

CRC for Contamination Assessment and Remediation of the Environment

National Remediation Framework

Technology guide: Soil vapour remediation

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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 contaminated land 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 contaminated sites industry, including site owners, proponents of works, contaminated land professionals, local councils, regulators, and the community.

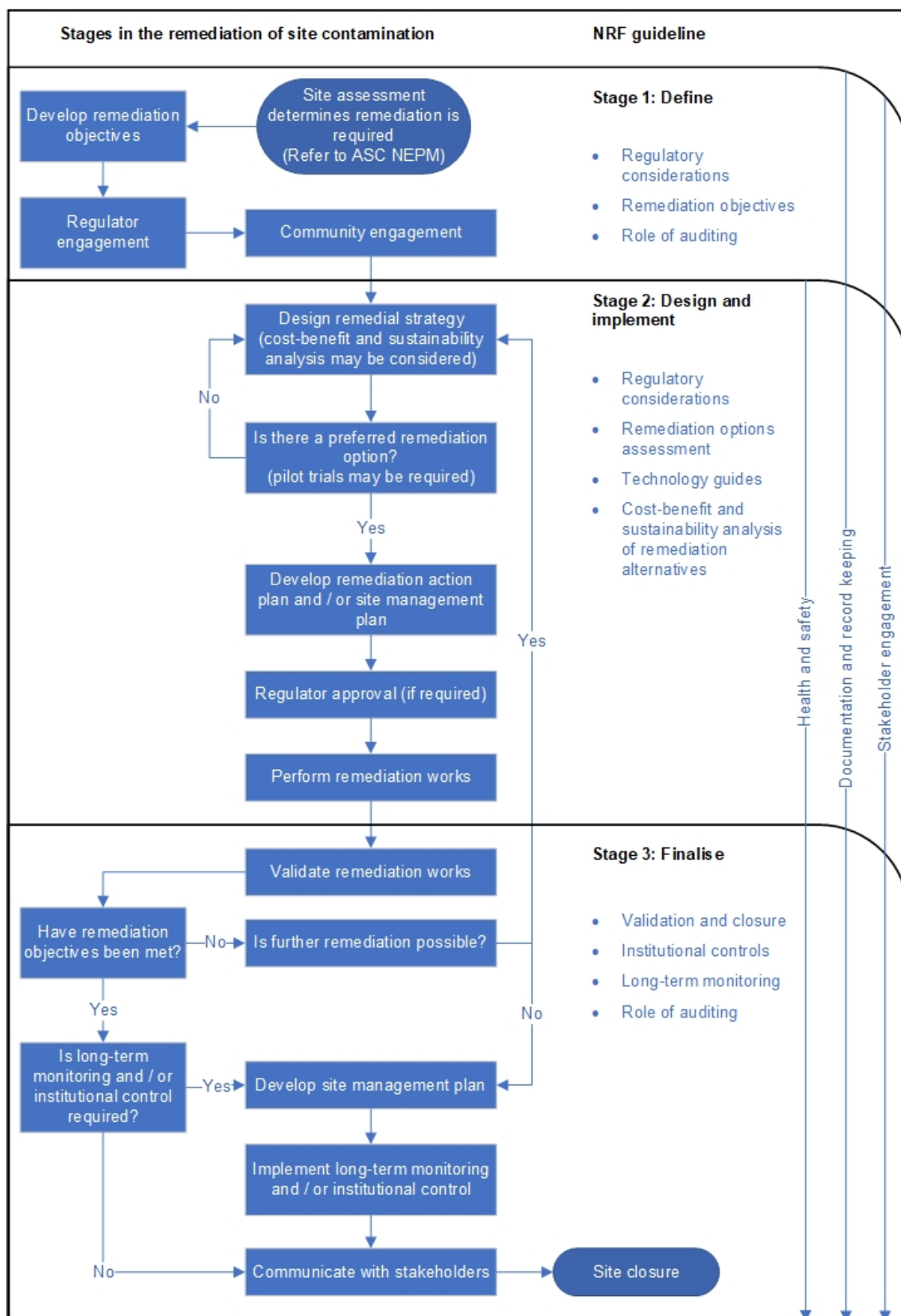
The NRF is intended to be consistent with local jurisdictional requirements, including State, Territory and Commonwealth legislation and existing guidance. To this end, the NRF is not prescriptive. It is important that practitioners are familiar with local legislation and regulations and note that **the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



Executive summary

Soil vapour contamination is typically present where a volatile contaminant is present within the soil profile and/or in groundwater at a sufficient concentration to give rise to a vapour phase within the unsaturated soil profile under normal environmental conditions.

Soil vapour remediation is a process whereby contaminated soil vapour is removed from the soil profile in situ, treated ex situ and then the treated vapour is then discharged to the environment.

The types of contaminants which can be treated by soil vapour remediation systems are volatile organic compounds (VOCs). The most common soil vapour contaminant types remediated using soil vapour remediation systems are:

- Petroleum hydrocarbons – A range of petroleum hydrocarbons can be treated, but remediation becomes more difficult (greater cost/higher energy input) and less effective (lower recoverability) the lower the volatile content of the contaminant (i.e. more effective on petroleum/gasoline type contaminants than heavier diesels and oils); and
- Chlorinated VOCs – Similarly to petroleum hydrocarbons, remediation is most effective on more volatile contaminants.

Soil vapour remediation is generally considered to be one of the most effective and cost-efficient methods of removing VOCs from the unsaturated zone in soils and/or fractured rock.

Soil vapour remediation systems typically involve three operations, each with various technology options, these are:

- Soil Vapour Extraction (SVE) – the method in which the soil vapour (SV) is extracted from the soil (vacuum);
- Soil Vapour Treatment (SVT) – the method by which the vapour extracted from the soil is treated; and
- Soil Vapour Venting (SVV) – the method by which the treated vapour is vented from the remediation system.

A variety of different technologies exist for each of the three stages of a soil vapour remediation system as listed above. This document provides a summary of a range of currently available technologies for each stage, with summary information regarding applicability and suitability for different contaminants and soil vapour settings

Abbreviations

BTEX	Benzene, Toluene, Ethylbenzene and Xylene
CatOx	Catalytic Oxidation
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
GAC	Granular Activated Carbon
ICE	Internal Combustion Engine
NAPL	Non-Aqueous Phase Liquid
NRF	National Remediation Framework
PCBs	Polychlorinated Biphenyl
ROI	Radius of Influence
SV	Soil Vapour
SVE	Soil Vapour Extraction
SVOCs	Semi-Volatile Organic Compounds
SVT	Soil Vapour Treatment
SVV	Soil Vapour Venting
VOCs	Volatile Organic Compounds

Glossary

Advection	Mass transport caused by the bulk movement of a fluid media. This applies to both molecules dissolved in groundwater, and to vapour molecules present in air.
Bench test	Remedial activity carried out as part of a treatability study on a small scale to assess the feasibility, efficacy, inputs, costs, time and risk of the planned remedial action. Normally conducted in an ex-situ laboratory with contaminated material collected from the site. May precede a pilot test.
Blowers	General term used for the majority of vacuum pumps used in SVE systems.
Concentration	The amount of material or agent dissolved or contained in unit quantity in a given medium or system.
Conceptual site model	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.
Contaminant	Any chemical existing in the environment above background levels and representing, or potentially representing, an adverse health or environment risk.
Contaminated site	A site that is affected by substances that occur at concentrations above background or local levels and which are likely to pose an immediate or long-term risk to human health and/or the environment. It is not necessary for the boundaries of the contaminated site to correspond to the legal ownership boundaries.
Contamination	The presence of a substance at a concentration above background or local levels that represents, or potentially represents, a risk to human health and/or the environment.
Data quality objectives	Qualitative and quantitative statements that define the type, quality and quantity of data necessary to support decision-making within the resource constraints of a project.
Diffusion	Migration of substances by natural movement of their particles along a concentration gradient.

Environment(al) protection authority / agency	The government agency in each state or territory that has responsibility for the enforcement of various jurisdictional environmental legislation, including some regulation of contaminated land.
Half-life	The time it takes for half of the original mass of a contaminant to be remediated by a chemical process.
Henry's Law	A fundamental law of chemistry that states the concentration of a dissolved gas is proportional to the partial pressure in the vapour phase. It allows calculations of the likely concentrations of a chemical in water based on the concentrations in air, and vice versa.
Pilot trial	Remedial activity carried out as part of a treatability study on a small scale to assess the feasibility, efficacy, inputs, costs, time and risk of the planned remedial action. Normally conducted in-situ on a restricted scale. May follow a bench test.
Practitioner	Those in the private sector professionally engaged in the assessment, remediation or management of site contamination.
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.
Remediation	An 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.
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.

Soil vapour contamination	One or more volatile contaminants are present within the soil profile and/or in groundwater at sufficient concentrations to give rise to a vapour phase within the unsaturated soil profile under normal environmental conditions.
Treatability studies	A series of tests designed to ascertain the suitability of the treatment for the contaminants under the site conditions

Measurements

Unit or symbol	Expansion
cm ²	Square centimetres
mm	Millimetre
mm Hg	Millimetres of mercury
°C	Degrees Celsius
ppmv	Parts per million in the vapour

Chemical symbols, formulae and abbreviations

Symbol or abbreviation	Meaning or expansion
HCl	Hydrogen Chloride
Hg	Mercury

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1. Introduction

The purpose of this guideline is to provide information on soil vapour remediation treatment technologies 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 utilised by remediation practitioners and those reviewing practitioner's work, however it can be utilised by other stakeholders within the contaminated sites industry, including site owners, proponents of works, and the community.

