NOBIS 95-1-13

IN SITU AIR SPARGING
-
A TECHNICAL GUIDE

Version 1.1

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Samenvatting
Dit Handboek (Technical Guide) is het resultaat van een vierjarig onderzoek naar ontwerp, dimensionering en uitvoering van persluchtinjectie als techniek voor sanering van verontreinigde bodem en grondwater. Het Handboek is gebaseerd op de huidige kennis van milieudeskundigen op het gebied van persluchtinjectie als saneringsmethode. Praktische ervaringen met de toepassing van persluchtinjectie in het veld zijn nadrukkelijk meegenomen.

Het Handboek moet worden gezien als een instrument voor ontwerpers en uitvoerders, om het saneringsproces te plannen en de luchtinjectie- en luchtonttrekkingssystemen te ontwerpen en uit te voeren. Met behulp van archetypes en nomogrammen ondersteunt het Handboek beslissingen voor de sanering van verschillende soorten sites, van kleine sites met doorlatende bodems tot grote industriële locaties met sterk heterogene en gelaagde bodems.

Trefwoorden

Gecontroleerde termen:
bioventing, kennissystemen, modelering, monitoring, persluchtinjectie

Vrije trefwoorden:
archetypes, haalbaarheid, ontwerp, sparging, tracer test

Titel project
Biosparging and Bioventing

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Abstract
The Technical Guide for the design of sparging systems to remediate contaminated soils and groundwater by in situ air sparging (IAS) is drawn up as the result of a four year research program on biosparging and bioventing. The guide is based on the current knowledge of the environmental engineers of in situ remediation systems based on biosparging. Practical experiences on the design of IAS systems are incorporated.

The Technical Guide is a tool for consultants/designers to help plan the remediation process and to design and operate an IAS/SVE system. With the help of nomograms and archetypes the guide supports decisions for the remediation of different types of sites ranging from small sites with permeable soil to large industrial estates with a strongly heterogeneous and stratified soil.

Keywords
Controlled terms:
bioventing, compressed air injection,
knowledge systems, modelling, monitoring

Uncontrolled terms:
archetypes, design, feasibility,
sparging, tracer test

Project title
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The guide is based on the current knowledge of the environmental engineers of in situ remediation systems. Practical experiences on the design of IAS systems are incorporated.

The Technical Guide is a tool for consultants/designers to help plan the remediation process and to design and operate a IAS/SVE system. The guide facilitates the development of different alternatives. The guide should be able to support decisions for the remediation of different types of sites ranging from small sites with permeable soil to large industrial estates with a strongly heterogeneous and stratified soil.

We hope that this guide will help understand the principles of sparging and will improve the quality of design of sparging systems.

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Chapter 1

Introduction

The lphysical difficulty to penetrate saturated media with air, the limited solubility of oxygen in water and the limited groundwater velocity makes aeration of the saturated zone a tedious problem. A possible solution is to increase the thickness of the unsaturated zone by lowering the groundwater table. The created unsaturated zone may then be remediated by venting or by soil vapour extraction (SVE). This technique has important drawbacks. Firstly it may enhance vertical migration of the contamination. Secondly the withdrawal of (contaminated) groundwater is costly because in most cases the groundwater will have to be treated before disposal or reinfiltration. Thirdly, it may cause damage to infrastructure due to subsidence of the soil. Furthermore lowering the groundwater table may cause desiccation of important ecosystems.

Another possible method to aerate the saturated zone is sparging. During sparging air is injected in the saturated zone of the soil system. Mass transfer from the gas phase to the aqueous phase results in oxygenation of groundwater.

The injected air escapes to the unsaturated zone, and because mass transfer in the saturated soil is too slow to consume oxygen completely, sparging also results in aeration of the unsaturated zone. Thus, sparging can result in a stimulation of the remediation of the saturated zone and the unsaturated soil.

By sparging and SVE the removal of the contaminants from the soil system is both due to biodegradation and, especially for volatile contaminants, to volatilization or stripping. Sparging may also enhance dissolution of the contaminants, which, when applied in combination, increases the efficiency of conventional pump and treat measures.

When air injection or extraction is applied for stripping the contamination rather then to stimulate biodegradation, the term in situ air sparging (IAS) is used instead of biosparging, and soil vapour extraction (SVE) instead of bioventing. In this IAS Technical Guide however we will use IAS and SVE as general terms for both stripping and biodegradation of contaminants when applying the air injection and air extraction technique respectively.

The IAS Technical Guide focuses on the technical aspects of designing and operating IAS. The guide also addresses SVE but more as a technique that may be used in conjunction of IAS to avoid migration of volatile contamination to areas of concern. The guide is based on the current knowledge of the environmental engineers of in situ remediation systems. Practical experiences on the design of IAS systems are incorporated in the guide.

The Technical Guide is a tool for consultants/designers to help plan the remediation process and to design and operate a IAS/SVE system. The guide facilitates the development of different alternatives.

care of an IAS remediation is discussed. Chapter 10 deals with the costs of different aspects of IAS like pilot testing, design and installation, maintenance and monitoring. At the end of the guide an index is added.

Chapter 2

Theoretical background

hydrostatic and capillary forces. The entry pressure, or the pressure of the air phase against the water phase, needs to be exceeded. In case of air injection this will cause groundwater flowing radically away from the injection well. The capillary force depends mainly on the pore size (distribution) of the soil.

In homogeneous soils the airflow from a sparging well will have a roughly conical shape (consisting of decreasing air saturation further away from the injection well). The air cone develops in time until a situation of equilibrium between the air and water phase is reached [NOBIS proj. nr. 95-1-13, Synthesis report Phase 1 and 2, September 1997]. In Figure 2.1 an illustration of remaining water saturation over time is shown at two distances from the sparging well.

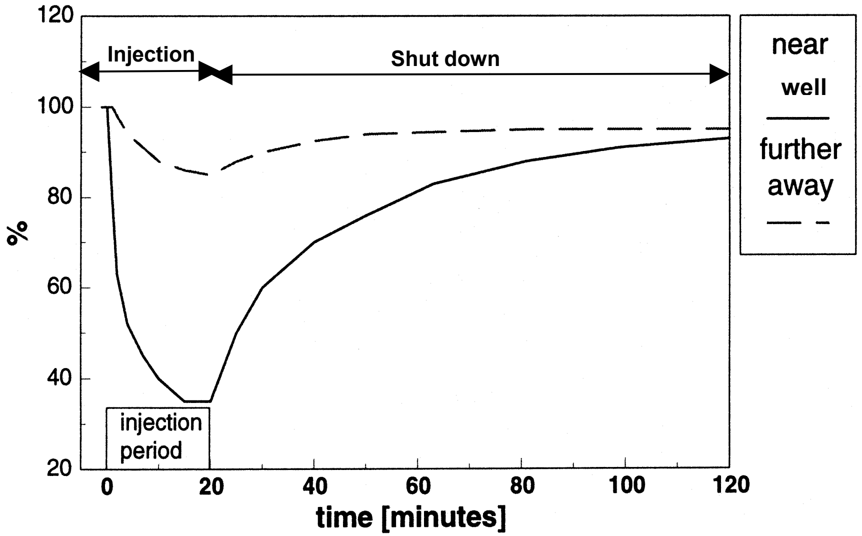

Fig. 2.1 Water saturation as function of time around a sparging well during pulsed air injection. Note that the injection period is only 20 minutes.

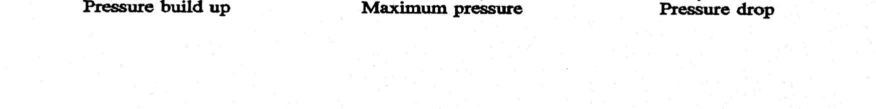

Fig. 2.2 Stages during sparging.

It is desirable in practical application of IAS to pulse air injection with a cycle time short enough to avoid achieving steady state airflow.

When sparging in very coarse soils (gravel), air bubbles can occur during the expansion stage of the air cone. In most cases air bubbles are not formed, or they immediately coalesce to form stable air channels. These channels will grow and after some time they reach the unsaturated zone. At this stage (collapse stage) the air pressure will drop and continuing air injection does not provide a larger aeration radius [Ji et al., 1993].

Not all of the air channels reach the vadose zone. It appears that two types of channels take part in the sparging process: widely spaced continuous air pores and dead-end pores [Clayton, 1996]. Near the injection well, the air saturation is high and the filled pores are mainly interconnected. As the distance to the injection well increases the air saturation decreases and most of the pores are dead-ended. The dead-end pores are found at centimetre scale up to large distances from the injection well [NOBIS proj. nr. 95-1-13, Technical report, Radius of influence Part 2, July 1998; Synthesis report Phase 4, Optimisation sparging concept, November 1998].

The effectiveness of an air sparging system largely depends on the air channel density in a formation. Increasing the airflow rate (and air pressure) has a positive effect on air channel density, but does not necessarily increase the radius of influence of the well (see section 2.1.2).

The air injection pressure cannot be raised infinitely, but has to stay below the soil pressure to avoid fracturing or cracking of the soil (see section 2.4).

Transfer of contaminants into air channels and oxygen into the saturated zone will be achieved by diffusion processes. The surface area of the air and water interface of each air channel is quite small, due to the small air channel diameter (this diameter is approximately the size of the soil pores). This results in limited mass exchange rates. In addition, the groundwater at some distance from the air channel can contain a quite high contaminant concentration, while the water in the air channel will have a reduced contaminant concentration. This often creates a concentration gradient within the saturated zone.

One of the first investigations that visualised airflow in saturated soil media has been reported by Ji et al. [Ji et al., 1993].

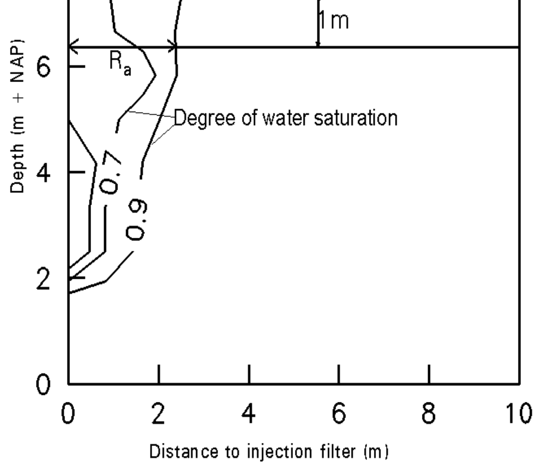

Fig. 2.3 Definition of the aeration radius.

In addition to the aeration radius, the concept of *'radius of influence'* (ROI) is introduced. This is defined as the radius around the sparging well, within which the oxygen concentration is high enough for biological degradation. The radius of influence determines the optimal distances between the injection wells and can be an important factor for the installation costs. For defining the radius of influence the limiting oxygen concentration in the water phase for biological degradation must be quantified.

Some pactitioners herefore preferably use the term zone of influence (ZOI). In this document we will however use the generally accepted terms aeration radius and radius of influence. The oxygen concentration around a sparging well and consequently the radius of influence not only depend on the migration of air around the sparging well (this is the 'aeration radius'), but also on the transfer of oxygen to the water phase and the oxygen consumption rate. When the oxygen consumption rate is high (high biological degradation rate), the expansion of the ROI will be slower than at a low biological activity.

With respect to the aeration radius, the relevant parameters are:

a. air injection pressure and injection rate, injection period and intermediate time period (injection frequency);
b. residual air saturation after sparging;

The total amount of oxygen that can be transferred depends on the contact surface between air and water.

A sparging system creates schematically three different zones of activity (see Fig. 2.4):

- an inner zone immediately around the injection well with air saturation over 10 - 20 % (the air cone in Fig. 2.4 with flowing air);
- an intermediate zone (surrounding the inner zone) in which low air saturation less than 10 % occur (the small 'air + water' zone with less airflow);
- an outer zone (enclosing both other zones) in which the airflow takes place through separate pore channels, which are enclosed by water saturated zones.

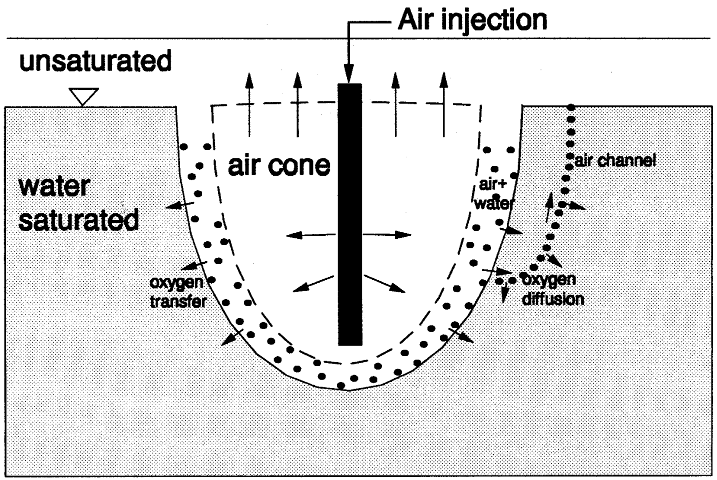

Fig. 2.4 Schematic representation of different zones of an air sparging system.

The occurrence of air bubbles and channelling in the water saturated outer sphere, provides the possibility of oxygen transfer to the water phase followed by (limited) water diffusion of oxygen.

When bubbles are present optimal oxygen transfer takes place, because the bubbles have a relatively large surface. Channels have a lower surface than bubbles so mass transfer in the stable channels is sub-optimal and controlled by diffusion.

lapse stage;

- water diffusion of oxygen due to level gradients of oxygen within the water phase; in stagnant water again diffusion will be the only oxygen transport process.

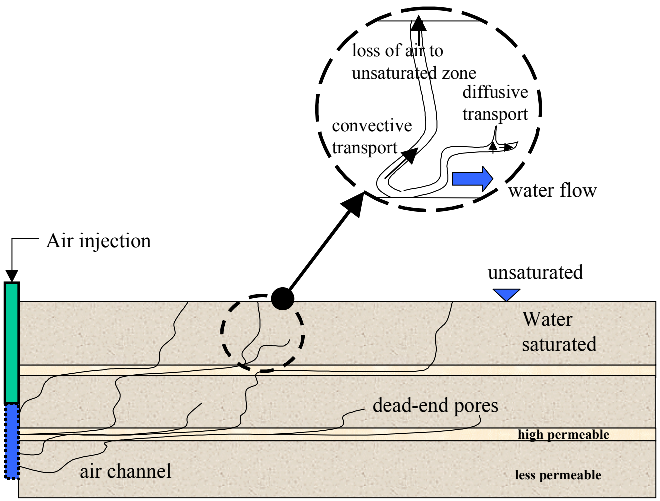

Fig. 2.5 Schematic representation of air channeling and dead-end pores with relevant transport mechanisms.

Oxygen consumption rate

The biological degradation processes take place mainly at the contact surface between the water phase and the soil matrix. Here a certain oxygen availability needs to be guaranteed in the water phase. The required minimal oxygen level corresponds with the earlier defined 'radius of influence'. In practice oxygen level delivery of 3 to 5 mg/l should be created.

The amount of oxygen that is consumed depends on the consumption rate and the residence time in the soil. For large injection rates in coarse soils the residence time is limited, causing only little oxygen (relative to the total amount injected) to be consumed (the radius of influence equals the aeration radius). In low permeable and anisotropic soils the injection rate needs to be small. In that case the aeration radius is relatively small compared to the radius of influence.

would be expected on the basis of the aeration radius alone. This is to correct for inhomogeneous distribution of air, which is likely to occur in low permeable and, typically Dutch, horizontally layered soil.

In chapter 5 a practical method for the design of a sparging system is worked out.

2.1.3 Air injection period and injection frequency

The air injection period and frequency are determined by :

- expansion phase;
- residual air after the injection;
- oxygen availability.

Expansion phase
During the sparging process air channels from the air injection point to the groundwater level are formed [NOBIS proj. nr. 95-1-13, Technical report, Radius of influence Part 2, July 1998]. Once the air has passed the freatic water level, a loss of air to the unsaturated zone and a pressure drop will result. This point corresponds with a transition from the expansion stage to collapse stage of the air cone. During the expansion of the air cone effective mass transfer takes place by creating new contact surfaces. For an efficient use of the injected air, the injection period should therefore be restricted to the expansion phase [NOBIS proj. nr. 95-1-13, Synthesis report Phase 4, November 1998].

So the injection period depends on the time required for the air to travel from the injection well to the groundwater table. This time is depending on the airflow rate and may vary from several minutes in coarse media up to several hours in fine grained soils.

Residual air after injection
When the air injection has been turned off, the groundwater will flow back resaturating the soil pores. When the next injection is started shortly after this, the remaining air in the soil will act as a preferential flowpath for the injected air, decreasing the aerated surface. The air injection theoretically should be started after the residual air in the soil pores has been significantly reduced (and replaced by water). The time this process takes depends on the soil permeability and can be estimated by determining the initial injection pressure at the injection well head, when the air injection starts and during following injections. During the first injection, the initial pressure and the time before the breakthrough of channels through the groundwater level can be determined. If air is still present in the soil at the next injection, preferential flowpaths will be created and the initial pressure will be lower. At the point in time when almost all of the air has disappeared, the initial pressure will be approximated. Then the next injection of air should take place.

costs of off gas treatment. Furthermore pulsed injection will create a redistribution of contamination and oxygen in groundwater due to microscale mixing effects, which are beneficial for the bioremediation process. Because of these effects pulsed air injection is recommended.

2.1.4 Mixing-effects

A pulsed air injection regime will increase the amount of mixing within the region of airflow. As a result a larger volume of groundwater will be supplied of oxygen than would be achieved by continuous system operation. Bromide tracer tests have proven that IAS results in substantial mixing of the groundwater within the radius of influence. A tracer injected within 2 meters of a sparge well in a push pull testwas diluted up to 10 % of the initial level after 1 day of pulsed (1 hour on, 1 hour down) sparging [NOBIS proj. nr. 95-1-13, Technical report, Push pull test - discrimination between volatilization and biodegradation, October 1998].

The observed rise of groundwater table (mounding) due to the injection of air into the soil does not imply movement of groundwater. Field observations evidenced only small scale movement of groundwater, in an order of magnitude of cm/day [Johnson et al., 1996b].

2.1.5 Effects on NAPL/free product

Sparging may also result in a release of NAPL previously trapped in soil pores. Many practitioners have observed appearance or increase of free product in groundwater monitoring wells during the start up of sparging systems. IAS may be used as a method to improve free product removal.

However, introduction of oxygen and energy in the subsoil may also enhance bioremediation of petroleum hydrocarbons consequently resulting in the formation of emulsifying carboxylic acids. These acids may enhance formation of water- stable NAPL emulsions that are difficult to remove from the soil. Therefor removal of free phase NAPL before sparging is started up is recommended.

When dealing with LNAPL on top of the groundwater table ('a smear zone'), mixing can break the consistency of these layers, thus improving the possibility for remediation. IAS is especially efficient when used for stripping NAPL from the capillary fringe.

2.1.6 Effects of soil heterogeneity

Successful use of biosparging technology depends on the ability of the system to effectively deliver air to the treatment area and the ability of the soil matrix to transmit the air. Therefore, site conditions that favour the air *delivery* and *transmission* through the matrix include relatively coarse-grained homogeneous soil types. Extreme coarse soils (e.g. gravel) however limit the *distance* to which the air is distributed from the injection well.

Fig. 2.6 Schematic representation of the sparging process in homogeneous (A) and heterogeneous soil (B).

The presence of these low permeable layers, on top of high permeable layers, turns out to have a favorable effect on the horizontal air *distribution*. Although the low permeability of the layers itself are not favorable for air transmission (lower air channel density), they create an enlarged aeration radius. The air will penetrate a low permeable layer if the air pressure below this layer is large enough. A large gradient in permeability will result in accumulation of air, which causes an increase of the aeration radius [NOBIS proj. nr. 95-1-13, Synthesis report Phase 1 and 2, September 1997].

For large contrasts (with a factor of about 10 or more) in permeability however, the possibility of heterogeneous flow occurs, resulting in a smaller part of the air penetrating the low permeable layers. Consequently, in case of multi-layered soil systems the upper layers might not be aerated at all, thus lowering the effectiveness of the technique and causing extended remedial times [NOBIS proj. nr. 95-1-13, Synthesis report Phase 1 and 2, September 1997].

