NATIONAL REMEDIATION FRAMEWORK

Technology Guide
Groundwater

In-situ air sparging

August 2019

CRC CARE
A safer, cleaner environmental future

Cooperative Research Centre for Contamination Assessment and Remediation of the Environment, National Remediation Framework

August 2019

ISBN: 978-1-921431-81-4

Enquiries and additional copies:
CRC CARE, C/- Newcastle University LPO, PO Box 18, Callaghan NSW, Australia 2308
Tel: +61 (0) 2 4985 4941
Fax: +61 (0) 8 8302 3124
admin@remediationframework.com.au
www.remediationframework.com.au

This report should be cited as:
CRC CARE 2019, *Technology Guide: Groundwater – In-situ air sparging*, National Remediation Framework, CRC for Contamination Assessment and Remediation of the Environment, Newcastle, Australia.

Note on the National Remediation Framework
This document is one component of the National Remediation Framework (NRF). The NRF was developed by CRC CARE to enable a nationally consistent approach to the remediation and management of contaminated sites. The NRF is intended to be compatible with the National Environment Protection (Assessment of Site Contamination) Measure.

Acknowledgements
CRC CARE acknowledges the contributions of the service providers and researchers who contributed to this document and the NRF as a whole, together with the NRF Steering Group.

CRC for Contamination Assessment and Remediation of the Environment

National Remediation Framework

Technology guide: In-situ air sparging

Version 1.0: August 2019

National Remediation Framework

The following guideline is one component of the National Remediation Framework (NRF). The NRF was developed by the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE) to enable a nationally consistent approach to the remediation and management of contaminated sites. The NRF is compatible with the *National Environment Protection (Assessment of Site Contamination) Measure* (ASC NEPM).

The NRF has been designed to assist the site contamination practitioner undertaking a remediation project, and assumes the reader has a basic understanding of site contamination assessment and remediation principles. The NRF provides the underlying context, philosophy and principles for the remediation and management of contaminated sites in Australia. Importantly it provides general guidance based on best practice, as well as links to further information to assist with remediation planning, implementation, review, and long-term management.

This guidance is intended to be utilised by stakeholders within the site contamination industry, including site owners, proponents of works, site contamination practitioners, local councils, regulators, and the community.

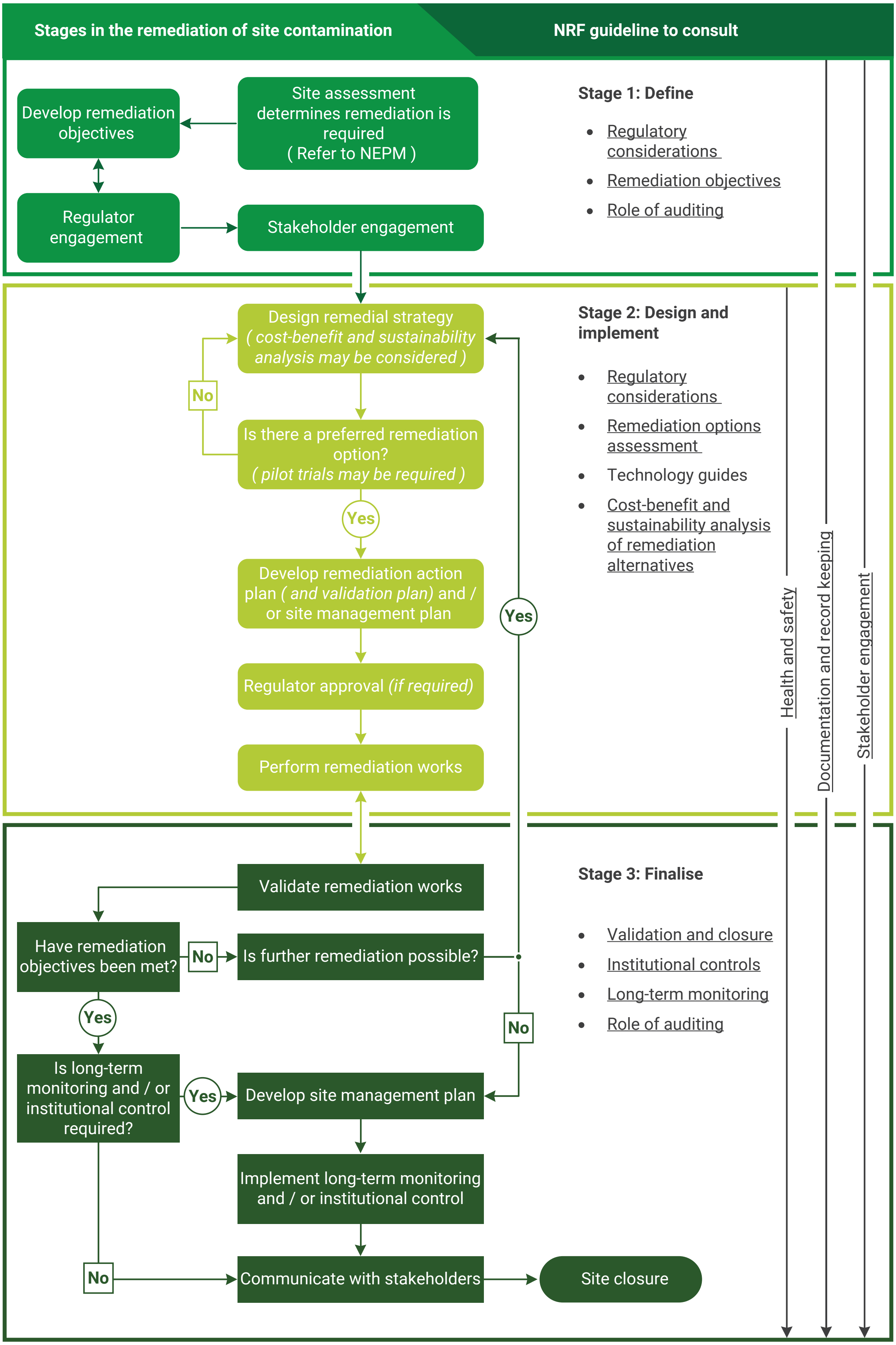
The NRF is intended to be consistent with local jurisdictional requirements, including state, territory and Commonwealth legislation and existing guidance. To this end, the NRF is not prescriptive. It is important that practitioners are familiar with local legislation and regulations and note that **the NRF does not supersede regulatory requirements**.

The NRF has three main components that represent the general stages of a remediation project, noting that the remediation steps may often require an iterative approach. The stages are:

- define
- design and implement, and
- finalise.

The flowchart overleaf provides an indication of how the various NRF guidelines fit within the stages outlined above, and also indicates that some guidelines are relevant throughout the remediation and management process.

It is assumed that the reader is familiar with the ASC NEPM and will consult other CRC CARE guidelines included within the NRF. This guideline is not intended to provide the sole or primary source of information.


Stages in the remediation of site contamination
NRF guideline to consult
Develop remediation objectives
Site assessment determines remediation is required (Refer to NEPM)
Regulator engagement
Stakeholder engagement
Stage 1: Define
Regulatory considerations
Remediation objectives
Role of auditing
Design remedial strategy (cost-benefit and sustainability analysis may be considered)
No
Is there a preferred remediation option? (pilot trials may be required)
Yes
Develop remediation action plan (and validation plan) and / or site management plan
Yes
Regulator approval (if required)
Perform remediation works
Stage 2: Design and implement
Regulatory considerations
Remediation options assessment
Technology guides
Cost-benefit and sustainability analysis of remediation alternatives
Health and safety
Documentation and record keeping
Stakeholder engagement
Validate remediation works
Have remediation objectives been met?
No
Is further remediation possible?
Yes
No
Is long-term monitoring and / or institutional control required?
Yes
Develop site management plan
Implement long-term monitoring and / or institutional control
No
Communicate with stakeholders
Site closure
Stage 3: Finalise
Validation and closure
Institutional controls
Long-term monitoring
Role of auditing

Executive summary

In-situ air sparging (IAS) is a process where air is injected directly into the saturated subsurface to:

- volatilise contaminants from the liquid phase to the vapour phase for treatment and/or removal in the unsaturated zone, and
- biodegrade contaminants in the saturated and unsaturated zone via stimulation by the introduction of oxygen (atmospheric).

Generally, volatilisation dominates when IAS systems are first initiated and for aerobically degradable compounds, biodegradation may dominate in later phases of treatment. Volatilised contaminants may also be biodegraded in the unsaturated zone or may be extracted via a coupled soil vapour extraction (SVE) system and treated or discharged, extending the applicability of SVE to saturated soils and groundwater through physical removal of volatilised groundwater contaminants.

Historically, IAS has been applied to:

- treat immiscible contaminant source zones at or below the capillary fringe
- remediate dissolved contaminant plumes, and
- provide barriers to prevent dissolved contaminant plume migration (plume containment).

IAS is a mature technology and its use has increased rapidly since the early 1990s. It is a relatively easy technology to implement, it is well known to regulatory agencies, and the equipment necessary for IAS is generally inexpensive and easily obtained.