Soil vapour remediation 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 barrier 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.

Soil vapour (SV) contamination is typically present where a volatile contaminant is present within the soil profile and/or in groundwater at a sufficient concentration to give rise to a vapour phase within the unsaturated zone of the soil profile under normal environmental conditions.

Soil vapour remediation is a process whereby contaminated SV is removed from the soil profile and treated, prior to releasing the treated vapour back into the environment as an off-gas/exhaust. Typically, this soil vapour extraction process is completed in situ, although the technologies applied to in situ SV remediation can be used in conjunction with other approaches such as in the remediation of ex-situ soils (e.g. enhanced biopiles).

Soil vapour remediation technologies rely on two key physical processes that occur in soils containing volatile contaminants. These are:

- Advection: Transport mechanism where soil gas movement is a result of changes or differences in pressure.
- Diffusion - Transport mechanism where soil gas moves due to a concentration gradient – from high to low concentration.

Generally, diffusion will be a much slower process and the mass flux involved will be much less than occurs with advection, although this is dependent on the transmissivity of the soil.

Figure 1 shows examples of advection and diffusion processes in soils.

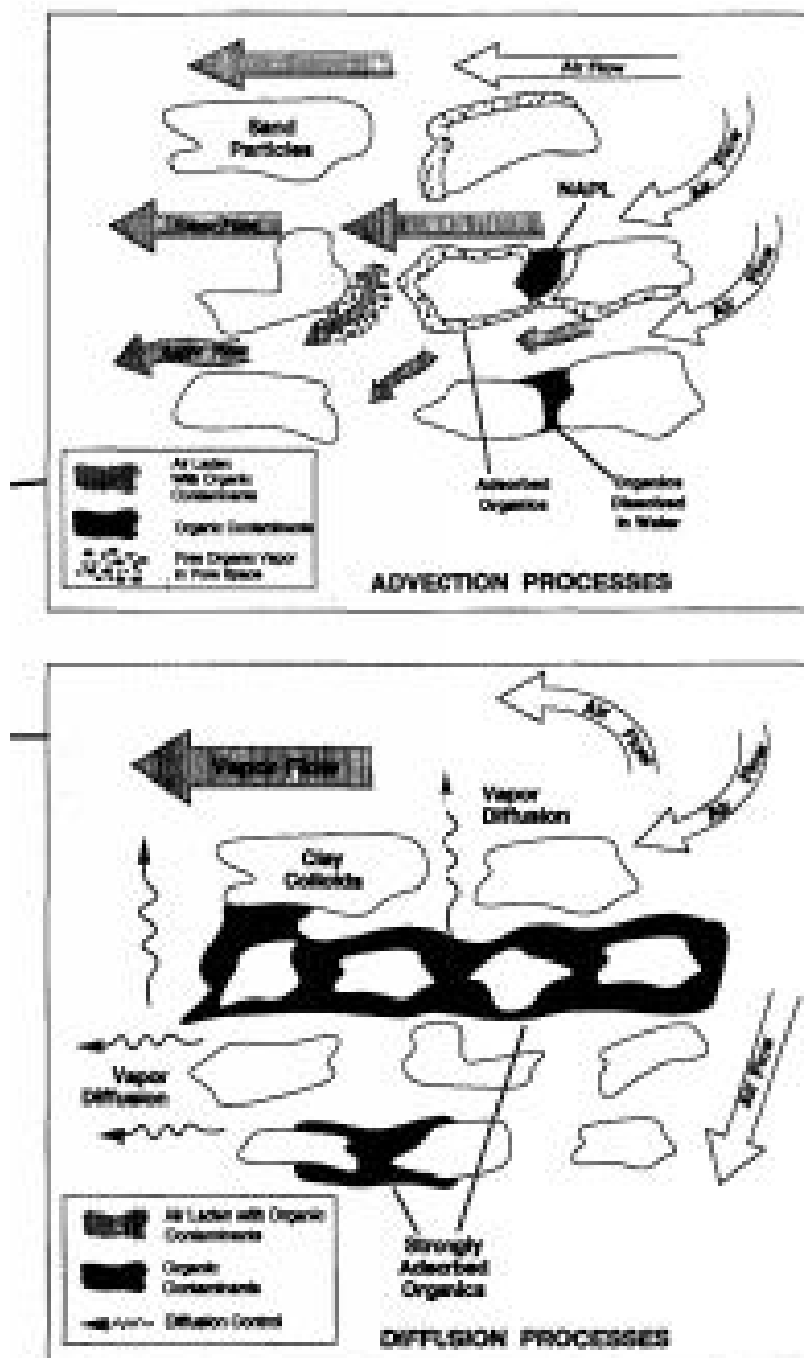


Figure 1: Advection and diffusion processes. Adapted from US EPA (1991)

SV remediation relies upon the soil in the unsaturated zone having sufficient air permeability to allow a remediation system to induce advective flow within the unsaturated zone (which will occur in permeable formations, but not in cohesive clays and/or massive rock) and the contaminant of concern should ideally have a vapour pressure of ≥ 10 mm Hg.

At sites where these criteria are met or exceeded SV remediation technologies can be one of the most effective and cost-efficient methods of removing VOCs from the unsaturated zone in soils and/or fractured rock.

Contaminants can be present in soils in one or more of the following forms:

- Non-Aqueous Phase Liquids (NAPLs) – pooled in pore spaces/voids or trapped between soil particles;
- A solution of organics in water – dissolved into pore water;
- Material adsorbed to soil particles – on the surface of, or within voids in the soil particles; and
- Free soil vapour.

Under static conditions these phases are in equilibrium, with the distribution between each phase determined by a combination of the characteristics of the physical environment, e.g. the physical characteristics of the soils, atmospheric conditions, etc

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

A SV remediation system typically consists of:

- One or more extraction wells screened in the unsaturated zone (above the water table);
- Blowers or vacuum pumps;
- Air injection or pressure venting wells;
- A low permeability cap at the ground surface;
- An air/water separator; and
- A vapour (or off-gas) treatment system.

In most SV remediation systems, flow rate monitors and volatile organic compound (VOC) detectors are used to monitor the extracted vapour stream prior to treatment and the treated vapour stream following treatment. This allows measurement of the initial and post treatment contaminant concentrations, estimation of recovered contaminant volumes, measurement of the efficiency of the system, and monitoring of emissions to atmosphere.

The main limitations of SV remediation systems are the need for vapour treatment, and the inability to extract most semi-volatile organic compounds (SVOCs).

The scope of this document is limited to providing a summary of the various technologies associated with the three key components of soil vapour remediation systems, these are:

- Soil vapour extraction (SVE) – the method in which the soil vapour (SV) is extracted from the soil (vacuum).
- Soil vapour treatment (SVT) – the method by which the vapour extracted from the soil is treated.
- Soil vapour venting (SVV) – the method by which the treated vapour is vented from the remediation system.

2.1 Soil vapour extraction

SVE can be used to remove contaminated SV from the unsaturated zone in a soil profile and/or fractured rock. Typically, SVE can be used to remediate VOCs with a Henry's Law constant >0.01 or vapour pressure > 0.5 mm Hg. Gas flow and airflow in the unsaturated zone is induced by creating a pressure gradient. This is typically achieved by the application of a vacuum to extraction wells (vertical) and/or trenches or wells (horizontal) which have been installed in the subsurface of the area to be remediated. The vacuum induces the controlled flow of SV, removing volatile (and some semi-volatile) organic contaminants from the soil profile. SVE most commonly is performed in-situ; however, in some cases, it can be used as an ex situ technology (e.g. in the ex-situ treatment of large soil stockpiles).

The generation of airflow in the system also enhances:

- Evaporation of NAPL;
- Volatilisation of contaminants dissolved in pore water; and

- Desorption of contaminants from the surfaces of soil particles.

Airflow may also be enhanced / controlled using air injection wells in the area to be remediated, creating flow between injection and extraction wells or at the site boundary to prevent recovery of an off-site co-mingled source. This air is typically introduced passively through on-site wells being left open during remediation or through active injection into groundwater (air sparging) or into the unsaturated zone itself. The injection wells may use ambient air or recycled, treated off-gas from the SV remediation system itself. Introducing air into the subsurface can also be beneficial in promoting biodegradation.

Where SVE is completed in an unsealed area, it is common for an impermeable cap to be placed over the surface of the area intended for remediation, to minimise the potential for short-circuiting of the SVE system, whereby ambient air is drawn into the ground by the SVE system, rather than actual SV.

SVE systems can be generic (e.g. remediation contractor mobile units) or site specific (designed for a site) in their design, but they all comprise three main components:

- Extraction points;
- Vapour/liquid separator;
- Vacuum pump;

Figure 2 provides a schematic of the major components of a generic SVE and remediation system.

