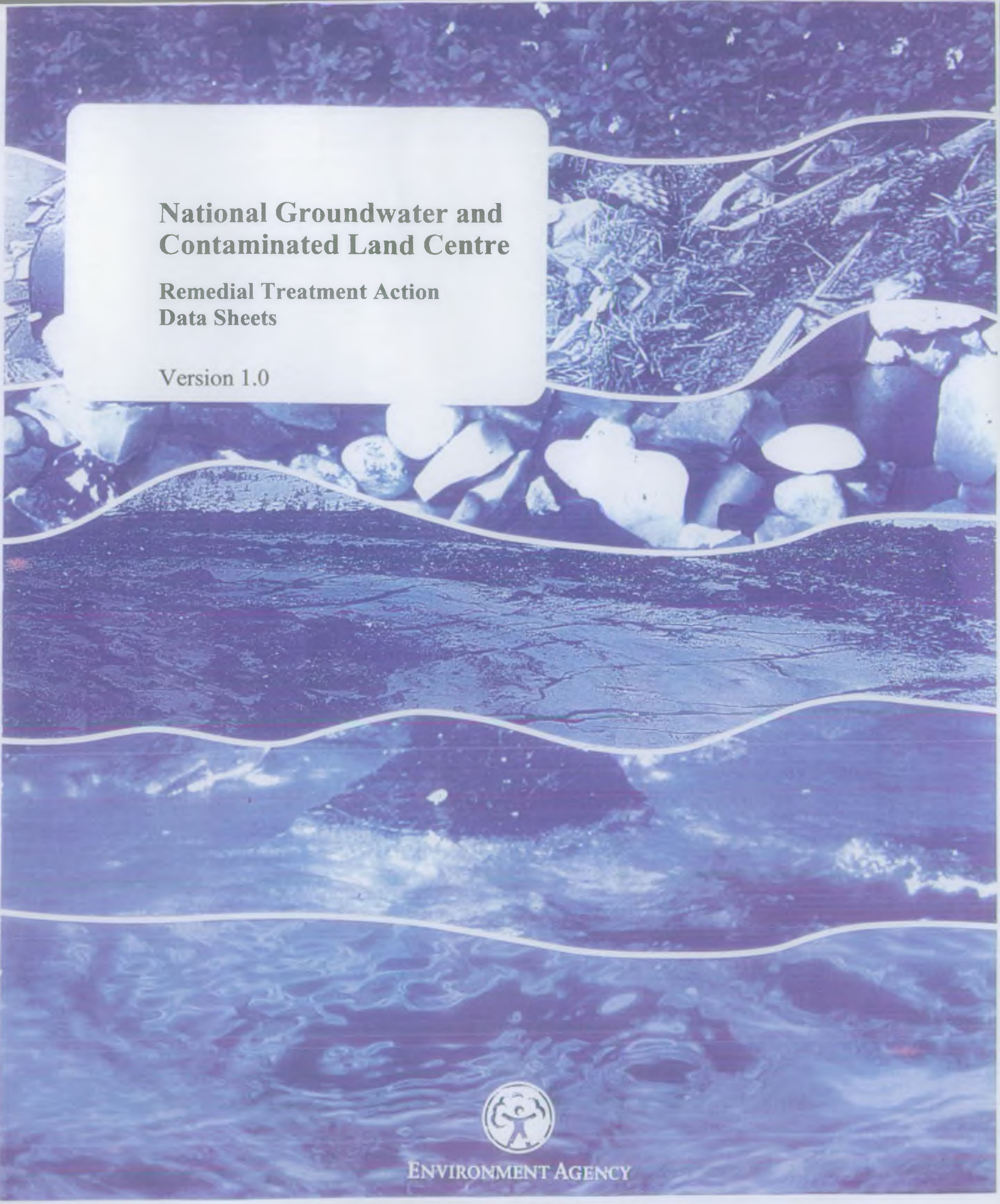
National Groundwater and Contaminated Land Centre

Remedial Treatment Action Data Sheets

Version 1.0



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From Theresa Kearney	Your ref
Ext. Number 722 4762	Date 30 March 2001

REMEDIAL TREATMENT ACTION DATA SHEETS

In support of the Agency's Part IIA Process Handbook, and in particular the Internal Standard on Remediation, the National Groundwater and Contaminated Land Centre has produced a series of Remedial Treatment Action Data Sheets for a number of civil engineering and process based treatments.

The aim of these Remedial Treatment Action Data Sheets is to provide Agency officers when considering the best practicable technique under Part IIA, with a concise and authoritative source of information on remedial techniques that are applicable for the remediation of contaminated soils and groundwaters, taking into account their commercial availability and track record in England and Wales. These data sheets may be used to:

- Assist with the rapid screening of different options for remediation of one or more SPL; and
- Identify relevant issues for further consideration during detailed options appraisal.

In the first instance five remedial treatment action data sheets have been completed and are provided in this package. These data sheets have been subject to periodic review by taking into account the experiences of UK technology vendors and end users. They are:

- Biopiles (DS-01);
- Windrow turning (DS-02);
- Landfarming (DS-03);
- Monitored Natural Attenuation (DS-04); and
- Bioventing (DS-05).

An additional 8 remedial treatment action data sheets are in draft, and a further 4 data sheets have been identified as indicated below. Once these data sheets are completed they will be forward to you for insertion in your file. Also as new innovative techniques become available and their applicability is demonstrated in the UK, the respective data sheets will be completed for them

Environment Agency
Olton Court, 10 Warwick Road, Olton, Solihull, B92 7HX
DX Address 702280 Solihull 3 Tel: 0121-711 2324 Fax: 0121-711-5830

RTAs in draft	RTAs identified but to be drafted
Soil Vapour Extraction (DS-08)	Bioremediation via Pump and Treat (DS-06)
Air Sparging (DS-09)	Additives to enhance Bioremediation (DS-07)
Vacuum Enhanced Recovery (DS-10)	Options for gas and vapour management (DS-14)
Soil Washing (DS-11)	Cover and capping systems for Containment (DS-15)
Cement based stabilisation / solidification (DS-12)	
Thermal Desorption (DS-13)	
In ground Vertical Barriers (DS-16)	
Pump and Treat (DS-17)	

At this stage these remedial treatment action data sheets are available for **INTERNAL USE ONLY** and we would therefore be grateful if they were not circulated outside the Agency. However, once we have agreed their format with PR, it is our intention to make them more widely available to external users.

In the meantime, should you have any feedback or comments on these data sheets, then do not hesitate to contact me.

THERESA KEARNEY
Senior Remediation Scientist
National Groundwater and Contaminated Land Centre

Direct dial 0121 711 5800
Direct fax 0121 711 5925

Distribution List:

Region / Area	Name	Job title
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BRISTOL / LQ Policy	Phil Crowcroft	Land Policy Manager
BRISTOL / LQ Policy	Jane Morris	Land Policy Advisor
BRISTOL / LQ Policy	Louise Hawkins	Part IIA Coordinator

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Environment Agency
National Groundwater and Contaminated Land Centre
Olton Court
10 Warwick Road
Olton
Solihull
West Midlands
B92 7HX

Publishing Organisation:
Environment Agency
Rio House
Waterside Drive
Aztec West
Almondsbury
Bristol BS12 4UD
Tel: 01454 624400 Fax: 01454 624409

This document has been prepared by the National Groundwater and Contaminated Land Centre. It should be noted that any recommendations contained herein do no represent an endorsement by the Environment Agency of this particular remediation treatment for contaminated land.

Dissemination status
Internal: **Released to Regions and Areas**
External: **Not Released to Public Domain**

Statement of use
This guide introduces to Agency Officers a series of Remedial Treatment Action Data Sheets in support of the Internal Standard on Remediation under Part IIA of the Environmental Protection Act (EPA) 1990. The remedial treatments described in these data sheets are representative of techniques that the Agency considers to be applicable to the remediation of contaminated soils and groundwater taking into account their commercial availability and track record in England and Wales.

Environment Agency's Project Manager
The Environment Agency's Project Manager for this project was: Theresa Kearney in the National Groundwater and Contaminated Land Centre. The Project Board consisted of Ian Martin, Theresa Kearney, John Davys, Brian Bone, Matthew Whitehead and Lamorna Zambellas.

National Groundwater & Contaminated Land Centre Project NC/00/04/01

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GUIDE TO USING THE REMEDIAL TREATMENT ACTION DATA SHEETS

Introduction

This guide introduces to Agency Officers the series of Remedial Treatment Action Data Sheets that have been prepared by the National Groundwater and Contaminated Land Centre (NGWCLC) to support the Internal Standard on Remediation under Part IIA. They are intended for use in conjunction with this Standard for duties under Part IIA of the Environmental Protection Act 1990 (EPA 1990). However, the technical information they contain may also be useful to Agency Officers carrying out the regulation of remediation technologies (under Part I and Part II of EPA 1990) and to those providing any response as a Statutory Consultee under the planning regime.