The viability of in-situ air sparging as a potential remediation option often will ultimately depend on the following site-specific considerations:

- whether air sparging will significantly reduce the risk posed by the contamination, or will significantly reduce the time over which the risk will be reduced to an acceptable level
- whether the contaminant is sufficiently volatile
- whether sparging will achieve the required outcome given the uniformity and permeability of the local geology, and distribution, concentration and extent of the contaminant, and
- whether the presence of air will be helpful in encouraging oxidation and reduction of the contamination.

The engineering design process has three main components:

- air injection system
- vapour extraction and treatment system, and
- monitoring network.

The primary lines of evidence for the validation IAS are usually:

- reduction in contaminant concentration over time or with distance through the reactive zone

- analysis of geochemical and biochemical parameters
- mass flux or mass discharge from treated materials, and
- groundwater monitoring to assess whether the plume is diverting around or beneath the system.

Abbreviations

BTEX	Benzene, toluene, ethylbenzene and xylene
cm/s	Centimetres per second
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
DCE	Dichloroethene
DNAPL	Dense non-aqueous phase liquid
DO	Dissolved oxygen
Fe(II)	Ferrous oxide, FeO
IAS	In-situ air sparging
kg	Kilogram
LNAPL	Light non-aqueous phase liquids
m	Metre
mg/L	Milligram per litre
mm	Millimetre
m^3/min	Cubic metres per minute
MTBE	Methyl tertiary butyl ether
NAPL	Non-aqueous phase liquid
NRF	National Remediation Framework
PCB	Polychlorinated biphenyl
PCE	Tetrachloroethylene
PCP	Pentachlorophenol
pH	Power of hydrogen
PPE	Personal protective equipment
ppmv	Parts per million in the vapour
PVC	Polyvinyl chloride
RAP	Remediation action plan
ROI	Radius of influence
SF_6	Sulphur hexafluoride
SVE	Soil vapour extraction
TCE	Trichloroethylene
VOC	Volatile organic compounds

Glossary

Aerobic	A process that occurs in the presence of free oxygen.
Anisotopic	Physical properties varying in different directions.
Aquifer	An underground layer comprising bedrock, unconsolidated natural material, or fill, that is capable of being permeated permanently or intermittently with groundwater, and that allows the free passage of groundwater through its pore spaces.
Baseline	Historical environmental data, and monitoring data collected from before an activity begins. Depending on the context, activity could mean a particular site use, site development, change in site use, or remediation.
Biodegradation	The transformation of a substance or chemical by microorganisms such as bacteria or fungi, resulting in a change in chemical structure mass within the environment.
Biosparging	A particular type of air sparging that operates without a vapour collection system, instead relying on biodegradation to remove volatile components
Capillary fringe	The zone of soil immediately above the water table into which groundwater can seep up via capillary action to fill pores.
Concentration	The amount of material or agent dissolved or contained in unit quantity in a given medium or system.
Conceptual site model (CSM)	A representation of site-related information including the environmental setting, geological, hydrogeological and soil characteristics together with the nature and distribution of contaminants. Contamination sources, exposure pathways and potentially affected receptors are identified. Presentation is usually graphical or tabular with accompanying explanatory text.
Confined aquifer	An aquifer that is overlain (confined) by an impermeable rock layer.
Contaminant	Any chemical existing in the environment above background levels and representing, or potentially representing, an adverse risk to human health and/or environment, and/or any other environmental value.
Contaminated site or land	A generic term referring to any land (including soil, surface water, groundwater and soil vapour) that is affected by substances that occur at concentrations above background or local levels and which represent, or potentially represent, a risk to human health and/or the environment, and/or any other environmental value.

Dewatering	Active pumping of water at a sufficiently high rate to temporarily remove water from the strata. Used both in reference to surface water (to dewater an excavation) and groundwater (to dewater a water bearing zone).
Environment(al) protection authority/agency (EPA)	The government agency in each state or territory that has responsibility for the enforcement of various jurisdictional environmental legislation, including some regulation of site contamination.
Groundwater	Water stored in the pores and crevices of the material below the land surface, including soil, rock and fill material.
In-situ air sparging	The process by which air is injected directly into the saturated subsurface to volatilise contaminants from the liquid phase to the vapour phase for treatment and/or removal in the unsaturated zone, and to biodegrade contaminants in the saturated and unsaturated zone via stimulation by the introduction of oxygen.
Non-volatile	A chemical that remains a solid above 260 ºC.
Practitioner	Those in the private sector professionally engaged in the assessment, remediation or management of site contamination. For example, these include consultants, auditors and certified practitioners.
Proponent	A person who is legally authorised to make decisions about a site. The proponent may be a site owner or occupier or their representative.
Radius of influence	The radial distance from the treatment location to the point where there is no discernible treatment occurring.
Remediation	Remediation is taking steps towards remedying something, in particular of reversing or stopping environmental damage. It may be action designed to deliberately break the source-pathway-receptor linkage in order to reduce the risk to human health and/or the environment to an acceptable level.
Risk	The probability that in a certain timeframe an adverse outcome will occur in a person, a group of people, plants, animals and/or the ecology of a specified area that is exposed to a particular dose or concentration of a specified substance, i.e. it depends on both the level of toxicity of the substance and the level of exposure. Risk differs from hazard primarily because risk considers probability.
Semi-volatile	A chemical that evaporates between 240–260 ºC

Site	A parcel of land (including ground and surface water) being assessed for contamination, as identified on a map by parameters including lot and plan number(s) and street address. It is not necessary for the site boundary to correspond to the lot and plan boundary, however it commonly does.
Smear zone	The area where hydrocarbons in the soil have been smeared across the soil as the water table has fluctuated between historic high and low elevations.
Treatability studies	A series of tests designed to ascertain the suitability of the treatment for the contaminants under the site conditions.
Vapour phase	The portion of the contaminant held within the matrix as a gas, or vapour. Chemicals in the vapour phase can be condensed to a liquid by increasing pressure without reducing the temperature.
Volatile	A chemical that evaporates between 50–100 ºC.
Volatile organic compound	Organic chemical compounds whose composition makes it possible for them to evaporate under normal indoor air atmospheric conditions.
Volatilisation	The process of a chemical turning from a liquid to a gas, or vapourising.

Table of contents

1. Introduction

The purpose of this guideline is to provide information on in-situ air sparging (IAS) as a treatment technology for the remediation of contaminated sites to assist with selection of remediation options. The document contains information to inform remediation planning and aid compilation of a remediation action plan (RAP).

This guidance is primarily intended to be used by remediation practitioners and those reviewing practitioner's work, however it can be used by other stakeholders within the contaminated sites industry, including site owners, proponents of works, and the community.

IAS is one of many technologies available for contamination remediation, and other technologies may be more appropriate. It is assumed that the information presented within will be used in a remediation options assessment to identify and select the preferred technologies for more detailed evaluation. This guideline provides information for both initial options screening and more detailed technology evaluation. This guideline does not provide detailed information on the design of IAS systems as this is a complex undertaking and should be carried out by appropriately qualified and experienced practitioners. Readers are directed to the NRF Guideline on performing remediation options assessment for detailed advice on assessing remediation options. In addition, the remediation objectives, particularly the required quality of the soil after treatment, are a critical matter and it is assumed that these have been determined and considered in the remediation options assessment and selection process. Readers are directed to the NRF Guideline on establishing remediation objectives for more detailed advice.

References to case studies are provided in **appendix A**.

A number of sources of information were reviewed during the formulation of this document to compile information on potential technologies. These are listed in references and provide an important resource to readers.

2. Technology description and application

IAS is a process where air is injected directly into the saturated subsurface to:

- volatilise contaminants from the liquid phase to the vapour phase for treatment and/or removal in the unsaturated zone, and
- biodegrade contaminants in the saturated and unsaturated zone via stimulation by the introduction of oxygen (atmospheric).

Generally, volatilisation dominates when IAS systems are first initiated, and, for aerobically degradable compounds, biodegradation may dominate in later phases of treatment. Volatilised contaminants may also be biodegraded in the unsaturated zone or may be extracted via a coupled soil vapour extraction (SVE) system and treated or discharged, extending the applicability of SVE to saturated soils and groundwater through physical removal of volatilised groundwater contaminants. For more detailed information on SVE, readers are directed to the *NRF Technology guide: Soil vapour remediation*.

Historically, IAS has been applied to:

- treat immiscible contaminant source zones at or below the capillary fringe
- remediate dissolved contaminant plumes, and
- provide barriers to prevent dissolved contaminant plume migration (plume containment).

IAS is a mature technology and its use has increased rapidly since the early 1990s. It is a relatively easy technology to implement, it is well known to regulatory agencies, and the equipment necessary for IAS is generally inexpensive and easily obtained.

Figure 1 is a schematic illustration of the basic elements of an IAS system.