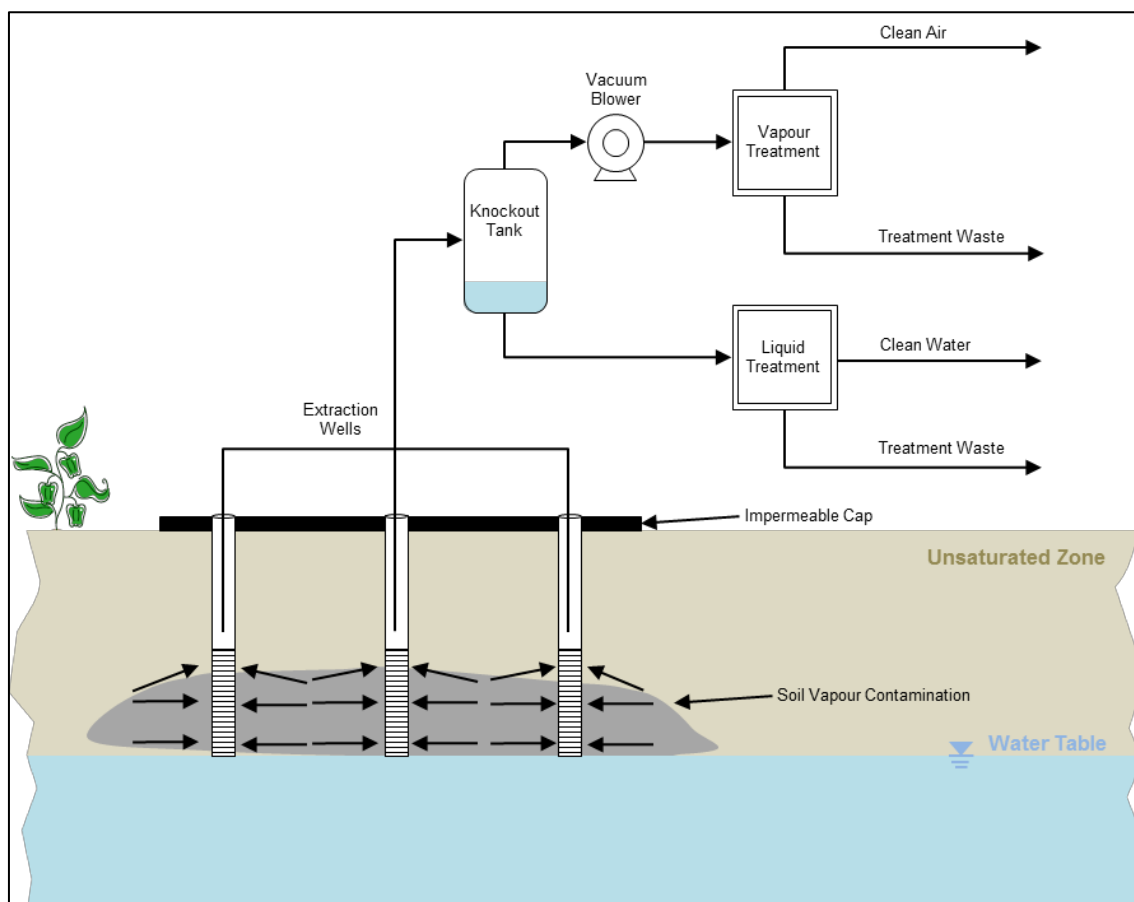


Figure 2: Major components of a generic SVE system. Adapted from US ACE (2002)

2.1.1 **Extraction points**

The extraction points for SV are typically installed with a screen across the target soil contamination or, in the case of contaminated groundwater, across the saturated/unsaturated zone boundary to capture vapour arising from the contamination source(s). Where entrained water will pose a problem with gas treatment or water disposal, the wells may be screened above the water table to minimise entrainment.

Commonly, extraction points are extraction wells of at least 100 mm diameter. Generally, the larger the pipe diameter the better as this reduces the loss of vacuum through friction in the pipe (less surface area to volume = lower friction loss and therefore greater efficiency of the system) and allows equipment to be installed down the hole. In general, pipes and valves should be sized to avoid high gas velocities (which will have high friction loss), and this will relate to the volume of gas to be removed. An extraction system should rely on control valves as well as pipe diameters to manage friction losses.

Where possible/practicable, the use of extraction trenches can greatly increase the volume of soil that can be subjected to SVE and can reduce the duration of operation of the SVE system. However, installing trenches may not be practicable due to access and/or cost constraints. A variation of this is to use horizontal wells; these can find application where a directional drilling capability is available.

In general, dedicated extraction points designed for SVE should be used to optimise SV recovery, though it may be possible to supplement the extraction point network with existing groundwater wells (providing the wells are suitably installed and screened appropriately).

Multi-phase vacuum extraction can be used to enable simultaneous removal of water, NAPL and vapour. This can be carried out using a vacuum pump connected to a siphon tube ('stinger') which the fluids are extracted through, or by using a liquid pump with a separate vacuum pump connected to the extraction well head.

2.1.2 **Vapour/liquid separator**

The vapour/liquid separator stage, often referred to as a "knock out pot", of an SVE system is used to separate out liquid that may be entrained with the extracted vapour stream. This protects the vacuum pump and vapour treatment system located downstream (flow) of the separator from potential damage from liquid ingress.

Condensation of water vapour from the extracted vapour stream can be a significant issue in SVE systems, occurring when ambient temperatures are greater than the extracted vapour stream temperature. Condensation can occur with a decrease of temperature (e.g. during winter) or where a pressure reduction of the stream occurs.

2.1.3 **Vacuum pump**

There are various types of vacuum pump / blowers used in SVE systems. Table 1 provides a summary of the characteristics of each type of vacuum pump discussed above.

Table 1: Summary comparison of vacuum pump characteristics

Vacuum pump type	Characteristics	Pressure /vacuum	Flow rate	Best suited to (soil type)
Blower	<ul style="list-style-type: none"> This is the general term used for most vacuum pumps used in SVE systems. There are a wide variety of types of blower used in SVE systems but the most common are rotary lobe ('Roots' blowers), rotary vane pumps and side channel blowers. All blowers rely on the compression of air through mechanical means. This technology has been available since the late 1800s and comes in a variety of sizes and types. 	Moderate	Moderate	Moderate permeability soils
Claw pump	<ul style="list-style-type: none"> These pumps are similar to rotary lobe blowers but utilise a claw shaped rotor to provide additional compression to the air taken into the pump. They can generate more vacuum than roots blowers. 	Low	High	Moderate/high permeability soils
Liquid ring	<ul style="list-style-type: none"> These are pumps which utilise a sealing liquid (water or oil) in the pump housing. They can generate higher levels of pressure/vacuum than either blowers or claw pumps, but generally at lower volumes. These are very durable pumps and simple (only one moving part) that will cope with ingress of groundwater and more aggressive contaminants into the vacuum system and are able to remain cooler, and therefore run for longer, than their counterparts due to the presence of the liquid component in the system. 	High	Low	Low permeability soils/ fractured rock and in conjunction with other technologies, such as multi-phase extraction

2.2 Soil vapour treatment

The soil vapour treatment (SVT) stage of a SV remediation system is where the extracted vapour stream is subjected to a process to remove the SV contaminant from the vapour stream.

There are four main types of SVT technologies in current use for the remediation of SV, these are:

- Granular activated carbon (GAC);
- Biofiltration;
- Combustive technologies:
 - Catalytic Oxidation (CatOx)
 - Internal Combustion Engine (ICE)
 - Thermal oxidation (ThermOx)
- Condensation.

A brief discussion of each of these technologies is provided in the followings sections.

2.2.1 **Granular activated carbon**

The use of GAC is the most common form of SVT technology as it is relatively low-cost option which is relatively simple and robust, suitable for the treatment of a wide range of contaminants under variable concentrations and flow rates.

GAC can also be used to treat the recovered liquid phase and condensate from the vapour/liquid separator, although this is usually in a separate liquid treatment system.

Typically, GAC comprises carbon-rich granular material such as charcoal, which has been processed so that it has an increased surface area upon which contaminants can adsorb from the extracted vapour stream or with which they can react chemically.

There are numerous types of GAC available for use in SVT systems, varying in grain size, parent material, surface area and application. Typically, SV remediation systems are optimised to work with one or a range of GAC types and consideration should be given to use of the most appropriate GAC type for the site specific conditions and system proposed.

Using GAC allows the rapid removal of contamination from the extracted vapour stream. However, a significant limiting factor to the remediation process is the rate at which vapour/ groundwater can be drawn out of the impacted soil formation and relative humidity must be controlled to a level < 50% in the system to keep the GAC media dry (when wet the adsorption capability of the GAC is significantly reduced).

GAC is typically stored in a GAC vessel which forms a filter in the SV remediation system, located down-stream (flow) of the vacuum pump. During operation of the SV remediation system, the extracted vapour stream passes through the GAC vessel which acts as a filter, removing the contamination within the extracted vapour stream. Over time the GAC will become saturated with the contaminant and its adsorption capacity will reduce, which will be indicated by an increase in the concentration of VOCs in the treated vapour stream exiting the GAC vessel.

To avoid breakthrough of the VOCs and their release to the atmosphere, it is common to have two GAC vessels in series, with piping and valving that allows the second

vessel to become the first in line, and the exhausted GAC to be replaced and returned as the second in line.

GAC vessels are often used in conjunction with other SV treatment technologies as a final polishing treatment for exhaust gases, capturing residual contaminants within the exhaust gas.

When the VOC concentration in the treated vapour stream reaches a level that indicates that the GAC has become saturated and is no longer able to remove the contamination from the extracted SV stream to a sufficient level, the GAC is either replaced or regenerated.

The need to replace or regenerate the GAC in a system can result in significant downtime for a remediation system. However, some remediation systems operate using multiple GAC vessels, switching between them when one is saturated, minimising this system down-time. The need to replace or regenerate the GAC when it becomes saturated means that the use of GAC is not well suited to the treatment of moderate to high concentrations of contaminant in the extracted vapour stream as the GAC will become saturated more quickly than in a lower concentration of contaminant and increases the vapour treatment cost. Replacement involves the removal of the spent GAC and replacement with a fresh batch of GAC. This typically entails mechanical emptying and refilling of the GAC vessel. When GAC is replaced, in the absence of a GAC regeneration facility (which is the case in Australia), it needs to be disposed of at a hazardous waste facility as it will then be contaminated with the contamination removed from the extracted vapour stream.