The Data Sheets and this guide are provided in a ring binder to enable the information to be readily updated, as new developments in the field of remediation become apparent. Any further information on this guide and the accompanying technology data sheets can be obtained from the NGWCLC.

Overview

The Data Sheets describe a range of remedial treatment actions for dealing with soil and groundwater contamination that have been arbitrarily categorised according to the groups in Table 1. The remedial treatment actions described are representative of techniques that the Agency considers to be applicable to remediation of contaminated land, taking into account their commercial availability and track record in England and Wales. It is intended that as new techniques become available and their applicability is demonstrated (e.g. through the CL:AIRE[1] Programme) then the respective data sheets will be issued accordingly.

Table 1: Classification scheme for different remedial treatment actions that has been used to prepare the Data Sheets.

Containment systems	Seek to physically break the pathway in a pollutant linkage thereby managing the risk. Examples include a fence, cover systems, cut-off walls, and liner systems.
Biological processes	Seek to destroy, transform, or concentrate contaminants by utilising biological organisms including bacteria, fungi, and plants. Examples include biopiling, bioventing and monitored natural attenuation.
Chemical processes	Seek to destroy, transform or concentrate contaminants by using chemical reagents. Examples include solidification / stabilisation and solvent extraction.
Physical processes	Seek to concentrate contaminants by exploiting differences in physico-chemical properties of the contaminant and the contaminated soil or groundwater. Examples include soil vapour extraction, air sparging, and soil washing.
Thermal processes	Seek to destroy or concentrate contaminants by heating the soil or groundwater. Examples include thermal desorption and incineration.
Others	Includes techniques for removal of contaminated soils and groundwaters off-site and mechanisms for receptor control.

[1] Contaminated Land: Applications in Real Environments (CL:AIRE) is a joint Government and industry initiative to encourage the application of remediation techniques to deal with typical UK site conditions. Further information about the programme can be obtained from the CL:AIRE web site at www.claire.co.uk, and the NGWCLC.

The Data Sheets present relevant information to Agency Officers considering the best practicable technique under Part IIA of EPA '90 that can be used to:

- Assist in the rapid screening of different options for remediation of one or more SPL.
- Identify the issues for further consideration during detailed options appraisal.

They are not intended to be exhaustive, and it is expected that Agency Officers will also take into account other published technical guidance and information available from individual companies. Further assistance on a case-by-case basis can be obtained from the NGWCLC on any of the remedial treatment actions listed.

Using the Data Sheets

The Data Sheets have been designed for use in conjunction with the Internal Standard on Remediation under Part IIA and therefore they are necessarily constrained by the requirements of Part IIA of EPA 1990[2]. This Standard describes a procedure for the evaluation and selection of the best practicable technique when dealing with one or more significant pollutant linkages. The important criteria for determining the best practicable technique are summarised in Table 2.

Table 2: Important criteria for determining the *best practicable technique* for remediation (taken from the Internal Standard on Remediation under Part IIA).

Criteria	Factors to consider
Effectiveness	Achievement of the *standard of remediation* (including as part of a *remediation package* or *remediation scheme*).
	Time taken for the *standard of remediation* to be achieved.
Reasonableness	Cost of *remediation* is justified by the benefit of breaking any SPL and/or mitigating the effect of any *significant harm* or *pollution of controlled water* that has already occurred.
Practicability	Technical constraints (e.g. availability of power or materials).
	Site constraints (e.g. area and access).
	Time constraints.
	Regulatory constraints (e.g. need to obtain a permit, licence, or operate within the conditions of that permit or licence).
	Interaction with any other works already proposed, in progress, or completed.
	Adverse environmental impacts.
Durability	The period of time over which the effectiveness of *remediation* will need to be maintained.
Others	Track record.
	Technological and scientific advances.
	Implementation in accordance with good practice and quality assurance procedures.

[2] This is important to note if the technical information presented in the Data Sheets is to be used in a context outside that of Part IIA of EPA 1990.

Structure and content of each Remedial Treatment Action Data Sheet

Each Data Sheet is no more than 5-7 pages in length. It can be divided into three parts:

(i) Basic process description;
(ii) Criteria for the best practicable technique; and
(iii) References for further information.

(i) Basic Process Description

This provides an introduction to the principles of the remedial treatment action, the practical ways in which it is implemented, and an overview of its track record in the UK. Where diagrams and/or photographs are available they are included to demonstrate what the technique looks like in practice.

(ii) Criteria for the Best Practicable Technique

Summary information relevant to the evaluation and selection of the best practicable technique is detailed in table 3.

(iii) References

Where available, sources of further information relevant to the specific remedial treatment action are provided.

Table 3: Relationship between the information provided in each Data Sheet and the criteria for assessment of the best practicable technique for remediation	
Criteria	**Data Sheet**
Effectiveness	This section considers: • Contaminants that have been identified as being treatable using the specified remedial treatment action. • Chemical properties of a contaminant that are important in making a decision about its potential treatability. • Important site conditions that influence the effectiveness of a remedial treatment action and a list of key data requirements for the purpose of designing any prior assessment action. • Requirements for an assessment action to determine the site specific effectiveness of a remedial treatment action through a lab-based treatability study or pilot/field trial. • Typical project implementation times and factors that can influence the timescale for remediation to be effective.
Durability	This section considers: • A brief statement concerning the durability of the overall approach, for example, whether the action will seek to reduce the source of contamination or manage the consequences along the pathway. • Characteristics for long-term performance, such as the need to specify a design life, management plan, maintenance, or monitoring protocol. Important factors that dictate the feasibility of long term effectiveness.
Practicability	This section considers: • Practical constraints to implementation of the remedial treatment action, for example, regional availability, space, or provision of site services. • Key areas of potential wider environmental impact and a list of permit or licence requirements that must be taken into account. • Practical operational advice on good practice management, for example, specifying verification or operational monitoring requirements. • Potential for integration directly with other remedial treatment actions.
Cost	This section considers: • An indication of the relative cost of implementing the remedial treatment action that takes account of design, operation, maintenance and closure. • Relevant factors that can significantly influence the cost of any remediation works.

Remedial Treatment Action Data Sheet on Biopiles

Data Sheet No. DS-01

BASIC PROCESS DESCRIPTION

Treatment of contaminated soils in static biopiles is a controlled process that involves constructing soil piles above ground, and promoting aerobic microbial degradation of organic contaminants.

Static biopiles are ex-situ engineered treatment systems, whereby contaminated soils are placed within a bunded area (Fig. 1). Their size and shape is largely influenced by the practical limitations of effectively aerating the soil. Generally they do not exceed 2.4 m in height, although they may be of any length with a proportional width. Biopiles are aerated using air injection or vacuum extraction to push or draw air through the soil respectively. This activity optimises the transfer of oxygen within soils as a means of promoting aerobic degradation of organic contaminants.

The main principles to consider when remediating contaminated soils in biopiles include:

1. Stimulation of microbial degradation within contaminated soils;
2. Controlled application of bioremediation; and
3. Containment of process emissions.

1. Stimulation of microbial degradation

Bioremediation is a process that uses naturally occurring micro-organisms (e.g. bacteria and fungi) for the elimination, attenuation or transformation of contaminating substances. Biodegradation of hydrocarbons occurs under both aerobic and anaerobic conditions, and results in an increase in microbial biomass, formation of intermediate products, carbon dioxide and water. In most cases, microbial consortia suitable for achieving effective remediation will be indigenous to the contaminated soil.

Hydrocarbons are biodegraded primarily by a wide variety of bacteria (e.g. *Acinetobacter, Alcaligenes, Arthrobacter, Bacillus, Flavobacterium, Nocardia, Pseudomonas* spp. and coryneforms) and fungi (e.g. *Phanerochaete, Trichoderma* and *Mortierella* spp.). Individually these microbial species are capable of utilising only a limited range of hydrocarbons. Contaminated soils normally contain many of these and other degradative species, and consequently by enhancing their environmental conditions, these microbes can be effective in degrading hydrocarbon mixtures in soils.