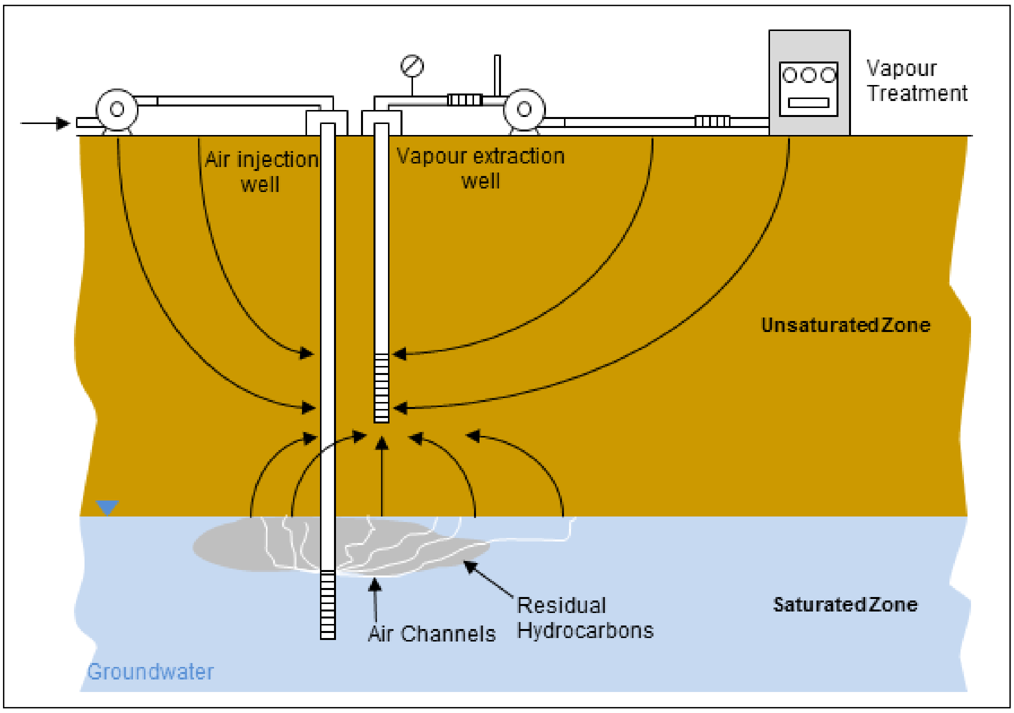


Figure 1: General design elements of an in-situ air sparging system.

Other variations on the basic air sparging system can be used to increase volatilisation or stimulate biodegradation; these include:

- soil heating
- injection of heated air
- injection of steam
- injection of other gases (e.g. oxygen, hydrogen, propane)
- nutrient amendments (in vapour phase, e.g. nitrogen), and
- air sparging design.

Figure 2 is a flowchart illustrating the steps involved in assessing and implementing IAS as a remediation technology. This flow chart was based on a review of pre-2000 IAS projects in the US within Leeson *et al* (2002).

It is important to note that the use of sulphur hexafluoride (SF_6) for gas distribution tests may not be acceptable under some regulatory frameworks as it is a potent greenhouse gas. However, only very small amounts are used. Readers are directed to the NRF Guideline on regulatory considerations for more information.

The advantages and disadvantages of IAS are presented in table 1.

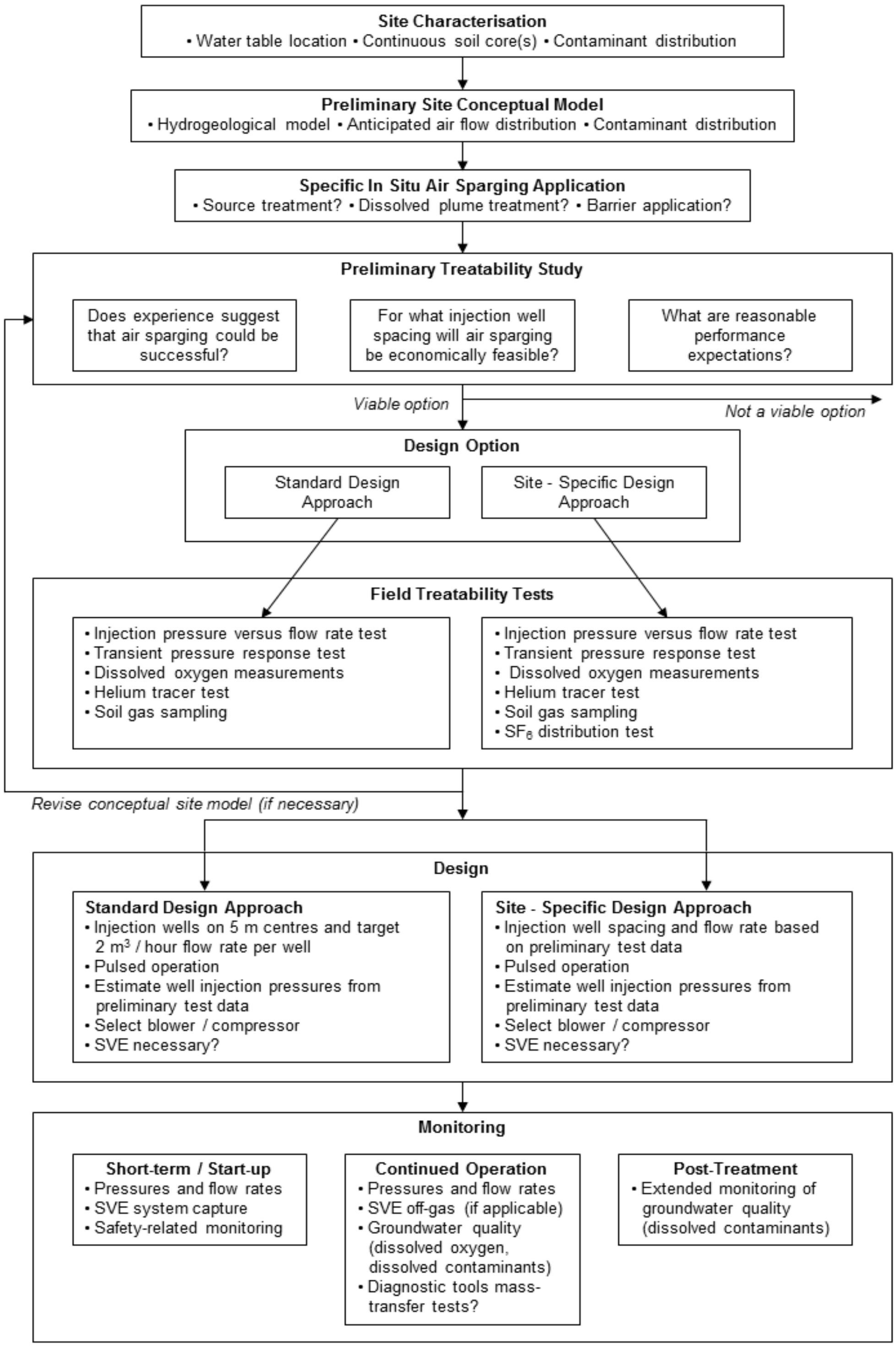


Figure 2: Sequence of activities during implementation of air sparging, from Leeson et al (2002).

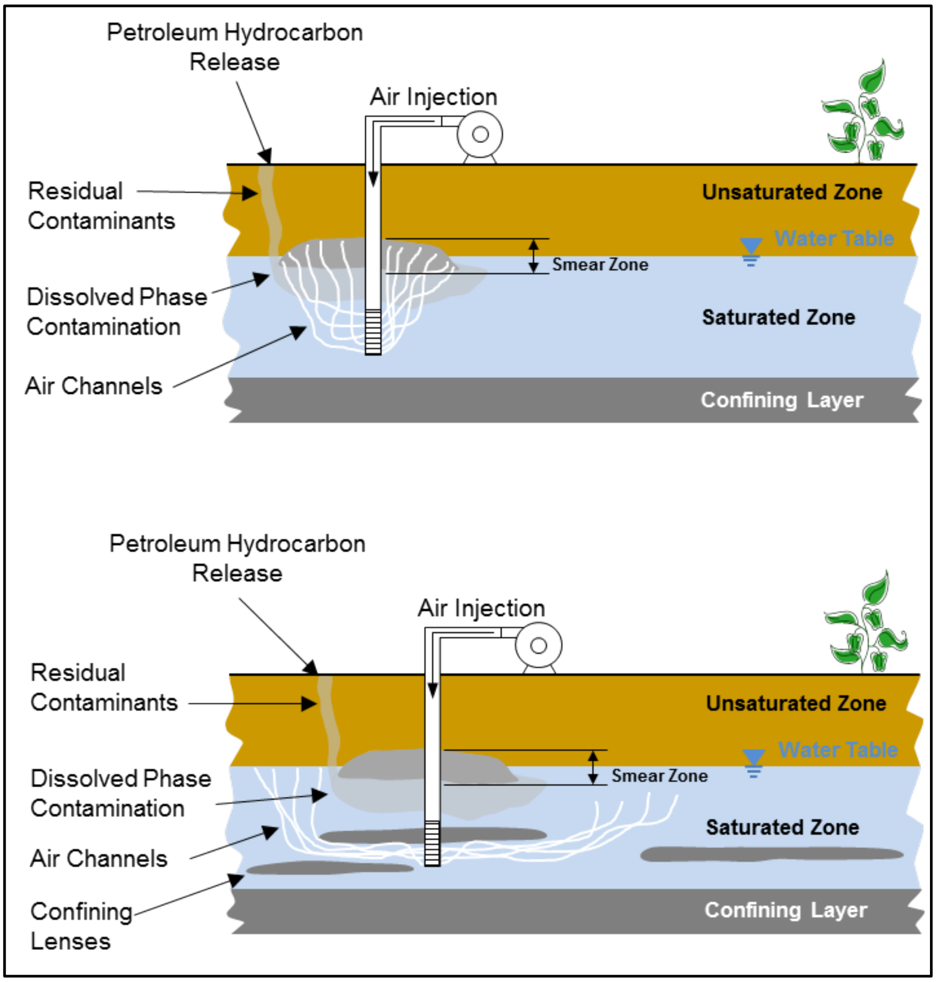


Figure 3: The effect of soil heterogeneity on injected air distribution, from NAVFAC (2001).