There are several types of regeneration for GAC, but the basic principle is the use of heat or in some cases steam to volatilise the adsorbed contaminant from the GAC, freeing up the active sites on the GAC, allowing it to then be reused to capture more contamination from the extracted vapour stream. The volatilised contaminant is then typically condensed back out of the GAC regeneration vapour stream and distilled as a liquid waste stream. Commercial facilities for regeneration of activated carbon are not available in Australia, although if there were an application with a large usage it might become an option to consider.

2.2.2 **Biofiltration**

In a biofiltration system the extracted vapour stream is humidified and then passed through a wetted porous packed bed filtration vessel (typically compost or peat based) which contains microbes (typically naturally occurring in the local environment) which can break down the target contaminant into less toxic gases.

These microbes form supported biofilms within the porous bed and are also circulated in suspension in the water trickled through the biofilter itself. As the vapour passes through the biofilter the contaminants adsorb onto the biofilms and/or the filter medium itself. Once adsorbed, the microbes in the biofilter 'feed' on the contaminants, breaking them down via bioremediation, ultimately to produce carbon dioxide and water vapour.

In this way, the life of the biofilter can be either extended or, depending on contaminant concentrations and flow rates, may not need to be replaced, with the microbes acting to regenerate the biofilter continuously.

Biofilter systems typically require a much lower energy input than other forms of vapour treatment, require minimal maintenance (other than ensuring that the biofilter ecology

is maintained), produce minimal or no waste by-products requiring disposal and are a more 'eco-friendly' option than most other technologies.

Biofilters are well suited to scenarios where low concentrations of simple, short chain VOCs (e.g. formaldehyde, acetaldehyde) are required to be treated (<100 ppmV) with low to moderate flow rates and relatively consistent loads (to maintain the feed level for the biofilter).

Biofilters must be maintained in good operating condition and monitored. Conditions can occur that lead to failure of the microorganisms, for example higher contaminant concentrations and/or flow rates, variable contaminant loads, drying, an insufficient food source, or there are contaminants that poison the organisms (such as salt accumulation or changed pH).

There are several types of bioreactor available, and selection of the most suitable biofilter type should be based on the site-specific conditions.

2.2.3 **Combustive technologies**

These three technologies have been grouped together as they use essentially the same methodology to treat soil vapour, which is the thermal oxidation (or combustion) of contaminants in the extracted vapour stream to carbon dioxide and water.

Catalytic oxidation

CatOx systems rely on a more active and energy intensive form of vapour treatment than GAC and Biofilter type systems, suited to sites with larger contaminant mass.

The heat for the oxidation of the contaminant comes initially from a supplemental heat source (typically electric heaters) and, once the system is running, by a combination of the supplemental heat and combustion of the contaminant itself (where there is sufficient calorific value in the extracted vapour stream).

Recuperative systems utilise a heat exchanger to capture the heat from the combustion process and then use this to pre-heat the vapour stream before it enters the system, increasing the efficiency of the system and reducing the need for the use of supplemental heat.

CatOx utilises a catalyst (typically platinum or palladium, supported on a ceramic or stainless steel honeycomb) to destroy the VOCs at much lower temperatures (315 – 430°C). The lower temperature prevents the potential to form dioxins.

If used to treat chlorinated VOCs, the thermal process can lead to the generation of acidic gases, with a high corrosion potential, although use of a different catalyst bed (metal oxides) in a CatOx system can be more effective at removing this issue when used in conjunction with scrubber systems for the off-gas.

Internal combustion engine system

An ICE system for SV remediation typically utilises an adapted common rail type automotive engine as the core of the soil vapour remediation system with simple unleaded fuel as a supplemental fuel. This makes ICE systems relatively cheap to produce and means that generic parts can be used in maintenance of these systems.

The engine is initially run using petroleum fuel and is then run on a mixture of supplemental fuel and the extracted vapour stream, with the engine providing the power source for the vacuum pump and all other components of the system. In an ICE system, the vacuum pump and the off-gas treatment system are combined in the

engine itself, but in some cases additional vacuum is provided by a supplementary vacuum pump system.

An engine management system is used to monitor the concentration of contaminant in the extracted vapour stream, the efficiency of the engine, the level of supplementary fuel used and the concentration of contaminant remaining in the exhaust stream. The data from the engine management system is recorded and can then be used to provide a relatively reliable estimate of the volume of contaminant consumed in the ICE unit during operation.

ICE units are available with varying engine capacities and as a general rule the engine capacity will determine the volume of vapour that can be processed (larger engine capacity = higher volume of vapour treated per hour).

As a bonus, these systems can also utilise recovered liquid phase contaminants from vapour/liquid separators and/or from systems where recovery of free product is targeted and consume these as additional supplemental fuels (e.g. recovered petroleum), provided the recovered contaminant is sufficiently clean (free of particulate matter) and of high enough calorific value to be consumed in the ICE unit as a fuel source.

The operation of an ICE unit is most effective where the contaminant load is consistent, low volume and of moderate to high concentration. Otherwise, the operation of the unit can be difficult to optimise and significant supplementary fuel is used to run the system.

Typically, the remaining exhaust gases from the ICE unit are then passed through an adapted automotive exhaust system with a catalytic converter to remove the majority of any residual contaminants from the off-gas stream. However, constant monitoring of the exhaust gas emissions is required to ensure that the ICE system is managing to consume sufficient contaminant so that high contaminant concentrations are not simply being vented to ambient air.

Thermal oxidation

Of all the combustive technologies, a thermal oxidation system can process the highest throughput. A thermal oxidation system is best suited for large contaminant plumes and can be combined with a catalytic oxidation system so that the vapour stream can be treated more economically when the concentrations decrease.

The heat for the oxidation of the contaminant comes initially from a supplemental fuel source and, once the system is running, by a combination of the supplemental fuel and combustion of the contaminant itself (where there is sufficient calorific value in the extracted vapour stream).

Recuperative systems utilise a heat exchanger to capture the heat from the combustion process and then use this to pre-heat the vapour stream before it enters the system, increasing the efficiency of the system and reducing the need for the use of supplemental fuel.

Thermal oxidation relies upon high temperature alone to destroy the VOCs in the vapour stream (730 – 815°C). The higher temperatures involved in thermal oxidation have the potential to lead to the formation of dioxins, particularly if there is a chlorine component (e.g. chlorinated organics or saline aerosols) which must be minimised by minimising the time taken for the temperature of the combustion gas to be reduced for final treatment and discharge (e.g. through a rapid quench system), or by utilising a final polishing filter (e.g. GAC).

If used to treat chlorinated VOCs, a thermal oxidation system can generate acidic gases with a high corrosion potential, and needs to be coupled with a scrubber system for the off-gas to remove HCl.

2.2.4 **Condensation**

Condensation SV treatment systems are considered to be the most effective technology for the treatment of large contaminant plumes and high VOC concentration (>4,000 ppmV) extracted vapour streams. This technology may also be referred to as cryogenic cooling and compression or C3 technology.

After extraction, the vapour stream is compressed prior to passing through a condensation system which cools the vapour stream cryogenically, typically to a temperature below -40°C ⁷, so that the VOCs in the extracted vapour stream condense out and can be collected in a liquid collection system. Exhaust gases are typically recycled through the system to maximise the capture of contaminants in the extracted vapour stream.

This type of system can be used to treat a wide range of VOCs, including chlorinated VOCs and is very efficient at capturing contaminants in the extracted vapour stream (95 – 99% under ideal conditions).

Where the contaminant involves a petroleum fuel, the recovered liquid can be of a high quality and may be able to be sold back to industry (e.g. recovered petroleum fuel), recycled to provide fuel for the ongoing operation of the condensation system or collected for separate treatment or disposal. Note that water vapour present in the gas stream will also be condensed, and the system must have provision for separation of water and avoiding the icing problems that can occur at low temperatures. Where the contamination is from a range of sources, the condensate may contain tarry material, and this may give rise to coating of surfaces and high maintenance of the condensation system.

Although condensation systems are very effective and can cope with removal of a high percentage of contaminants at a high concentration, they are probably the most energy intensive soil vapour remediation technology. The operation of a condensation system requires a significant and constant supply of electricity to run the multiple compressors and the cryogenic cooling systems.

Considering this, condensation SV remediation systems are best suited to locations with large volumes of contamination at high concentrations. Also, while they do not rely on consistent loads of contaminants to function, the high operational costs mean that they are likely to not be cost effective for sites with intermittent contaminant loads.

In some cases, the higher costs of operation for a condensation system can be offset by the revenue generated by the sale of recovered product.

2.3 **Soil vapour venting**

The SVV stage of a soil vapour remediation system is the final stage of the remediation process.

Most systems simply vent the off-gas/exhaust from the SVT system to the atmosphere, often passing the gas stream through a final polishing filter (typically containing GAC) prior to discharge, in order to capture/treat residual contaminants in the exhaust stream.

Depending on the size of the SV remediation system and the volume of vapour processed, and local requirements regarding mobile or fixed treatment systems, the venting stage of a SV system may require regulatory approval. This may lead to the requirement for continuous or periodic monitoring of the off-gas/exhaust for contaminants, and the use of an exhaust stack to discharge and disperse the gas to the atmosphere.

SVV is a term that can also apply to SV remediation systems which recycle the exhaust / off-gas back into the subsurface unsaturated zone via injection wells (bioventing) and alternative SV remediation systems utilising passive techniques for SVV. These are discussed further in the following sections.