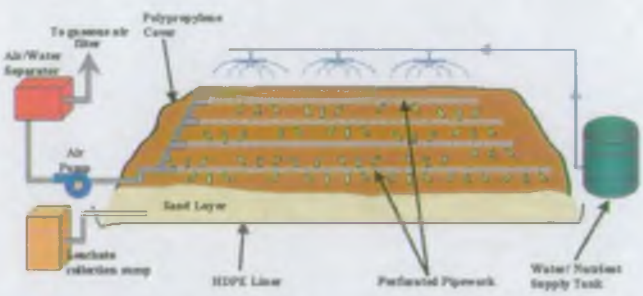

Fig.1. Schematic of a biopile

However, there may be situations in which contaminated soils do not have suitably active microbial populations for achieving effective biodegradation of the contaminants. In such instances, commercially available microbial inocula may be added to the nutrient solution and sprayed onto the soil prior to biopile construction, alternatively additional microbes may be added to the soil when adjusting its moisture content during remediation. Such microbial inocula may contain a number of naturally isolated microbes that have been laboratory cultured under hydrocarbon selective conditions. *Phanerochaete chrysosporium* (a white rot fungus) is an example of an organism that may be added to contaminated soils when recalcitrant compounds (e.g. polyaromatic hydrocarbons) are present. In addition to bacteria and/or fungi, some commercial products are reported to contain mixtures of nutrients and/or surfactants. Microbial amendments increase the overall cost of remediation, but have rarely demonstrated a benefit in the performance of bioremediation of contaminants such as petroleum hydrocarbons.

2. Controlled application of bioremediation

Biodegradation of organic contaminants by indigenous microbial consortia is enhanced by optimising and controlling a number of key environmental parameters, of which oxygen is the most critical. Other environmental parameters important to process performance include; soil moisture, nutrient levels, pH and temperature.

Oxygen is the terminal electron acceptor for bacteria during aerobic biodegradation, and in many cases it is the rate limiting parameter. It is therefore crucial that aeration of biopiles is sufficient to promote optimal microbial degradation of the contaminants, but is low enough to prevent excessive volatilisation of volatile compounds (e.g. BTEX).

Either active or passive air supply systems may be used, although the former is the preferred option since it provides a more controllable airflow through a biopile. Active aerating configurations commonly used in biopiles are air injection and air extraction systems.

Another environmental factor that is important in optimising biopile performance is soil moisture. Soil moisture can be readily adjusted during the initial preparation of the soil. Bulking agents may be added during pile construction to increase soil moisture content (e.g. wood chippings) or soil permeability (e.g. sand). Generally, soil moisture should be maintained between 40 and 85% of field capacity during treatment.

Temperature also has a significant effect upon the rate of biodegradation. During summer time, temperatures of 25-35°C may be realised within the soil piles, whilst during winter slower degradation rates may be achieved when temperatures drop.

Organic contaminants and natural organic compounds in soils typically provide an adequate supply of carbon to promote biological degradation, but the availability of other essential nutrients such as nitrogen, phosphorus, or potassium may be insufficient for optimum treatment. Requirements for additional nutrients should be evaluated through site specific treatability studies. Typically one or more of the following approaches may be used to amend soils with additional nutrients:

(i) addition of animal manure or other composting materials (2-10% w/w);
(ii) slow release nutrients added to soil when constructing soil piles; or
(iii) nutrient solutions sprayed onto soil pile prior to, or after, construction.

3. Containment of process emissions

Biopiles should be constructed upon an impermeable base, individually bunded and covered to prevent the ingress of rainwater. Biopiles may be covered with a semi-permeable polypropylene membrane that allows air to flow through but not water. In addition the design and construction of the biopiles needs to take into consideration a number of other environmental protective measures for the purpose of containing process leachates, and other emissions. Such containment measures include:

- Constructing biopiles upon an impermeable liner (e.g. clay layer, sealed concrete pad or HDPE membrane) and a layer of clean soil or sand/gravel;
- Ensuring soil base slopes in one direction for channelling leachate to a single leachate collection sump.
- Locating leachate collection tanks within a bunded area.
- Recycling leachate to maintain moisture level of soils;
- Treating extracted volatile emissions by applying appropriate filtration prior to atmospheric release.

EFFECTIVENESS OF BIOPILES

Contaminant types

Biopiles are reported as having been effective for treating soils with one or more of the following contaminants:

- BTEX (benzene, toluene, ethylbenzene and xylene)
- Phenols
- Polyaromatic hydrocarbons (PAHs - e.g. lower ringed aromatic compounds such as naphthalene and phenanthrene)
- Petroleum hydrocarbons (e.g. diesels, light lubricating oils, crude oil)
- Nitroaromatics
- Herbicides / Pesticides (e.g. atrazine)

Microbial degradation of hydrocarbons varies according to their molecular weight and structure. Biodegradation rates are generally higher for saturates (e.g. alkanes) followed by monoaromatic (e.g. BTEX, phenols) and the lighter polyaromatic hydrocarbons (e.g. 2, 3 and 4 ringed PAHs). Biopiles are less suitable for treating chlorinated compounds or high molecular weight PAHs (e.g. 5 or 6 ringed aromatic compounds).

Contaminant chemical properties

Chemical properties of contaminants that should be considered when determining the suitability of this remedial treatment action include:

- Contaminants with a carbon chain length of C_6-C_{20} are more readily biodegradable than larger compounds. Compounds in the range of C_{21}-C_{29} may be more slowly degraded, whilst $>C_{30}$ compounds are less degradable;
- Straight chain hydrocarbons are generally more degradable than branched aliphatic compounds or PAHs (e.g. 2-5 ringed PAHs);
- Soluble contaminants will be more readily degradable than those adsorbed onto the surfaces of soil particles;
- Concentration and types of contaminants will vary considerably both within and between sites. The effectiveness of this remedial treatment action should be demonstrated for the contaminated soils on a site-specific basis through treatability studies prior to implementation.
- High concentrations of heavy metals, cyanides or organic contaminants may inhibit microbial degradation.

Site conditions that influence effectiveness

The treatment area must provide:

- Adequate space for constructing a sufficient number of biopiles to treat the volume of contaminated soil on site;
- Utilities such as water and electricity when pretreating and operating the biopiles;
- Suitable climatic conditions;
  - temperature on site during treatment should ideally be in the range of 10-25°C;
  - cover soil to protect from the ingress of heavy rainfall and retain heat;
  - soil pH typically in the range of 6 to 8.
- Treatment area available to complete remediation.

Treatability studies for determining site specific effectiveness

Treatability studies may be required for collecting information prior to selecting this remedial treatment action for the identified SPL(s). They may be used as a means of determining the practicability and likely effectiveness of the remediation, and for estimating the time-scales required to achieve the standard of remediation. These treatability studies should be laboratory based and/or field based.

Laboratory and field based studies are suitable for determining the degradative activities of indigenous soil populations. Field based studies would also be valuable in optimising process parameters and determining the likely effectiveness of this remedial treatment action given the nature of the contamination and circumstances of the site.

Treatability studies may be used to assess:

- Biological activity within contaminated soils as measured by the rates of oxygen consumption or carbon dioxide production under typical site conditions;
- Biodegradation rates of specific contaminants under typical site conditions;
- Identification and optimisation of critical process parameters (e.g. quantities of nutrients, air flow rates, leachate generation, etc.);
- Requirements for any microbial amendments, and their effect on the biodegradation rates.

Time-scales to achieve effective remediation

Time-scales for achieving the standard of remediation will vary greatly depending on a range of factors including; the nature of the contaminants and their respective concentrations, soil type, volume of material to be treated, the standard of remediation to be achieved, and the space available for on site treatment. However, some indicative time-scales are provide below:

Time factors	Time-scales
Regulatory permits / consents	≤ 3 months
Treatability Studies	1-4 months
Site visit and design full-scale remedial treatment action	1-4 weeks
Soil excavation (100 m^3/hr) and Pretreatment	1-4 weeks
Biopile construction	500-1,000 m^3/day
Process commissioning and operation	3-12 months
Sampling and analysis	3-12 months

Factors influencing time-scales for achieving effective remediation

The effectiveness of remediating contaminated soils in biopiles will depend largely on:

- The nature of the contaminants and their concentration;
- Ability of the indigenous microbial communities to degrade the contaminants;
- Environmental conditions that prevail within the soil pile (e.g. oxygen levels, pH, temperature)
- Presence of toxic inhibitors (e.g. toxic heavy metal concentrations).
- Soil conditions (e.g. soil permeability and porosity, etc.)
- Volume of soil requiring treatment, and the space available for constructing biopiles (see practical constraints).

DURABILITY OF BIOPILES

Remediation of contaminated soils in biopiles can be effective in breaking the significant pollutant linkage (SPL) by source treatment such that the level of contamination is no longer significant.

Characteristics for long term performance

No post remediation monitoring is required for evaluating the performance of this remedial treatment action. Time taken to achieve remediation generally ranges from 3-12 months, during which an appropriate monitoring programme should be in place to ensure that the performance of the remediation is maintained over the required time-scale.
Monitoring data collected during remediation will demonstrate the progress of the treatment and the final compliance with the standard of remediation. However, compliance with the standard of remediation should be based on the statistical validation of the analytical data collected (e.g. reduction of contaminant mass, rates of CO_2 production, etc.). This data should continue to be collected until the standard of remediation for the soil has been verified over a specified period of time (ranging from 1-3 months), that is, after achieving the standard of remediation, treatment may be continued for a period to ensure that this is indeed so.