Table 1: Advantages and disadvantages of IAS.

Advantages	Disadvantages
• Mature technology, relatively easy technology to implement, well known to regulatory agencies and the equipment necessary for IAS is generally inexpensive and easily obtained. • Implemented with minimal disturbance to site operations. • Short treatment times (usually less than 1 to 3 years under optimal conditions). • Requires no removal, treatment, storage, or discharge considerations for groundwater. • Can enhance removal by SVE. • It is possible that existing monitoring wells can be used for air sparging (depending on the well screening as the response zone would need to be located below the water table). • Contaminants desorb more readily into the gas phase than into groundwater. • Air sparging can be used to treat contamination in the capillary fringe and/or below the water table (in contrast to SVE techniques). • Because of the low operation and maintenance costs of this technology, it can be particularly effective when large quantities of groundwater must be treated.	• Might not be appropriate if light non-aqueous phase liquid (LNAPL) is present (LNAPL may need to be removed prior to air sparging), although trials have shown IAS to be effective for treatment of weathered non-aqueous phase liquid (NAPL). • Cannot be used for treatment of confined aquifers, as air is unable to carry vapours into the unsaturated zone for removal. • Stratified soils may cause air sparging to be ineffective. Fine-grained, low-permeability soils limit air flow through groundwater and in the unsaturated zone. Where the lithological profile includes a low-permeability layer overlying the aquifer, the vapour stream may be prevented from being effectively captured by vapour extraction wells. • Some interactions among complex chemical, physical, and biological processes are not well understood. • Lack of field and laboratory data to support design considerations. • Potential for inducing vapour intrusion to subsurface confined spaces present at or near the site. Potentially dangerous constituent concentrations could accumulate in basements unless a vapour extraction system is used to control vapour migration. • Requires detailed treatability testing and monitoring to ensure vapour control and limit migration. • Contaminants that form complexes with the soil matrix, decreasing volatilisation rates. • Heterogeneous soils, which may cause channelling (preferential movement of air through high conductivity layers or preferential migration

Advantages	Disadvantages
	pathways such as tree roots or service trenches, and possibly away from the area of contamination) or other complex air flow conditions that may be difficult to predict and/or control. • Relatively large saturated thicknesses are required – greater than 2 m of water column is required and depths to groundwater should be greater than 2 m as mounding will result in water rising into the vadose zone and may lead to water being entrained in the SVE system. The length of the saturated thickness and the depth below the water table at which air is injected are factors that determine the area of influence of a sparging well. • Where IAS is applied using a high air injection rate in a barrier sparging formation, this can result in a zone of reduced hydraulic conductivity and could result in diversion of the plume and a reduction in the effectiveness of treatment. Monitoring and management is required to avoid this. • Aquifer clogging or plugging may occur when increased iron precipitation or biomass accumulation caused by oxygen injection changes aquifer characteristics.

3. Feasibility assessment

The viability of IAS as a potential remediation option often will ultimately depend on the following site-specific considerations:

- whether air sparging will significantly reduce the risk posed by the contamination, or will significantly reduce the time over which the risk will be reduced to an acceptable level
- whether the contaminant is sufficiently volatile
- whether sparging will achieve the required outcome given the uniformity and permeability of the local geology, and distribution, concentration and extent of the contaminant, and
- whether the presence of air will be helpful in encouraging oxidation and reduction of the contamination.

Table 2 provides a general summary of these considerations. Secondary considerations include adjacent receptors (infrastructure issues such as power availability, and access including safety and security and the existence of underground services and proximity to active plant and machinery. Figure 4 is a screening decision matrix/flowchart for assessing the feasibility of IAS.

Table 2: Conditions amenable to IAS

Applicability	Likely to be effective	Likely to have limited effectiveness	Unlikely to be effective
Contaminant types	• petrol • aviation fuel • BTEX • diesel • halogenated solvents[1]	• acetone • MTBE	• weathered fuels • lubricating oils • hydraulic fluids • dielectric fluids • polychlorinated biphenyls (PCBs)
Geology	• uniform coarse-grained soils (gravels, sands) • uniform silts	• weakly stratified soils • sandy silt • gravelly silt • highly fractured clay • fractured bedrock	• silt and clay (interbedded) • massive clay • highly organic soils • stratified soil • confining layers
Contaminant phase	Dissolved	Adsorbed	Separate phase (NAPL) (NB table 1)
Contaminant location	Near water table of unconfined aquifer	Within shallow unconfined aquifer	Within confined aquifer, near bottom of unconfined aquifer
Contaminant extent	Small plumes	Moderate sized plumes	Large plumes[2]
Hydraulic conductivity (cm/s)	$>10^{-4}$	$10^{-5} – 10^{-4}$	$<10^{-5}$
Aquifer anisotropy	Isotropic	Moderate degree of anisotropy	High degree of anisotropy

[1] IAS is generally applicable to halogenated ethenes, ethanes, and methanes; [2] greater than a few hectares. Sparge curtains may be effective in managing migration within large plumes.

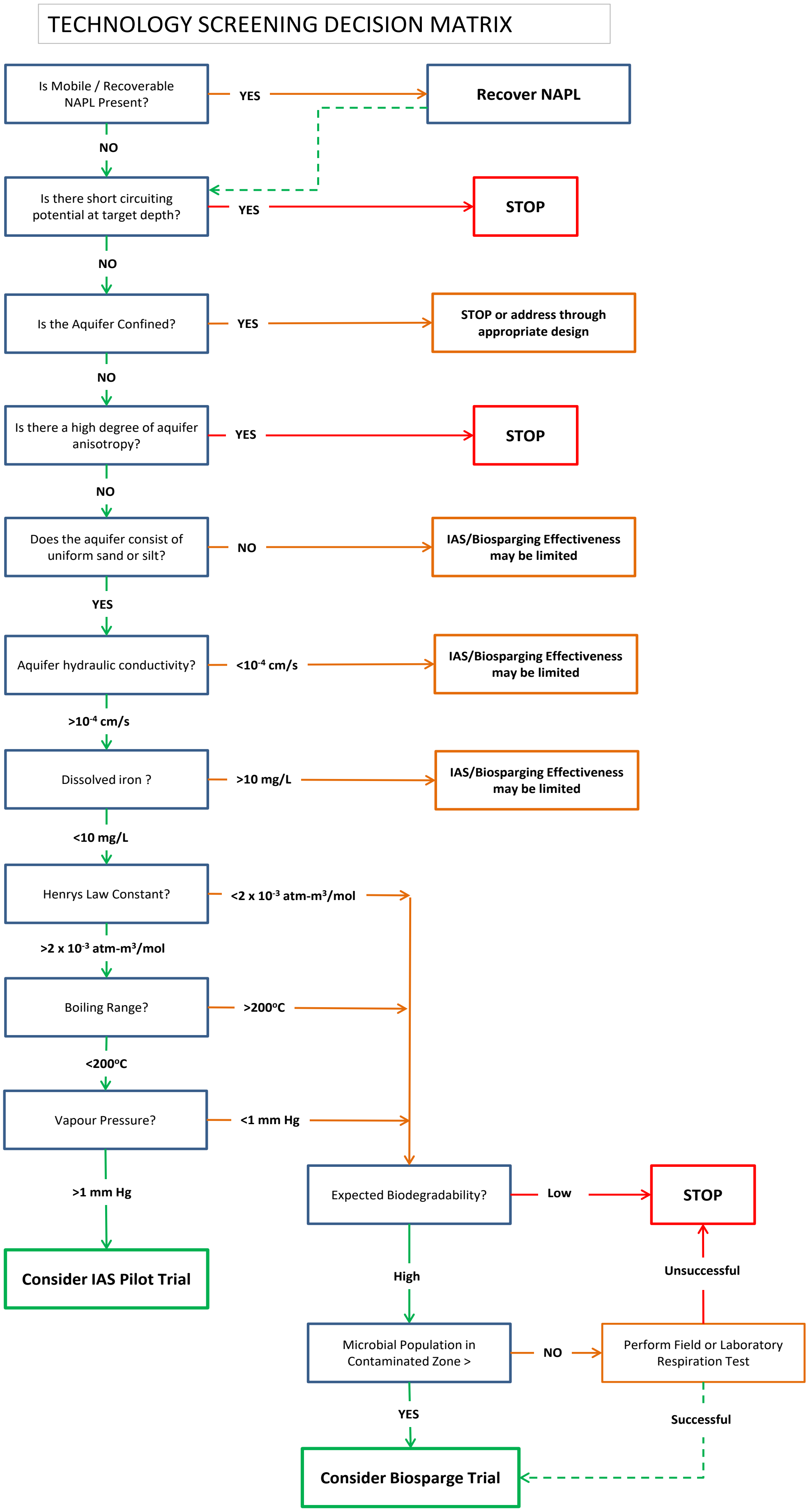


Figure 4: IAS technology screening decision matrix/flowchart.