A point of attention is the possible uncontrolled migration of contaminants, as a result of the heterogeneous flow of the air. A technique that can be used to increase the vertical permeability of a multi-layered soil is through the use of 'air relief wells' (or sand piles). Air relief wells are sand-packed drillings installed through low permeability layers. They provide passive airflow between the subsurface layers.

Sparging in dense, fine-grained or highly stratified soils may require high injection pressures. It is however important that the soil cracking (or fracturing) pressure is not exceeded. The creation of cracks (or fractures) in the soil matrix is permanent and can result in a loss of system efficiency and soil stability (see section 2.4).

Layering affects the aerobic biodegradation process, because it will have an adverse effect on the ability to *direct* the oxygen distribution and thus the remediation into the desired direction. The total volume of affected sub-phreatic soil on the contrary is impacted in a favourable way. It may be necessary to sparge for a longer period of time to get the air to the desired places, but provided that conductivity is low at intermediate layers, the soil volume treated will be larger.

In a layered soil system it depends on the aeration radius and oxygen consumption whether pulsed air sparging or continuous air spaging will be most optimal. Pulsed injection is applied if a much

Iron precipitation
When air and consequently oxygen is injected in the soil, soluble iron, present in the groundwater, is oxidised resulting in iron-(hydr)oxide precipitation. Hydraulic conductivity changes in the soil, caused by iron precipitation around a sparge well, however is not yet observed, because the total mass of iron precipitation within the ROI is limited. Water extraction wells, situated within the aeration radius or close to sparge wells, may however suffer from iron precipitation.

The accumulated mass of iron delivered to the well in the extracted groundwater may after some time be high enough to cause clogging of the well.

Movement of fine particals
Attention has to be paid to possible clogging of the injection well by fines in the well screen. Pulsed operation of the air injection system produces flow of groundwater from and to the well. Because the water is not extracted from the well the fines can accumulate and cause clogging of the sparge well. This effect can be reduced by using a filter sock on each well, which in practice appears to work well. Clogging of filter packages has not been observed yet.

Biofouling
Clogging of the sparging well or well screen by an excessive growth of micro-organisms (biofouling) may be a potential cause of clogging. However this has not been observed yet in practice presumably because the injected air keeps the slots open. Also the positioning of the sparge wells underneath the source of the contamination and the corresponding low bacterial growth has no impact on the soil permeability around sparge wells.

2.2 Volatilization and biodegradation

The process of biosparging, possibly in combination with bioventing, is similar to air sparging and air venting (or soil vapor extraction). However, while air sparging and venting favour the contaminant removal through volatilization, biosparging and bioventing promotes the biodegradation of the contaminants. In practice, some degree of volatilization and biodegradation occurs when either air sparging/venting or biosparging/bioventing is used.

When IAS is started up, initially the volatile contaminants are removed [NOBIS proj. nr. 95-1-13, Technical report, Push pull test - discrimination between volatilization and biodegradation, October 1998]. Gradually the rate of vapor removal will decrease and the relative rate of biodegradation will increase. During the remediation process the biodegradation of less volatile, more strongly adsorbed contaminants becomes the dominant removal mechanism. The relative rates of volatilization versus bioremediation at any point in the remediation process depend on factors such as site geology and hydrogeology, contaminant characteristics, and the design of the air sparging system itself.

matrix, the contaminants are not available for the micro-organisms to degrade.

3. *Temperature of the groundwater*
   At temperatures below 10 ºC or above 45 ºC the microbial activity of most bacteria diminishes considerably. Within this temperature range, microbial activity is generally greater at higher temperatures.
4. *pH level*
   The optimal pH level for bacterial growth ranges between 6 and 8.

In few cases adjustments in the nutrient level are made by infiltration of nutrients containing water. Infiltration of nitrogen (nitrate or ammonium) and phosphate dissolved in water should be performed with care, to avoid additional migration of groundwater contamination to the surrounding area. An increase of in situ biodegradation however is rarely observed due to the poor distribution of nutrients (fixation of phosphates).Also vapor phase nutrients may be added with the sparge air, such as triethyl phosphate, nitrous oxide and ammonia.

Another important factor is the organic content of the soil. The absence of organic material will result in low microbial activity. High levels of organic material however will cause adsorption of contaminants and can result in microbial activity focusing on naturally occurring organics instead of the target contaminants, resulting in longer remediation times and/or high end values. An organic content between 0 - 5 % is most optimal for bioremediation.

Biological activity can be estimated by measuring the ability of the soil to consume oxygen (respiration tests). Oxygen consumption measurements can either be performed in the laboratory or in situ. Bacterial counts can be used as an indicator for biological activity, but is of less value compared to respiratory tests.

When high levels of biodegradable contaminants are present in the soil, oxygen consumption will be higher compared to the consumption in a clean soil. If the oxygen consumption is equal to the consumption in a clean soil then biological removal processes are no more functioning (due to e.g. a shortage of nutrients or a decreased bioavailability of contaminants). This may lead either to additional measurements to re-establish (addition of nutrients or addition of surfactants to increase bioavailability) or to the end of the in situ operation when remediation goals are met.

To monitor the biological process in soil when operating biosparging and bioventing at a site, it is recommended to monitor the O_2 level in the groundwater and the O_2 and CO_2 levels in the soil vapor.

2.3 Remediation time and end values

The remediation time of the biosparging process and the final contaminant levels in soil depend on the specific conditions present at a polluted site.

The final contaminant levels or end values of the remediation process differ significantly, depending on the above mentioned conditions. Gasoline-like contamination (C_6 - C_{14} volatile and aerobically degradable) can be removed completely from the soil. Diesel-like contamination (C_9 - C_{26} non volatile and aerobically degradable) may be removed up to 60 to 80 % of their initial levels in soil, due to the presence of a substantial amount of low soluble and branched hydrocarbons. It must be noted that the given percentages are average values and depend on the initial concentrations in the soil and the conditions mentioned above. Heavier hydrocarbons (> C_{25}) cannot be treated by IAS or SVE.

Plume remediations (groundwater) with IAS may result in 60 to more-over 99 % reduction of groundwater levels. It is generally believed that sparging can completely remediate water dissolved petroleum hydrocarbons. If however LNAPL is still present a *rebound* is likely to occur, appearing several weeks up to months after the sparging has ceased [Bass, 1996].

Especially for heavy hydrocarbons (> C_{15}) special attention has to be paid to the presence of free product LNAPL. Free product removal will have to be performed to achieve acceptable end values. However even after an in situ removal of free product, followed by IAS, rebound effects will have to be accounted for.

Rebound
The concentrations of contaminants in the groundwater and soil vapor have often been observed to increase in the initial period after shutdown of the sparging system. This increase in concentration is called 'rebound'.

For more details on the rebound effect is referred to section 9.2.

2.4 Geotechnical aspects

When operating an air sparging process, the injection pressure is an important parameter. The injection pressure is often restricted to maximum values with respect to the possible geotechnical effects on the soil matrix.

2.4.1 Pile settlement

A high injection pressure can result in a lowering of the effective stress of the soil. When for example a pile for foundation is present within a few metres of the injection well, the bearing capacity of this pile can be affected, if the pile is (partly) founded on vertical friction. This is called ***pile settlement***. The possibility of adverse effects of pile settlement, in terms of damage, not only depends on the soil characteristics and the reduction in effective stress, but also strongly depends on the type of construction. Whether the construction is a storage tank, fully or partially filled, a pile foundation or a pipeline, is an important factor. The sensitivity of the construction and its condition determine the extent of the geotechnical evaluation necessary.

Case 1 - groundwater level below soil level

$$P_{inj} < \gamma_d \cdot (h_s - h_w) + (\gamma_s - \gamma_w) \cdot (h_w - h_t) + \gamma_w \cdot (h_w - h_{wf,act.}) \quad (1)$$

Case 2 - groundwater level above soil level

$$P_{inj} < (\gamma_s - \gamma_w) \cdot (h_s - h_t) + \gamma_w \cdot (h_w - h_{wf,act.}) \quad (2)$$

With:

- P_{inj} is the injection pressure (kN/m^2);
- γ_d is the dry unit weight of soil (kN/m^3);
- γ_s is the wet unit weight of soil (kN/m^3);
- γ_w is the unit weight of water (kN/m^3);
- h_s is the soil level;
- h_w is the (ground)water level;
- h_t is the level of the sparging well (top);
- $h_{wf,act.}$ is the actual water level in the sparging well.

All the levels are related to the reference level in m.

Case 1 is generally applicable. Case 2 may be applied to sites located harbours or other waters. It describes the effects of IAS on under water sediments.

2.4.3 Crack formation

When air is injected with a pressure that exceeds the total soil pressure, undesirable cracks (or fractures) can be formed in the soil. This ***crack formation*** is an irreversible process and can have an adverse effect on the air distribution in the soil and thus on the effectiveness of the sparging process.

On the other hand, in some cases cracking can actually improve channel distribution. The technology known as fracturing focuses on the deliberate creation of fractures in low permeability soils to improve soil permeability. Air (or liquid) is injected with pressures up to 200 to 300 kPa, during short periods of time [CUR/NOBIS, 1997].

However, generally cracking of the soil must be avoided, so the injection pressure applied must be lower than the total soil pressure. This maximum injection pressure is as high as the pressure caused by the complete soil and water column above the top of the sparging filter.

γ_d is the dry unit weight of soil (kN/m^3);
γ_s is the wet unit weight of soil (kN/m^3);
γ_w is the unit weight of water (kN/m^3);
h_s is the soil level;
h_w is the (ground)water level;
h_t is the level of the sparging well (top);
$h_{wf,act.}$ is the actual water level in the sparging well;
$h_{wf,eq.}$ is the water level in the sparging well at equilibrium.

In most cases $h_{wf,eq.}$ equals h_w, except when dealing with differences in hydrostatic pressure (in seepage and infiltration zones).

It is clear from the given equations that liquefaction will occur more easily than cracking of the soil, especially when dealing with homogeneous and sandy soils. So when the maximum injection pressure must be calculated for a given situation, the formulas (1) and (2) provide the greatest safety factor.

Chapter 3

Remediation concepts

Sparging and venting can be applied for several remediation concepts. The following concepts can be determined:

- *Source treatment*
  The contamination is present as mobile or non-mobile LNAPL or DNAPL. Remediation is focused on the pure product removal from the source.
- *Plume treatment*
  The contamination is dissolved in groundwater, there is no pure LNAPL or DNAPL present. Remediation is focused on removal of the contamination from the plume.
- *Containment*
  Contamination is present dissolved in groundwater. Remediation focused on interception and prevention of migration of contamination through groundwater.

A source treatment of contamination requires a sparging system with closely spaced injection wells, based on the aeration radius, and with intensive air injection sequences. To ensure a high stripping effect, the air channels will physically have to be in contact with the contamination. Biological processes take place in or close to air channels. Full biological removal of sources generally is a time consuming process because the mass transfer of dissolved oxygen to and in groundwater is insufficient for a fast clean-up due to the high oxygen demand. Therefore a high channel density is required in the source area.

Generally IAS is not applied to dissolved plumes. The dissolved plume is usually allowed to attenuate naturally when the source area is remediated or contained. IAS, used as a downgradient barrier for containment of a plume involves a less intensive system than for source treatment. Well spacing can be based on the estimated radius of influence. The screen is placed perpendicular to the groundwater flow. IAS aerates the groundwater resulting in elevated DO levels. The removal processes (volatilization and biodegradation) determine air injection frequency. Oxygen consumption rates will be low due to the low contaminant mass and hence biodegradation activity. By diffusion and micro scale mixing oxygen will be distributed. Treatment time is infinite, as long as the source is not removed.

3.2.2 Floating layers/LNAPL

When a LNAPL of more than 5 - 10 cm thickness is present, other methods like MPVE or SVE must be considered.

The mobilization of LNAPL when air sparging is initiated is sometimes misinterpreted as lateral mobilization of LNAPL, but in fact it is usually a good thing, because the resulting floating layer is much easier to remediate using soil vapor extraction or other product recovery methods than is residual product trapped below the water table.

a non permeable layer is reached. The aeration radius of an IAS injection well that is placed just at or in the non permeable layer is relatively small at the injection point. The effect of IAS on pools of DNAPL on top of a non permeable layer is therefore limited.

Technologies such as steam injection, that can create a stable unsaturated zone, that can be treated by a lateral flow of steam, are considered to be more suitable for treatment of DNAPL.

The zone above the pool of DNAPL up to the groundwater table may however be treated successfully by IAS. The main process of removal is volatilization. An SVE system should capture volatilized contaminants.

IAS may initially result in mobilization of trapped DNAPL, increasing levels of contamination in groundwater monitoring wells. After several injection periods, concentrations will decrease to below pre-sparging levels.

To give an impression of the applicability of IAS and SVE in the Netherlands, the different soil types are simplified into archetypes. With the risk of overlooking specific soil types, four archetypes are distinguished.

Contaminated sites and in situ remediation systems are described in the context of different archetypes to derive generally applicable rules.

1. Homogeneous soil.
2. Homogeneous soil with a partly saturated low permeable or high organic matter top layer.
3. Cultivated territories (typical for Amsterdam and Rotterdam harbor).
4. Heterogeneous multi-layered soil.

3.2.4 Archetype 1: Homogeneous permeable soil

Archetype 1 is typical for homogeneous sandy soil layers, as they are found in the eastern and southern part of the Netherlands (see Fig. 3.1).

Remedial options
1. IAS/SVE system (source or plume treatment).
2. Bioscreen of sparging wells (containment).

Experiences
Source/plume remediation (see Fig. 3.2).
Bioscreen (see Fig. 3.3).

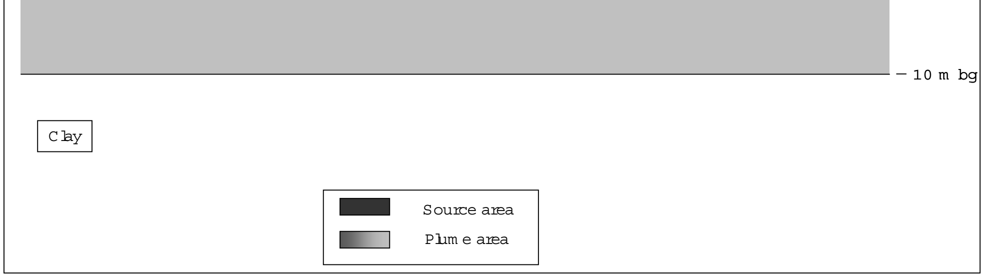

Fig. 3.1 Archetype 1.

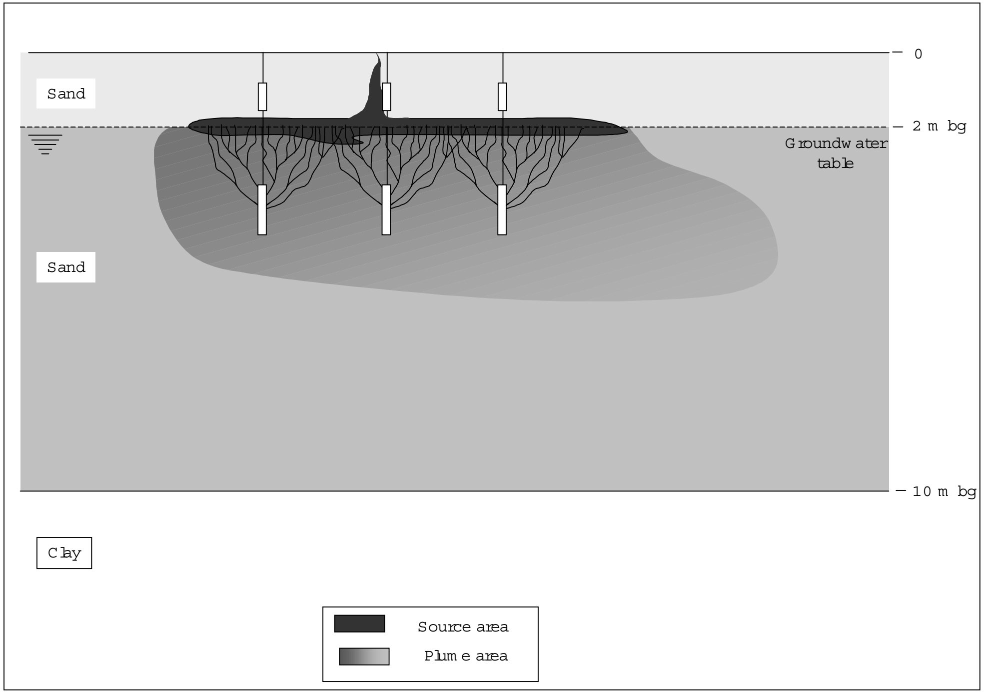

Fig.3.2 Sparging source zone in archetype 1.

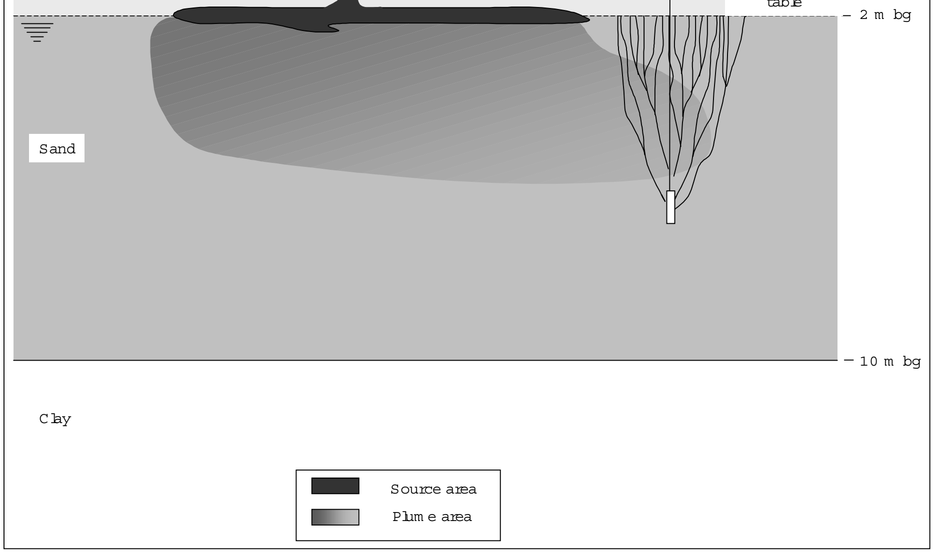

Fig. 3.3 Sparging bioscreen in archetype 1.

3.2.5 Archetype 2: Homogeneous with partly saturated low permeable or high organic matter top layer

Contamination is migrated through the low permeable layer (see Fig. 3.4).

Remediation options
Most preferable is to remove the top layer by excavation. After improving physical structure of the soil, 'in situ' landfarming of the top layer above the groundwater table is possible.

Complete in situ options:

1. Biosparging and bioventing system. Injected air may have to be withdrawn from air pockets to prevent uncontrolled migration of soil vapour. Optionally intensive soil venting system in the top layer (source/plume treatment).
2. Bioscreen of sparging wells (containment).

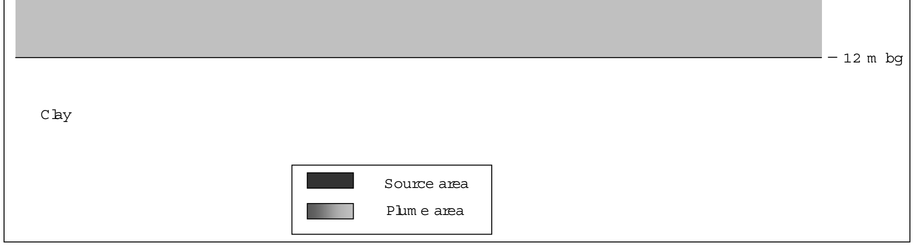

Fig. 3.4 Archetype 2.

