D_o = density of oxygen gas at 25°C (mg/ℓ)
C = mass ratio of hydrocarbon to oxygen required for mineralisation.

The following parameter values are typical (Hinchee et al., 1992):

- Porosity = 0.3
- Soil bulk density = 1 440 kg/m^3
- D_o = 1 330 mg/ℓ
- C = 1/3.5

Results

Radius of influence

The response obtained during the feasibility test, showed that a constant pressure was reached after the first 15 min for each of the three monitoring wells (as shown in Fig. 3). The radius of

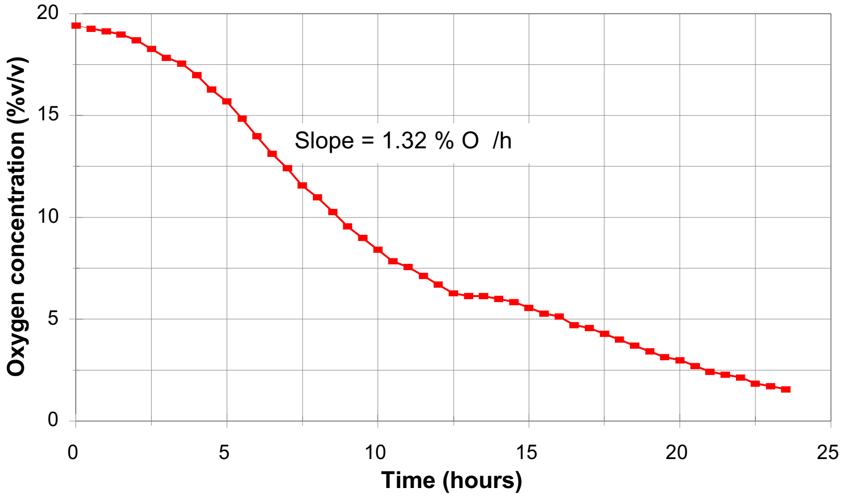


Figure 5
In situ *method to calculate OUR*

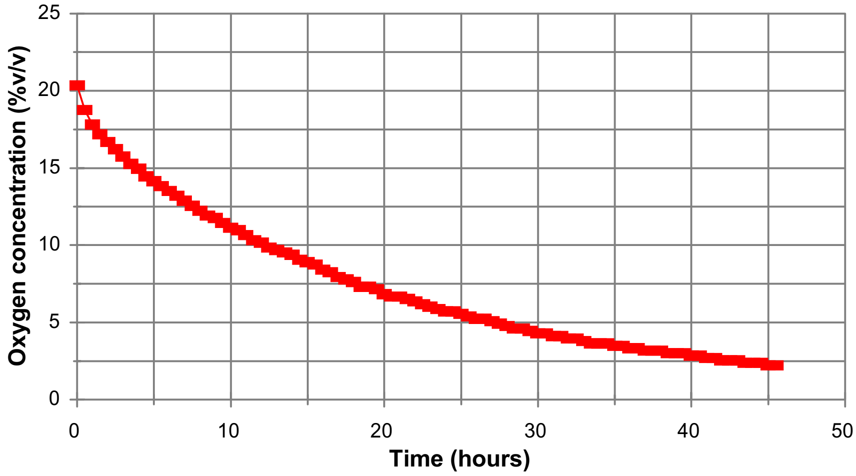


Figure 6
Oxygen utilisation curve from the background monitoring well

influence was determined graphically to be 9.5 m (as shown in Fig. 4).

This falls within the R_i values reported in the literature of between 8 and 49 m (Downey et al., 1995; Phelps et al., 1995; Kittel et al., 1994), and is a feasible distance for a bioventing system. Each vent well would therefore have an effective treatment diameter of 19 m.

Soil gas permeability

As the steady-state pressure was reached within 15 minutes, the steady-state method of calculating k was used. The soil gas permeability was calculated to be 3.8 Darcy.

The soil gas permeability indicated the appropriateness of bioventing for the remediation of the site. Phelps et al. (1995) have found bioventing suitable at sites with lower soil gas permeabilities. Values reported (Downey et al., 1995; Phelps et al., 1995; Kittel et al., 1994) typically range from 1.8 to 1 400 Darcy.

OUR

The results obtained are shown in Fig. 5. The OUR was calculated from the first linear section of the graph between 3 and 12.5 h ($r^2 = 0.99$). The OUR was calculated to be 1.32% (v/v) oxygen/h.

The rate of 1.32% (v/v) O_2/h is within the upper range of OURs reported in the literature. Phelps et al. (1995) determined an OUR of 0.09 to 1.2 % (v/v) O_2/h for a predominantly clay soil contaminated with 17240 mg diesel fuel/kg soil, while Ratz et al. (1995) had a similar rate for a rubble stone and sand soil contaminated with 42 mg jet fuel/ kg soil. It would thus support the hypothesis that the OUR is dependent on a number of factors, and not only on the concentration of the contaminant.

The OUR at the background monitoring well was determined from the gradient of the slope between 4 and 16 h ($r^2 = 0.99$) as shown in Fig. 6.

The background OUR was calculated to be 0.53 % O_2/h. This is lower than the rate found in the contaminated area. This is expected, as the carbon source available to the microorganisms is less than in the contaminated area.

Biodegradation rate

The biodegradation rate was determined to be 752 mg hydrocarbon as hexane/ kg soil·month or 9 025 mg hydrocarbon as hexane/ kg soil·year . This biodegradation rate is within the upper values reported (Kittel et al., 1994; Ratz et al., 1995). It is expected that this initial rate will decrease as the product concentration in the soil decreases. A lower mass of hydrocarbons in the subsurface will result in less of a food source for the micro-organisms, and hence a lower OUR, and biodegradation rate.

Conclusions

The following conclusions were drawn:

- The radius of influence was determined to be 9.5 m, which will result in a practical number of wells to cover the contaminated area.
- The soil gas permeability was determined to be 3.8 Darcy. This is lower than the norm reported in the literature, but not too low to negate bioventing.
- It was possible to increase the oxygen concentration *in situ* to non-limiting levels in the subsurface, thus *in situ* biodegradation can be stimulated in this manner.
- The biodegradation rate was determined to be 752 mg hydrocarbon as hexane/kg soil.
- Bioventing can be implemented on this site should the other factors (contaminant type and concentration, micro-organism species and population count, the availability of nutrients (nitrogen and phosphorus), soil moisture content and the pH) affecting bioremediation be suited to biological degradation of the contaminant.

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