3.1 Data requirements

Table 3 summarises the site characterisation data required to allow a feasibility assessment of IAS to be completed.

3.2 Treatable contaminants

Various volatile, semi-volatile, and non-volatile organic contaminants in dissolved, adsorbed, and vapour phases can be treated using air sparging. IAS can be applicable for the treatment of less volatile and/or tightly adsorbed chemicals that could not be remediated using vapour extraction alone, however modifications may be required (see below). Contaminants that may be removed by the volatilisation and biodegradation processes of air sparging include:

- petroleum hydrocarbons
- oils and greases
- benzene, toluene, ethylbenzene and xylene (BTEX) compounds, and
- chlorinated solvents – for example tetrachloroethylene (PCE), trichloroethylene (TCE) and dichoroethene (DCE).

IAS can also be modified to treat other chemicals by, for example, using an ozone generator with the standard air sparging technique to extend the capabilities of the technology to chlorinated phenols (pentachlorophenol), alcohols, ketones, and other industrial solvents. The injected ozone breaks the chlorine bonds, facilitating biodegradation of the resulting compounds.

IAS technology is not effective at treating soils or other materials contaminated solely with inorganics such as metals or asbestos. It may also not be effective for the treatment of organic corrosives and reactive oxidisers and reducers, depending on the chemical composition of these contaminants.

Air sparging can be applied to situations in which dewatering (to allow the application of vapour extraction to residually contaminated soils) is not feasible, such as sites with high yield aquifers and thick smear zones.

Table 3: Site characterisation parameters for assessing feasibility of air sparging.

Item	Parameter	Comments

Item	Parameter	Comments
Site history/data gap analysis	• Site engineering plans • Chemical inventory records • Site history	Identify data gaps.
Site geology/ hydrogeology	• Subsurface geology • Soil type/stratification • Groundwater depth • Groundwater velocity • Groundwater direction • Hydraulic gradient	Collect data within the target treatment area. This can involve collecting soil cores, installing groundwater wells, performing aquifer characterisation tests and monitoring groundwater elevations. It is useful to take water-level measurements at several times during the year (ideally over several years) where possible so seasonal and long-term variations in groundwater flow velocity and direction can be evaluated.
Contaminant type and distribution	• Contaminant type • Contaminant(s) of concern • LNAPL thickness (if present) • LNAPL recovery potential • Volume of contaminant released	It is necessary to collect data that is sufficient to define the extent of the contaminant plume both horizontally and vertically, as well as to understand plume movement over time. Contaminant distribution data should be plotted on contour plans and on cross-section profiles to visualise the lateral and vertical extent of the plumes.
Geochemical assessment	• Dissolved oxygen • Redox potential • pH • Conductivity • Nitrate • Fe(II) • Methane	Define horizontal and vertical distribution through multilevel wells for thicker contaminant plumes and define horizontal distribution for thinner contaminant plumes. These parameters are optional for most air sparging sites, but critical when the application is meant to enhance bioremediation.
Receptor assessment	• Identify potential receptors of groundwater contamination. • Identify potential receptors of vapour migration.	Conduct a site visit and examine site boundaries. Identify human health and environmental receptors that could be impacted by the contamination and remediation process.
Regulatory and stakeholder engagement	• Identify regulatory authorities and define the remedial objectives. • Similarly other stakeholders should be consulted if remedial or monitoring activities are likely to encroach on their activities.	Early contact with the appropriate regulatory agencies is encouraged, as regulatory guidelines may exist that must be followed during site characterisation.

4. Treatability studies

Treatability studies are an important tool for improving understanding of the applicability of IAS at a site and are a useful method for identifying show-stoppers prior to installation of full-scale systems. As IAS is an in-situ method, bench tests are not usually performed, and treatability studies are likely to involve only pilot trials. In this context, IAS treatability studies are useful to:

- identify indicators of infeasibility (show-stoppers)
- characterise the distribution of air that is likely to occur (i.e. the effectiveness of IAS), and
- identify safety hazards to be addressed in the full-scale design.

Prior to planning the IAS treatability study, the following should be undertaken:

- define the target treatment zone (the volume) which is to be treated by the air sparging system
- select a model for the air distribution in the treatment zone (e.g. based onsite information, determine if the aquifer is homogeneous or stratified)
- determine the minimum injection well spacing that can be achieved
- select the depth, location, and construction specifics of a test well, and
- determine the expected range of operating pressures for the injection well.

Pilot trials are necessary to adequately design and evaluate an IAS system. The sparge well(s) used for pilot testing should be in an area of no more than moderate contaminant concentrations. Testing the system in areas of extremely low contaminant concentrations may not provide sufficient data, and because sparging can induce migration of constituents, pilot tests are generally not conducted in areas of extremely high contaminant concentrations. The IAS treatability study should also include an SVE treatability study.

The first stage of treatability testing for an IAS system generally comprises a single well sparge trial to determine design parameters such as injection pressures, flow rates, radius of influence and required well spacing.

Table 4 summarises the typical tasks involved in a treatability study and how the information gathered during the trial is used to assess the feasibility of full-scale implementation.

If the preliminary assessment indicated that dense injection well spacing (approximately 5 to 7 m) is cost effective, the first six activities in table 4 should be undertaken. If larger well spacing is required, additional site-specific activities should be undertaken, including tracer gas tests to estimate the radius of influence (ROI) and possibly geophysical tests to define the zone of aeration, as set out in tasks 7 and 8 in table 4.

Table 4: Summary of IAS treatability study activities.

Task number	Activity description	Data objectives
1.	Baseline sampling:	What are aquifer conditions prior to air

Task number	Activity description	Data objectives
	• dissolved oxygen (DO) • pressure • soil gas, and • geophysical.	sparging start up?
2.	Injection pressure/flow rate test.	Is it possible to sustain air flow at the set injection pressure?
3.	Groundwater pressure response test.	What are the general characteristics of the air distribution (assess migration of injection air by measuring subsurface pressures at various distances from the injection well)?
4.	Helium tracer test.	What is the approximation of lateral extent of the air distribution? Are there indications of preferred directions?
5.	Soil gas/off-gas sampling.	What is the volatilisation rate? Are there any obvious safety hazards?
6.	DO measurements.	What is the approximation of lateral extent of the air distribution? Are there indications of preferred directions?
7. (only for larger well spacing)	Tracer distribution test.	Is there effective air distribution in the target treatment zone? What are the oxygen transfer rates to groundwater?
8. (only for larger well spacing)	Other geophysical tools (e.g. neutron probe).	What is the vertical and lateral extent of the air distribution in the target treatment zone?

The following sections provide information on field equipment and monitoring well network, as well as more detailed descriptions of tasks 1–6.

4.1 Equipment

The following equipment is needed to conduct the activities:

- at least one air injection well equipped with a well-head pressure gauge, flow meter and valve
- an air compressor, with associated air supply/discharge lines and fittings
- one to three groundwater monitoring wells (GWMWs)
- several groundwater and unsaturated zone monitoring points, and
- procedures to test the vapour extraction system to assess the effectiveness of capturing vapours liberated during the IAS.

4.2 Injection and monitoring well

When selecting the monitoring layout, it is important to recognise that air distributions often have unpredictable preferred migration pathways and therefore a spatially distributed monitoring network is generally more effective than installations having monitoring points emanating out from the injection well in a line in one or two directions only. Furthermore, the locations should reflect the hydrogeological setting. In near homogeneous sandy geological settings, the monitoring network may not need to extend more than approximately 5–7 m out from the injection well.

4.3 Baseline sampling

Baseline sampling is a critical task to be completed pre-trial. For several of the parameters, it is important to collect the following data prior to IAS activities taking place to ensure that initial conditions are understood:

- dissolved oxygen, and
- baseline pressure transducer data with a data-logger. The pressure data should be collected for a sufficiently long period to assess diurnal changes in water level (e.g. tidal fluctuations) if they are believed to be significant.

The SVE system should be operated for a period prior to IAS start up to ensure that the SVE system is operating properly to capture the initial high mass loading. During this period, the SVE off-gas should be monitored for contaminants of interest in order to distinguish, if possible, the mass loading from volatilisation from the unsaturated zone compared to volatilisation from groundwater only.

4.4 Air injection flow rate and injection pressure

Prior to pilot trials, it is important to evaluate the expected operating injection pressure for the IAS system. This is important both for the selection of the correct air injection system and for the prevention of pneumatic fracturing of the aquifer.

4.5 Groundwater pressure measurements during IAS start and stop

Once the flow and pressure conditions for sparging have been established, the required groundwater pressures can be evaluated. The primary objective of this test is to assess the time required for air flow distribution to stabilise.

Pressure measurements provide an easy and sensitive means of assessing if sparge air is stratigraphically trapped below the water table. The pressure measurements can also provide a measure of site permeability, based on the magnitude of the response.