2.3.1 **Bioventing**

US ACE (2002) defines bioventing as:

'the process of advecting gases through subsurface soils to stimulate in situ biological activity and enhance bioremediation of contaminants.'

A bioventing system injects oxygen rich ambient air into the unsaturated zone of the contaminated soil profile under pressure via injection wells. This air may be simply taken from atmospheric air, or it may be a mixture of exhaust gas from a SV system and ambient air. Ideally, a bioventing system will maintain an oxygen concentration in the unsaturated zone of $\geq 5\%$.

The introduction of oxygen into the subsurface will stimulate aerobic microbial activity and enhance the biodegradation of soil contaminants. A bioventing system relies on the microbes present in the unsaturated zone to biodegrade the contaminants present in soils into less complex hydrocarbons and eventually to CO_2 and water.

Bioventing relies on higher soil moisture than many of the SVE and SVT techniques discussed in this document. Indeed, moisture content may represent the limiting factor to bioventing systems. Ideally, the moisture content in the unsaturated soils should be between 5 and 20%. Lower moisture soils often contain reduced numbers of microbes and higher moisture content soils often prevent the movement of air in soils due to occlusion of the pore spaces, leading to a reduction of biodegradation rates through reduced available oxygen.

This method is best suited to the remediation of those contaminants that are susceptible to aerobic biodegradation, including aliphatic (and some aromatic) hydrocarbons and mono aromatic hydrocarbons (e.g. BTEX) and some polycyclic aromatic hydrocarbons (e.g. naphthalene). Bioventing is also capable of remediating low volatility contaminants, such as kerosene and diesel, but this relies on a much longer remediation timescale as the microbes require more time to break down these longer chain hydrocarbons.

Bioventing can be used in conjunction with a SVE system to enhance the performance and efficacy of the system or on its own as a stand-alone remediation technology. This combination method also allows for capture and treatment of potential incompletely biodegraded contaminants and management of off-gas from the bioventing system in areas where control of the system is important (e.g. in areas where neighbouring properties may be affected).

Typical bioventing systems utilise a low rate of injection of air so as to maximise the rate of biodegradation of the contaminants, whereas most SVE systems use a higher rate of extraction with the objective of volatilising contaminants from the unsaturated

zone. Therefore, where bioventing is used in conjunction with SVE, both systems need to be carefully optimised to allow the benefits of both remedial approaches to be realised (i.e. sufficient extraction rates to allow SVE and the reduction of contaminant mass where biodegradation may be limited (e.g. where NAPL is present), but at a low enough rate that biodegradation can also usefully occur). In general, the use of combined biodegradation and SVE techniques will be best suited to situations where a lower mass extraction rate is involved. In some cases, the application of technologies can be staged, with the initial use of the more aggressive SVE and SVT technologies to remove the more volatile component of soil contamination, and subsequent use of bioventing as a slower 'polishing' technique for remaining lower volatility or dispersed lower concentration contamination.

Figure 3 shows a decision tree for the application of SVE and/or bioventing approaches at a site.

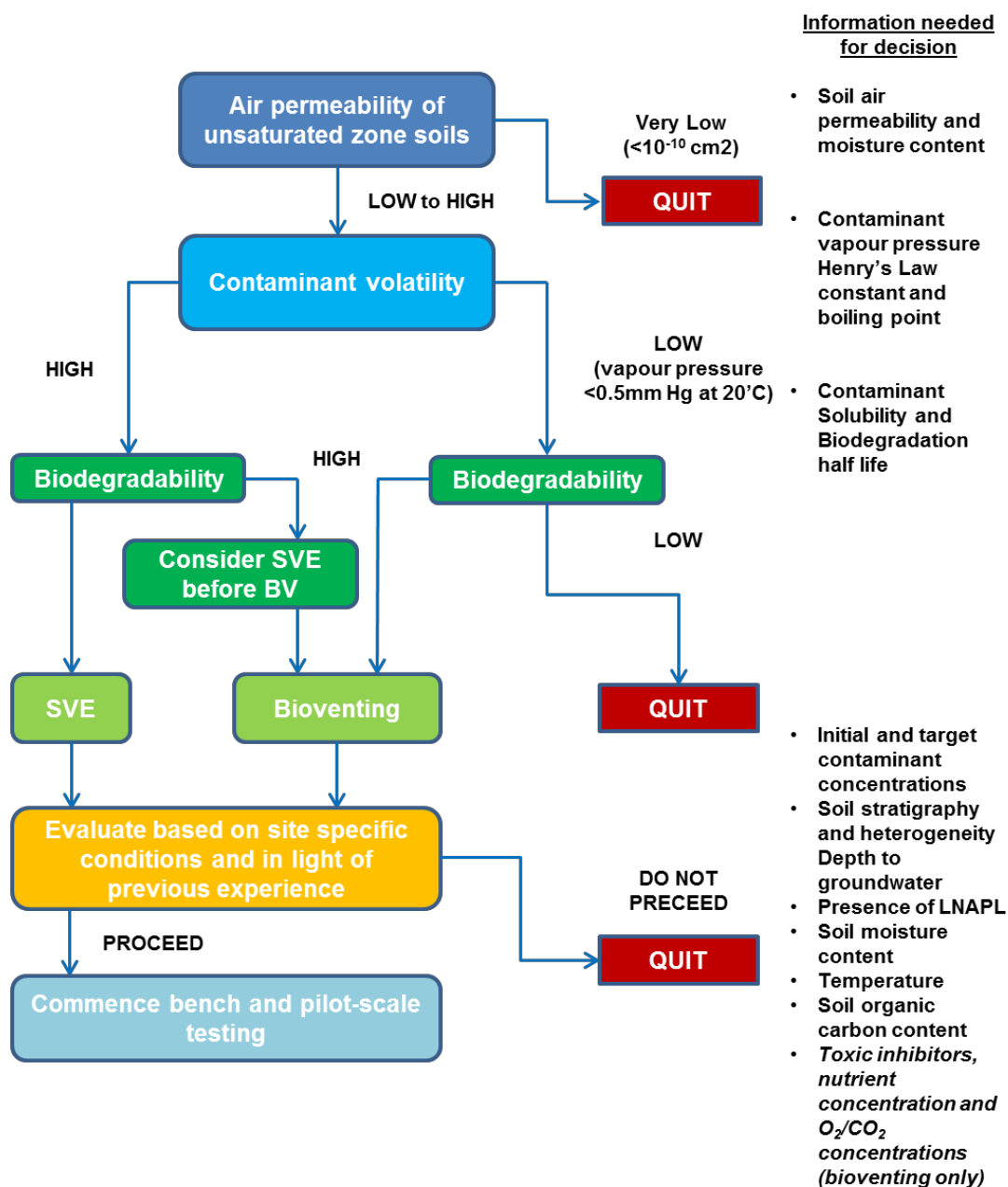


Figure 3: SVE and bioventing technology screening decision tree. Adapted from US ACE (2002)

2.3.2 **Passive venting**

Passive venting can offer an alternative to active extraction for SV remediation.

A passive venting system relies on natural atmospheric pressure changes (causing barometric pumping), and temperature differences to induce air flow in the subsurface and biodegradation of the contaminants in the unsaturated soil profile.

A passive venting system relies on the presence of a low permeability layer above the contamination within the unsaturated zone. This can either be a naturally occurring low permeability layer (e.g. a clay band) or an engineered barrier (e.g. a liner installed at or near to surface). The low permeability layer allows for a time lag between atmospheric pressure changes and equilibration with the unsaturated zone, resulting in a pressure differential between the two, inducing airflow either into or out of the subsurface via extraction and/or injection wells installed at the site. Temperature differences, e.g. of a vent pipe exposed to the sun, can also give rise to gas density differences and an induced air flow (e.g. a chimney effect).

Passive venting can be used as a SVE remedial system, a bioventing system or a combination of the two technologies, depending on how it is set up. One way is to fit valves to the extraction and/or injection wells, allowing atmospheric air into the system or soil vapour out of the system.

Passive venting is not suitable for sites with a high level of contamination. Typically, it is used for remote sites with low level contamination (no neighbouring properties which may be affected by venting) and/or sites which have been previously remediated using more aggressive active techniques, utilising passive venting as a polishing phase of remediation. In this way the extraction and/or injection wells act to short circuit the low permeability layer, allowing movement of soil vapour and/or ambient air through the system.

Modifications of passive venting systems include:

- **Assisted passive venting** – where renewable energy sources (solar, wind, etc.) are used to power low energy ‘micro-blowers’ to extract soil vapour or inject ambient air into the system.
- **Passive venting flares** – where a well head system monitors the accumulation of soil vapour in a well, and once a sufficient pressure/concentration of contaminant is present, a small spark (often piezoelectric) is used to ignite and consume accumulated soil vapour with higher volatile contamination present, flaring off the contamination.

Passive venting systems rely on slow but consistent removal of soil vapour contaminants from a system, and generally operate on a timescale of months to years. These systems are designed to require minimal maintenance, with the simple passive venting systems relying on only a simple mechanical device to operate and the more complex assisted systems being self-contained, requiring no external power source and requiring minimal maintenance. This makes these systems ideal for remote locations and or locations where minimal maintenance is required.