Verification of this remedial treatment action should be in accordance with appropriate Agency guidance.

Treatment of contaminated soils in biopiles

PRACTICABILITY

Practical constraints

The volume of soil to be treated and the size of the soil piles themselves have a significant impact on the practicability of implementing this remedial treatment action on site. In determining its practicability, consideration should be given to the following factors:

Practical constraint	Explanation
Space requirements	Simple calculations should be done at an early stage to identify the likely space requirements (1.5-2 tonnes /m^3), based on the volume of soil to be treated and the biopile design.
Topography	Treatment area should be relatively flat with a slight slope (0.5-1%) for drainage of leachate to a collection sump
Access	Access around each biopile is required for maintenance and/or monitoring.
Location	Biopiles should not be located in areas prone to flooding. Also, consideration should be given to the presence of buildings and operational activities in the vicinity of the proposed treatment area for the purpose of assessing potential impacts such as traffic movements, volatile emissions and dusts.
Provision of utilities	Identify those utilities (e.g. water supply and electricity) essential during treatment.
Site security	Prevent public access to the treatment beds.

Wider environmental impacts of remediation

The potential for uncontrolled emissions (e.g. VOCs, leachates) and other adverse effects arising during soil excavation, pretreatment, or operation needs to be considered on a site specific basis taking into account the nature of the contamination and the conditions of the site. Potential adverse environmental impacts that may arise during this remedial treatment action include:

- Emission of volatile organic compounds (VOCs) during excavation, pretreatment and remediation;

- Generation of contaminated leachates and process effluent streams;

- Leakage of leachates to the subsurface that may lead to the generation of new SPLs on site;

- Leakage or accidental release of concentrated nutrient solutions (e.g. conc. nitrate solutions) and other process additives;

- Generation of dusts during excavation, stockpiling and mixing;

- Generation of toxic intermediates. Contaminants identified earlier in this data sheet are unlikely to generate any toxic intermediates under aerobic conditions within the biopiles. However, soils containing additional contaminants such as chlorinated solvents (e.g. PCE, TCE) may generate toxic intermediates where anaerobic conditions exist within the biopile.

Regulatory requirements

Contaminated soils treated in biopiles will normally need to be licensed under Part II of the Environmental Protection Act 1990.

Biopiles are regulated through the use of Mobile Plant Licences (MPL). The legislation (Waste Management Licensing Regulations 1994) requires that such licences are issued to the operators of the remedial process. Licensed processes can be moved from one site to another, but in doing so, the operator needs to agree a new site-specific working plan for each site. The working plan should ensure that an appropriate level of environmental control is in place given the circumstances of the site.

Further information on the regulation of remediation technologies is provided in: *Guidance on the Application of Waste Management Licensing to Remediation (Environment Agency, 2001*).

Also, soil excavation and construction of the soil piles will be subject to Construction (Design and Management) Regulations 1994 (CDM).

In addition, biopile construction and operation may also require:

- Planning Control;
- Discharge consent for discharges to controlled waters;
- Groundwater Regulations authorisation for discharge into or onto land; and/or
- Trade effluent consent for discharge to sewer.

Such requirements should be determined on a site-specific basis.

Practical operational advice on good practice management

Performance of biopiles should be monitored on a regular basis for the purpose of evaluating the ability of this remedial treatment action to achieve the standard of remediation within the given time-scale. During remediation this can be evaluated by monitoring:

1. Reduction of contaminant mass;

2. Rates of CO_2 production and biodegradation (generation of intermediates);

3. Environmental parameters in the soil pile (e.g. oxygen levels, soil moisture, nutrient levels, temperature, pH, etc.) necessary for effective degradation of the contaminants; and

4. Maintenance requirements of the system (e.g. addition of nutrient amended solutions, check flow rates of aeration and leachate pumps, repair of covers, etc.) and;

5. Mass balance of contaminants.

Technology track record

Remediation of contaminated soils using biopiles is commercially available and practised within the UK. It is considered to be an established remedial treatment action for soils contaminated with petroleum hydrocarbons.

Potential for integration with other remedial treatment actions

Biopiles may be one of a number of remedial treatment actions within a remediation package or remediation scheme with the purpose of:

- Treating the source of contamination; or
- Treating the source in combination with other remedial measures for controlled waters.

For example, it may be that identified hot spots are excavated and disposed at a licensed landfill, while less contaminated material is treated using biopiles. Alternatively, biopiles may be used to treat petroleum contaminated soils in combination with other remedial treatment actions suitable for free phase removal and treatment of the dissolved phase remaining in the groundwater.

COSTS

Factors that influence relative cost of remediation

Factors that most influence the cost of this remedial treatment action are represented qualitatively below as three ticks, whilst those that least influence costs are represented as a single tick.

Cost factors	Relevance
Regulatory Licence (MPL)	✓
Treatability Studies	✓✓
Planning and Design	✓
Soil Excavation & Pre-treatment	✓✓
Process Operation	✓✓
Analysis	✓✓✓
Process Decommissioning	✓
Process Management	✓

Costs of this remedial treatment action

The costs of this remedial treatment action will vary depending upon several factors including:

- Nature of the contaminants and their respective concentrations;
- Standard of remediation to be achieved;
- Soil type;
- Volume of soil to be treated;
- Space available for on site treatment; and
- Predicted treatment times to achieve the standard of remediation.

Indicative treatment costs for soils contaminated with petroleum hydrocarbons (≤ 10,000 ppm) range from £10-25/m^3. However, soils containing high levels of more recalcitrant organic compounds (e.g. PAHs) may incur a higher tariff ranging from £20-40/m^3.

REFERENCES

1. Harris, M.R, Herbert, S.M and Smith, M.A. 1995. Remedial treatment for contaminated land. Volume VII: Ex situ remedial methods for soils, sludges, and sediments. SP107. Construction Industry Research and Information Association, London.

2. King, R.B., Long G.M. and Sheldon, J.K. 1998. Practical environmental bioremediation: the field guide. CRC Lewis Publishers, Boca Raton, USA.

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Further information

Further details on the application of this, and other remedial treatment actions can be obtained from the National Groundwater and Contaminated Land Centre, Olton Court, Solihull B92 7HX. Tel 0121 711 5885.

Acknowledgements

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ENVIRONMENT AGENCY

Remedial Treatment Action Data Sheet on Windrow Turning

Data Sheet No. DS-02

BASIC PROCESS DESCRIPTION

Treatment of contaminated soils in windrows is a controlled process that involves constructing and turning soil piles as a means of promoting aerobic microbial degradation of organic contaminants.

Windrows are similar to soil composting systems. Contaminated soils are mixed with composting materials (e.g. animal manure, straw, wood chippings, etc.) and loosely placed in windrows. Their size and shape is largely influenced by the practical limitations of effectively aerating the soil. Generally they do not exceed approximately 2 m in height and 2-4m in width, although they may be of any length. Windrows are aerated periodically by rotavating the soil pile with a machine called a straddler (Fig. 1). This optimises the transfer of oxygen into contaminated soils and promotes aerobic degradation of organic contaminants.

The main principles to consider when remediating contaminated soils by windrow turning include:

1. Stimulation of microbial degradation within contaminated soils;
2. Controlled application of bioremediation; and
3. Containment of process emissions.

1. Stimulation of microbial degradation

Bioremediation is a process that uses naturally occurring micro-organisms (e.g. bacteria and fungi) for the elimination, attenuation or transformation of contaminating substances. Biodegradation of hydrocarbons occurs under both aerobic and anaerobic conditions, and results in an increase in microbial biomass, formation of intermediate products, carbon dioxide and water. In most cases, microbial consortia suitable for achieving effective remediation will be indigenous to the contaminated soil.

Hydrocarbons are biodegraded primarily by a wide variety of bacteria (e.g. *Acinetobacter, Alcaligenes, Arthrobacter, Bacillus, Flavobacterium, Nocardia, Pseudomonas* spp. and coryneforms) and fungi (e.g. *Phanerochaete, Trichoderma* and *Mortierella* spp.). Individually these microbial species are capable of utilizing only a limited range of hydrocarbons. Contaminated soils normally contain many of these and other degradative species, and consequently by enhancing their environmental conditions, these microbes can be effective in degrading hydrocarbon mixtures in soils.