In general terms, during air sparging start up, groundwater pressures will increase because air is being pushed into the formation faster than the water can move away from the air sparging well.

Typically, while the volume of air below the water table is increasing, the groundwater head will be above pre-air sparging levels. The time required for groundwater head to return to pre-air sparging values can be a good measure of the time required for the macro-scale air distribution to come to steady state.

For sandy formations, the time required for air sparging pressures to return to pre-air sparging values will generally be measured in tens of minutes to a few hours. If the site is stratified with lower-permeability layers, then the groundwater pressure may remain elevated for tens of hours to days.

The magnitude of the groundwater pressure response can be from millimetres to a few metres of water. Coarse materials can be expected to result in more rapid pressure responses and usually result in lower mounding.

4.6 Tracer test to assess recovery

The tracer recovery tests described here are designed to be conducted on an air sparging system that is already operating, and after the air flow patterns have stabilised. It can be conducted as part of a treatability study or during full-scale operation.

Tracers for air sparging systems can help to:

- Assess the effectiveness with which the SVE system is capturing the sparge air; and
- Identify the locations where sparge air moves from the saturated zone to the unsaturated zone.

To be most useful, the air sparging and SVE wells should be co-located. The test is simple to conduct and interpret. An inert tracer (usually helium) is introduced into the sparge air at a constant, known rate and the concentration of tracer is monitored in the SVE off-gas. After some period (e.g. an hour or less for many systems), the concentration of the tracer in the SVE off-gas begins to rise. It continues to rise and eventually reaches a stable plateau. The percentage of the sparge air that is captured can then be calculated.

Tracer tests can be repeated, usually with delays of only a few hours or so between tests. This allows the effects of process changes (e.g. distribution of air flow from various wells) to be quickly assessed.

Helium is the most common tracer gas used, since it is relatively inexpensive, readily available and analytical instrumentation is available for field use. Typically, vapour samples are collected in Tedlar® bags or canisters, and then measured using a field instrument. Alternatively, the helium detector can be modified to sample continuously, to provide real time data during the test.

The tracer recovery test can be used as a show stopper for air sparging system performance – if the recovery of helium is low, then it is possible that air (and helium) is being trapped below the water table beneath lower permeability strata and may be moving laterally beyond the reach of the SVE system. In some cases, it is possible that no helium will return to the well due to the presence of continuous, low permeability layers. The presence of these layers should also be detectable by monitoring groundwater pressure during air sparging start up and shutdown. Therefore, it is recommended that the helium recovery test be conducted in conjunction with groundwater pressure measurements.

If tracer recovery is high (e.g. >80%), then the SVE system is performing well and lateral migration of vapours is unlikely to be a problem.

4.7 Dissolved oxygen monitoring

Dissolved oxygen (DO) data has the potential to identify the zone where oxygen is being delivered by the IAS system, which is important for assessing biodegradation potential associated with the sparging.

If baseline measurements show low dissolved oxygen concentrations (e.g. <2 mg/L) it may be possible to identify areas where air sparging has resulted in increases of DO. To determine this, dissolved oxygen should be measured in all GWMWs immediately following the pilot trials. It is important to note that several factors can complicate the interpretation of DO, including:

- at many sites where active biodegradation is ongoing, there may be significant quantities of reduced species (e.g. Fe(II) that act as rapid sinks for oxygen and that mask oxygen delivery to that region
- microbial activity may be high, effectively consuming oxygen as fast as it is delivered to the area, or
- false positives can be caused by air entry into monitoring wells and preferential aeration within the well – because of this short-screened monitoring wells in the treatment zone are recommended for the field test.

4.8 Field observations

Often during field treatability studies there will be operational factors observed that are important to the viability of IAS. It is important to note qualitative indicators of air distribution, such as bubbling or gurgling noises in wells, water escaping out of monitoring points. It is also important to be aware of odours due to the contaminants, noise due to the equipment, or other environmental factors. While these factors may not lessen the successful implementation of IAS, they can make the system less feasible from a community/stakeholder impact perspective.

5. Operational system

If results of the treatability studies are favourable, then the full-scale design may be developed and implemented. If buildings or underground corridors may be impacted, vapour migration management must be accommodated in the system design.

The essential goals in designing and operating IAS systems are to configure the wells and monitoring points in such a way to:

- maximise the removal efficiency of the system, and
- provide optimum monitoring and vapour extraction points to ensure minimal migration of the vapour plume and that migration of either the dissolved phase or vapour phase plumes is not going undetected.

The engineering design process has three main components:

- air injection system
- vapour extraction and treatment system, and
- monitoring network.

5.1 Design

The placement and number of air sparge points required to address the dissolved phase plume is influenced primarily by soil permeability and structure as these affect the sparging pressure and distribution of air in the saturated zone. Coarse grained soils have greater intrinsic permeability than fine-grained soils and it is easier to move air (and water) through more permeable soil. Greater lateral dispersion of the air is likely in fine grained soils and can result in lateral displacement of the groundwater and contaminants if groundwater movement is not controlled.

The ROI for air sparging wells is the most important parameter to be considered in the design of the air sparging system. The ROI is defined as the greatest distance from a sparging well at which sufficient sparge pressure and airflow can be induced to enhance the mass transfer of contaminants from the dissolved phase to the vapour phase. The ROI will help determine the number and spacing of the sparging wells. Air sparging wells should be placed so that the ROIs overlap, to avoid introducing stagnant zones (i.e. zones where no stripping occurs).

Also important is the development of finely dispersed air channels, which increase the surface contact area between the introduced air and the contaminant being treated.

The sparging air flow rate required to provide sufficient air flow for mass transfer from dissolved to vapour phase is site specific and is evaluated during the pilot trials.

Table 5 summarises the critical design considerations involved in full-scale implementation of an IAS remediation program.

5.2 Air injection system

The air injection system is the primary component of the IAS system and consists of an air compressor, rotary vane or rotary claw blower, air filter, piping, valves/controls (manifolds), and injection wells, as shown in figure 5. The following sections discuss injection well placement and design.

Table 5: Critical design considerations for air sparging installations.

Installation	Design parameter
Air injection system	Potential to use micro porous screen to produce smaller bubbles and greater potential to disperse into the surrounding rock/soil without the formation of air channels.
	Injection well screen begins a minimum of 2 m below the water table to increase the ROI as the air travels further laterally in a permeable formation.
	Separate pressure control and flow meter for each injection well.
	Competent well seal immediately above well screen.
	Injection flow rate between 0.15 to 0.6 m^3/min.
	Pulsed injection in banks of 2 to 5 wells.
Vapour extraction and treatment system	Extract 2 to 3 times the air injected and maintain vacuum in soil vapour monitoring points.
	Granulated activated carbon treatment is typically cost effective for VOC <150 ppmv but a site-specific design is required to assess cost-effectiveness.
Multi-level groundwater and soil vapour monitoring points	GWMWs should have at least 50 mm diameter to allow installation of pressure transducers.
	At least two sampling depths – in contaminated groundwater area and in unsaturated zone approximately 30–70 cm above water table.
	Discrete sampling intervals (i.e. short screens) – 10–20 mm in length, and 5–10 mm in diameter.

For more detailed information on SVE, readers are directed to the *NRF Technology guide: Soil vapour remediation*.

Air injection wells should be placed in locations consistent with the selected well spacing within the target treatment area. A relatively dense well spacing of 5 to 7 m is recommended, however, pilot trials will confirm site-specific spacing. Studies have shown that the most successful air sparging systems consist of multiple wells spaced less than 10 m apart. Typically, a triangulated spacing is preferred because it increases the amount of overlap of the ROI of the individual wells.

Care must be taken when installing injection wells near utilities, especially in predominately sandy locations. The action of air sparging can move sand into spaces in the backfill around utilities. This in turn can lead to sinkholes appearing in areas from where sand has been moved.