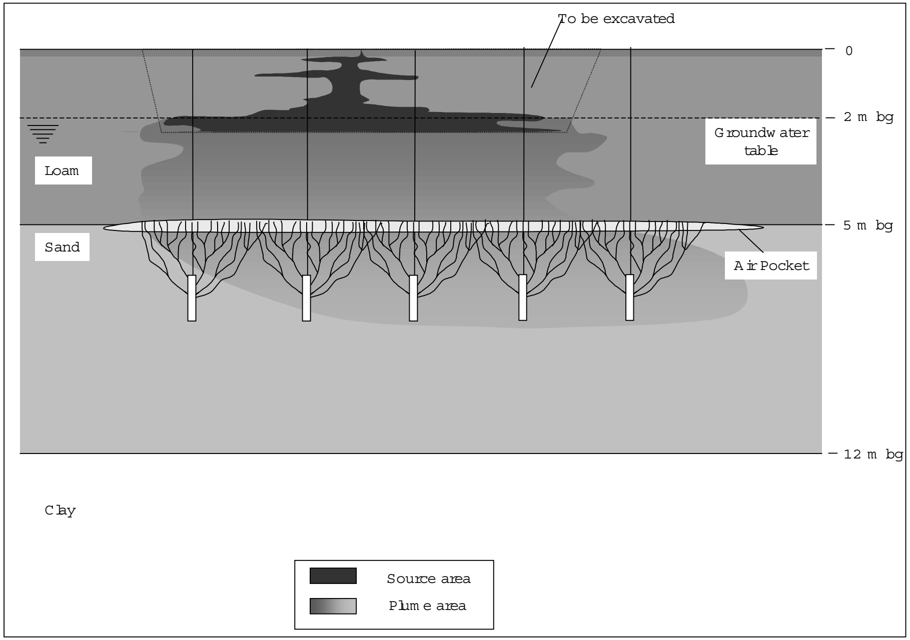

Fig. 3.5 Sparging source zone in archetype 2.

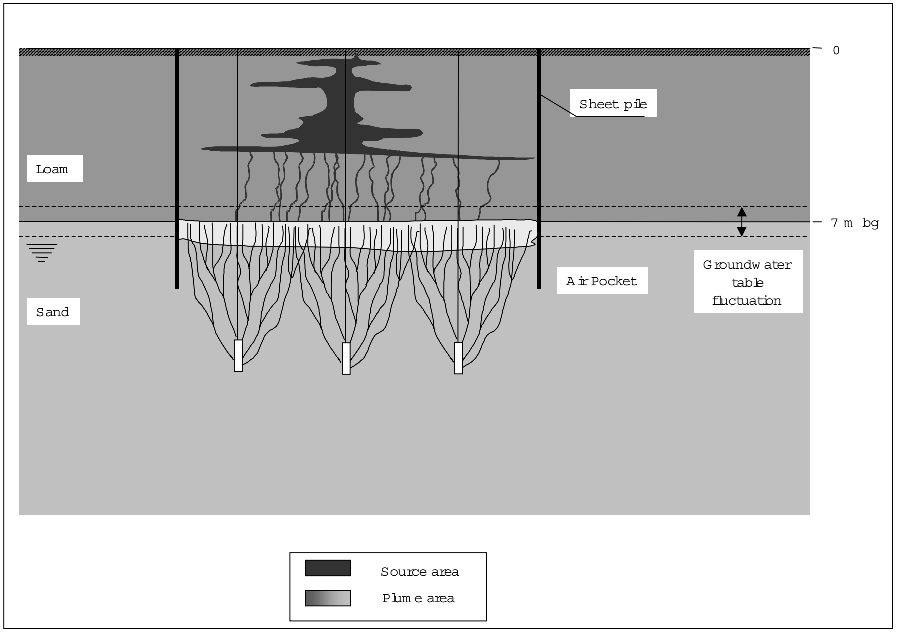

Fig. 3.6 Sparging of source zone in NOBIS project 'HEISA' [CUR/NOBIS, 1999a].

The contamination, which had migrated through the root channels, could be removed effectively by sparging underneath the low permeable soil. The air did however not accumulate beneath the clay layer due to air transport through the root channels present in the clay matrix.

Several bioscreens based on sparging have been implemented and proven to be effective and low in maintenance cost (see Fig. 3.7).

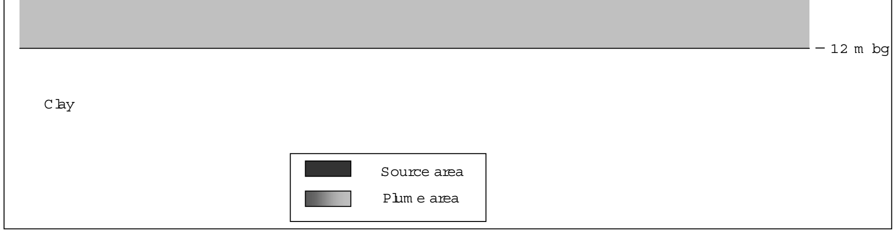

Fig. 3.7 Sparging bioscreen in archetype 2.

3.2.6 Archetype 3: Cultivated industrial areas

The cultivated industrial areas are typical for the Rotterdam and Amsterdam harbor area and many other industrialized sites. The area is raised by a 3 to 5 m sandy layer on top of the old soil surface. The sandy layer may be highly stratified with small layers of high and low permeable material due to the process of wet sand filling. Depending on physical behavior the contaminants may have migrated through the low permeability layer into stratified and more sandy layers (see Fig. 3.8).

Remediation options

1. Sparging in the top layer requires an intensive sparging system. Effectiveness may be low due to low vertical permeability. Sparging in second layer is possible (see archetype 2). Injected air may possibly have to be withdrawn from air pockets by release wells to prevent uncontrolled migration of soil vapour (source and plume treatment).
2. Bioscreen of sparging wells (containment) either in the top soil or in the deeper groundwater.

Experiences

Sparging/venting (see Fig. 3.9 and Fig. 3.10).
Bioscreen (see Fig. 3.11).

The sparging system in the top soil in general is comparable to the system in archetype 1. Special attention has to be paid to air distribution due to the high stratification of the soil. An injection of air on multiple depths within the top soil and the deeper soil will have to be considered to achieve optimal air distribution (see Fig. 3.9).

A remediation of an LNAPL, present in the underlying stratified layers, based on sparging was tested in the NOBIS project nr. 95-1-16 in Rotterdam (see Fig. 3.10) [CUR/NOBIS, 1998]. The research proves that aeration and bioremediation of the LNAPL in the sandy layer was possible. The air injection also caused migration of the free product.

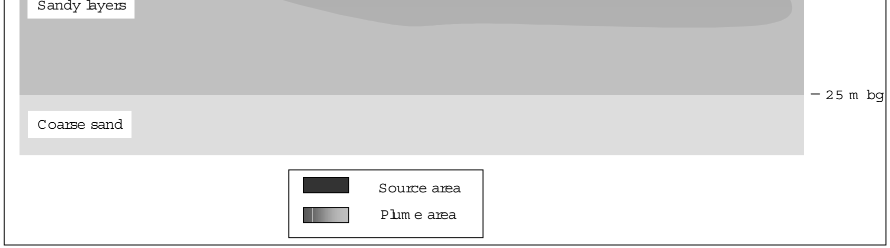

Fig. 3.8 Archetype 3.

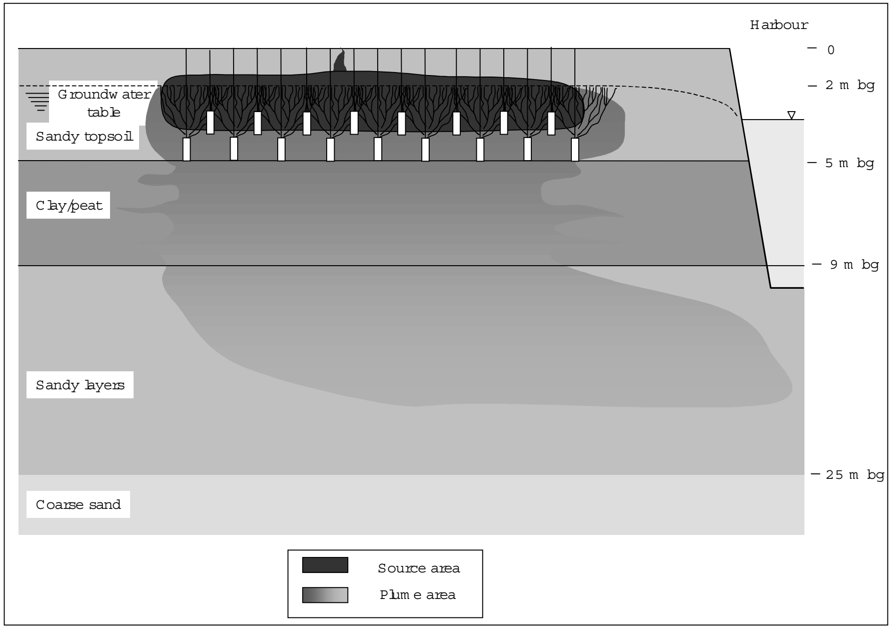

Fig. 3.9 Sparging source zone in archetype 3.

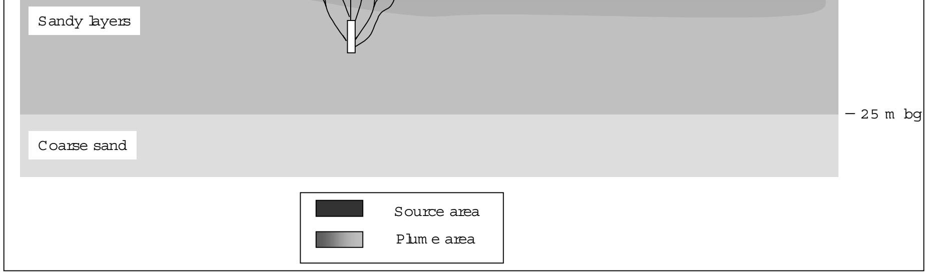

Fig. 3.10 Sparging of source zone in NOBIS project nr. 95-1-16 [CUR/NOBIS, 1998].

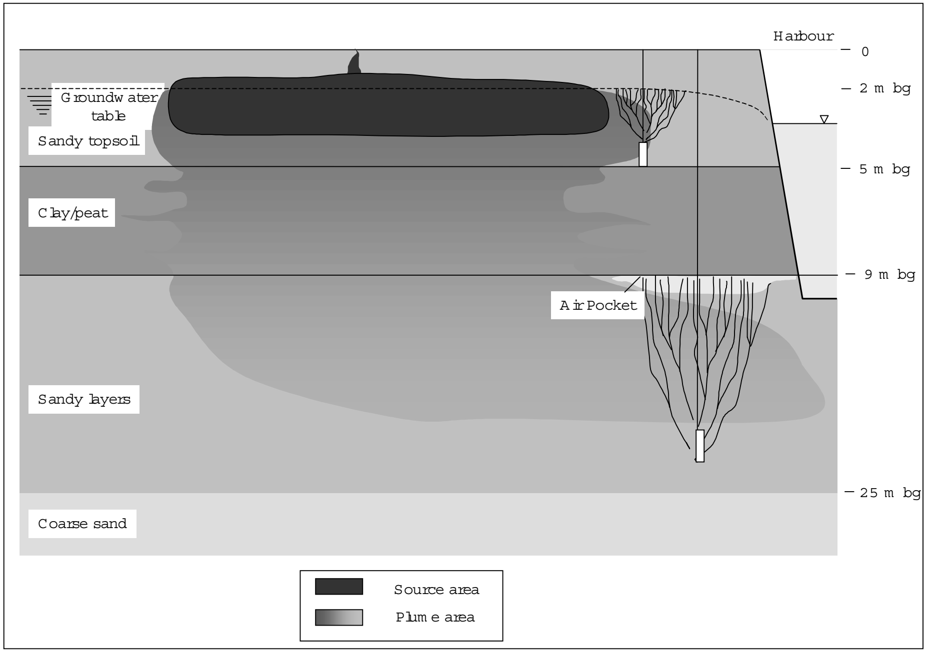

Fig. 3.11 Sparging bioscreen in archetype 3.

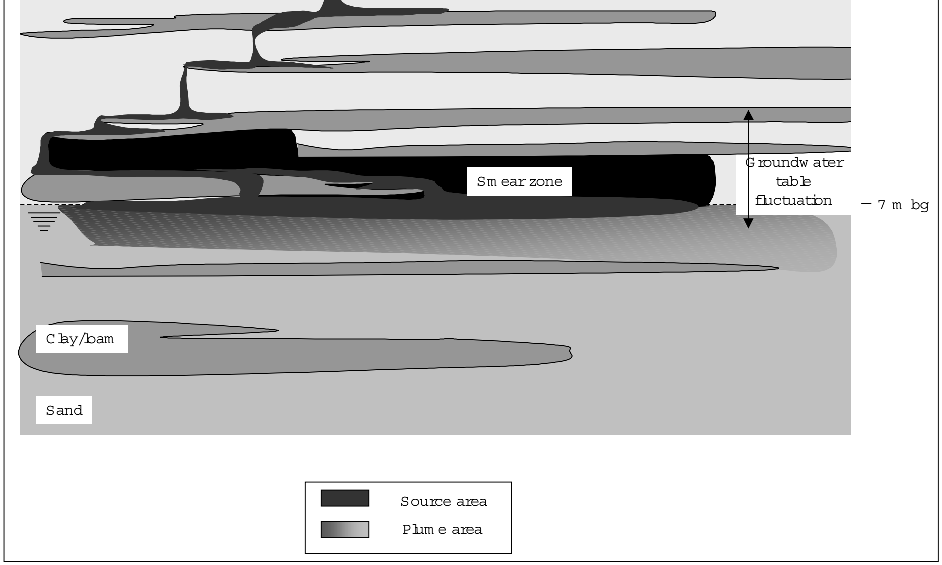

Fig. 3.12 Archetype 4.

Remedial options

1. Sparging in lower sections may be possible if a reasonable radius of influence can be achieved. Otherwise groundwater extraction and bioventing should be carried out (source and plume treatment).
2. Bioscreen of sparging wells (containment).

Experiences

Sparging/venting (see Fig. 3.13).

The technology may be applicable provided that a high intensity sparging system is installed. The technology was investigated at the EPON site in Nijmegen [NOBIS proj. nr. 95-1-13, Technical report, Monitoring progress in situ remediation, January 1997] (see Fig. 3.13).

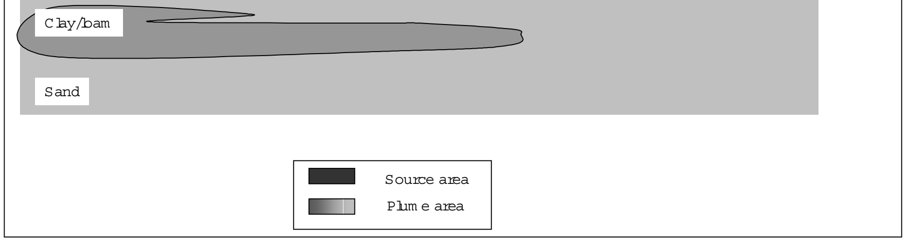

Fig. 3.13 Sparging source zone in archetype 4.

3.3 Sparging related technologies

Several sparging and sparging related technologies are practiced. In this section three technologies are described that are in some manner related to the sparging.

UVB
A special type of in situ sparging-like system is the UVB (Unterdruck Verdampfer Brunnen) system (see Fig. 3.14). The system consist of a deepwell which is perforated on a shallow and on a large depth. The water in the deepwell is aerated by a vacuum system. The aerated water is infiltrated in the soil in another section of the deepwell. The UVB system creates an upgradient or downgradient flow of water in the deepwell by pumping of the water from one compartment to the other.

The technology is often compared with sparging, but the mechanism of remediation is principally different from sparging of air directly into the soil. The aerated water within the deepwell is the main supplier of oxygen to the soil, whereas in sparging the soil is aerated by direct contact of air and soil. The technology is therefore not considered a sparging technology.

IWAS
The IWAS (In Well Air Sparging) system is comparable to the UVB system and also consists of a deepwell which is perforated on a shallow and on a large depth. The IWAS systems creates an up-gradient water flow in a deepwell, due to the injection of air in the well (air lift) created by injection of air in the deepwell (see Fig. 3.15).

The IWAS system has comparable technology specifications as the UVB system, and is also not considered a sparging technology.

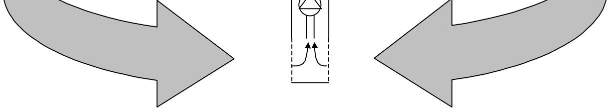

Fig. 3.14 UVB system.

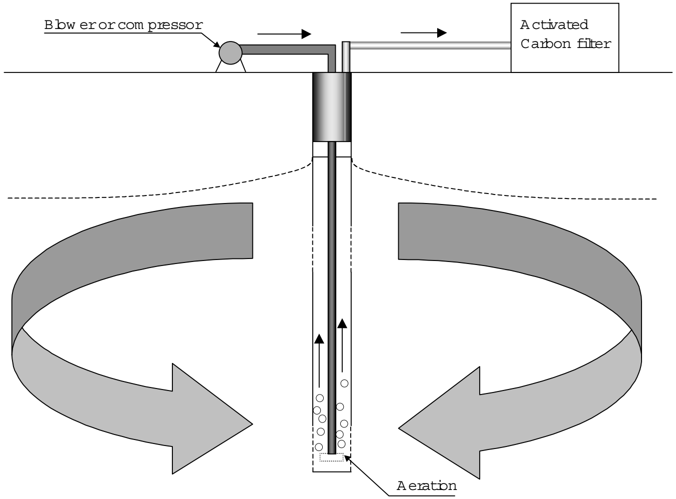

Fig. 3.15 IWAS system.

C-Sparge™

A sparging system can be used to introduce ozone into the soil. Ozone is a very reactive chemical that can oxidize organic compounds. The C-sparge™ system is a system that injects ozone into the soil and at the same time creates a groundwater flow around the sparge well with a UVB-like water recirculation system. The C-sparge developers claim that micro bubbles created by a fine screened injection well, will remain as bubbles in groundwater (see Fig. 3.16). The micro bubbles are transported through the soil. The distribution is enhanced by a UVB-like system.

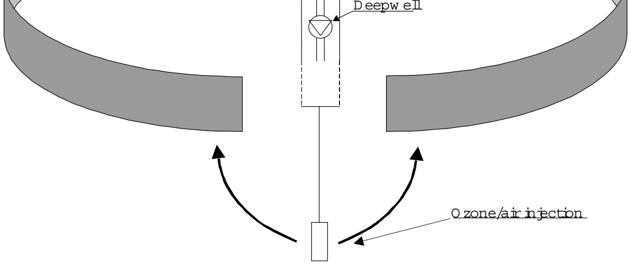

Fig. 3.16 C-Sparge™ system.

Chapter 4

Feasibility studies and modelling

4.1.1 Site characteristics

With respect to site information that is necessary to decide whether sparging is applicable, the following aspects are of importance:

- geological information of the site;
- geohydrology of the site;
- soil profile and stratification (incl. organic matter content);
- presence and thickness of floating layer;
- water table fluctuation interval;
- extent of the soil contamination;
- depth of the contamination;
- basis of the aquifer.

The most important parameter is the soil permeability and stratification, reflected in the K-factor. The organic matter content is of importance because of its influence on the adsorption/desorption ratio of the contamination in the soil. Tables 4.1 and 4.2 describe the applicability of IAS based on the permeability and the organic matter content of the soil.

Table 4.1 Applicability of sparging based on soil type and permeability.

Soil type	K-factor (m/day)	In situ treatment by IAS possible?
Gravel	> 100	Yes
Very coarse sand	10 - 100	Yes
Coarse sand	5 - 10	Yes
Fine sand	0.5 - 5	Yes
Loam	< 0.5	Yes/No*
Clay	< 0.5	Yes/No*
Peat	< 0.5	Yes/No*

* Also for clayey and loamy soils, in some cases current techniques has been proven successfully [CUR/NOBIS, 1998; CUR/NOBIS, 1999a]. Pilot testing is however recommended.

Table 4.2 Applicability of sparging based on soil organic matter content.