Fig.1. Windrow treatment courtesy of Shanks Waste Solutions

However, there may be situations in which contaminated soils do not have suitably active microbial populations for achieving effective biodegradation of the contaminants. In such instances, commercially available microbial inocula may be added to the nutrient solution and sprayed onto the soil prior to constructing the soil piles, alternatively additional microbes may be added to the soil when adjusting its moisture content during remediation. Such microbial inocula may contain a number of naturally isolated microbes that have been laboratory cultured under hydrocarbon selective conditions. *Phanerochaete chrysosporium* (a white rot fungus) is an example of an organism that may be added to contaminated soils when recalcitrant compounds (e.g. polyaromatic hydrocarbons) are present. In addition to bacteria and/or fungi, some commercial products are reported to contain mixtures of nutrients and/or surfactants. Microbial amendments increase the overall cost of remediation, but have rarely demonstrated a benefit in the performance of bioremediation for hydrocarbons such as petroleum hydrocarbons.

2. Controlled application of bioremediation

Biodegradation of organic contaminants by indigenous microbial consortia is enhanced by optimising and controlling a number of key environmental parameters, in which oxygen is the most critical. Other environmental parameters important to process performance include; soil moisture, nutrient levels, pH and temperature.

Oxygen is the terminal electron acceptor for bacteria during aerobic biodegradation, and in many cases it is the rate limiting parameter. It is therefore crucial that oxygen levels within windrows are sufficient to promote and optimise microbial degradation of the contaminants (e.g. BTEX) present. Windrows are aerated regularly (e.g. once per week) by a machine called a straddler which stands over the windrow and turns the soil using a rotating drum (approx. 6m wide). Operators will themselves determine the necessary frequency of windrow turning based on the nature of the contaminated material and their experience.

Another environmental factor that is important in optimising the performance of windrows is soil moisture. Soil moisture can be readily adjusted during the initial preparation of the soil. Bulking agents may be added during the pile construction for increasing soil moisture content (e.g. wood chippings) or soil permeability (e.g. sand). Generally, soil moisture content should be maintained between 40 and 85% of field capacity during treatment.

Temperature also has a significant effect upon the rate of biodegradation. During summer, temperatures of 25-35°C may be realized within the windrow, whilst during winter, slower degradation rates may be achieved when temperatures drop to 10-15°C.

Organic contaminants and natural organic compounds in soils typically provide an adequate supply of carbon to promote biological degradation, but the availability of other essential nutrients such as nitrogen, phosphorus, or potassium may be insufficient for optimum treatment. Requirements for additional nutrients should be evaluated through laboratory or field based treatability studies. Typically one or more of the following approaches may be used to amend soils with additional nutrients:

(i) addition of animal manure or other composting materials (2-10% w/w);
(ii) slow release nutrients and mixed with the soil when constructing soil piles; or
(iii) nutrients solutions sprayed onto the soil piles prior to, or after construction.

3. Containment of process emissions

Windrows should be constructed on an impermeable base, individually bunded and covered to prevent the ingress of rainwater. Windrows may be covered with a semi-permeable polypropylene membrane that allows air, but not water to penetrate. In addition the design and construction of soil piles needs to take into consideration a number of other environmental protective measures for the purpose of containing process leachates. Such containment measures include:

- Constructing the windrow upon an impermeable liner (e.g. clay layer, sealed concrete pad or HDPE membrane) and a layer of clean soil;
- Ensuring soil base slopes in one direction for channelling leachate to a single leachate collection sump;
- Locating leachate collection tanks within a bunded area;
- Recycling leachate to maintain moisture level of soils.

EFFECTIVENESS OF WINDROWS

Contaminant types

Windrows are reported as having been effective for treating soils contaminated with one or more of the following contaminants:

- BTEX (benzene, toluene, ethylbenzene and xylene);
- Phenols;
- Polyaromatic hydrocarbons (PAHs - e.g. lower ringed aromatic compounds such as napthalene and phenanthrene);
- Petroleum hydrocarbons (e.g. diesels, light lubicating oils, crude oil);
- Nitroaromatics;
- Herbicides / Pesticides (e.g. atrazine).

Microbial degradation of hydrocarbons varies according to their molecular weight and structure. Biodegradation rates are generally higher for saturates (e.g. alkanes) followed by monoaromatic (e.g. BTEX, phenols) and the lighter polyaromatic hydrocarbons (e.g. 2, 3 and 4 ringed PAHs). Windrows are less suitable for treating chlorinated compounds or high molecular weight PAHs (e.g. 5 or 6 ringed aromatic compounds).

Contaminant chemical properties

Chemical properties of contaminants that should be considered when determining the suitability of this remedial treatment action include:

- Contaminants with a carbon chain length of C_6-C_{20} are more readily biodegradable than larger compounds. Compounds in the range of C_{21}-C_{29} may be more slowly degraded, whilst $>C_{30}$ compounds are less degradable;
- Straight chain hydrocarbons are generally more degradable than branched aliphatic compounds or PAHs (e.g. 2-5 ringed PAHs);
- Soluble contaminants will be more readily degraded than those adsorbed more firmly onto the surfaces of soil particles;
- Concentration and types of contaminants will vary considerably both within and between sites. The effectiveness of this remedial treatment action should be demonstrated for the contaminated soils on a site specific basis through treatability studies prior to implementation;
- High concentrations of heavy metals, cyanides or organic contaminants may inhibit microbial degradation.

Site conditions that influence effectiveness

The treatment area must provide:

- Adequate space for constructing a sufficient number of windrows to treat the volume of contaminated soil on site;
- Utilities such as water and electricity during pretreatment and treatment;
- Suitable climatic conditions:
  - temperature on site during treatment should ideally be in the range of 10-25°C;
  - cover soil to protect from the ingress of heavy rainfall;
  - soil pH typically in the range of 6 to 8.
- Treatment area available to complete remediation.

Treatability studies for determining site specific effectiveness

Treatability studies may be required for collecting information prior to selecting this remedial treatment action for the identified SPL(s). They may be used as a means of determining the practicability and likely effectiveness of the remediation, and to estimate the time-scales required to achieve the standard of remediation. These treatability studies may be laboratory based and/or field based.

Laboratory and field based studies are suitable for determining the degradative activities of indigenous soil populations. Field based studies would also be valuable in optimising process parameters and determining the likely effectiveness of this remedial treatment action given the nature of the contamination and circumstances of the site.

Treatability studies may be used to assess:

- Biological activity within contaminated soils as measured by the rates of carbon dioxide production under typical site conditions;
- Biodegradation rates of specific contaminants under typical site conditions;
- Identification and optimisation of critical process parameters (e.g. quantities of nutrients, aeration, leachate generation, etc.);
- Requirements for any microbial amendments, and their effect on the rate of degradation.

Time-scales to achieve effective remediation

Time-scales for achieving the standard of remediation may vary greatly depending on a range factors including; the nature of the contaminant(s) and their respective concentrations, standard of remediation to be achieved, soil type, volume of material to be treated and the space available for on site treatment. Some indicative time-scales are provide below:

Time factors	Time-scales
Regulatory permits / consents	≤ 3 months
Treatability Studies	1-4 months
Site visit and design of full-scale remedial treatment action	1-4 weeks
Soil excavation (100 m^3/hr) and Pretreatment	1-4 weeks
Windrow construction	500-1000 m^3/day
Process commissioning & operation	2-12 months
Sampling and analysis	2-12 months

Factors influencing time-scales for achieving effective remediation

The effectiveness of remediating contaminated soils in windows will depend largely on:

- The nature of the contaminants and their concentration;
- Biodegradative capability of the indigenous microbial communities;
- Environmental conditions that prevail within the windrow (e.g. oxygen levels, pH, temperature);
- Presence of toxic inhibitors (e.g. toxic heavy metal concentrations);
- Soil conditions (e.g. soil permeability and porosity, etc.);
- Volume of soil requiring treatment, and the space available for constructing soil piles (see practical constraints).

DURABILITY OF WINDROWS

Remediation of contaminated soils in windrows can be effective in breaking the significant pollutant linkage (SPL) by source treatment such that the level of contamination is no longer significant.

Characteristics for long-term performance

No post remediation monitoring is required for evaluating the performance of this remedial treatment action. Time taken to achieve remediation generally ranges from 2-12 months, during which an appropriate monitoring programme should be in place to ensure that the performance of the remediation is maintained over the required time-scale.

Monitoring data collected during remediation will demonstrate the progress of the treatment and the final compliance with the standard of remediation. However, compliance with the standard of remediation should be based on the statistical validation of the analytical data collected (e.g. reduction of contaminant mass, rates of CO_2 production, etc.). This data should continue to be collected until the standard of remediation for the soil has been verified over a specified period of time (ranging from 1-3 months), that is, after achieving the standard of remediation, treatment may be continued for a period to ensure that this is indeed so.

Verification of this remedial treatment action should be in accordance with appropriate Agency guidance.