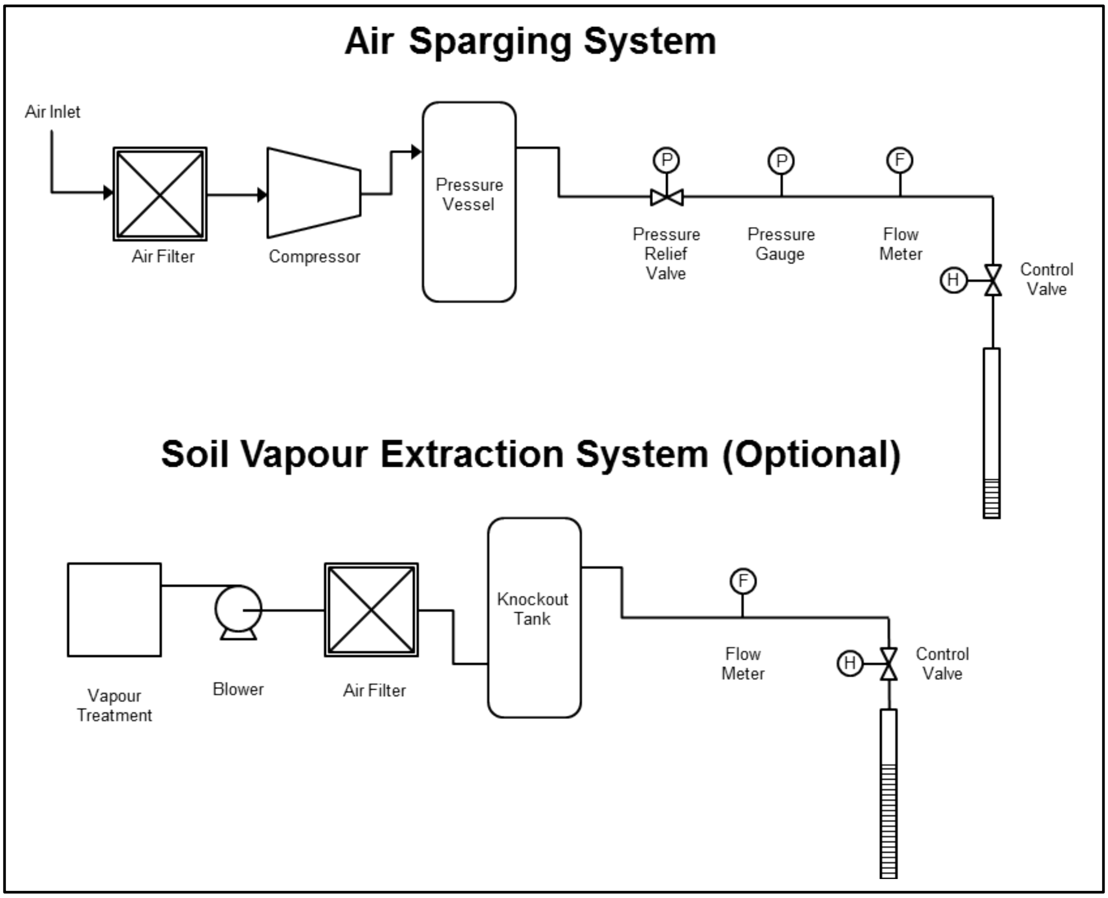


Figure 5: Components of a typical air sparging system, with SVE control system (NAVFAC 2001).

The installation of the injection wells needs to be designed such that each has its own dedicated pressure control and flow meter. This design allows observation and optimisation of airflow into each well and unless flow can be regulated to each individual injection well, air injection will not be uniform throughout the system. Figure 6 shows a typical injection well design.

Horizontal injection wells are occasionally installed to inject air below structures within or through which drilling is not possible. However, horizontal wells have the disadvantage of higher installation costs and the potential for non-uniform aeration if the screen slot distribution is not specially designed. In shallow applications, in large plume areas, or in locations under buildings or pavements, horizontal vapour extraction wells can be very cost effective and efficient for controlling vapour migration.

Soil profile heterogeneities or fractured rock conditions which normally would preclude IAS can sometimes be addressed by installation of a sparge trench or sparge barrier, where the natural heterogeneity is replaced by a uniform, highly permeable trench backfill. This configuration can be used to, for example, prevent offsite plume migration across a site boundary.

In some formations, the use of micro porous sparge points can be used instead of a standard polyvinyl chloride (PVC) slotted screen. The use of a micro porous screen leads to the generation of small bubbles that can migrate through pore throats in tighter formations without the creation of air channels around the slotted section of an injection screen. This may lead to a more even distribution of air through the saturated formation and potentially increases the ROI.

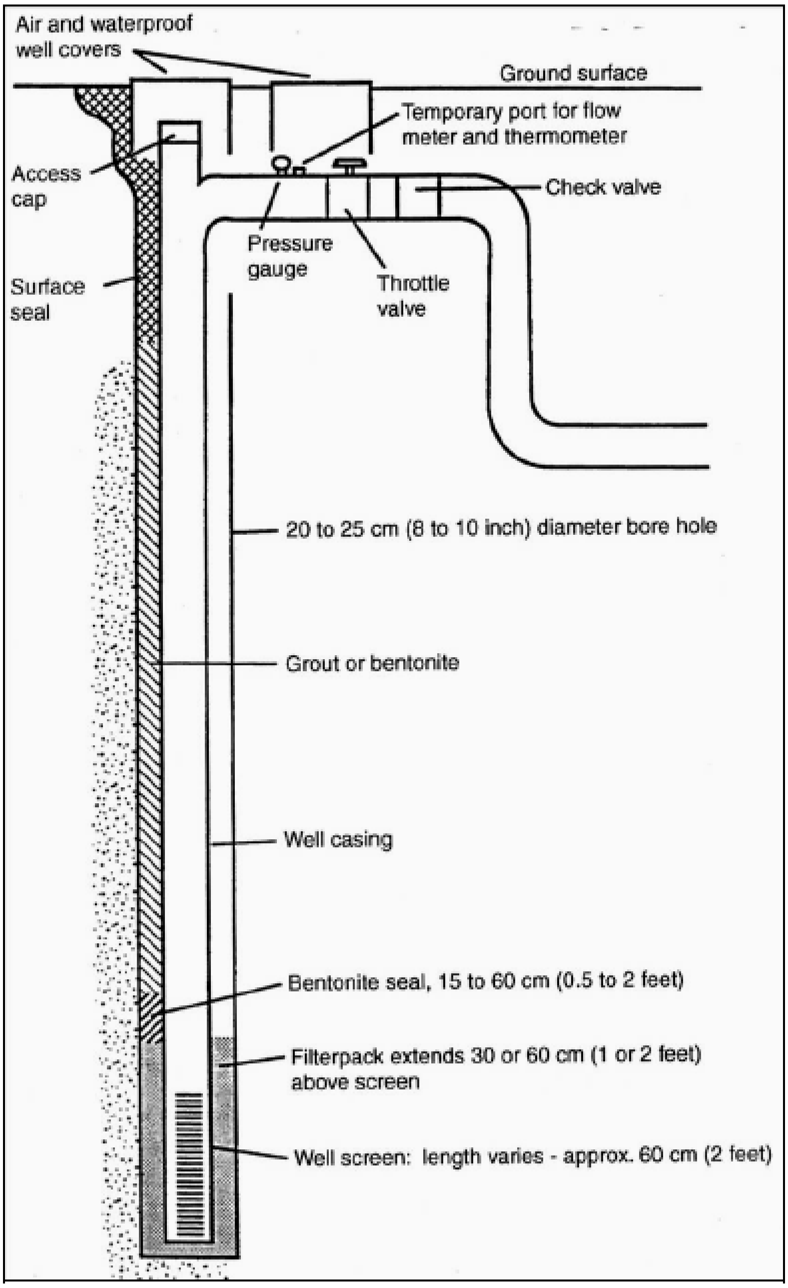


Figure 6: Typical IAS injection well design.

5.3 Operation

IAS systems can be operated in either a continuous or pulsed mode, but pulsing air injection in each injection intermittently is thought to achieve more extensive air distribution. The optimum pulsing frequency can be assessed during pilot trials.

Cyclical or pulsed operation of banks of two to five injection wells is recommended for the following reasons:

- studies suggest that mass removal can be increased by 20% to 30% through pulsed operation
- the difficulty of controlling a multi well air injection system increases as the number of wells manifolded together increases

- the total required system injection flow capacity is lower in pulsed mode, resulting in lower costs for air compressors, and
- pulsed operation may be necessary in sparge barrier applications to prevent groundwater bypassing due to water permeability reductions in the formation caused by air injection.

The most effective pulsing frequency is site-specific and depends on the characteristics of site soils, the distribution of the dissolved contaminants and the system configuration. Pulsing frequencies in sparge barrier applications, for example, would be based on the groundwater residence time within the barrier, which in turn would be dependent on the groundwater seepage rates and the barrier width.

SVE system data provide a direct measure of volatilisation removal rates, and therefore can be used to assess how changes in pulsing conditions affect volatilisation rates.

5.4 Performance monitoring

The general objectives of system monitoring are to provide current information regarding progress toward remedial objectives.

System monitoring provides the opportunity to:

- maintain contaminant removal efficiency
- improve operation strategies
- track progress toward remedial goals, and
- stop operations when cost efficiency is lost or remedial goals are achieved.

During continued operation, measurements should be made as set out in table 6.

Enough data should be available to track the performance and cost trends of the air sparging system and the following should be incorporated into reports to track the SVE system performance:

- influent VOC concentration versus time
- cumulative mass recovered versus time, and
- cumulative treatment costs versus cumulative VOCs recovered.

Table 6: Regular measurement frequency.

Frequency	Measurement
Weekly	• Air sparging system injection flow rates. • SVE system inlet and outlet concentrations (as required by the air discharge permit) and flow rate monitoring.
Monthly	• System controls that regulate cycling.
Quarterly to six monthly	• Groundwater quality monitoring of dissolved oxygen and contaminant concentrations. • Soil vapor, VOCs, oxygen and carbon dioxide.
Seasonal	• Groundwater level measurements in wells unaffected by air injection (seasonal) to assess the position of the groundwater table relative to the injection and extraction wells' screened intervals.

6. Validation

The following information describes the specific validation appropriate for IAS, to assist validation planning within the RAP. Readers are directed to the NRF Guideline on validation and closure, which among other things, provides further information on each of the lines of evidence.

The primary lines of evidence for the validation IAS are usually:

- reduction in contaminant concentration over time or with distance through the reactive zone
- analysis of geochemical and biochemical parameters
- mass flux or mass discharge from treated materials, and
- groundwater monitoring to assess whether the plume is diverting around or beneath the system.