3. Feasibility assessment

The key assessment criteria for an initial assessment of SV remediation technology as a method for the remediation of soil vapour contamination at any site are:

- The air permeability of the unsaturated zone soils – soils must be permeable to air to allow extraction of soil vapour and/or injection of air into the unsaturated zone soils;
- The volatility/biodegradability of the contaminants of concern – contaminants must be suitably volatile to be able to be extracted (typically VOCs with a Henry's Law constant >0.01 or vapour pressure > 0.5 mm Hg) and/or susceptible to biodegradation by naturally occurring microbes where bioventing may be considered. and
- The depth and extent of contamination – costs increase exponentially with increasing depth of contamination and the size of the contaminated area. SVE is most effective where the contamination is present within near surface soils and is relatively discrete in aerial extent.

If there is reasonable confidence that SV remediation technology will achieve the required treatment outcome, then other issues will need to be considered to determine if SV remediation technology is likely to be appropriate for the site. These include:

- Will the relevant regulatory agencies accept SV remediation technology as a viable means of remediation?
- Is it likely that other stakeholders (such as local government or members of the public) will accept the use of the technology, particularly those stakeholders that can have a significant bearing on whether the technology is applied at the site? Are there sensitive sites nearby that would not be compatible with the proposed operation?
- Is there a time constraint, and can the application of SV remediation technology meet this constraint?
- Are power, water and other services available at the site in adequate supply?
- Is sufficient space available at the site for the SV remediation system?
- Is the expected order of cost of treatment acceptable (cost/benefit)?

Figure 4 provides a summary of the key stages in the assessment of the suitability and application of SV remediation technologies at a site.

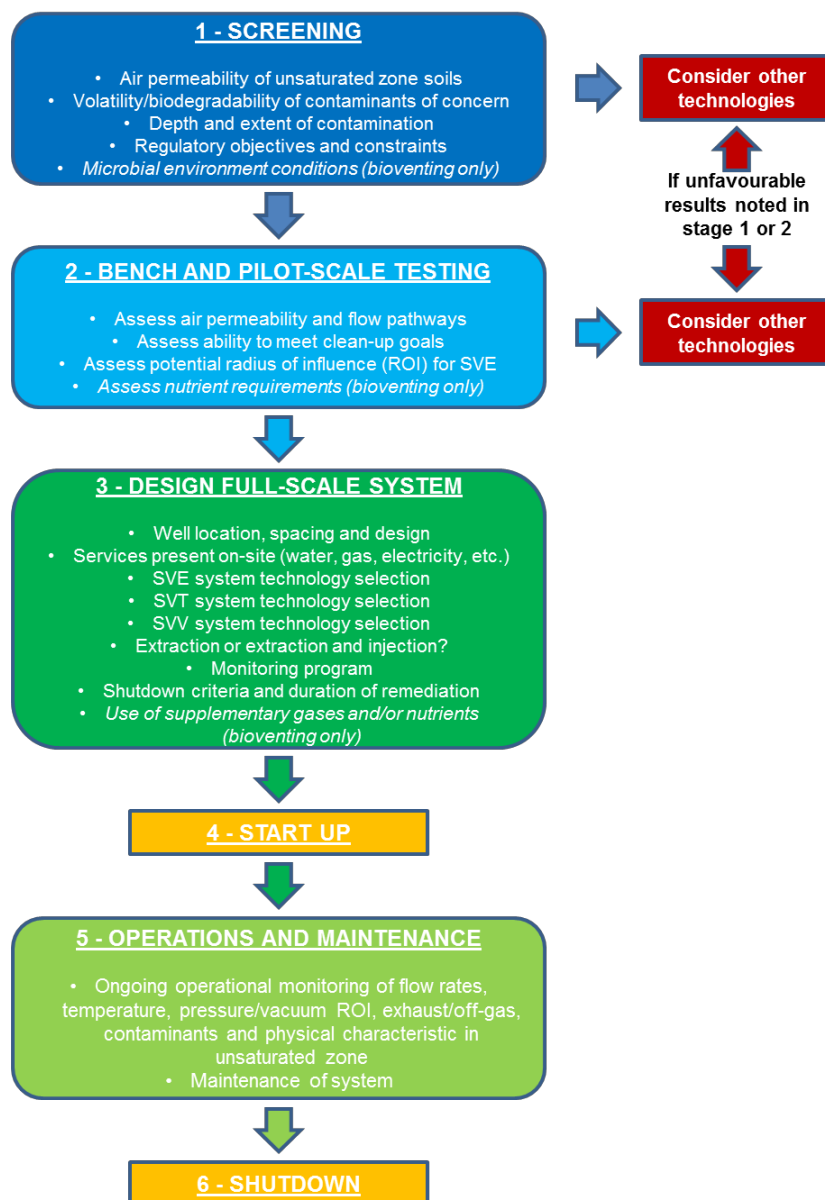


Figure 4: Soil vapour remediation technology application strategy. Adapted from US ACE (2002)

3.1 Treatable contaminants

The types of contaminants which can be treated by SV remediation systems are VOCs. The most common SV contaminant types remediated using SV remediation systems are:

- Petroleum hydrocarbons – A range of petroleum hydrocarbons can be treated, but remediation becomes more difficult (greater cost/higher energy input) and less effective (lower recoverability) the lower the volatile content of the contaminant (i.e. more effective on contamination associated with petroleum/gasoline than heavier diesels and oils).
- Chlorinated VOCs – Similarly to petroleum hydrocarbons, remediation is most effective on more volatile contaminants.

Soil vapour extraction and treatment technologies have the potential for application in the treatment of VOCs and SVOCs in soil vapour, ranging from aliphatic (and some

aromatic) hydrocarbons and mono aromatic hydrocarbons (e.g. BTEX) to chlorinated VOCs (e.g. trichloroethene).

Table 2 summarises the contaminant types for which the SV remediation technologies discussed in this document may be suitable.

Table 2: Contaminant treatability using SVE and SVT technologies

Affect	Contaminant Groups		Example Contaminants	Effectiveness
Contaminant groups with potential to be affected	Organics	Halogenated VOCs	Tetrachloroethene, Trichloroethene	1
		Halogenated SVOCs*	Para-dichlorobenzene	2
		Non-halogenated VOCs	Petroleum (unleaded fuels)	1
		Non-halogenated SVOCs*	Diesel and kerosene	1
	Reactive	Reducers	Hydrogen sulphide	2
Contaminant groups unlikely to be affected	Organics	PCBs	Arochlor - 1242	3
		Pesticides and herbicides	Chlordane, DDT, Dieldrin	3
		Dioxins/Furans	2,3,7,8-Tetrachlorodibenzo-p- dioxin	3
		Organic Cyanides	-	3
		Organic Corrosives	-	3
		Explosives	-	3
	Inorganic	Volatile Metals	Mercury, tetraethyl lead	3
		Non-volatile metals	Nickel, Chromium	3
		Asbestos	-	3
		Radioactive materials	-	3
		Inorganic corrosives	-	3
		Inorganic cyanides	Sodium Cyanide	3
	Reactive	Oxidisers		3
1 – Has been demonstrated to be effective in commercial application. 2 – There is potential for the technology to be effective in commercial application.			3 – Unlikely that the technology will be able to be applied effectively at a commercial level * - Demonstrated effectiveness on some compounds in this group	

3.2 Treatable matrices

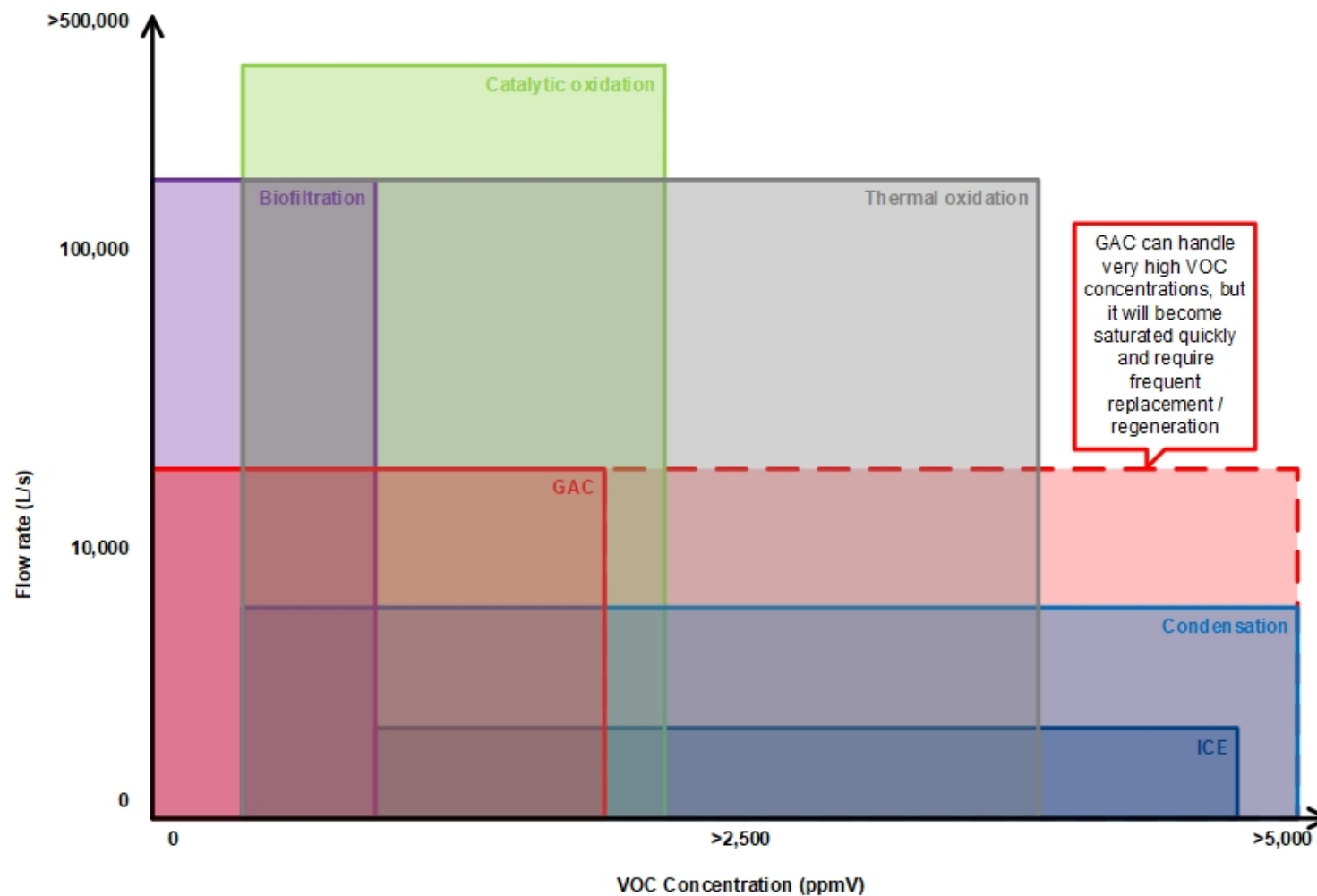
In general:

- GAC and biofiltration can be used with low VOC concentrations in the extracted vapour stream (<500 ppmV).
- Combustive technologies can be used with a wide variety of input concentrations and is dependent on flow and thermal properties of the vapour stream; and
- Condensation technologies can be used for relatively large NAPL plumes and high (>4000 ppmV) VOC concentration streams.

Table 3 and Figure 4 provide a comparison of the capabilities and characteristics of the soil vapour treatment technologies discussed in this document, their suitability for the treatment of contaminated soil vapour, under a selection of variables and scenarios.

Table 3: Comparison of the capabilities, characteristics and suitability of various SVE technologies under a selection of variables and scenarios

SVT type	Vapour contaminant type	VOC concentration range (ppmV)	Flow rate (L/s)	Contaminant mass load	Removal efficiency	Secondary wastes	Advantages	Limitations	Relative costs
GAC	Wide range of VOCs including chlorinated VOCs	0 – 5,000	47 – 28,000	Limited mass load: Continuous OR Intermittent	90-95%	Spent carbon and collected condensate and organic material	Relatively simple system.	<ul style="list-style-type: none"> Humidity must be adjusted to Ketones and aldehydes are not efficiently adsorbed 	Low
Biofiltration	Short chain VOCs (e.g. formaldehyde, acetaldehyde, benzene and toluene)	0 – 1,000	42 – 230,000	Limited mass load: Continuous OR Intermittent	90-98%	Spent biofilter bed material (compost or peat) Cleaning generates wastewater with biosolids	Direct conversion of biodegradable VOCs to carbon dioxide and water. Operates at ambient temp and pressure with low relative cost and is seen to be 'eco- friendly'.	<ul style="list-style-type: none"> Only applicable for biodegradable VOCs. Vapour stream typically needs to be humidified to preserve the biofilters and prevent drying. 	Low
Catalytic oxidation	Wide range of VOCs including chlorinated VOCs	100 – 2,000	94 – 230,000/430,000	Can be large: Continuous	95-99%	Combustion products	Up to 95% / 70% energy recovery possible	<ul style="list-style-type: none"> Halogenated compounds may require additional control equipment downstream. Not recommended for batch operations. Thermal efficiency in Catalytic Oxidation suffers with changes in operating conditions. Certain compounds can poison the catalyst (lead, arsenic, chlorine, sulphur and particulate matter). 	Low to medium
Internal Combustion Engine	Typically, only petroleum hydrocarbons (fuels)	1,000 - >4,000	24 - 48	Can be large: Continuous	90-98%	Combustion products	Combined vacuum pump and off-gas treatment (engine)	<ul style="list-style-type: none"> Requires emissions monitoring; Little additional treatment possible 	Low to medium
Thermal Oxidation/ Catalytic Oxidation	Wide range of VOCs including chlorinated VOCs	100 – 4,000	94 – 230,000/430,000	Can be large: Continuous	95-99%	Combustion products	Up to 95% / 70% energy recovery possible	<ul style="list-style-type: none"> Halogenated compounds may require additional control equipment downstream. Not recommended for batch operations. 	Medium
Condensation	Wide range of VOCs including chlorinated VOCs	500 - >5,000	47 – 9,400	Continuous	95-99%	Condensate	Product recovery can off-set costs (in certain systems and situations)	<ul style="list-style-type: none"> Not recommended for material with boiling points < 310°K. Condensers can be subject to scale or tarry material build-up, which can cause fouling. 	High
<p>Notes</p> <p>The information in this summary table is general in nature and individual SV remediation systems will vary in their characteristics.</p> <p>¹ Removal efficiency shows the maximum potential under ideal conditions. This level of performance is dependent on careful tuning of the remediation system to match site specific conditions.</p>									



Notes:

The above graph provides a general summary of soil vapour treatment technology capabilities only. This is not specific to contaminant type.

In general the upper VOC concentration limit and flow rates for most technologies will reduce when treating chlorinated VOC contaminants, with the exception of condensation which only has a reduction in flow rate for chlorinated VOCs

Figure 5: Schematic demonstrating the treatable VOC concentration and flow rate range of different SVR technologies

4. Treatability studies

In general, SV remediation is a well understood technology and there is considerable experience in its application. At certain sites there may be sufficient experience with similar situations to provide confidence that SV can be applied, and this may avoid or reduce the need for treatability studies, particularly if only a small area of contamination is to be remediated.

Where there is uncertainty as to whether SV remediation technologies will achieve the desired clean-up goals for a soil vapour contaminated site, or there are other issues which make it uncertain as to whether SV remediation technologies will prove to be effective or the required system is large and considerable capital expenditure is involved, it may be necessary to conduct treatability tests to resolve the issues and provide greater certainty as to the design requirements.

Treatability studies provide site-specific data to support remedial option selection and implementation of remediation at sites. They also allow remedial costs and technology efficiency to be better determined.

US EPA (1991) provides guidance for three levels of treatability studies for SV remediation technologies, these are:

- Remedy screening (Laboratory screening);
- Remedy selection (Bench-scale testing);
- Remedy design (Pilot-scale testing);

Depending on the level of information available for a site, some or all of these stages of treatability studies may be required to be completed prior to completing remediation.

This guideline follows the three-level approach used in the USEPA 1991 guidance document as the basis for completing treatability studies. Each of the three treatability study levels is discussed in more detail in the following sections. However, this document only provides a summary and it is recommended that the reader consult the USEPA 1991 guidance document for more detailed information.

Figure 6 provides flow diagram showing a summary of the decisions for application of the three-level process as defined in the USEPA 1991 guidance document.

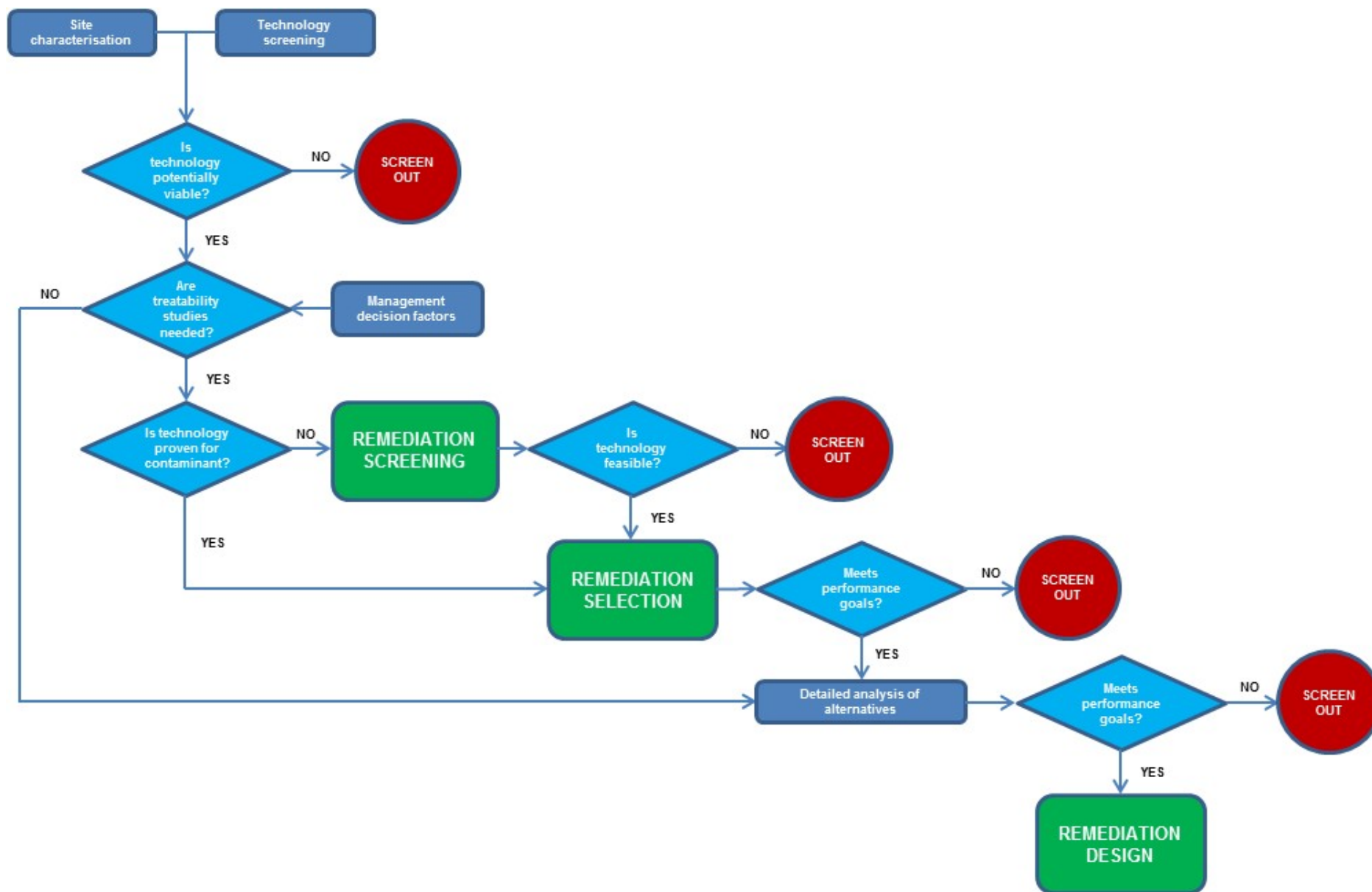


Figure 6: Three level approach to treatability studies. Adapted from US EPA (1991)

4.1 SVE screening

This is the initial level of treatability study in the three-level approach. It is used to screen whether SVE has the capability to treat the contaminants present in soils at a site.