Organic matter content in %	In situ treatment by IAS possible?
0 - 1 low	Yes
1 - 5 medium	Adsorption can cause long remediation time and/or high end values
> 5 high	Adsorption will cause long remediation time and/or high end values, possible settlement due to oxidation of organic matter

		Non-come-tabolic	Come-tabolic			
Hydrocarbons						
Gasoline (C_4 - C_{12})	+	+		-	+	Yes
Kerosine (C_6 - C_{15})	±	+		-	+	Yes
Gasoil (C_9 - C_{26})	-	±		-	- *	Yes
Domestic fuel (C_9 - C_{24})	-	±		-	- *	Yes
Lubricants (C_{15} - C_{40})	-	-		-	-	No **
Aromatics (BTEX)						
Benzene	+	+		+/-	+	Yes
Toluene, Ethylbenzene, Xylenes	+	+		+	+	Yes
Poly Aromatic Hydrocarbons						
light (2-3 rings)	±	+		-	± *	Yes
heavy (4-5 rings)	-	-		-	- *	No **
Chlorinated Hydrocarbons						
PCE, TCE, Cis-chloroethenes	+	-	+	+	+	Yes
Chloorbenzene	+	+		-	+	Yes
Pesticides	-	±		-	-	No **
PCB	-	-		-	-	No **
Other compounds						
MTBE	±	±		-	+	Yes

* Solubility can be enhanced by detergents.
** Using current techniques a successful short term remediation cannot be guaranteed. However, in future, in situ techniques may be available for the removal of these 'non-degradable' compounds. For the present, longterm control combined with extensive remediation may be an option.
$ IAS may be used in conjunction with SVE, when risks may occur as a result of volatilization of volatile compounds.

It must be emphasized that IAS is not a suitable technique to remove heavy oil components (C_{25} - C_{40}). Biological decay is slow and incomplete.

4.1.3 Above ground and subsurface infrastructure

The presence of infrastructure may obstruct the execution of sparging. It may not be possible to install vertical injection or extraction wells at built-on areas.

The installation of sparging horizontal wells using the directional drilling technique is a possible option. A small thickness of the treatable zone below a building (< 1 m) and the presence of foundation however may obstruct the installation of the drains. The use of horizontal wells for sparging has however not been widely implemented. The main issue related to the use of horizontal wells is the uncertainty on the distribution of the injected air over the length of the drain.

The target clean-up values are determined in consultation with the authorities. These clean-up values may be based on strict regulatory values or on risk based values.

4.2 Pilot testing

4.2.1 General

The primary goal during standard pilot testing is to look for impossibilities of sparging. For testing the applicability of IAS for contaminants of which the behaviour is not yet studied, laboratory research, like column and batch experiments, are recommended (see table 4.4). During these experiments the soil parameters and biodegradation rates are determined. Through modelling, the results of the laboratory experiments will have to be extrapolated and translated to field conditions.

Table 4.4 Laboratory feasibility studies.

Laboratory experiments		
Goal	***Methods***	***Estimated duration***
Determination of equilibrium adsorption	Batch experiment	2 days
Determination of biological processes	Batch experiment	1 week
Determination of sorption	Column experiment	4 weeks
Determination of sorption and biodegradation	Column experiment	6 weeks

If the feasibility of the technology in the field is uncertain, the feasibility can also be tested in pilot tests under field conditions at selected parts of a site (see table 4.5). In these experiments process parameters are monitored during the sparging process.

The results of laboratory and/or field experiments are combined with earlier collected soil investigation data in order to predict the effectiveness of remediation techniques at full scale.

Table 4.5 Field feasibility studies.

Field experiments		
Goal	***Methods***	***Estimated duration***
ROI sparging and venting	1 sparge well and 6 vent wells, several vapour and groundwater monitoring wells	4 weeks
ROI sparging and venting + estimation of stripping vs biological processes	1 sparge well and 6 vent wells, several vapour and groundwater monitoring wells	6 weeks
Estimation of biological and stripping processes	Push pull test 1 sparge well	1 week
Mapping stratification	Soil boring with continuous mapping	few days

should be investigated using sulfur hexafloride (SF_6) as a tracer gas or another tracer as an analog. SF_6 is an inert gas that has comparable properties to oxygen. In Appendix C a SF_6 pilot test is described [Johnson et al., 1996a].

When as result of sparging volatilized contamination migrates to areas of concern, sparging should be used in conjunction with SVE. To investigate the recovery of injected air by SVE, a helium tracer test is recommended. This test is described in Appendix D [Johnson et al., 1996a].

The biodegradation rate can be determined by:

- laboratory tests;
- in situ respiration tests;
- estimate from a database from past experience.

Biodegradation rates found in groundwater generally range from 0 - 5 mg C/kg d^{-1}. In soil vapour rates are higher and generally range from 0 - 10 mg C/kg d^{-1}.

Table 4.6 Overview of methods for determination of ROI of sparging.

Method	Parameter	Application/remarks
Dissolved oxygen	Oxygen in groundwater	Routine in piezometers, not routine in discrete monitoring points
Pressure	Overpressure in soil	Few applications; can give overestimate of ROI, when measured in the vadose zone
Groundwater mounding	Groundwater level in piezometer	Routine but can overestimate ROI
Helium tracer	He in soil gas	Only research projects (Europe) Routinely used (US)
SF_6 tracer	SF_6 in soil gas and groundwater	Only research projects (Europe) Routinely used (US)
ERT (Electrical Resistance Tomography)	Water saturation	Only research projects
TDR (Time Domain Reflectometry)	Water saturation	Very few applications
Neutron probe logging	Water saturation	Few applications in research
Radar GPR	Water saturation	Very few applications in research

The determination of the in situ degradation rate with a laboratory test is difficult, because the structure of the soil sample, the temperature and the moisture content must be identical to the field situation. In most cases in a laboratory experiment the maximal biodegradation rate is determined. Field tests are expected to be more suitable for determination of the actual in situ degradation rate.

and expense, and is only worth while for this purpose on the largest sites.

4.2.2 Setup of a standard pilot test

The primary goal during standard pilot testing is to look for impossibilities of sparging. The important questions that are addressed are:

1. can the air be injected into the soil at the desired flow rate and pressure;
2. is the air distributed asymmetrically in the soil (i.e is sparge air deflected before it reaches the vadose zone).

The pilot usually is a one well test. For the installation of the well is referred to section 6.1.1. When using an existing monitoring well as injection well, the well must meet some minimal requirements: it must be sealed (grouted) below the water table and the well must be placed at least 1.5 m below the water table.

The number and the configuration of the monitoring wells depend on the budget available for the test. It is recommended to place the monitoring wells at three distances from the well (see Fig. 4.1 and Fig. 4.2). In case the depth from the water table to the top of the well screen exceeds 5 m, distances to the sparge well should be 3, 5 and 9 m. When the depth from the well screen to the water table is smaller, the radial distance of the monitoring wells should also be smaller (2, 4 and 7 m). When the depth interval of the contaminated zone - the treatment zone - is known, the monitoring wells should be placed in this interval. That allows to maximize the number of monitoring wells in that zone.

Small discrete monitoring wells (∅ 2.5 cm, screen length 20 cm) are recommended instead of the use of piezometers with large screens. Generally the wells are placed at two different depths. Advantage of the use of small discrete wells over the use of piezometers is the small dead volume (fast sampling) and the small chance of preferential aeration of the wells through air channels hitting the well. The use of discrete wells enables the installation of nested wells (wells at the same location at different depths). Nested wells should be used when the contamination is located over great depth.

It must be noted that monitoring wells have to be occluded and sealed at the top, to avoid preferential airflow through the wells. For the same reason nested wells should be separated by bentonite fill.

The monitoring wells placed in line should give insight in the ROI of the injection. The wells placed at the other sides must indicate whether the distribution of dissolved oxygen is anisotropic. If the wells already have oxygen in them (due either to previous operation or oxygen in the groundwater) using oxygen as the primary indicator for the size of the ROI is confusing. In this case a tracer like SF_6 or some other tracer as an analog should be used.

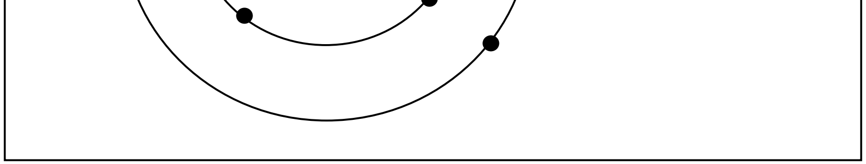

Fig. 4.1   Suggested configuration of monitoring wells during a standard pilot test.

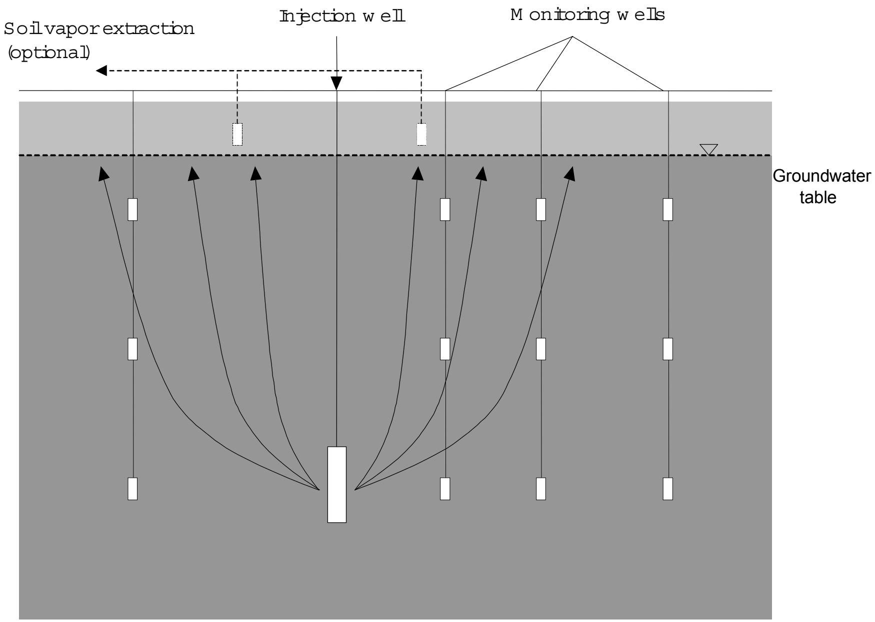

Fig. 4.2   Cross section of the standard pilot test.

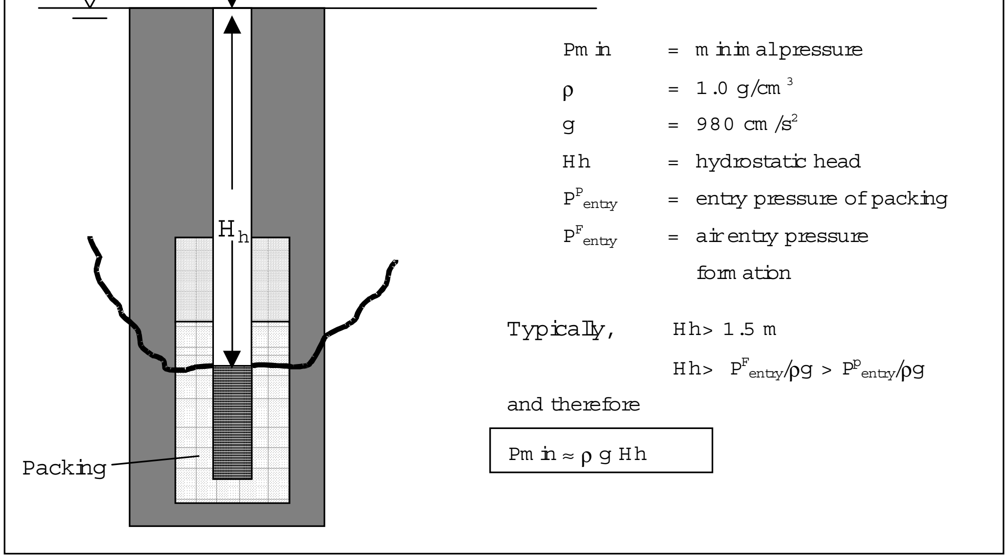

Fig. 4.3 Minimal air pressure.

Maximum pressure

When the maximum pressure at the desired flow rate is exceeded, IAS is not feasible at a site. The maximum pressure can be calculated as follows (see Fig. 4.4; see also section 2.4.2 equation (1)):

$$P_{inj} < \gamma_d \cdot (h_s - h_w) + (\gamma_s - \gamma_w) \cdot (h_w - h_t) + \gamma_w \cdot (h_w - h_{wf,act.})$$

With:

- P_{inj} is the injection pressure (kN/m^2);
- γ_d is the dry unit weight of soil (kN/m^3);
- γ_s is the wet unit weight of soil (kN/m^3);
- γ_w is the unit weight of water (kN/m^3);
- h_s is the soil level;
- h_w is the (ground)water level;
- h_t is the level of screen of the sparge well (top);
- $h_{wf,act.}$ is the actual water level in the sparge well.

All the levels are related to the reference level in m.

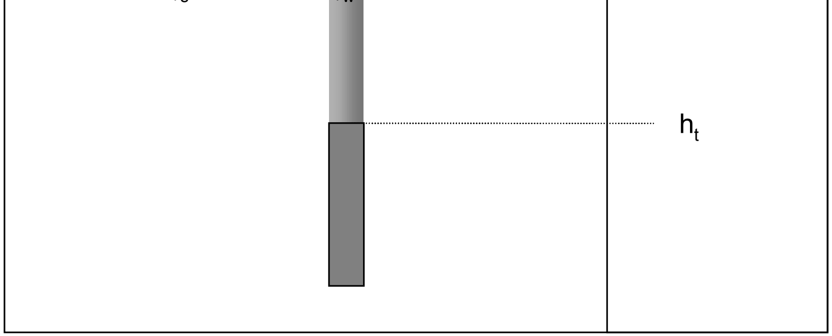

Fig. 4.4 Injection well filled with water.

To calculate the maximum injection pressure, an example is given. In table 4.7 the essential parameters are given.

Table 4.7 Example values for the parameters to calculate the maximum injection pressure.

Parameter	Description	Value	Unit
γ_d	Dry unit weight of soil	1500	kN m^{-3}
γ_s	Wet unit weight of soil	1700	kN m^{-3}
γ_w	Unit weight of water	1000	kN m^{-3}
h_s	Soil level	0	m
h_w	(Ground)water level	-2	m
h_t	Level of top sparging well	-6	m
$h_{wf,act}$	Actual water level in well	-2	m

Hence the injection pressure during the start up (when the well is filled with water) must be limited to:

$$\{1500 \cdot 2 + (1700 - 1000) \cdot (-2+6)\} \cdot 9.8 = 57 \text{ kPa} \quad (0.57 \text{ bar})$$

When the well is empty (during sparging) than $h_{wf,act.}$ equals -6 m. The maximum allowable pressure then becomes:

$$\{1500 \cdot 2 + (1700 - 1000) \cdot (-2+6) + 1000 \cdot (-2+6)\} \cdot 9.8 = 96 \text{ kPa} \quad (0.96 \text{ bar})$$

injection and the vadose zone.

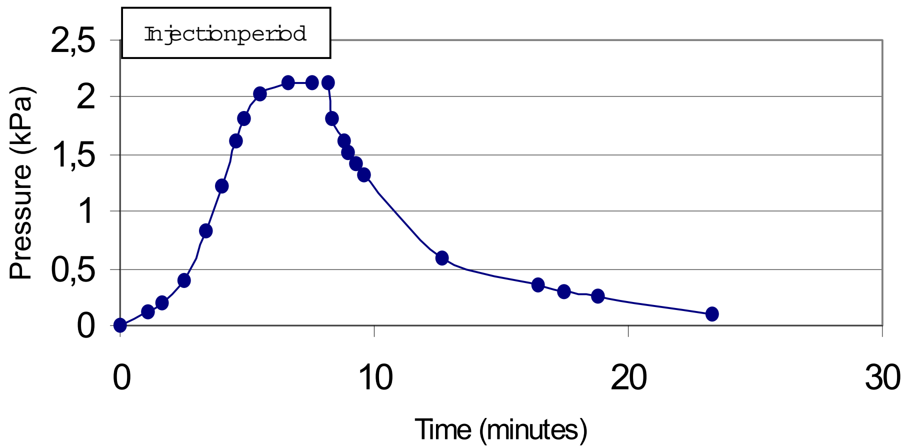

Fig. 4.5 Pressure at a groundwater monitoring well (3 m bgs) at 3 m distance of the sparge well (screen depth 8 m bgs).

Dissolved oxygen (DO) should be measured to examine the air distribution. It should be noted that the radius of influence based on the distribution of DO might be underestimated in contaminated areas. Low oxygen levels measured at a certain distance from a sparge well may be the result of a rapid consumption of the oxygen that has reached that point.

4.3 Modelling

A large number of models can be used for the design of sparging (and venting) systems. In the past years different models have been developed to describe the sparging process and its effects. In general models focus on two aspects of sparging:

1. determination of the aeration radius (MUFIS, TOUGH2, SWANFLOW);
2. determination of the mass transfer. Focuses on oxygen transfer, only used for research purposes (TOUGH2).

Chapter 5

Design

I. Installation:
   - the depth of the screen;
   - screen length;
   - the well diameter;
   - the well spacing.
II. Operation:
   - the injection regime (duration and frequency of the air injection);
   - the injection pressure and air flow rate.

5.2.1 Screen depth and screen length

Air injected in the saturated soil moves upward to the ground water table. Therefore, the screen must be installed beneath the contaminated zone. A depth of some meters beneath the contaminated zone is preferred, unless fine soil layer(s) between the injection well and the contaminated layer may prevent the vertical transport of the air. In this case the screen can be placed just beneath the contaminated zone.

For coarse soils and small injection rates the air escapes only at the top of the well because here the hydrostatic pressure is lowest. Then the screen length can be very small (for instance 0.5 m). In finer soils the air may escape through the whole screen length, depending on the homogeneity of the soil. As the screen length increases, the injection rate can be larger and the aeration radius increases.

Special attention on the screen depth must be paid in sensitive locations such as locations close to or in open water. Soil liquefaction may occur (see section 2.4.2).

5.2.2 Well diameter

The required well diameter depends on the injection rate and the soil permeability. Adjusting the well diameter to the injection flow rate can prevent an excessive pressure drop in the injection well pipe. Inner injection well diameters of 25 mm or higher are usually sufficient to prevent significant pressure drops at the injection flow rates used in sparging.

5.2.3 Well spacing

The required well spacing depends on the aeration radius and on the design concept (see section 5.3). The soil characteristics and the injection flow rate determine the aeration radius. In section 5.4 the estimation of the aeration radius from the soil characteristics and the injection rate is described.

5.2.4 Injection regime

When IAS is applied to enhance biological degradation of the contamination, sparging after the breakthrough of the water table has limited efficiency. Because air is flowing though preferential density within the aeration radius but will only slightly increase the aeration radius.

The injection pressure is however limited by:

- *Risk of crack formation*. If the pressure in the well increases, the soil pressure cracks can be formed. Crack formation is an irreversible process. A filter in cracked soil does not function well.
- *Risk of soil liquefaction*. Especially when dealing with coarse sandy soils and locations close to or in open water, a high injection pressure can cause the soil to be 'liquefied'.
- *Risk of pile settlement*. Within a few meters of the injection well the effective stress of the soil decreases. If the pile is (partly) founded on vertical friction, this can have consequences for the bearing capacity of the pile. Then this effect should be evaluated.

The airflow rate may be a limiting factor itself, in case of technical limitations (e.g. blower capacity).