PRACTICABILITY

Practical constraints

The volume of soil to be treated and the size of the soil piles themselves have a significant impact on the practicability of implementing this remedial treatment action on site. In determining its practicability, consideration should be given to the following factors:

Practical constraint	Explanation
Space requirements	Simple calculations should be done at an early stage to identify the likely space requirements (e.g. 1.5-2 tonnes/m^3), based on the volume of soil to be treated and the windrow design. For example, windrows with dimensions of 20m x 3m and a pile height of 2m can treat approx. 120m^3.
Topography	Treatment area should be relatively flat with a slight slope (0.5-1%) for drainage of leachate to a collection sump.
Access	Access around each soil pile is required for maintenance and/or monitoring.
Location	Windrows should not be located in areas prone to flooding. Also, consideration should be given to the presence of buildings and operational activities in the vicinity of the proposed treatment area for the purpose of assessing potential impacts such as traffic movements, volatile emissions and dusts.
Provision of utilities	Identify those utilities (e.g. water supply and electricity) essential during treatment.
Site security	Prevent public access to the soil piles.

Wider environmental impacts of remediation

The potential for uncontrolled emissions (e.g. VOCs, leachates) and other adverse effects arising during soil excavation, pretreatment, or operation needs to be considered on a site specific basis taking into account the nature of the contamination and the conditions of the site. Potential adverse environmental impacts that may arise during this remedial treatment action include:

- Emission of volatile organic compounds (VOCs) during excavation, pretreatment and remediation;

- Generation of contaminated leachates and process effluent streams;

- Leakage of leachates to the subsurface that may lead to the generation of new SPLs on site;

- Leakage or accidental release of concentrated nutrient solutions (e.g. conc. nitrate solutions) and other process additives;

- Generation of dusts during excavation, stockpiling and mixing;

- Generation of toxic intermediates. Contaminants identified earlier in this data sheet are unlikely to generate any toxic intermediates under aerobic conditions within windrows. However, soils containing additional contaminants such as chlorinated solvents (e.g. PCE, TCE) may generate toxic intermediates where anaerobic conditions exist within soil piles.

Regulatory requirements

Contaminated soils treated in windrows will normally need to be licensed under Part II of the Environmental Protection Act 1990.

Windrows are regulated through the use of Mobile Plant Licences (MPL). The legislation (Waste Management Licensing Regulations 1994) requires that such licences are issued to the operators of the remedial process. Licensed processes can be moved from one site to another, but in doing so, the operator needs to agree a new site specific working plan for each site. The working plan should ensure that an appropriate level of environmental control is in place given the circumstances of the site.

Further information on the regulation of remediation technologies is provided in: *Guidance on the Application of Waste Management Licensing to Remediation (Environment Agency, 2001*).

Also, soil excavation and construction of the soil piles will be subject to Construction (Design and Management) Regulations 1994 (CDM).

In addition, construction and operation of windrows may also require:

- Planning control;
- Discharge consent for discharges to controlled waters;
- Authorisation under Groundwater Regulations for discharge into or onto land; and/or
- Trade effluent consent for discharge to sewer.

Such requirements should be determined on a site specific basis.

Practical operational advice on good practice management

Performance of windrows should be monitored on a regular basis for the purpose of evaluating the ability of this remedial treatment action to achieve the standard of remediation within the given time-scale. During remediation this can be evaluated by monitoring:

1. Reduction of contaminant mass;

2. Rates of CO_2 production and biodegradation (generation of intermediate products);

3. Environmental parameters in the soil pile (e.g. oxygen levels, soil moisture, nutrient levels, temperature, pH, etc.) necessary for effective degradation of the contaminants;

4. Maintenance requirements of the system (e.g. addition of nutrient amended solutions, flow rates of pumps, repair of covers, etc.); and

5. Mass balance of contaminants.

Technology track record

Remediation of contaminated soils using windrows is commercially available and practised within the UK. It is considered to be an established remedial treatment action for treating soils contaminated with petroleum hydrocarbons.

Potential for integration with other remedial treatment actions

Windrows may be one of a number of remedial treatment actions within a remediation package or remediation scheme with the purpose of:

- Treating the source of contamination; or
- Treating the source in combination with other remedial measures for controlled waters.

For example, it may be that identified hot spots are excavated and disposed at a licensed landfill, while less contaminated material is treated using windrows. Alternatively, windrows may be used to treat petroleum contaminated soils in combination with other remedial treatment actions suitable for free phase removal and treatment of the dissolved phase in the groundwater.

COSTS

Factors that influence relative costs of remediation

Factors that most influence the cost of this remedial treatment action are represented qualitatively below as three ticks, whilst those that least influence costs are represented as a single tick.

Cost factors	Relevance
Regulatory Licence (MPL)	✓
Treatability Studies	✓✓
Planning and Design	✓
Soil Excavation & Pretreatment	✓✓
Process Operation	✓✓
Analysis	✓✓✓
Process Decommissioning	✓✓
Process Management	✓

Costs of this remedial treatment action

The costs of this remedial treatment action will vary depending upon several factors including:

- Nature of the contaminants and their respective concentrations;
- Standard of remediation to be achieved;
- Soil type
- Volume of soil to be treated;
- Space available for on site treatment (i.e. if 1 or more treatment batches are required); and
- Predicted treatment times to achieve the standard of remediation.

Indicative treatment costs for relatively large quantities of soils (>10,000 m^3) range from £8-15 m^3. However, windrow turning for treating smaller quantities of contaminated soils (<10,000 m^3) may incur higher costs ranging from £10-20m^3.

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1. Harris, M.R, Herbert, S.M and Smith, M.A. 1995. Remedial treatment for contaminated land. Volume VII: Ex situ remedial methods for soils, sludges, and sediments. SP107. Construction Industry Research and Information Association, London.

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3. United States Environmental Protection Agency. 1991. Guide for conducting treatability studies under CERCLA: aerobic biodegradation remedy screening. US Environmental Protection Agency EPA/54012-91/-13A.

4. von Fahnestock, F.M., Wickramanayake, G.B., Kratzke, R.J. and Major, W.R. 1998. Biopile design, operation, and maintenance handbook for treating hydrocarbon contaminated soils. Battelle Press, Columbus, Richland.

Further information

Further details on the application of this, and other remedial treatment actions can be obtained from the National Groundwater and Contaminated Land Centre, Olton Court, Solihull B92 7HX. Tel 0121 711 5885.

Acknowledgements

The National Groundwater & Contaminated Land Centre would like to thank colleagues and remedial technology vendors for their comments when developing this data sheet.

ENVIRONMENT AGENCY

Remedial Treatment Action Data Sheet on Landfarming

Data Sheet No. DS-03

BASIC PROCESS DESCRIPTION

Landfarming has been traditionally used at petroleum refineries as a means of remediating tank sludges and contaminated soils. In its simplest form it may be used for treating superficial hydrocarbon contaminated soils, alternatively it involves constructing engineered treatment beds. This technology data sheet considers landfarming applications where engineered treatment beds are employed.

Landfarming typically requires a large area (i.e. ≥ 0.5ha) for undertaking the treatment on site. Contaminated soils are spread over the designated lined treatment areas where a leachate collection sump has been constructed (Fig. 1). Soil is normally placed in the treatment area to a maximum thickness of approximately 0.3m. Landfarming treatments are designed to maximise the transfer of oxygen within soils for the purpose of optimising aerobic degradation of organic contaminants.

The main principles to consider when operating this remedial treatment action include:

1 Stimulation of microbial degradative processes within contaminated soils;
2 Controlled application of bioremediation; and
3 Containment of process emissions.

1 Stimulation of microbial degradation

Bioremediation is a process that uses naturally occurring micro-organisms (e.g. bacteria and fungi) for the elimination, attenuation or transformation of contaminating substances as a means of minimising the risks to human health and the environment. Biodegradation of petroleum hydrocarbons in landfarming operations occurs under aerobic conditions, and gives rise to an increase in microbial biomass, formation of intermediate products, carbon dioxide and water. In most cases, microbial consortia suitable for achieving effective remediation will be indigenous to the contaminated soil.

Hydrocarbons are biodegraded primarily by a wide variety of bacteria (e.g. *Acinetobacter, Alcaligenes, Arthrobacter, Bacillus, Flavobacterium, Nocardia, Pseudomonas* spp. and coryneforms) and fungi (e.g. *Phanerochaete, Trichoderma* and *Mortierella* spp.). Individually these microbial species are capable of utilizing only a limited range of hydrocarbons. Contaminated soils normally contain many of these and other degradative bacterial species, and consequently by enhancing their environmental conditions, these microbes can be effective in degrading hydrocarbon mixtures in soils.