In most cases this level is preceded by an initial pre-screening phase of works, where a review of available literature, professional judgement based on previous experience and consideration of site specific factors is completed. At this stage the identity, concentration and distribution of contaminants should be known, and there should be a reasonable understanding of the residual contamination that will remain after SVE has been applied and whether this will meet the regulatory objectives, and the composition of the SVE gas that is to be treated.

This level of study is typically the lowest cost and can be completed in a period of weeks. The study requires assessment of the basic principles of whether a technology can be used to remediate a contaminant via use of column testing.

Column testing for remedy screening involves a test where approximately 2000 pore volumes of air are passed through a column of undisturbed soil from the unsaturated zone of the site. This is representative of the typical throughput volume of air at a site where an SV remediation system has been operating for 3 to 6 years, depending on the details of the technology (USEPA [1991]). At this stage of study, a limited number of column tests are completed and only one or two may be necessary, depending on the complexity of the site.

Prior to the column test, the soil vapour contaminant concentration is measured. This is then used as the benchmark for the performance of the column test, with the concentrations of contaminants in the extracted vapour stream monitored during the test and a final measurement made of the soil vapour contaminant concentration once the column test is finished. The US EPA (1991) guidance suggests that a reduction of $\geq 80\%$ of the original soil vapour contaminant concentration indicates that SVE is a viable remediation approach for the site and that if a reduction of $\geq 95\%$ is noted further column tests for SVE performance assessment may be skipped.

The screening stage is not required where one or a range of SV remediation technologies have been previously proven to have the capability to treat a known contaminant type at a similar site and/or where the vapour pressure of the target contaminant is ≥ 10 mm Hg (USEPA [1991]).

4.2 SVE selection

The technology selection stage follows on from the screening stage or is the first level of treatability study for previously proven technologies or situations where a contaminant is known to have a suitably high vapour pressure (≥ 10 mm Hg).

This second level of treatability study is used to assess the performance of a technology on a contaminant specific basis for a specific SV remediation technology, its ability to meet the remediation criteria and objectives for a site and to provide sufficient information to allow analysis of alternatives. This level of study has a moderate cost and is more time consuming than the remediation option screening study level, typically taking months to complete. The remediation option selection level study may include a combination of the following tests:

- **Further column tests** – multiple tests assessing variability in soils and varying contaminant types which are run until an endpoint is achieved (either total clean-up or when target is achieved).
- **Field air permeability tests** – conducted at the site in situ to assess:
 - SVE applicability.
 - In situ soil air permeability across different geological formations in the unsaturated zone.
 - Flow patterns and vacuum radius of influence (ROI).
- **Mathematical modelling** – calculations of maximum potential remediation of known contaminant types in site specific conditions, assessment of partition functions for certain contaminants and estimation of clean-up times (including sensitivity analysis for critical variables).
- **Pilot trials** – Where warranted, pilot-scale testing can be completed at this stage to test the proposed technology in site conditions. At this stage, pilot-scale tests are usually conducted only for complex sites where remediation is in fractured bedrock or site with complex/heterogeneous geology in the unsaturated zone.

Column tests may not be warranted at either the remediation screening or selection levels of study, where:

- Contaminants are very volatile (vapour pressure ≥ 10 mm Hg); or
- Column tests from the screening level study have already indicated that the remediation criteria can be met.

Field air permeability tests may not be warranted where high air permeability for soils ($k \geq 10^{-6} \text{ cm}^2$) is known or reasonably thought to exist at the site.

Pilot trials may not be warranted at this stage and these tests are often completed within the third level of study (remedy design).

4.3 Remediation design

Remediation design is the third and final level of treatability study for SV remediation technologies.

This level is typically completed following the selection of a single remediation technology from the preceding levels of treatability study and this can be the only treatability study stage required for sites where volatile contaminants are present and a proven technology is available for remediation at the site.

This stage is used to provide detailed and quantifiable cost, performance and design information for the implementation of the selected SV remediation technology. This level of study has a moderate to high cost and like the selection level studies typically takes months to complete.

The remediation design level study may include a combination of the following tasks:

- **Pilot trials** – In the remediation system design stage these tests are used to provide detailed information to allow optimisation of the selected technology and often comprise use of the selected technology for a short initial period in

order to obtain benchmark data for use in a later deployment. These also often focus on a smaller area of the site.

- **Desk based design** – Use of data from all three levels of treatability study (or all levels undertaken) to complete a detailed design for a suitable remediation system, including information from the pilot scale tests for system optimisation (e.g. ideal flow rates, vacuum ROI, contaminant concentrations in extracted vapour stream), operational approach (continuous, daily, pulsing, etc.) and project budgeting.

5. Validation

The following information describes the specific validation appropriate for SVR, 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 of SVR technologies are:

- Reduction in contaminant concentration over time or with distance through the reactive zone;
- Analysis of geochemical and biochemical parameters; and
- Assessment of the mass discharge from treated materials,

6. Health and safety

The health and safety aspects involved with SVE remediation systems predominantly comprise potential exposure to contaminated vapours, and the occurrence of an explosive atmosphere. Potential hazards associated the application of SVE should be considered, alongside mitigation measures as part of the remediation action plan (RAP).

Common health and safety hazards associated with SVE are highlighted in Table 4, together with possible control measures. Many of these matters will be subject to regulatory control measures, and relevant national and state regulations should be referred to. The list is intended to provide an indication of the hazards potentially associated with SVE application. They will vary significantly from site to site and the list is not intended as a substitute for a detailed hazard assessment which should be provided in the RAP.

Table 4: Common SVR hazards and suggested controls

Hazard	Source of hazard	Suggested controls
Contaminant exposure	<ul style="list-style-type: none"> • Dermal or inhalation exposure to vapour or contaminated media. 	<ul style="list-style-type: none"> • Use of appropriate personal protective equipment (PPE), including gloves protective • clothing that are suitable for the task e.g. ensure they • provide chemical resistance to the hazardous chemicals. Refer AS/NZS 2161, AS/NZS • 1336, and AS/NZS 4501. • If necessary, use respiratory protection that is suitable for the task and selected used and maintained in accordance with AS/NZS 1715.
Explosion and fire	<ul style="list-style-type: none"> • Vapour concentrations • exceed the lower explosion level, or flammable and combustible liquid or solid material is present 	<ul style="list-style-type: none"> • Use of appropriate hazard • rated equipment and storage. Refer to, for example: AS • 1940-2004 The storage and handling of flammable and combustible liquids, AS • 2380.1-1989 Electrical equipment for explosive • atmospheres
Ergonomic risks	<ul style="list-style-type: none"> • Lifting or performing any other movement with too much force and/or in an awkward position, or repeating the lift/movement too often. 	<ul style="list-style-type: none"> • Provide conveniently located equipment for the job, like carts, adjustable work stations (operators), and correctly sized tools. • Train workers on ergonomic risks and prevention.

Hazard	Source of hazard	Suggested controls
Slips, trips and falls	<ul style="list-style-type: none"> • 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. • Working in confined spaces • Using damaged steps into vehicles. 	<ul style="list-style-type: none"> • Keep walking and working areas free of debris, tools, electrical cords, etc. • Keep walking and working areas as clean and dry as possible. • Install handrails, and guardrails on work platforms. • Clean and inspect ladders and stairs routinely. • Perform a Job Hazard Analysis. • Ensure workers use proper 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.

Appendix A – Case studies

There are several case studies documenting remediation projects that have included the application of SVE on the Federal Remediation Technologies Roundtable (FRTR) website, including the following examples:

- In-situ bioremediation and SVE at Former Beaches Laundry and Cleaners, Florida, US
 - SVE system included 11 horizontal extraction wells and vacuum transmission lines to a SVE trailer containing control valves, a moisture separator, vacuum blower, particulate filter and carbon treatment unit.
 - The contaminants were PCE, TCE, cis-1,2-DCE and VC.
- Eaddy Brothers Service Station, South Carolina, US
 - SVE system comprised a 70 m horizontal well installed immediately beneath the asphalt car park with extracted vapours treated in a thermal oxidiser.
 - The contaminants were MTBE, BTEX and naphthalene.

Appendix B – References

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