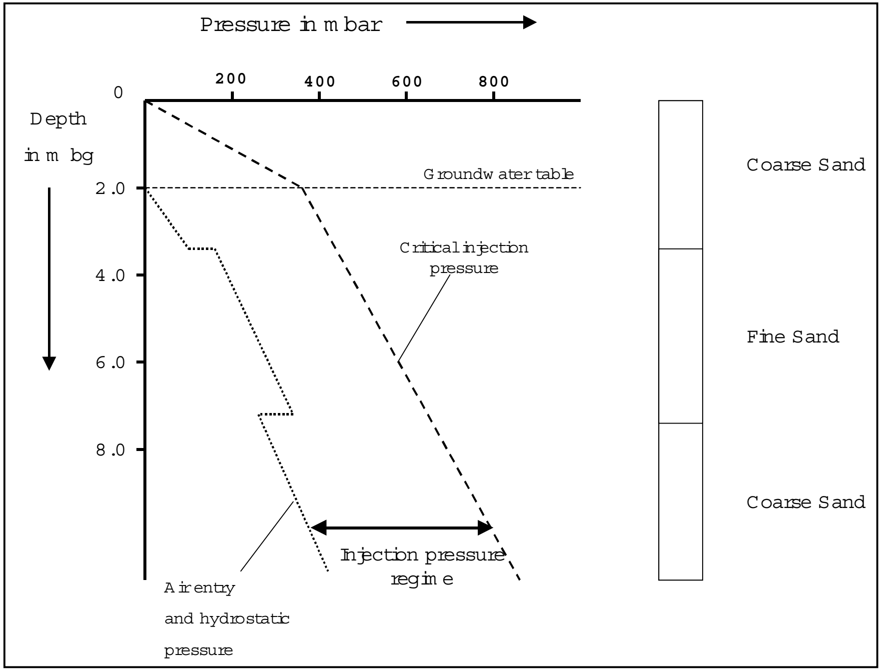

Fig. 5.1 Air pressure limitations.

The design approach for small sites (~ 200 m^2) with LNAPL contamination is a standard approach, based on expert judgement. In most of these 'simple' cases the number of wells is limited and not very critical for the cost of the installation. Based on the soil and contaminant characteristics (LNAPL) and previous experience the air injection system is designed.

Typical parameters used in practice are:

- a well depth of 3 to 4 m below the groundwater table (depending on the orientation of the contamination);
- a screen length of 1 m;
- an internal diameter of 40 to 50 mm (HDPE);
- well spacing of approximately 5 m;
- injection pressure of 80 kPa to 150 kPa;
- pulsed air injection with an average airflow rate of 5 to 20 m^3/hour.

5.3.2 Field experiments

Field experiments are generally considered as the most reliable design method. The design parameters determined during a field test are:

1. *Air distribution* by monitoring of:
   - Oxygen level. The oxygen level is measured in the groundwater at different distances from the injection well. The interpretation of the results for the determination of the well spacing is complicated because in the beginning of the process much oxygen is consumed near the injection well. In the course of time the oxygen level will rise (see also section 2.1.2).
   - Inert tracer. The tracer level is measured in the groundwater (e.g. SF_6) or in the soil vapour recovery well (e.g. He) at different distances from the injection well. Although this is a better method (for determining the aeration radius) than monitoring the oxygen level, some difficulties exist concerning the choice of a suitable tracer.
2. *Injection pressure and flow rate*
   The injection rate and pressure are required for the design of the blower.

5.3.3 Model calculations

The flow of air in the saturated zone can be described with a multiphase flow model. Multiphase flow calculations can give an estimate of the distances between the air injection wells (aeration radius) and the capacity (pressure and flow rate) of the blower. For an accurate prediction of the aerated region a detailed knowledge of the soil profile and the soil properties is required. The most important properties are the intrinsic and relative permeability and the water retention curve. Multiphase flow modelling has found limited use in sparging design practice because it is complex and time consuming and therefore rather expensive.

small sparging systems a conservative design has only little effect on the total remediation cost.

In the following section a design method based on nomograms is presented.

5.4 Nomograms

5.4.1 Selection of the soil parameters

The nomograms are developed for the following soil types (see table 5.1). The properties of the soils are taken from Rijtema [Rijtema, 1969].

Table 5.1 Vertical water permeability of selected soil types for the simulation of the aeration radius.

Soil code	**Soil description**	**Vertical water permeability**	
		(m s^{-1})	**(m d^{-1})**
C	coarse sand	1.3×10^{-4}	11.2
MC	medium coarse sand	3.4×10^{-5}	2.9
MF	medium fine sand	1.3×10^{-5}	1.1
F	fine sand	5.7×10^{-6}	0.5

The occurrence of stratification has been taken into account in the anisotropy factor (1, 3 and 10). Soil stratification is reflected in the difference between vertical and horizontal (water) permeability in the soil. The anisotropy factor is the quotient of the horizontal permeability and the vertical permeability given in table 5.1.

In general the soil stratification will have to be derived from soil profiles. A certain amount of expert judgement is required to determine the anisotropy. Also the geological history of the soil may be an important factor in assessing the anisotropy factor.

Three different soil categories can be distinguished (see Fig. 5.2):

1. Coarse /medium coarse sands with no clear stratification - anisotropy factor 1 - 3.
2. Medium fine slightly stratified sands mixed with silty, clayey compounds - anisotropy factor 4 - 9.
3. Clearly stratified soils with less permeable layers of fine sand or silt. These layers may introduce a large deflection of air. In this case injection wells on multiple depths in each layer to be treated should be considered. The aeration radius has to be estimated for each layer separately. An anisotropy factor of 10 is found for instance in silty Holocene layers [Wit, 1963].

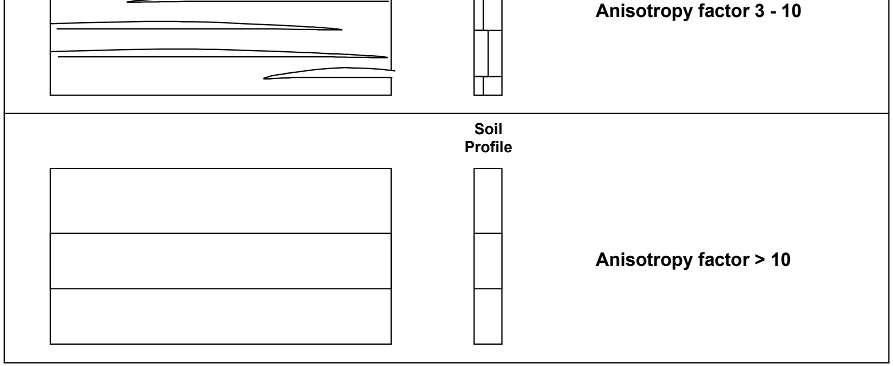

Fig. 5.2 Estimate of the anisotropy factor.

5.4.2 Selection of the system parameters

The selected parameters for the modelling, by which the nomograms were derived, are given in table 5.2.

The nomograms have been calculated for four different injection regimes, in order to show the possible effect on the aeration radius for the different soil types and anisotropy factors. For continuous air injection a period of 4 days was considered sufficient to reach steady state. The intermittent sparging regime calculated through several subsequent injections rounds until a steady state in aeration radius was observed (3 days).

The calculation of the nomograms has been performed using the model SWANFLOW (developed by the International Groundwater Modeling Center (IGWMC), 1994). For more information on the calculation of the nomograms we refer to the NOBIS project 'Biosparging and Bioventing' [NOBIS proj. nr. 95-1-3, Technical report, Modelling of Biosparging and Bioventing - Final report Phase 1 and 2, August 1997].

ground water table		contaminated layer (maximum depth 2 m below the ground water table). This is the typical position of the smear zone of petroleum hydro-carbon products and other contaminants that can be degraded aerobically.
Injection pressure	0.5 bar (50 Kpa) + h.p.*	This is the maximum pressure if an unsaturated zone of circa 1.5 m is assumed and if the maximum injection rate (50 m^3/h.) is not exceeded.
Injection rate	max. 50 m^3/h.	Only if the maximum injection pressure 0.5 bar (50 Kpa) + h.p.* is not exceeded.
Injection regime	continuous and pulsed	I Continuous II 0.33 h. injection and 2.66 h. rest III 0.66 h. injection and 2.33 h. rest IV 2 hours injection and 1 hour rest The duration of the cycle is 3 hours. This is based on the estimated consumption rate of the oxygen. If the aerobic degradation rate is low then the rest period can be lengthened.

* h.p.: hydrostatic pressure

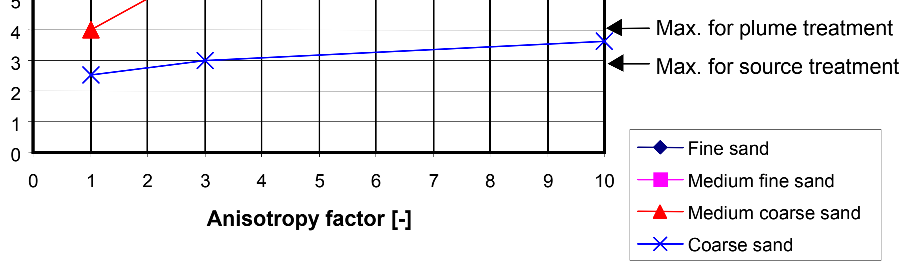

Fig. 5.3 Aeration radius for continuous air injection regime I.

Table 5.3 Pressures (p) and injection rates (φ_v) for continuous air injection.

Anisotropy factor	**Fine sand**		**Medium fine sand**		**Med. coarse sand**		**Coarse sand**	
	p* (bar)	φ_v $m^3/h.$	p* (bar)	φ_v $m^3/h.$	p* (bar)	φ_v $m^3/h.$	p* (bar)	φ_v $m^3/h.$
1	+0.50	10	+0.50	25	+0.50	50	+0.10	50
3	+0.50	20	+0.50	50	+0.20	50	+0.05	50
10	+0.50	50	+0.20	50	+0.05	50	+0.025	50

* In addition to hydrostatic pressure.

Figure 5.3 indicates that the aeration radius increases as the permeability decreases and the anisotropy factor increases. The nomograms indicate that in fine and middle fine sand with a large anisotropy factor aeration radii can be found of 15 and 16 m. This implies a well spacing of approximately 25 m. In practice the aerated region around the injection well will not be circular shaped. In most cases preferential flow in one or more directions will occur, especially at large distances from the injection well.

In practice continuous injection with large injection rates will not be applied. Then only a limited portion of the available oxygen would be consumed. The alternative is continuous injection with a lower injection rate or pulsed air injection.

Pulsed air injection is recommended because pulsed air injection creates a higher air pressure and a more homogeneous aeration of the soil. Besides this, pulsed air injection causes more water movement and an improved transfer of oxygen.

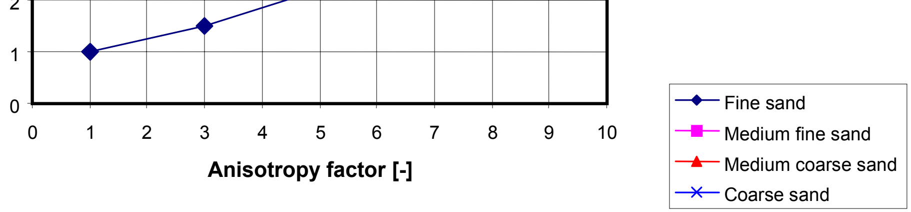

Fig. 5.4 Aeration radius for injection regime II.

Table 5.4 Pressures (p) and injection rates (φ_v) for injection regime II.

Anisotropy factor	**Fine sand**		**Medium fine sand**		**Med. coarse sand**		**Coarse sand**	
	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.
1	+0.50	0.7	+0.50	2.5	+0.50	5	+0.43	50
3	+0.50	1.5	+0.50	7.5	+0.50	12	+0.17	50
10	+0.50	7.5	+0.50	25	+0.50	35	+0.06	50

* In addition to hydrostatic pressure.

In fine graded soils this injection regime produces a much smaller aeration radius than continuous air injection. The injection rate is also small because of the large resistance for pushing the groundwater away (high injection pressure).

As a result of the small airflow rate the aeration radius for a fine graded, low heterogeneous, soil is smaller than for (medium) coarse soils. However, in case of a high anisotropy factor the aeration radius for a (medium) fine soil becomes even larger than for (medium) coarse soils, as a result of a limiting air injection rate.

In coarse soils the aeration radius hardly differs from continuous air injection. The injection rate is 50 m^3/h.

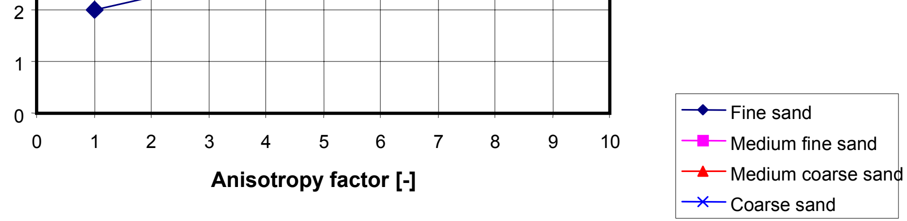

Fig. 5.5 Aeration radius for injection regime III.

Table 5.5 Pressures (p) and injection rates (φ_v) for injection regime III.

Anisotropy factor	Fine sand		Medium fine sand		Med. coarse sand		Coarse sand	
	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.
1	+0.50	1.5	+0.50	3.5	+0.50	12	+0.28	50
3	+0.50	2.5	+0.50	9.2	+0.50	30	+0.11	50
10	+0.50	9.2	+0.50	26	+0.25	50	+0.04	50

* In addition to hydrostatic pressure.

Figure 5.5 shows that the aeration radii are larger than for injection regime II. The aeration radius in fine sand is still small compared with continuous aeration.

Figure 5.5 also shows that in coarse soils, the aeration radius for pulsed injection can be larger than for continuous air injection. This is explained by the expanding aeration radius during the initial period of air injection. As soon as the injected air reaches the water table, the 'air cone' collapses causing a decrease in aeration radius, as is illustrated in figure 2.2.

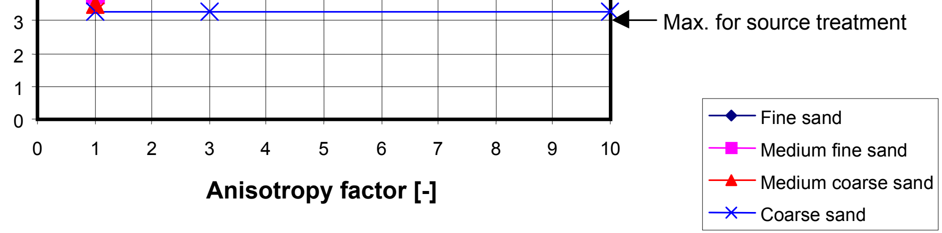

Fig. 5.6 Aeration radius for injection regime IV.

Table 5.6 Pressures (p) and injection rates (φ_v) for injection regime IV.

Anisotropy factor	**Fine sand**		**Medium fine sand**		**Med. coarse sand**		**Coarse sand**	
	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.	p* (bar)	φ_v m^3/h.
1	+0.50	4	+0.50	5	+0.50	28	+0.13	50
3	+0.50	8	+0.50	17	+0.50	44	+0.06	50
10	+0.50	20	+0.50	38	+0.17	50	+0.03	50

* In addition to hydrostatic pressure.

Figure 5.6 shows that the aeration radii for coarse sand are smaller than for injection regime III (during the initial stage of the aeration process the airflow is more horizontal). The aeration radii in fine sand and middle fine sand are 50 - 60 % of the radii for continuous air injection.

From available soil descriptions (profiles), grain size distributions, etc. the soil is characterized as fine, medium fine, medium coarse or coarse.

If the soil is highly homogeneous, an anisotropy factor of 1 is selected. If the soil is characterized as highly stratified, an anisotropy factor of 10 is selected. In other cases an anisotropy factor of about 3 can be selected.

Screen depth and length

The depth of the top of the screen is set 1 to 2 m below the contaminated zone. The following screen lengths are proposed:

- fine sand: 2 m
- medium fine sand: 1.5 m
- medium coarse sand: 1 m
- coarse sand: 0.5 m

Well spacing and injection regime

The nomograms of sections 5.4.3 to 5.4.6 can be used to select the well spacing and the injection regime. The well spacing and the injection regime are chosen so that the aeration radii cover the site completely. Because the aerated region around the injection well will not be circular shaped, *it is recommended to limit the well spacing to a maximum of 8 m*.

When the *source* of a contamination (instead of a plume) has to be treated, a more intensive design concept will have to be used. In such a concept, in which minimization of the restoration time is more important (instead of an efficient use of the oxygen applied), the injection wells have to be installed at shorter distances. So well spacing and injection regime are chosen in a way that the aeration radii substantially overlap (especially for finer soils). *It is recommended to limit the well spacing to approximately 6 m*.

Because of the anisotropy in the soil, it is possible that the design well spacing will not produce complete and uniform remediation. In this respect additional wells may need to be added as part of a mid-course correction.

An important condition is that the injection period must be long enough to achieve aerobic conditions in the contaminated zone. After the wells are installed, the injection period can be adjusted based oxygen measurements in the groundwater.

Another method of presenting the nomograms to observe the effect of the injection time on the aeration radius is given in figure 5.7. In this figure the aeration radius is presented as function of the injection time for anisotropy factor 3. Also the aeration radius of a continuous injection is presented.

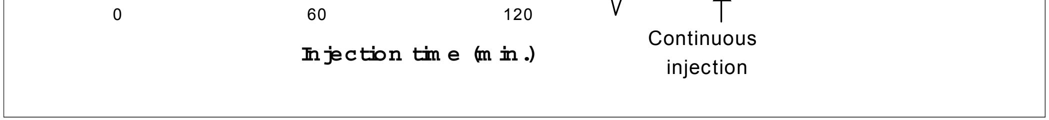

Fig. 5.7 Aeration radius as a function of the injection time for anisotropy factor 3.

It can be seen that in coarse media a long injection period does not improve the aeration radius. In finer grained soils however the aeration radius increases as a result of continued air injection.

Injection pressure
The injection pressure depends on the soil type and the screen depth. The injection pressure is related to the rate of the airflow through the soil matrix.

The minimum pressure that the blower/compressor must deliver is approximately 10 kPa (0.1 bar) per m under the groundwater table increased with the entry pressure of the soil (see table 5.7).

Table 5.7 Values of entry pressure for different soil types.

Soil type	Entry pressure (bar)
Coarse sand	0.012
Medium sand	0.025
Fine sand	0.04
Silt	0.10

In section 4.2.4 a method for calculating the maximum allowable injection pressure is given. The compressor or blower is installed and operated in such a way, that air injection pressures remain below 90 % of the maximum allowable air pressures (with a margin of safety).

Injection rate
The injection rates can be estimated from the tables corresponding to the nomograms.

5.4.8 Example for the design of an air injection system

Characterization of the site
Middle coarse sand, estimated anisotropy factor 3, contaminated 2 m below the groundwater table, groundwater table 2 m below ground surface. Contaminated surface area 1000 m^2.

2 h. on, 1 h. off	5.5 m	44 m^3/h. (30 m^3/h.)	+0.5 bar

* In addition to hydrostatic pressure.

Because pulsed aeration is preferred (see section 2.1.3), a pulsed injection regime with a fairly large aeration radius is selected. In this case the selected injection regime is 0.66 h. on and 2.33 h. off. With an aeration radius of 3.9 m, the selected well spacing will be approximately 6 m. Therefore the number of wells that will be installed is 27.

Injection rate
The mean flow rate per well is 6.6 m^3/h. The required injection capacity is approximately 180 m^3/h. (90 kPa or 0.9 bar). When a more intensive restoration process is preferred, the well spacing will be approximately 4 m, with a required injection capacity of 400 m^3/h. (90 kPa or 0.9 bar).

Injection pressure
Using equation (1) from section 2.4.2 the maximum initial injection pressure can be calculated.

During start up of the sparging, when the sparge well is filled with water, the maximum injection pressure is:

$$\begin{aligned} P_{inj} &= \gamma_d \cdot (h_s - h_w) + (\gamma_s - \gamma_w) \cdot (h_w - h_t) + \gamma_w \cdot (h_w - h_{wf,act.}) \\ &= [1500 \cdot (0 - (-2)) + (1700 - 1000) \cdot (-2 - (-6)) + 1000 \cdot (-2 - (-2))] \cdot 9.8 \\ &= 56.8 \text{ kPa} \quad (0.57 \text{ bar}) \end{aligned}$$

If the well is empty, damage of the soil (liquefaction) may occur at an air pressure of:

$$\begin{aligned} P_{inj} &= \gamma_d \cdot (h_s - h_w) + (\gamma_s - \gamma_w) \cdot (h_w - h_t) + \gamma_w \cdot (h_w - h_{wf,act.}) \\ &= [1500 \cdot (0 - (-2)) + (1700 - 1000) \cdot (-2 - (-6)) + 1000 \cdot (-2 - (-6))] \cdot 9.8 \\ &= 96.0 \text{ kPa} \quad (0.96 \text{ bar}) \end{aligned}$$

To prevent damage of the soil, the injection system is operated in such a way that the water is removed from the wells with a low air pressure. When the well is empty the air pressure is limited to 0.5 bar + hydrostatic pressure = 89.2 kPa (or 0.89 bar).