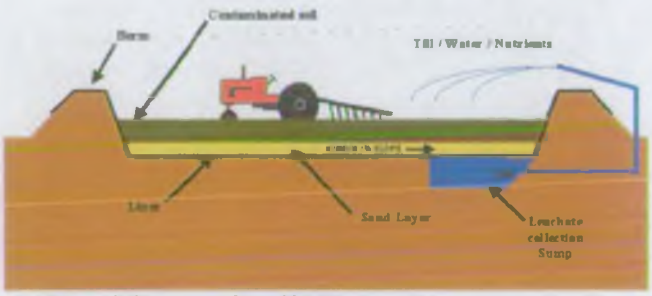

Fig.1. Schematic of landfarming

However, there may be situations were hydrocarbon contaminated soils do not have suitably active microbial populations for achieving effective bioremediation. In such instances, commercially available microbial inocula may be added to the nutrient solution and sprayed onto the soil prior and/or during treatment. Such microbial inocula may contain a number of naturally isolated microbes that have been laboratory cultured under hydrocarbon selective conditions. *Phanerochaete chrysosporium* (a white rot fungus) is an example of an organism that may be added to contaminated soils when recalcitrant compounds (e.g. polyaromatic hydrocarbons) are being treated. In addition to bacteria and/or fungi, some commercial products are reported to contain mixtures of nutrients and/or surfactants. Microbial amendments increase the overall cost of remediation, but have rarely demonstrated an overall benefit in the performance of bioremediation of contaminants such as petroleum hydrocarbons.

2 Controlled application of bioremediation

Biodegradation of organic contaminants by indigenous microbial consortia is enhanced by optimising and controlling a number of key environmental parameters, in which oxygen levels are the most critical. Other environmental parameters important to the process performance include; soil moisture, nutrient levels, pH and temperature.

Oxygen is the terminal electron acceptor during aerobic biodegradation, and for many contaminants it is the rate limiting parameter. It is therefore crucial that oxygen levels within soil treatment beds are sufficient to promote and optimise microbial degradation of the contaminants present.

Soils are aerated using tractors with agricultural tilling equipment (e.g. rotovators). Generally, soils are tilled 1-2 times per week, but under extremely wet conditions (>1" of rainfall / 24 hrs) the soils may need to be tilled each day. This extra tilling activity will improve soil permeability and oxygen levels, and help minimize the development of anaerobic conditions.

Another environmental factor that is important in optimising landfarming treatment is soil moisture. Generally, soil moisture should be maintained between 40 and 85% of field capacity during treatment. Soil moisture may be readily adjusted by spraying during the initial preparation of the soil and/or during treatment by sprinkling collected leachate onto the soil beds.

Temperature also has a significant effect upon the rate of biodegradation. During summer, temperatures of 25-35°C may be realized within the treatment beds, whilst during winter slower degradation rates may be achieved when temperatures decline.

Organic contaminants and natural organic compounds in soils typically provide an adequate supply of carbon, but the availability of other essential nutrients such as nitrogen, phosphorus, or potassium may be insufficient for optimum treatment. Requirements for additional nutrients should be evaluated through laboratory or field based treatability studies. Typically one or more of the following approaches may be used to amend soils with additional nutrients:

(i) addition of animal manure or other composting materials;
(ii) slow release nutrients added to the soil; or
(iii) nutrient solutions sprayed onto the soil beds prior to, or after construction.

3 Containment of process emissions

Landfarming treatment areas should be constructed upon an impermeable base, within a bunded area for the purposes of collecting process leachate. In addition, the design and construction of the treatment units needs to take into consideration a number of other environmental protective measures for the purpose of containing process leachates. Such containment measures include:

- Constructing the treatment bed upon an impermeable membrane (e.g. clay layer, sealed concrete pad or HDPE membrane) and a layer of clean sand/gravel. Care needs to be taken to avoid damaging the membrane during rotovation;
- Ensuring the treatment area slopes in one direction for channelling leachate to a suitable collection sump;
- Locating leachate collection tanks within a bunded area;
- Monitoring air quality in the vicinity of the treatment area particularly during the early tiling period.

EFFECTIVENESS OF LANDFARMING

Contaminant types

Landfarming is reported as having been effective for treating soils contaminated with one or more of the following contaminants:

- BTEX (benzene, toluene, ethylbenzene and xylene)
- Phenols
- Polyaromatic hydrocarbons (PAHs - e.g. lower ringed aromatic compounds such as napthalene and phenanthrene)
- Petroleum hydrocarbons (e.g. diesels, light lubicating oils, crude oil)

Microbial degradation of hydrocarbons varies according to their molecular weight and structure. Biodegradation rates are generally higher for saturates (e.g. alkanes) followed by monoaromatic (e.g. BTEX, phenols) and the lighter polyaromatic hydrocarbons (e.g. 2, 3 and 4 ringed PAHs). This remedial treatment action is less suitable for treating chlorinated compounds or high molecular weight PAHs (e.g. 5 or 6 ringed aromatic compounds).

Contaminant chemical properties

Chemical properties of contaminants that should be considered when determining the suitability of this remedial treatment action include:

- Contaminants with a carbon chain length of C_6-C_{20} are more readily biodegradable than larger compounds. Compounds of C_{21}-C_{29} may be more slowly degraded, and those $>C_{30}$ are less degradable;

- Straight chain hydrocarbons are generally more degradable than branched aliphatic compounds or PAHs (e.g. 2-5 ringed PAHs);

- Soluble contaminants will be more readily degradable than those adsorbed more firmly onto the surface of soil particles;

- Concentration and types of contaminants will vary considerably both within and between sites. The effectiveness of this remedial treatment action should be demonstrated for the contaminated soils on a site specific basis through treatability studies prior to implementation;

- High concentrations of heavy metals, cyanides or organic contaminants may inhibit microbial degradation.

Site conditions that influence effectiveness

The selected treatment area must provide:

- Adequate space to prepare a sufficient treatment area on site for treating the necessary volume of contaminated soil;

- Suitable climatic conditions:
  - temperature should ideally be in the range of 10-25°C;
  - soil pH typically in the range of 6 to 8; and
  - heavy rainfall will impact on the quantities of leachate generated. If, practical, the treatment area should be covered, alternatively the time of year needs to be carefully considered in planning the work.

- Adequate space to prepare a sufficient treatment area on site for treating the necessary volume of contaminated soil

Treatability studies for determining site specific effectiveness

Treatability studies may be required to collect information prior to selecting this remedial treatment action for the identified SPL(s). They may be used as a means of determining the practicability and likely effectiveness of the remediation, and to estimate the time-scales required for achieving the standard of remediation. These treatability studies may be laboratory based and/or field based.

Laboratory and field based studies are suitable for determining the degradative activities of indigenous soil populations. Field based studies would also be valuable in optimising process parameters and determining the likely effectiveness of this remedial treatment action given the nature of the contamination and circumstances of the site.

Treatability studies may be used to assess:

- Biological activity within the contaminated soils as measured by rates of oxygen consumption or carbon dioxide production under typical site conditions;

- Biodegradation rates for specific contaminants under typical site conditions;

- Identification and optimisation of critical process parameters (e.g. quantities of nutrients, leachate generation, etc.);

- Requirements for any microbial amendments, and their effect on the biodegradation rates.

Time-scales to achieve effective remediation

Time-scales for achieving the standard of remediation may vary greatly depending on a range of factors including: the nature of contamination and their respective concentrations, standard of remediation to be achieved, soil type, volume of material to be treated and the space available for on site treatment. However, some indicative time-scales are provide below:

Time factors	Time-scales
Regulatory permits / consents	≤3 months
Treatability studies	1-4 months
Site visit and design of full scale remediation	1-4 weeks
Soil excavation (100 m^3/hr) & Pretreatment	1-4 weeks
Construction of treatment beds	1-2 weeks
Process commissioning and operation	3-24 months
Monitoring and analysis	3-24 months

Factors influencing time-scales for achieving effective remediation

The effectiveness of landfarming for treating contaminated soils will depend largely on:

- The nature of the contaminants and their respective concentrations;
- Degradative capability of the indigenous microbial communities;
- Environmental conditions that prevail within the soil (e.g. oxygen levels, pH, temperature, moisture levels);
- Presence of toxic inhibitors (e.g. toxic heavy metal concentrations);
- Soil conditions (e.g. soil permeability and porosity, etc.); and
- Volume of soil to be treated, and the space available for undertaking this remedial treatment action.

DURABILITY OF LANDFARMING

Landfarming contaminated soils can be an effective means of breaking the significant pollutant linkage (SPL) by source treatment such that the level of contamination is no longer significant.

Characteristics for long term performance

No post remediation monitoring is required for evaluating the performance of this remedial treatment action.

Monitoring data collected during remediation will demonstrate the progress of this treatment and its final compliance with the standard of remediation. However, compliance with the standard of remediation should be based on the statistical validation of the analytical data collected (e.g. reduction of contaminant mass, etc.). This data should continue to be collected until the standard of remediation for the soil has been verified over a specified period of time, that is, after achieving the standard of remediation, treatment may be continued for a period (ranging from 1-3 months) to ensure that this is indeed so.