Groundwater sampling and analysis can be used to determine when concentrations of contaminants of concern have dropped to the point where remedial objectives have been met, or whether further extraction is no longer efficient. It is important to note that concentrations may rebound to exceed validation criteria, due to diffusion from secondary sources or fluctuations in the water table mobilising contaminants. Contaminated groundwater is likely to persist in areas with lower permeability and transmissivity following the extraction of contaminants from areas of higher hydraulic conductivity and may serve as a secondary source to re-contaminate these areas.

Groundwater monitoring wells should be located:

- up-gradient of the plume
- within the plume
- down-gradient of the plume
- aligned parallel to the direction of groundwater flow, and
- aligned cross-gradient to the direction of groundwater flow.

This arrangement allows the delineation of the lateral and vertical extent of the plume following remediation to assess the subsurface distribution of contaminants and their mobility. Data collected from outside the remediation area are essential to determine background concentrations and can be used to assess and quantify the migration of contaminants beyond the remediation area.

7. Health and safety

IAS systems, like many types of industrial equipment, pose hazards to workers. If these hazards are properly evaluated and controlled, the technology can be used safely.

Some of the hazards associated with IAS and control mechanisms are outlined in table 7. The list is intended to provide an indication of the hazards potentially associated with IAS application. They will vary significantly from site to site and the list is not intended as a substitute for a detailed hazard assessment of the operation, which should be provided in the RAP.

Readers are directed to the NRF Guideline on health and safety for further information on health and safety on remediation sites, including risk assessment, the hierarchy of controls and suggested documentation.

Table 7: Common IAS hazards and controls.

Hazard	Sources of hazard	Control method
Site contaminants	Vapour migration into sub surface structures or occupied surface structures.	An SVE system should be appropriately designed to collect vapours and prevent the ingress into subsurface or above ground structures.
Compressor (storing pressurised air)	Sudden release of pressurised air resulting in severe injury, hearing damage or loss.	• PPE, including hearing protection, safety glasses and a hard hat around high pressure equipment. • Whip checks on air lines. • Equipment tested and certified.
Ergonomic risks	Lifting or performing any other movement with too much force and/or in an awkward position or repeating the lift/movement too often.	• Provide conveniently located equipment for the job, like correctly sized tools. • Train workers on ergonomic risks and prevention.
Fire and explosion	Vapour concentrations exceed the lower explosion level, or flammable and combustible liquid or solid material is present	Use of appropriate hazard rated equipment and storage appropriate for such liquids, including avoiding static electricity hazard.
Electrical hazards	• Working with standard 440 V, three-phase electrical service. • Using ungrounded or unguarded electrical equipment. • Working on or testing an electrical system or any electrically powered equipment without properly locking/tagging out energy sources. • Touching (worker or equipment operated by worker) underground and aboveground utilities.	• Because hydrocarbon vapours can be involved, electrical systems should be intrinsically safe and comply with regulatory requirements, • Implement lockout/tagout procedures. • Allow live testing only by employees that are properly trained and qualified. • Ensure workers use proper electrical work practices. • Ensure workers use proper electrical protective equipment and insulated tools while working live. • Locate and mark any underground utilities. • Ensure proper clearance between power lines and elevated equipment (e.g. crane or drill rig booms, scaffolding) and designate an observer.

Hazard	Sources of hazard	Control method
		• De-energise utilities, when necessary. • Install ground-fault circuit interrupters when feasible. • Routinely inspect electrical cords and equipment.
Slips, trips and falls	• Storing construction materials or other unnecessary items on walkways and in work areas. • Creating and/or using wet, muddy, sloping, or otherwise irregular walkways and work surfaces. • Constructing and/or using improper walkways, stairs, or landings or damaging these surfaces. • Creating and/or using uneven terrain in and around work areas. • Working from elevated work surfaces and ladders. • Using damaged steps into vehicles.	• Keep walking and working areas free of debris, tools, etc. • Keep walking and working areas as clean and dry as possible. • Perform a job hazard analysis. • Ensure use of PPE, including fall arrest systems. • Train workers on fall hazards and use of ladders. • Use an observer (spotter or signal person) when visibility is limited.

References and recommended reading

Bass, HA & Brown, RB 1996, *Air sparging case study database update*, presented at the 1st International Symposium on in situ air sparging for site remediation, Las Vegas, NV, USA.

Groundwater Remediation Technologies Analysis Centre (GWRTAC) 1996, *Technology overview report: Air sparging*, TO-96-04, Groundwater Remediation Technologies Analysis Centre, Pittsburgh, PA, USA.

Holbrook, TB, Bass, DH, Boersma, PM, Diguilio, DC Eisenbeis, JJ, Hutzler, NJ, & Roberts, EP, 1998, *Innovative site remediation technology design and application: Volume 7 – Vacuum extraction and air sparging,* American Academy of Environmental Engineers, Annapolis, USA.

Johnston, CD, Rayner, JL & Briegel, D 2002, 'Effectiveness of in situ air sparging for removing NAPL gasoline from a sandy aquifer near Perth, Western Australia', *Journal of Contaminant Hydrology* vol. 59, no. 1–2, pp. 87–111.

Leeson, A, Johnson, PC, Johnson, RL, Vogel, CM, Hinchee, RE, Marley, M, Peargin, T, Bruce, CL, Amerson, IL, Coonfare, CT, Gillespie, RD & McWhorter, DB 2002, *Air sparging design paradigm,* prepared by Battelle, Columbus, OH, USA for Environmental Security Technology Certification Program, Arlington, VA, USA.

Lundegard, PD 1995, 'Air sparging: much ado about mounding', in Hinchee, RE, Miller, RN & Johnson, PC (eds.) *In situ aeration: Air sparging, bioventing and related remediation processes*, Battelle Press, Columbus, OH, USA.

Mohr, DH 1995, *Mass transfer concepts applied to in situ air sparging*, Presented at the 3rd International symposium on in situ and on site bioremediation. April 24-27, San Diego CA, Chevron research and technology corporation, Richmond, CA, USA.

Naval Facilities Engineering Command (NAVFAC) 2001, *Air sparging guidance document*, Technical report TR-2193-ENV, Naval Facilities Engineering Service Centre, USA.

NAVFAC 2005, *Cost and performance report multi-site in-situ air sparging*, Technical report TR-2260-ENV, Naval Facilities Engineering Service Centre, USA.

US Army Corps of Engineers (ACE) 2013, *Environmental quality: In-situ air sparging*, EM 200-1-19, Department of the Army, United States Corp of Engineers, Washington, DC, USA.

US Department of Labor, 2003, *Remediation technology health and safety hazards: in situ air sparging*, Occupational safety and health administration, Office of science and technology assessment, Washington, DC, USA.

US Environmental Protection Agency (EPA) 1991, *In situ air sparging treatment*, Engineering bulletin EPA/540/2-91/008, United States Environmental Protection Agency, USA.

US EPA 1992, *Guide for conducting treatability studies under CERCLA: In situ air sparging remedy selection (interim guidance)*, EPA/540/R-92/074 A, United States Environmental Protection Agency, USA.

US EPA 2016, *How to evaluate alternative cleanup technologies for underground storage tank sites. A guide for corrective action plan reviewers. Chapter VII: Air sparging*, EPA 510-B-16-005, United States Environmental Protection Agency, Washington, DC, USA.

Appendix A – Case studies

Information on all the following (and more) US based case studies presented in table 8 can be found in the Federal Remediation Technologies Roundtable case studies database[1].

Table 8: IAS case studies.

Location	Description	Technology
Hookers Drycleaners (Charlevoix, Michigan, USA)	• Contaminant: PCE (1,290 µg/L) • Geology: predominantly sandy • Remediation works ongoing at time of writing.	• Air sparging • SVE
Sunny Village (Livonia, Michigan, USA)	• PCE (27,825 µg/L) • TCE (248 µg/L) • Mixed sediments (sand and silty clay) • Results: ~130 kg PCE recovered from soils and ~16 kg removed from groundwater.	• Air sparging • SVE • Carbon adsorption.
Vicksburg Laundry and Dry Cleaners (Vicksburg, Michigan)	• PCE (2,780 µg/L) • TCE (260 µg/L) • Topsoil overlying sand • Results: groundwater concentrations reduced to acceptable drinking water standards.	• Air sparging • SVE
Service station (Hemingway, South Carolina, USA)	• MTBE (5,110,000 µg/L) • Benzene (226,000 µg/L) • Toluene (301,000 µg/L) • Ethylbenzene (280,000 µg/L) • Xylene (278,000 µg/L) • Silty clays with interbedded clay and sand lenses. • Results: Reduced total mass of toluene, ethylbenzene and xylenes to below the site-specific screening criteria and reduced the total mass and maximum concentrations of MTBE, benzene and naphthalene by >90%. Remediation ongoing.	• Air sparging • SVE

Other case studies are available in:

- Johnston, Rayner & Briegel (2002), and
- NAVFAC (2005).

[1] costperformance.org/search.cfm

Australian Government
Department of Industry, Science, Energy and Resources

Business
Cooperative Research Centres Program