Additional remarks
As mentioned in section 5.3.4 the results obtained by the nomograms may seem quite accurate, but are actually based on a limited number of cases. The results must therefore be interpreted as well chosen estimates that suffice for the design of sparging systems of small to moderate size.

Extracted air in most cases will have to be treated before disposal into the environment. Depending on the levels in soil vapor the techniques that can be applied are given in table 5.9.

Table 5.9 Soil vapor treatment technologies.

Soil vapor treatment technique	Airflow rate	Soil vapor level
Carbon adsorption	Low/High	Low (< 2 gr/m^3)
(Catalytic) Incineration	Low/High	High (> 2 gr/m^3)
Biofilter (compost)	Low	Low (1 gr/m^3)

Carbon adsorption

Air is fed into an activated carbon adsorption filter. The contaminations are adsorbed onto the activated carbon . Activated carbon has an adsorption capacity of about 10 to 20 % of its own weight. Activated carbon can treat almost all volatile organic compounds commonly encountered in soil. Removal efficiencies are in general above 95 %.

Incineration

The contamination is oxidized to carbon dioxide and water, either within a direct flame at 600 ºC to 800 ºC, or over a catalyst at 300 ºC to 400 ºC. If the contaminant levels are sufficient, catalytic and even direct incinerators may work autotherm. When running autotherm, no additional fuel (hydrocarbon source) needs to be added to system to keep up the temperature. If contamination levels drop to below 3 - 5 gr/m^3, incinerators become less efficient due to the additional amount of fuel that needs to be added to keep up the temperature. The removal efficiency is about above 95 - 98 %.

Chlorinated hydrocarbons may cause severe damage to incinerators due to the formation of hydrochloric acid. Specialized catalytic incinerators are being developed to deal with these specific compounds.

Biofiltration

In biofiltration micro-organisms attached to compost or other organic material in a filter biodegrade the volatile compounds. The organic compounds are first adsorbed on the organic material. In the second step micro-organisms degrade hydrocarbons to carbondioxide and water. A hydrocarbon level of 1 gr/m^3 is considered a maximum level that can be mineralized. Removal efficiencies vary from 50 to 75 %.

In general volatile chlorinated hydrocarbons cannot be bioremediated aerobically in a biofilter, they are merely adsorbed on the organic material.

Chapter 6

Hardware/equipment

In table 6.1 an overview is presented of different techniques to install vertical wells. A hollow stem auger is the most commonly used drilling method. A typical construction is illustrated in figure 6.1.

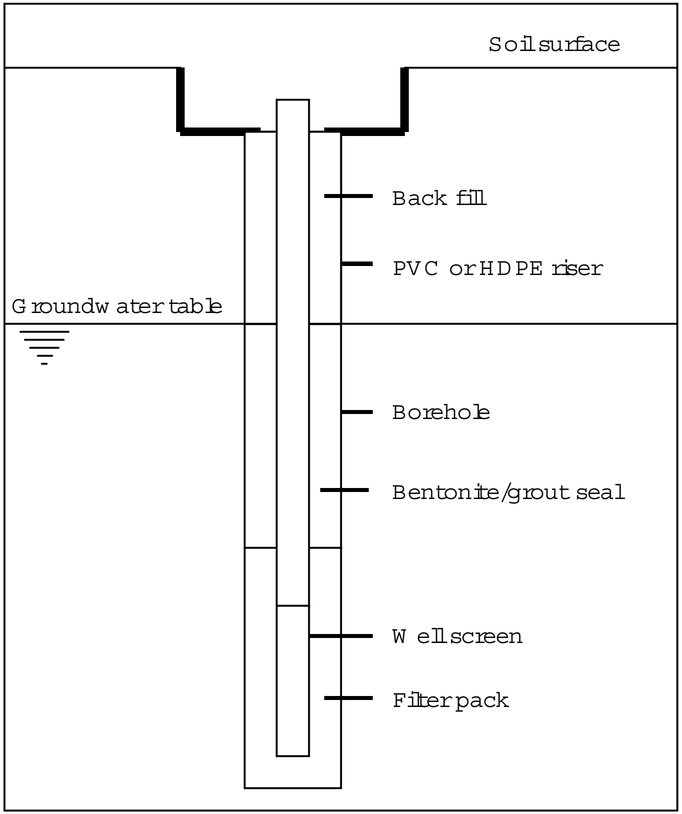

Fig. 6.1 Vertical aeration well.

On top of the vertical well a T-piece should be constructed, to enable regeneration of the well if required and to enable monitoring of pressure or groundwater levels.

		tances

6.1.2 Horizontal wells

Horizontal wells can be installed in a trench or placed by horizontal drilling techniques (see table 6.2). Sparge trenches are used for containment. The sparge air will move preferentially upward through the trench and will not treat the surrounding native soil. So sparge trenches cannot be used for source treatment.

Soil vapor extraction trenches can be applied for source remediation. The quality of a horizontal well used for soil vapor extraction in a source area, in a trench is better than a well placed by horizontal drilling, if an adequate top sealing is provided. However the excavation of trenches in the contaminated soil reduces the advantages of in situ techniques considerably and cannot be applied beneath building, storage tanks etc.

With directional drilling a bore hole is created in which a horizontal drain is installed. A bentonite or polymer suspension, which is used as drilling fluid, can be flushed out with water. The polymer suspension is supposed to be biologically degradable.

There is only little experience in aeration of the saturated zone with horizontal wells for IAS. Lateral differences in soil permeability may result in an uneven lateral distribution of the injected air [CUR/NOBIS, 1999b].

Table 6.2 Methods for installation of horizontal wells - advantages and disadvantages.

Method	Advantage	Disadvantage
In a trench	• Inexpensive • As for a sparge trench: uniformity of airflow through the trench	• Not for source area treatment • Backfill on top of drain sensitive for settlement • Not possible for installation beneath buildings • Large inconvenience for neighbourhood
Directional drilling	• Possibility for installation beneath buildings	• Short-circuiting along the drain likely • Expensive • Boring fluid may be a problem to remove from borehole

Bioventing	10 - 50 (0.1 - 0.5)	Air extraction	Risk of groundwater extraction	Resistance for flow (soil permeability)
		Air injection	Risk of soil fracturing	Resistance for flow (soil permeability)
Biosparging	50 - 250 (0.5 - 2.5)			• Pressure required to overcome the static water level • Entry pressure of the soil • Resistance for flow (soil permeability)

Table 6.4 Properties of different types of blowers and compressors.

Blowers and compressors	Applied for	Pressure limits kPa (bar)	Application	Advantages	Disadvantages
Lateral rotary blowers	Large volume, low pressure	60 (0.6)	Venting	Produce oil free air	
Rotating lobe blowers (Roots blower)	Large flow rates	100 (1.0)	Venting Sparging	Produce oil free air	Noisy Regular main-tenance required
Rotary sliding vane blower	Smaller flow rates	160 (1.6)	Sparging	Produce oil free air	Noisy and hot
Reciprocating compressors		> 100 (> 10)	Sparging		Filter to remove oil required
Rotary screw compressors		> 100 (> 10)	Sparging	Produce oil free air	

In appendix B an overview is given of the different types of blowers and compressors. To prevent overheating of the injection system, the working pressure (design capacity) of the selected injection equipment should not exceed a maximum pressure of 120 % of the required and expected air pressure. For example : when a pressure of 0.9 bar is required to injected the amount of air in the soil, an injection system with a capacity of 1.1 bar is required.

In air sparging the pressure is limited by the risk of fracture formation. In this case rotary vane pumps and roots blowers are used (see table 6.4). Roots blowers are used for large flow rates and rotary vane pumps are used for smaller flow rates. Both types of equipment produce oil-free air. Generally roots blowers have to be placed in an insulating box, because they produce much noise.

Air can be injected continuously or pulsed. Continuous injection is generally applied for SVE and pulsed injection for IAS.

The design of the distribution system for biosparging depends on the injection strategy (injection time and pulse intervals). If less than 10 - 20 injection wells are installed on a contaminated location only one well is processed at the same time. Automatic valves are used to activate or deactivate the wells or groups of wells (see Fig. 6.2).

In the Netherlands mostly HDPE is used as piping material. Sometimes the outlet temperature of the blower or the compressor is too high for HPE. Then a part of the piping is made of another material for instance steel.

As for soil vapor extraction piping, the piping should be installed under a small angle downwards to the well so condensed water flows back into the well. Small diameter piping (∅20 - 25 mm) should only be used in straight parts. Tension on the material may result in bending of the piping and the formation of water locks.

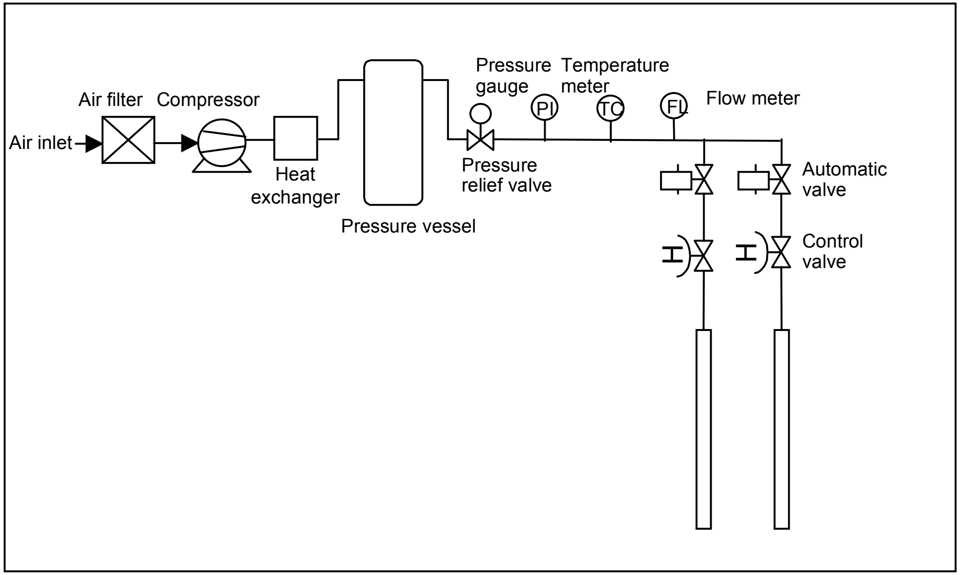

Fig. 6.2 A system for pulsed air sparging.

devices.

- Biosondes (see Fig. 6.3)
  Biosondes are well characterized in situ replaced soil samples, that simplify sampling and may optimize monitoring results. A biosonde consists of a perforated pipe which is inserted into the soil. The soil, collected from the borehole in which the pipe is inserted, is homogenized, characterized and divided in a number of subsamples. The subsamples are put in permeable bags and placed in the pipe. Periodically a bag is taken out and the contamination content or bioactivity is measured.

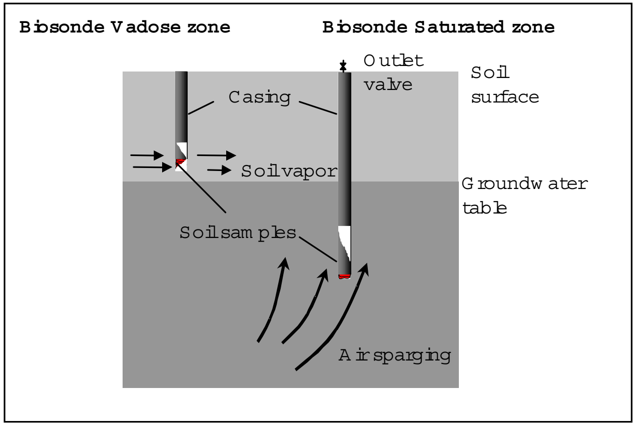

Fig. 6.3 Biosondes.

The advantage of using biosondes over periodically sampling the soil by drilling is the exclusion of spatial variability.

An important point of consideration is that results from the biosonde technique represent a semi in situ situation. Homogenization of soil usually triggers microbiological activity and causes overestimation of the bioactivity (i.e. the rate of progress of the remediation).

Another point is that physical transfer processes between the naturally surrounding soil and the biosonde are not yet assessed. For instance it is not clear yet if in the biosonde during sparging, conditions are established (e.g. oxygen level) which are comparable to those in the surrounding soil.

Biosonde	Drilling by hand	No disturbance by heterogeneity	• Not suitable for volatile contaminants • Enhanced bioavailability (due to mixing of the soil) gives an optimistic result

6.4.2 Groundwater and soil vapor sampling

Groundwater sampling devices generally are distinguished in the way they are installed; by hand or mechanically. The mechanical installation may be executed through direct penetration of the well into the soil (mini/midi wells and environmental well) or by predrilling through pulsing and subsequent installation of the well. The soil vapor can be sampled using the same techniques as used for groundwater sampling with the difference that the wells are installed in the unsaturated zone.

Several aspects of the sampling device and the method of installing are important in the decision whether or not to use this particular device such as:

- the possibility to avoid preferential flow along the tube. Large well volumes tend to create preferential flow towards the well;
- the volume of water needed to be pumped through for the collection of a representative sample. If a large dead volume is present in the well, no quick response to changes in the soil can be obtained;
- operational security;
- possibility of installing more devices in the same borehole (non-penetrating methods), establishing better interpretation of data by reducing spatial variability.

When groundwater from deep monitoring wells with volatile contaminants is withdrawn risks of volatilization of contaminants have to be accounted for. Therefore appropriate pump systems must be used to avoid the development of under pressure in the pumping system. Systems that may be used are:

- in situ pump, to be lowered in the monitoring well;
- foot valve pump.

In table 6.6 the installation procedure, the advantages and the disadvantages of the different groundwater sampling/monitoring devices are listed.

(Ø 2.5 cm, > 1 m well length)		through befor sampling	• Groundwater table cannot be measured
Environmental well (Ø 2.5 cm, > 1 m well length)	Penetration of cone, well and tube by truck mount equipment	• Operationally secure • Fast installation • Small volume of water is needed to be pumped through before sampling • Sealing over total length (reduced risks on cross-contamination)	• Not possible to install other wells or equipment
Meso filter (Ø 2.5 cm, 20 cm length)	Predrilling by hand or mechanically	• Operationally secure • Possible to avoid preferential flow along the piezometer using bentonite sealing • Small volume of water is needed to be pumped through before sampling • Enough space in the bore hole for installing other wells or equipment	

6.4.3 Geophysical techniques

In this section the different geophysical and analytical devices are listed. These techniques generally are only used in pilot tests or for research purposes. Several types of techniques can be distinguished.

Geophysical methods can be used for:

- detection of the soil structure (soil type and saturation);
- detection of contaminants in the soil;
- detection of air saturation (mostly derived from conductivity)

Techniques are:

- Electrical resistance tomography (ERT). ERT is frequently used in research programs for determination of the ROI of sparging.
- Time Domain Reflectometrie (TDR).
- Ground Penetrating Radar (GPR). GPR is a known technique for the determination of soil structures and heterogeneity, and might be a suitable technique to determine ROI of sparging.
- Neutron probe logging.

pound.

In table 6.7 and 6.8 an overview is given of the different analytical techniques for groundwater and soil vapor monitoring. A distinction is made between techniques that are generally used as a standard tool and techniques that are used in pilots or for research purposes.

Monitoring parameters	Applications	Analytical technique	Type of analyses	On-line	Remarks
Carbondioxide	Biological activity	Total Inorganic Carbon, measuring carbonate	Laboratory	No	No applications known
Hydrocarbons	Remediation and process control	UV-fluorescence in oil probe	In situ	No	Focuses on PAH, not suited for gasoline
		Conductivity in chemosonde	In situ	No	
		Refractrometry (light or laser induced sensors)	On site	Yes	In development
Electrical conductivity		Electrical conductivity	On site	Yes	
		Chemosonde	In situ		
pH		Electrochemical	On site	Yes	
		Chemosonde	In situ		
Saturation	ROI	Electrical Resistance Tomograpy	In situ	No	Research tool
		TDR	In situ	No	Research tool
		Neutron probe logging			Research tool, few applications
Redox	ROI	Electrochemical	On site	Yes	
		Chemosonde	In situ		
Nutrients (N & P)	Activity	Colorimetric	Laboratory	No	
Hydraulic permeability	Check quality of sparge well	Hydrostatic pressure	In situ	No	
SF_6	ROI, activity	GC-ECD	On site	No	Research tool

Pressure in monitoring wells	Remediation and process control	Pressure transducer	On site	Yes	
System operation parameters					
Pressure	Process control, operation of the blowers	Pressure transducer	On site	Yes	
Flow	Process control, operation of the blowers	Flow meter	On site	Yes	

b)	**Used in pilots and for research purposes**						
Monitoring parameters	**Applications**	**Analytical technique**	**Type of analyses**	**On-line**	**Selectivity hydrocarbons**		**Remarks**
					Indiv.	**Total**	
Oxygen	ROI, activity, process control	Paramagnetic	On site	Yes			
		GC-TCD	On site	No			Requires carrier gas
Carbondioxide	Activity	GC-TCD	On site	No			Requires carrier gas
Hydrocarbons		Infrared	On site	Yes	x	x	Sensitive to moisture
		FT infrared	On site	Yes	x	x	Sensitive to moisture
		GC-TCD	On site	No	x		Requires carrier gas N_2
He	ROI, activity	GC-TCD	On site	No			Requires carrier gas
		Hand held He-analyzer	On-site	No			-
SF_6	ROI, activity	FT-IR	On site	Yes			Sensitive to moisture
		GC/TCD	On site	No			Requires carrier gas, high detection limit (100 ppm)

Chapter 7

Installation of the system

- Check specifications of well material and piping.

Installation of the wells

- Observe the soil stratigraphy and degree of contamination, if the drilling method allows visual judging of the soil structure and determination of the degree ofcontamination.
- Store bore hole material in a container. Cover the container with a liner. Treatment of the soil is to be determined after sampling of the soil.
- Check that well is placed in the center of the bore hole.
- Take care for emissions of gaseous contaminations during placement of bentonite or well sand.
- Remove sand from newly installed sparge wells before sparging is started up.

Piping

- Check air tightness of piping and especially connections. Air tightness can be checked by applying water or air pressure to the piping.
- Before piping is finished, mark the individual pipes.
- Take pictures of the system before it disappears in the soil.

Air injection system

- Check the temperature housekeeping of the air inside the injection and withdrawal equipment container.
- Check for noise reduction requirements of the injection equipment and withdrawal container.
- Check connections of (electronic) valves and piping.

Start up

- Seal all occluded groundwater monitoring wells and other possible short circuits of soil and ground surface. All water table wells (not occluded well) must be abandoned and grouted.
- Agree upon a start up protocol between contractor and consultant.

7.3 Complications during installation

During installation of the system several complications may occur. In table 7.1 some reoccurring complications are listed and possible actions to overcome problems arising from these complications are given.

Chapter 8

Operation of the system

tend to rise, this does not imply a movement of groundwater. Bubbling of nearby (up to 20 or 30 m from the injection wells is not unlikely) surface water and ditches may be observed.

Check for possible effects within buildings present on top of the sparging system. Especially basements and open cellars should be watched. Injected air may also escape through leaking subsurface sewer systems and enter areas that use the sewer systems.

High evaporation rates may be observed in the soil vapour extraction systems just after start up, due to stripping of the volatile contamination. Especially in the first few days and weeks volatilization is most pronounced. The soil vapour treatment system should be capable of handling the varying levels of contamination in the soil vapour during sparging.

Dilution of contamination in soil vapour by injected air has been observed as well, especially if the vadose zone is heavily contaminated.

8.2 Monitoring

During the operation of the remediation system, periodical checks must be performed to ensure the system is working optimally and to verify that remediation goals will be achieved within the set period.

Two different types of monitoring can be distinguished:

- remediation progress;
- process performance.

8.2.1 Monitoring remediation progress

Monitoring the remediation progress involves the assessment of the state of the remediation and the check whether remediation objectives are met.

Remediation parameters that can be distinguished are:

1. level of contaminants in the soil and the groundwater (in some cases the level in the soil vapor can be a remediation objective);
2. leaching of the contaminants from the soil matrix.

The remediation process is commonly monitored by levels in soil and groundwater. In fewer cases, leaching of the existing contaminants is determined.

In table 8.1 an overview is given of remediation parameters and different important aspects concerning monitoring.

	contamination in groundwater	monitoring well	analyses	goal	
Soil vapor					
Contaminants	Quantification of con-tamination in soil vapor	- Soil vapor monitoring well - Extraction well	Standard lab. analyses	Remediation goal	1

Different sampling/monitoring devices and analytical equipment are described in more detail in Chapter 5.

8.2.2 Monitoring process performance

Monitoring the process performance involves the check whether the in situ remediation system is functioning adequately. The following parameters to monitor the process performance of an IAS or SVE system are presented in table 8.2.

Table 8.2a Parameters to be checked to monitor the process performance of sparging.

Parameter	Objective	Sampling point	Performance goal	Frequency
IAS				
Pressure and flow	Operation of the compressor Quantification of processes	Injection system	Flow and pressure must be within set parameters	Continuously
Run time	Operation of the compressor	Compressor	Within set para-meters	Continuously
Oxygen in groundwater	Oxygen distribution in the groundwater	Groundwater monitoring well	Level oxygen > 2 - 3 mg/l	Monthly
Oxygen in soil vapor	Oxygen transfer efficiency	Soil vapor monitoring well (soil vapor extraction well)	Level oxygen > 5 %	Monthly
Nutrients in groundwater	Control of distribution of nutrients	Groundwater monitoring well	N > 5 mg/l P > 0.5 mg/l	Monthly
Biological activity estimated by in situ oxygen consump-tion rate *	Quantification of biological activity	Groundwater monitoring well	Biological activity must be higher than reference sample in clean soil	3 Months

* For more details concerning respiration tests is referred to Appendix A.

Hydrocarbons	Quantification of the amount of hydrocarbons withdrawn Control of the load and efficiency of the vapor treatment unit	Extraction well (soil vapor monitoring well)	Set maximum load of the treatment unit	Weekly
Underpressure	Control of venting in the unsaturated zone	Soil vapor monitoring well		3 - 6 Months
Biological activity estimated by in situ oxygen consumption rate *	Quantify biological activity	Soil vapor monitoring well Soil vapor extraction well	Biological activity must be higher than reference sample in clean soil	3 Months

* For more details concerning respiration tests is referred to Appendix A.

8.3 Mid-course correction

The concept of a mid-course correction is important for air sparging. Despite best efforts and most conscientious pilot testing, full scale sparge systems rarely behave as planned. Sometimes the surprise is pleasant, and a less aggressive system will produce impressive remediation results. More frequently, there are areas of the site which do not respond to the initial sparge system, and additional wells or changes in system operation are required.

It may be possible that during IAS air is not distributed to some of the contaminated areas. This can be due to e.g. a less permeable layer that was not detected before installation of the system, or a too large well spacing for that typical area. When operational adjustments of the IAS system (e.g. higher flow rates for a longer period) do not result in a better oxygenation of the area of concern, a correction of the system is necessary. This may involve the installation of more injection wells or the installation of wells at different depth.

Chapter 9

Shutdown and after care

up.

The extent and intensity of the necessary post-closure measures depend on the type of contamination, the future use of the site and the risks of possible migration of the rest contaminations.

The status quo at the start of the post-closure period will have to be described. It follows from the evaluation of the remediation operation. It will comprise the documentation of the remediation and its results:

- remediation start;
- technical approach;
- installations used;
- results.

On basis of this evaluation the after care program is formulated.

9.2 Rebound

The level of contaminants in the groundwater and soil vapor have often been observed to increase in the initial period after shutdown of the sparging system. This increase in levels is called 'rebound'.

A rebound can have several causes. The most important are mentioned below:

1. In the soil pores, that were not treated thoroughly, some pure product (NAPL) is still present. The contaminant can desorb from these stagnant pores and solubilise in the ground water, causing a recontamination.
2. The soil around the monitoring well has been preferentially flushed, caused by the improved vertical permeability of the soil directly surrounding the monitoringfilter (copared to the permeability of the soil nearby). It is therefore advised to use short filters (0.2 to 0.3 m) that can be sealed during the sparging process. After shutdown of the sparging process, also new monitoring filters could be placed.

For the determination of a possible rebound-effect it is advised to conduct contaminant sampling again after a post-shutdown period of at least three months.

$$R = \left[1 - \frac{C_r}{C_0}\right] \times 100\ \%$$

With:

C_r is the dissolved contaminant concentration at termination of IAS (µg/L).

The rebound is then calculated as follows:

$$\text{Rebound} = \frac{\log\left(\frac{C_r}{C_F}\right)}{\log\left(\frac{C_0}{C_F}\right)}$$

A rebound value of less than 0.2 has been determined to be representative of permanent reduction, while a rebound value of greater than 0.5 has been determined to indicate that there is significant rebound [Bass and Brown, 1996].

Even if no rebound is observed it is strongly recommended to install a series of new monitoring wells to determine the end situation of the sparging remediation. This additional monitoring round should be performed prior to the removal of the sparging system and the start up of an after care monitoring program.

9.3 After care program

9.3.1 Setup of a plan

Before implementing an after care program, a plan must be setup in which the following aspects are mentioned:

- aim of the post-closure measures;
- the parties involved;
- those responsible for the program;
- the specific activities;
- information and reporting;
- moments for evaluation;
- determination of the end situation.

In an organization chart the different activities should be addressed to one or more bodies. This may follow from the remediation operation or may be established at the start of the post-closure period.

From the parties involved a 'manager' of the after care program should be appointed. The manager is responsible for the continuation of and control on the after care program.

The different activities and tasks for the manager should at least include the following:

- site management;
- registration of monitoring activities and the results obtained;
- informing the authorities about the current status or critical situations;
- obtaining and updating legal permits;
- obtaining the insurances that are considered to be necessary.

The after care plan should contain protocols for:

- monitoring emissions and migration of contaminants;
- monitoring unforeseen residues and processes;
- monitoring of the technical measures taken to prevent re-contamination;
- reporting;
- quality control;
- establishing trigger values and actions to be taken in case of exceedance of trigger values.

Post-closure measures start when the regulatory authorities have accepted the results of the remediation operation and the plan for after care.

9.3.2 Implementation and follow-up

Based on the after care program, the necessary monitoring devices are installed and the monitoring system is started.

The determination of the intensity of the post-closure operation depends on:
- organization chart;
- financial settings, for financing models as well as for securities;
- technical possibilities concerning monitoring (frequencies, intensities of sampling and analysis);
- required protection level:
  - of the site;
  - of the surroundings of the site.

Through monitoring at different locations surrounding the site, the changes in level of residual contaminants are measured in time.

it can eventually be considered to stop the post closure measures.

If the after care program is ended an evaluation will be made to describe the end situation.

Chapter 10

Remediation cost

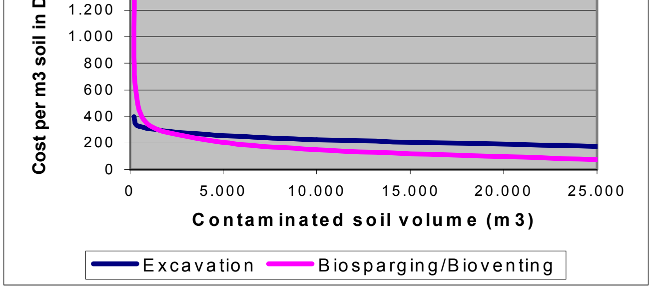

Fig. 10.1 Remediation cost of an excavation compared to in situ source treatment by biosparging and bioventing

In general the remediation cost of an in situ treatment by biosparging and bioventing of a soil contamination with a shallow aquifer is cost effective, compared to excavation, if the amount of soil to be treated is more than 500 to 1,000 m^3 of soil. Large amounts of contamination (> 5,000 m^3) can be treated at cost of 100 to 200 DFl/m^3.

In this chapter the general remediation cost of an in situ remediation and the cost of equipment is given.

10.2 Overall remediation cost

The cost of an in situ remediation by sparging can be expressed in several tasks. In this section typical cases of source treatment and containment are described to show the costs involved with the different tasks, that have to be performed for the realisation of in situ sparging system.

Table 10.1 expresses the cost of a typical 2 year in situ remediation of the source treatment of a LNAPL contamination at a gasoline station. The volume of soil contaminated is about 1,000 m^3. Withdrawn soil vapors will be treated biologically. Maintenance and monitoring cost are expressed as a percentage of the total cost for a 2 year remediation.

If the remediation times are longer than 2 years, maintenance and monitoring cost will become a substantial part of the total remediation cost.

In table 10.2 the remediation cost of a bioscreen containment with a length of about 100 m and a depth of about 15 m is given.

Table 10.2 Air sparging for containment (bioscreen) cost.

Task	Cost in DFl
Site assessment	20,000 - 40,000
Design	30,000
Installation	100,000 - 150,000
Maintenance (yearly)	5,000
Monitoring (yearly)	15,000
Capitalized yearly cost including depreciation (30 yr.)	350,000

The overall costs are dominated by the cost of the installation of the system. Once the system is installed, maintenance and monitoring cost are low. However, if the remediation time is longer than predicted, maintenance cost can become a substantial part of the total remediation costs.

Pilot tests may be performed to determine sparging feasibility and to determine design parameters (e.g. ROI, volatilization rate). In table 10.3 the cost of a typical 2 month pilot test to determine feasibility and ROI for a petroleum hydrocarbon contamination are given.

Table 10.3 Air sparging pilot testing cost.

Task	Cost in DFl
Site assessment	15,000
Design	5,000
Installation	15,000
Maintenance	10,000
Monitoring	25,000
Total cost	70,000

Due to the cost a pilot test may only be cost effective if the amount of soil to be treated is more than 2,000 to 3,000 m^3.

Blowers and compressors			
SVE pump	Pcs	DFI	4,000 - 10,000
Blower (P < 100 Kpa (1 bar))	Pcs	DFI	15,000 - 20,000
Compressor (P > 100 Kpa (1 bar))	Pcs	DFI	25,000 - 40,000
Appendages			
Electric valves (1 inch	Pcs	DFI	250
Manual valves	Pcs	DFI	150
Flow meter analog	Pcs	DFI	600
Flow meter (electronic)	Pcs	DFI	6,000
PLC control			
PLC	Pcs	DFI	5,000 - 15,000
Datalogger	Pcs	DFI	5,000
Communication unit	Pcs	DFI	5,000 - 15,000
Soil vapor treatment (excl. installation cost)			
Catalytic/thermal incinerator	Wk^{-1}	DFI	800 - 1,500
Activated carbon	kg	DFI	8 - 10
Biofilter	Wk^{-1}	DFI	50 - 100
Maintenance of compressor			
Maintenance (hours and material)	Wk^{-1}	DFI	150
Energy (12 kWh compressor, 50 % of time in operation)	Wk^{-1}	DFI	250
Energy consumption			
SVE	kWh		1 - 5
Blower	kWh		5 - 10
Compressor	kWh		8 -15

Chapter 11

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Appendices

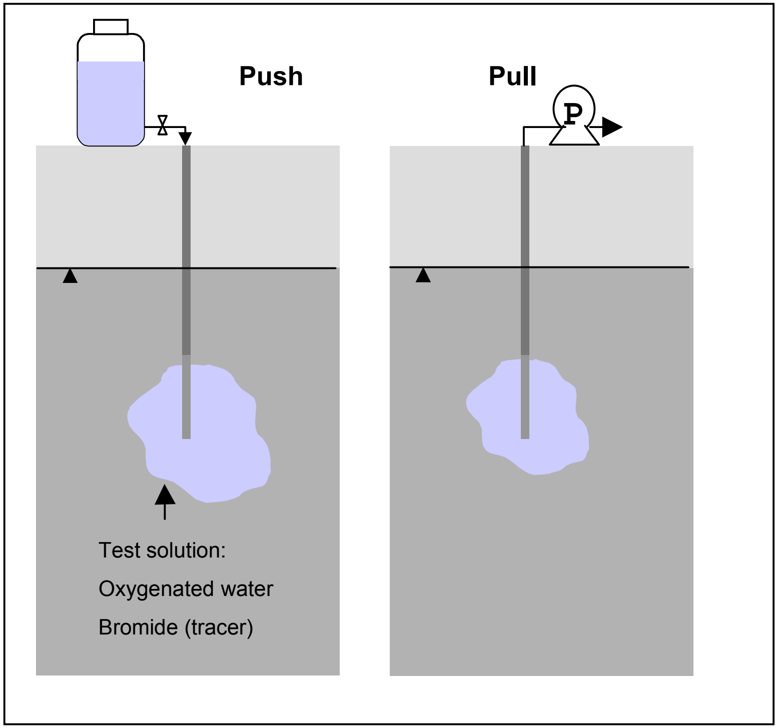


Fig. A1 Push pull test.

Applicability
A PP test can be used as a diagnostic tool; other components may be added to the water that is introduced into the soil. For example, the addition of nutrients can be used to investigate whether nutrient limition for biological decay occurs.

Since oxygenated water is introduced, the PP test can be used at a site were no IAS system is present.

Limitations of the test
When processing IAS, air will be trapped in the pore space and may persist for a long time. This so-called residual air may be a source of oxygen to water that is introduced into the soil. Therefore, in

groundwater samples are collected to measure the decrease of the oxygen concentration. The rate of the oxygen decrease is an estimate for the in situ respiration rate.

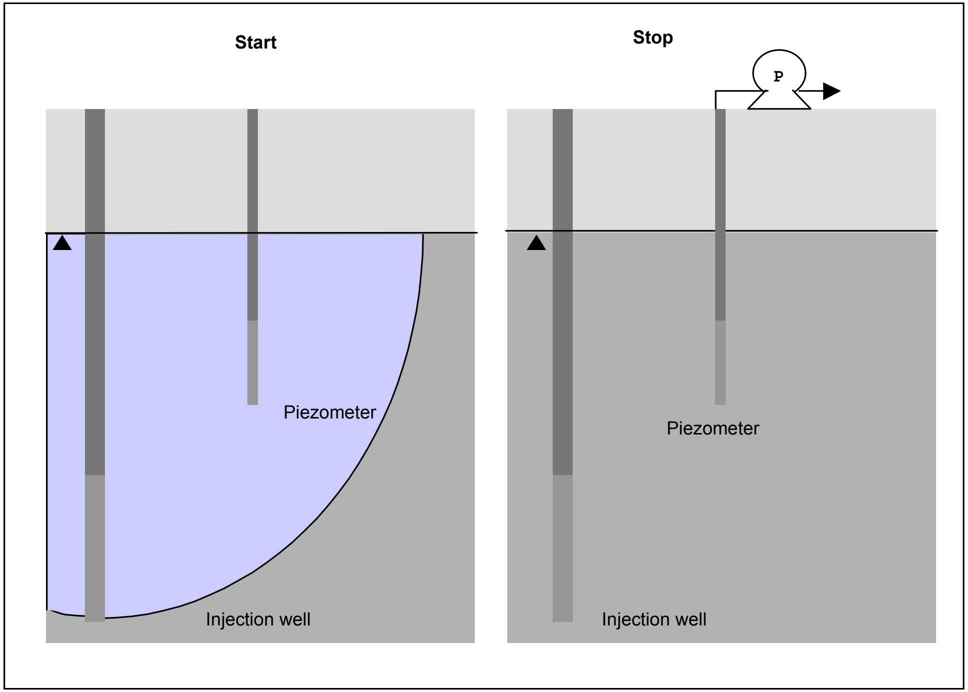


Fig. A2 Start stop test.

Applicability
SS tests only can be used when a IAS system is present to oxygenate the groundwater. The SS test should be carried out when the IAS has been processed for some time. Then micro-organisms are adapted to oxygenated conditons and a lag phase does not occur.

Limitations of the test
As for the PP test, residual air may have impact on the SS test results. Theoretical calculations indicate that the biodegradation rate may be underestimated considerably.

Feasibility	With pilot test	Yes (1)	Yes (3)
	Without pilot test	Yes (2)	No
Design and dimensioning - remediation plan		Yes (4)	Yes (5)
Process monitoring		No (6)	Yes (7)
Optimization		Yes (8)	No

Feasibility
The PP and SS tests indicate whether biological degradation occurs and give an answer to the question whether IAS will stimulate biological degradation at that location.

PP test
The PP test gives an estimate of the respiration rate at optimal aeration, since well oxygenated water is added. The PP test can be carried out either with or without an IAS system (1 and 2).

SS test
The SS test gives estimate of the actual respiration rate at the ambient oxygen concentration. To execute a SS test, an IAS system must be present (pilot test), otherwise the groundwater cannot be aerated (3).

Design and dimensioning
For designing and dimensioning a IAS system, information on the in situ biodegradation rate and the distribution of air in the soil (radius of influence, ROI, of the injection wells) are essential.

PP test
The PP test provides information on the biodegradation rate at optimal aeration. However, without an aeration system, the PP test cannot give an estimate of the ROI. When an IAS systen is present, the ROI can be estimated by measuring the DO concentration at several distances from the injection well. By subsequently executing PP tests at these locations, the in situ degradation rate at the ambient DO concentration may be estimated from the respiration curve. For instance the degradation rate at a DO concentration Y is the derivative of the curve at that particular DO concentration (4).

SS test
The SS test gives an indication of the actual degradation rates at ambient DO concentrations. When carrying out tests at different distances of the sparging well, the test can be considered as a tool estimating the ROI and degradation rates within the ROI (see Fig. A3) (5).

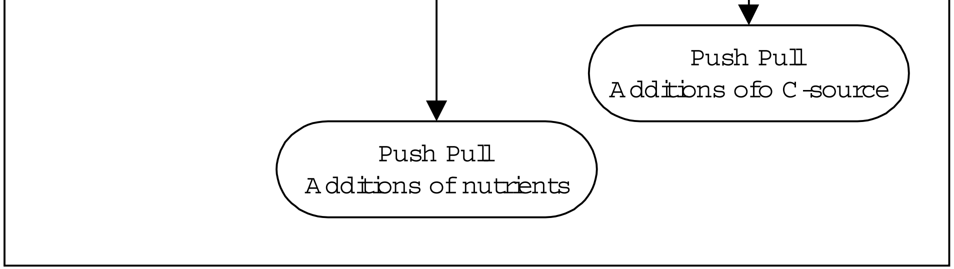


Fig. A3 Push pull test as a diagnostic tool.

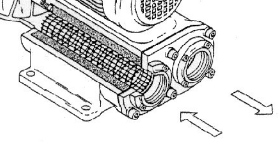
Process monitoring
PP and SS test can be considered as tools for monitoring in situ biological degradation rates.

PP test
The PP test can be used as a monitoring tool when applied periodically during remediation. The test however is more elaborate than the SS test (6).

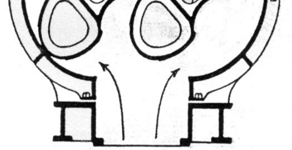
SS test
The SS test can be used for monitoring the biological activity at locations on the contaminated site. It is a useful tool to register the biological activity as a zero-situation at the start of a remediation. The SS test is a powerful tool especially at the end of the remediation, when must be checked whether there is enough biological activity left to ensure a significant progress of the remediation (7).

Optimization
When contamination at a subarea of the site does not decrease as it should, the system needs to be checked. One of the aspects to investigate is whether enough biological degradation occurs at the site where remediation does not proceed succesfully.

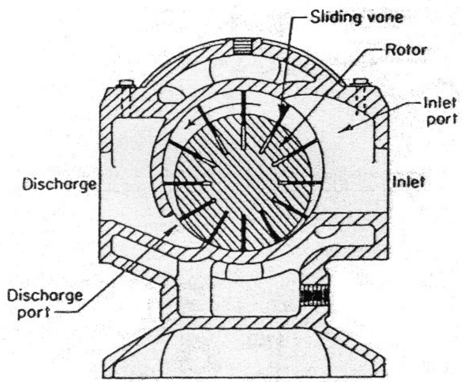
First one must be sure that ambient DO (dissolved oxygen) concentration in the groundwater is high enough to (theoretically) achieve measurable degradation (> ± 4 mg l^{-1}). If the DO concentration is too low, the IAS system must be checked on its air distribution. If DO concentrations are high enough, the PP test can be used as a diagnostic tool to investigate which factors are limiting biological degradation. In figure A3 three different PP test are presented.



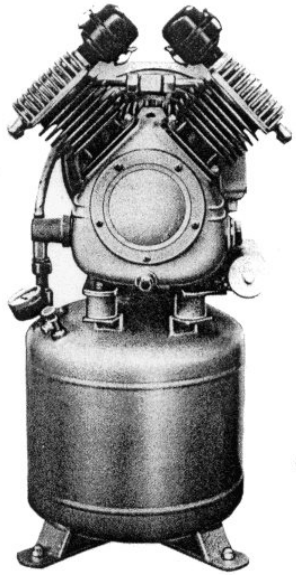
Lateral rotary blower



Rotating lobe blower
(Roots blower)



Rotary sliding vane blower



Reciprocating compressors

ally accomplished by driving a small (e.g., 1-inch) diameter pipe into the ground. The leading edge of the pipe usually consists of a drive point followed by a screened interval through which water can be drawn. The pipe assembly can be advanced by hammering, vibrating or simply pushing.

Water samples can be drawn to the surface using a variety of devices. If the water table is within the suction limit, water can be drawn to the surface through a tube connected to a peristaltic pump. If the water table is deeper, then a small diameter bailer or bladder pump may be used. Vertical profiles are generally made at a number of locations and distances around the IAS well to create a three-dimensional picture of the air distribution.

Test objectives

The primary objective of tracer test described here is to characterize the distribution of air pathways below the water table at IAS sites.

Air pathways produced by IAS are highly erratic. As a consequence, it is difficult to define the 'radius of influence' using conventionally-measured parameters (e.g., dissolved oxygen in wells, water level changes). Tracer tests and vertical profiling during IAS provide a means of not only characterizing the radius over which the air is moving, but also the vertical distribution of the air. The latter is important because for the IAS process to be effective at remediating zones of residual NAPL contamination, there must be good contact between the contaminated zones and the sparge air.

The IAS air distribution test described below should be applicable to porous media sites where the permeability is greater than 0.001 cm/s (e.g., fine sand or coarser). At permeabilities below this range it will be difficult to withdraw water from the subsurface using the small-diameter driven sampler. In this case, core samples may be appropriate for characterizing the air distribution.

Theory

The principal underlying the IAS air distribution tests is that as the air moves through the groundwater zone, some of the tracer introduced with the sparge air will partition from the air to the groundwater during the sparging process. For the water in immediate contact with the sparge air, tracer concentrations will rise to or near saturation values with respect to the tracer input concentration. An injection period of one week is adequate to give a representative picture of airflow patterns, but short enough to minimize advective transport of the tracer in the groundwater. In areas not in direct contact with the sparge air, tracers can arrive by diffusion or groundwater advection and concentrations will generally be significantly lower.

In order to successfully conduct an IAS air distribution test it is necessary to be able to collect groundwater samples at discrete depth below the water table. In addition, the groundwater samples must be collected without headspace or volatilization losses during sampling. This can generally be accomplished by vertical profiling and careful groundwater extraction.

The rates of air and SF_6 injection determine the concentration in the IAS air, and the concentrations which will be observed at 100 % saturation in the groundwater.

The SF_6 concentrations in the groundwater are determined by gas chromatography using an electron capture detector. There are a wide variety of commercially-available gas chromatographs ranging from sophisticated research instruments to more 'user friendly' instruments. For this particular application an instrument which is robust enough and portable enough for field use is desirable. In addition it should have a very low detection limit and an automatic data acquisition system. An SF_6-specific gas chromatograph, available from Lagus Applied Technologies (LAT) in San Diego, CA satisfies all of the above criteria. It is automated and has a detection limit of ~ 10 parts-per-trillion (0.01 ppbV) by volume. In the following discussion it will be assumed that a LAT Autotrac is being used.

Test protocols

Experimental activities can be divided into the following components:

1. Injection of the tracer.
2. Determination of the tracer injection concentration.
3. Groundwater sample collection.
4. Analysis of SF_6 in groundwater samples.
5. Data analysis.

Each is described briefly in the following sections.

1. *Injection of the tracer*

The setup for injection of the tracer is shown schematically in figure C1. Basically, the tracer is added to the sparge air between the compressor and the point the air enters the subsurface. Because the air injection line is at a positive pressure relative to the atmosphere, the tracer must be injected at a greater pressure. To ensure a stable flow of tracer, it is recommended that the cylinder valve and backpressure valve be adjusted such that the desired flow is achieved at a pressure of ~ 50 psi. In general this will be sufficiently above the air injection pressure that the tracer flow will remain constant despite changes in airflow conditions.

To produce the desired SF_6 concentration in the sparge air, values similar to the following can be used. If the IAS airflow is 150 L/min (~ 5 scfm), then an SF_6 flow rate of 45 mL/min will produce an input concentration of 3×10^5 ppbV.

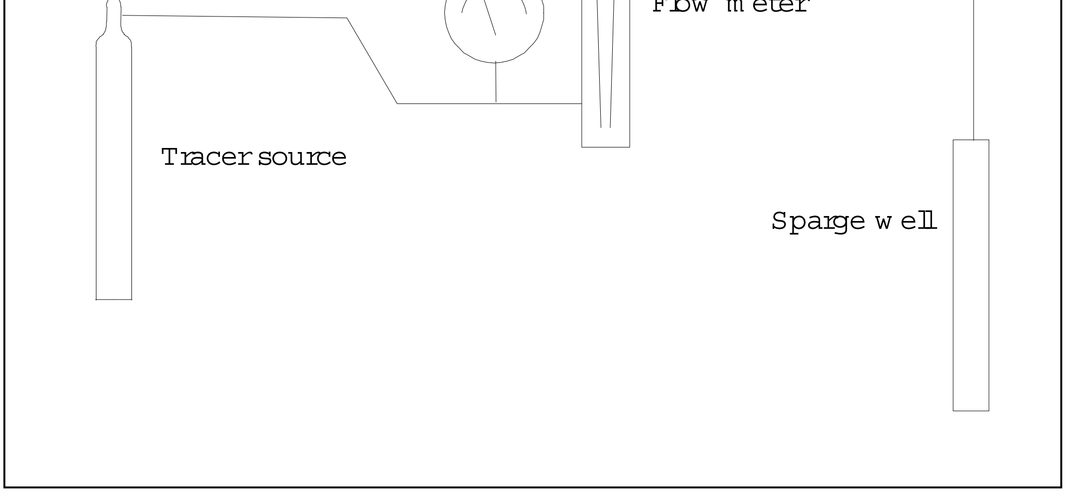


Fig. C1 Schematic drawing of the tracer gas injection system.

2. *Determination of the tracer injection concentration*
As described in section 1, SF_6 is injected at a known rate directly into the IAS manifold. To determine the SF_6 input concentration, an air sample is collected from the manifold after the SF_6 injection point and the tracer concentration in the air sample is determined. For example, if an injection concentration of ~ 3×10^5 ppbV was used, then the samples must be diluted approximately 10,000-fold to get them in the range of the LAT detector. This can be easily accomplished, for example, by filling a Tedlar bag with 10 liters of SF_6-free air and injecting 1 mL of the IAS air into the bag (~ 2 minutes should be allowed for the air to mix in the bag).

3. *Groundwater sample collection*
The collection of good quality groundwater samples is key to the success of this tracer test. The sample collection technique must be capable of collecting samples from discrete depths and to deliver those samples to a storage vessel (e.g., a 40-mL vial) without volatilization loss. As described in section 2, there are a variety of ways to accomplish this. Most involve advancing a pipe with a screened tip using a percussion hammer or vibration.

If the water table is less than ~ 25 feet, it is generally possible to use suction to draw water through the pipe to the surface using a peristaltic pump. If a steady stream of water can be produced (e.g., no air bubbles in the sampling line) then the water flowing from the pump can be delivered to a sample bottle for storage. To ensure that a good sample is collected, the tube from the peristaltic

In order for profiling to provide an accurate picture of air distribution in the groundwater zone, an accurate measure of concentration is required. This can be accomplished using a variety of analytical approaches on a gas chromatograph with an electron capture detector (e.g., headspace, direct aqueous injection). In the discussion below the LAT detector will be used. It has excellent sensitivity for SF_6, however, it requires a 10-mL air injection which somewhat complicates sample preparation.

As discussed above, because SF_6 is analogous to oxygen, it is useful to report concentrations as a percent of saturation. In that context it is useful to report values which range from 100 % of saturation with respect to the input concentration down to ~ 1 %. As described below, to calculate the percent saturation, the first step is to measure the aqueous concentration of the tracer in the water sample, and then convert that value to a percent of saturation based on the input air concentration.

The easiest way to measure aqueous concentrations of SF_6 using the LAT detector is by headspace analysis. This requires that conditions be adjusted to provide a headspace concentration which is within the range of the LAT. The following example outlines how this can be done.

If an SF_6 input concentration of 3×10^5 ppbV is used, then based on a solubility of 40 mg/L (a dimensionless Henry's constant of 150), concentrations in the groundwater could reach ~ 1.2×10^{-5} g/L. If a headspace of equal volume to the water is created by removing half of the water, then essentially all of the SF_6 (> 99 %) will partition to the headspace. This will produce a headspace concentration of ~ 2000 ppbV, which is greater than the maximum concentration for the LAT detector. A maximum headspace concentration on the order of 20 ppbV is desired.

To accomplish this a headspace to water ratio of ~100 should be used. This is achieved by injecting 0.4 mL of water sample into 40-mL vial which had been previously flushed with SF_6-free air. The water and air should be allowed to equilibrate for 1 - 2 minutes before an air sample is withdrawn.

As mentioned above, the LAT detector requires that ~ 10 mL of air be injected into the sample loop. This is accomplished by withdrawing the air through the septum cap using a 10-mL syringe. However, using a syringe to withdraw that volume from a 40-mL vial will cause a significant reduction in the internal pressure of the vial. When the syringe is exposed to the atmosphere, ambient air will be drawn into the syringe. If the ambient air contains SF_6, this will lead to errors in the analysis. To prevent this, 10 mL of clean air should be injected into the vial as the sample is withdrawn. If this is done carefully (e.g., one needle tip at the top of the vial, one at the bottom) then dilution of the sample by the injected air can be avoided.

Once the concentration of SF_6 in the headspace is determined, the concentration in the aqueous phase can be determined by calculating the total mass in the headspace and dividing that number by the volume of water in the vial. The aqueous concentration can then be expressed as a percent of the saturation value.

between the air and the NAPL is important for clean-up to occur within a reasonable timeframe. If the vertical distribution of contaminants is known, the test described here can provide a good measure of the contact between the NAPL and the air. If vertical profiles have been made at a number of locations at the site, then the test can also provide a good indication of the area over which the IAS well is effective. If the vertical distribution of the contaminants is not known, the test can still provide useful information about the vertical and areal distribution of the sparge air, however it may be difficult to assess the effectiveness of the IAS well for remediating the site.

One of the most commonly measured parameters with regard to an IAS well is the 'radius of influence') of that well. Most measures of ROI (e.g., groundwater mounding, vadose zone pressure) produce a picture which is areally much more uniform than field data suggest is the case at many sites. The test described here provides a much more accurate picture of the zone over which IAS is active, both in the vertical and areal directions.

The example described above used a single IAS well. The test can also be applied at sites where multiple sparge wells are in operation. In the latter case, the same profiling and analysis procedures can be used. However, it may be desirable to increase the number of profile locations in order to adequately describe the distribution of air at the site.

the recovery efficiency of air injected during IAS.

In order to prevent off site migration of vapors during IAS, combined IAS/SVE systems are often designed in such a way that extracted airflow exceeds air injection by some multiplicative factor (e.g., 5x). In addition, to demonstrate that the design is working, soil gas vacuum surveys in the vicinity of the IAS/SVE system are usually conducted. It is generally concluded that if no pressures greater than ambient are observed, then all of the IAS air is being captured by the SVE system. However, it is generally difficult to relate vacuum data to recovery of IAS air. This is the case because numerous potential airflow patterns in the groundwater zone can exist. For example, if IAS air is injected into sand below a continuous clay layer, the air may move laterally beyond the radius of influence of the SVE well before it has the opportunity to reach the water table. In this case, the sparge air might not be captured by the SVE system.

The previous example implies that under some circumstances pressure measurements alone will not conclusively demonstrate that IAS air is being captured. As a consequence, it is important to conduct tests which can unambiguously determine that all of the IAS air is being captured by the SVE system.

Theory

The principal underlying the helium recovery tests is simple. Helium is injected into the subsurface at a known rate and the rate of helium recovery at the SVE is calculated from the observed helium concentration in the SVE effluent and the SVE flow rate.

In order to successfully conduct a helium tracer test it is necessary to accurately measure flow rates and helium concentrations. As a result, calibration of the analytical equipment (both flow meters and the helium detector) is extremely important. It is also very important to have a system which if free of leaks. This means not only the injection and extraction systems, but also the sampling and analysis systems.

Test equipment

In order to simplify interpretation, the tests should be conducted by injection of helium into a single IAS well and recovery from a single SVE well. In nearly all cases, tracer tests will be conducted in conjunction with vapor extraction and injection operations. In that context, the design and installation of the extraction/injection wells will be dictated by the remediation design. As a consequence, design and installation of the extraction/injection wells will not be discussed here.

little flow to the SVE well at that point. Large vacuums may indicate areas of active flow, however, these values can also occur within low-flow regions adjacent to higher flow regions. Nevertheless, these data can frequently be helpful in understanding the general nature of airflow at the site.

The general approach will be to measure soil vacuum with Magnehelic™ gauges. However, the same measurements could also be made with a manometer or other calibrated vacuum gauge. For most sites it will be necessary the have gauges in the following ranges (in inches of water): 0 - 1", 0 - 10", and 0 - 100".

When the remediation system has been operating for more than one day, determine the soil vacuum at each point in the system by connecting the appropriate gauge to the point. After connection to the monitoring point, sufficient time should be allowed for the vacuum to stabilize (commonly 1 minute).

2. *Measurement of background helium concentrations*

In most cases, background concentrations of helium will be essentially zero. However, it is important to make that determination prior to starting any test. These measurements can be made while the extraction system is in continuous operation. If previous tracer tests have been conducted at the site, then initial concentrations may be non-zero. If concentrations are decreasing with time (i.e., on the tail of the previous test), then if possible conditions should be allowed to stabilize prior to initiation of the next test. If it is not practical to wait additional time prior to initiating the test, then the volume of injected tracer can be increased. However, helium concentrations in the influent air should be kept below 10 %.

3. *Determination of the rate of pure helium to be injected*

A volume fraction of helium in the effluent stream from the SVE system in the range of 0.01 (1 %) is desired. To estimate the rate of helium injection necessary to produce this concentration some initial estimate of SVE airflow must be made. The input rate for helium is simply the approximate SVE airflow rate times the target volume fraction. If the IAS rate is low (e.g., < 20 % of the SVE rate), then the target effluent volume fraction should be kept below ~ 10 % to avoid buoyancy effects in the injection air

To determine the helium flow rate, first install a good vacuum pump (metal bellows or diaphragm) to the manifold and connect the helium detector to the effluent of the pump (see Fig. D1). (This will be the same setup as for the tracer tests.) Make sure the pump has adequate flow for the helium detector and does not leak at the SVE system vacuum. Next connect the helium source to the manifold near the extraction point. Monitor tracer concentration in the extraction system and adjust the injection rate to achieve a concentration of 1 % by volume. This value represents the '100 % recovery' concentration.

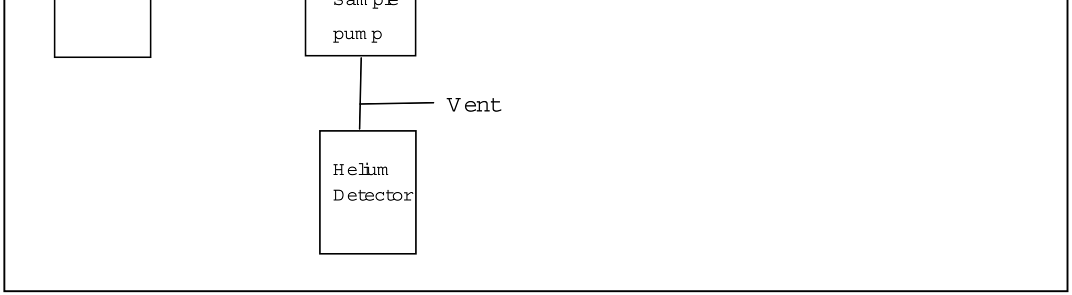


Fig. D1 Schematic drawing showing the system for establishing helium flow rate.

4. *Introduction of helium into the subsurface*

Once the preliminary data has been collected, the tracer test can be initiated. The IAS/SVE system should have been in operation for a period of several days prior to initiation of the tracer test. The first step is to start the analytical instrument and confirm background concentrations. If those concentrations are adequately low, the helium source can be connected to the IAS well and injection at the rate determined in section 3 can be initiated.

5. *Sample collection*

Samples should be collected prior to the extraction pump to avoid dilution and other errors which may occur in the extraction pump (see Fig. D2). (Samples can be collected after the extraction pump if the system is correctly calibrated, however, that procedure will not be discussed here). The pressure at this point will be below atmospheric so care must be taken to insure that a good sample is collected. In general, samples can be taken from the extraction manifold using a good quality diaphragm pump or metal bellows pump, or manually by syringe. (Once again, care should be taken to insure that the pump does not leak and introduce dilution air.) Pressures below 0.5 atm require extreme care to insure that a good sample is collected. In high-vacuum situations, the capacity of the pump on the helium detector may exceed the capacity of the sample pump. This problem must be addressed by using a sampling pump with adequate capacity.

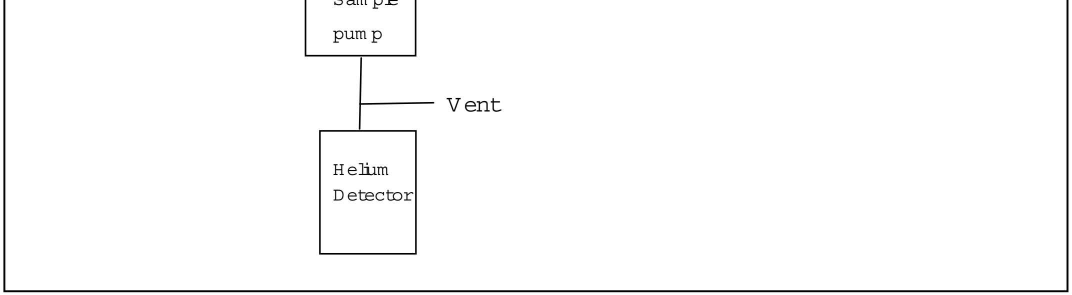


Fig. D2 Schematic drawing showing the setup for sample collection during the tracer recovery test.

6. *Data analysis*

The recovery efficiency at any point during the test is simply calculated as the ratio of the observed concentrations to the "100 % recovery" concentration determined at the beginning of the test.

In most cases helium will begin to be recovered within an hour of the initiation of tracer injection Helium concentrations can be expected to rise rapidly initially and then to asymptotically approach some final value. It may be necessary to continue the test for a period of 24 hours or more to establish the final value of recovery efficiency.

This time delay is due to travel times in the vadose zone as well as mixing of the tracer into air previously injected into the subsurface by the Ias system.

Stable recovery efficiencies of less than 100 % imply that some of the IAS air is escaping the SVE system. The significance of the lost air will depend upon the potential risks posed by off site migration of the sparge air. There is, of course, some uncertainty in the measurement of recovery efficiency. That uncertainty stems from uncertainty in flow measurements (injected helium extracted air) and measured helium concentrations. In this context, recoveries of greater than 80 % probably indicate adequate recovery and efficiencies of less than 50 % generally indicate incomplete recovery