Verification of this remedial treatment action should be in accordance with appropriate Agency guidance.

PRACTICABILITY

Practical constraints

Volume of soil to be treated has a significant impact on the practicability of implementing this remedial treatment action on site (Fig. 2). In determining the practicability of implementing this remedial treatment action on site, consideration should be given to the factors listed below.

Practical constraint	Explanation
Space requirements for engineered treatment units	Simple calculations should be done at an early stage to identify the likely space requirements, based on the volume of soil to be treated.
Topography	Treatment area needs to be relatively flat but with a slight slope (1-2%) for drainage of leachate to a collection sump.
Access	Access to the treatment area with a tractor is needed for rotovating the soil and adding additional moisture and/or nutrients.
Location	Landfarming should not be undertaken in areas prone to flooding. Also, consideration should be given to the presence of buildings and operational activities in the vicinity of the proposed treatment area for the purpose of assessing potential impacts such as traffic movements, volatile emissions and dusts.
Site security	Prevent public access to the treatment area

Wider environmental impacts of remediation

The potential for uncontrolled emissions (e.g. VOCs, leachates) and other adverse effects arising during treatment needs to be considered on a site specific basis taking into account the nature of the contamination and the conditions of the site. Potential adverse environmental impacts that may arise during this remedial treatment action include:

- Dust and volatile emissions during excavation, pretreatment and remediation;
- Generation of contaminated leachates and leakage to the subsurface. This may generate new SPLs on site;
- Leakage or accidental release of concentrated nutrient solutions (e.g. conc. nitrate solutions) and other process additives;
- Generation of dusts during excavation, stockpiling and mixing;
- The contaminants identified earlier in this data sheet are unlikely to generate any toxic intermediates under aerobic conditions in the soil treatment areas. However, contaminated soils containing additional contaminants such as chlorinated solvents (e.g. PCE, TCE) may generate toxic intermediates where anaerobic conditions exist within the treatment area;
- Generation of a dense layer of contamination at the base of the treatment beds. Effective sampling should be in place to monitor this.

Fig. 2 Landfarming treatment

Regulatory requirements

Treatment of contaminated soils by landfarming will normally need to be licensed under Part II of the Environmental Protection Act 1990.

Landfarming is regulated through the use of Mobile Plant Licences (MPL). The legislation (Waste Management Licensing Regulations 1994) requires that these licences are issued to the operators of the remedial process. Licensed processes can be moved from one site to another, but in doing so, the operator needs to agree a new site specific working plan for each site. The working plan should ensure that an appropriate level of environmental control is in place given the circumstances of the site.

Further information on the regulation of remediation technologies under Part IIA of EPA 1990 is provided in; *Guidance on the Application of Waste Management Licensing to Remediation (Environment Agency, 2001*).

Also, soil excavation and construction of the soil treatment beds will be subject to Construction (Design and Management) Regulations 1994 (CDM).

In addition, landfarming operations may also require:

- Planning Control;
- Discharge consent for discharges to controlled waters;
- Groundwater Regulations authorisation for discharge into or onto land; and/or
- Trade effluent consent for discharge to sewer.

Such requirements should be determined on a site specific basis.

Practical operational advice on good practice management

Performance of landfarming treatments should be monitored on a regular basis for the purpose of evaluating the ability of the remedial treatment action to achieve the standard of the remediation within the given time-scale. During remediation this can be evaluated by monitoring:

1. Reduction of contaminant mass;

2. Rates of CO_2 production and biodegradation (generation of intermediate products);

3. Environmental parameters in the soil treatment beds (e.g. oxygen levels, soil moisture, nutrient levels, temperature, pH, etc.) necessary for effective degradation of the contaminants;

4. Maintenance requirements of the system (e.g. additional compost or nutrient amended solutions to maintain nutrient and moisture levels, flow rates of leachate pumps, etc.); and

5. Mass balance of contaminants.

Technology track record

Remediation of contaminated soils by landfarming has been commercially available and practiced in the UK for several decades. It is considered to be an established remedial treatment action for treating petroleum hydrocarbons in soil.

Potential for integration with other remedial treatment actions

Landfarming may be one of a number of remedial treatment actions within a remediation package or remediation scheme with the purpose of:

- Treating the source of contamination; or
- Treating the source in combination with other remedial measures for controlled waters.

For example, it may be that identified hot spots are excavated and disposed at a licensed landfill, while less contaminated soils are treated by landfarming.

COSTS

Factors influencing the relative cost of remediation

Factors that most influence the cost of remediation are represented qualitatively below as three ticks, whilst those that least influence costs are represented as a single tick.

Cost factors	Relevance
Regulatory Licence (MPL)	✓
Treatability Studies	✓✓
Planning and Design	✓
Soil Excavation & Pretreatment	✓✓
Operational Costs	✓
Monitoring and Analysis	✓✓
Process Decommissioning	✓
Process Management	✓

Costs of remedial treatment action

The costs of this remedial treatment action will vary depending upon several factors including:

- Nature of the contaminants and their respective concentrations;
- Standard of remediation to be achieved;
- Soil type;
- Volume of soil to be treated;
- Space available for on site treatment (ie. if 1 or more treatment batches are required); and
- Predicted time-scales to achieve the standard of remediation.

Indicative costs for landfarming to treat contaminated soils ranges from £5/m^3 or less to £10-30/m^3.

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Further information

Further details on the application of this, and other remedial treatment actions can be obtained from the National Groundwater and Contaminated Land Centre, Olton Court, Solihull B92 7HX. Tel 0121 711 5885.

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Remedial Treatment Action Data Sheet on Monitored Natural Attenuation (MNA)

Data Sheet No. DS-04

BASIC PROCESS DESCRIPTION

Natural attenuation (NA) is the effect of naturally occurring physical, chemical, and biological processes or any combination of these processes to reduce the load, concentration, flux or toxicity of polluting substances in groundwater. For natural attenuation to be an effective remedial treatment action, the rate at which these processes occur, must be sufficient to prevent polluting substances impacting on identified receptors and to minimise expansion of contaminant plumes into unpolluted groundwater. Dilution within a receptor, such as a river or borehole, is not natural attenuation.

Natural attenuation therefore describes the effect of natural processes, whilst **monitored natural attenuation** (MNA) is used to refer to the remedial technique, which by definition is a monitored activity. MNA requires sufficient evidence to be collated for the purpose of demonstrating that attenuation processes are occurring at a rate that:

- Protects the wider environment; and
- Achieves the standard of remediation within a reasonable time-frame.

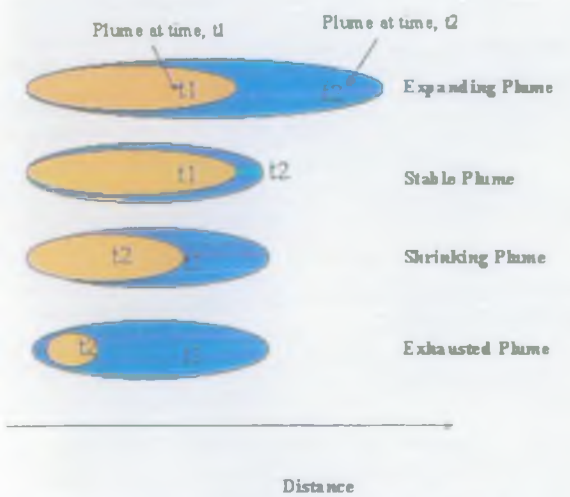

Fig.1 Types of contaminant plumes. The extent of the plume at time, t1, is compared with the size of the plume at a later time, t2.

When evaluating MNA as a remedial option, four contaminant plumes may be considered; expanding, shrinking, stable or exhausted plumes (Fig. 1). In general, reliance on natural attenuation processes will be acceptable where it can be shown that the plume is exhausted, shrinking or stable and where there are no unacceptable impacts or risks to receptors.

The main steps to understanding MNA as a remedial treatment action for a site are:

1. Screening;
2. Demonstration and assessment; and
3. Performance monitoring.

1. Screening stage

Developing a conceptual model using information acquired during the initial site investigation is the first step in understanding natural attenuation processes within a groundwater plume. This conceptual model is used to describe the nature of the contamination (e.g. phase, location, status, extent, concentration), its pathways and the receptors (e.g. abstraction points, watercourses, springs and groundwater resources) at risk. Further development of the conceptual model will be an iterative process, whereby information gaps identified in the initial model will guide the collection of additional site data and develop a more complete and accurate picture.

The decision to proceed to a more detailed assessment of MNA will be determined by having:

i. No fundamental constraints in accepting MNA;
ii. Initial indications that MNA may be effective in achieving the standard of remediation; and
iii. Understanding the level of uncertainty associated with the available data.

2. Demonstration and assessment of MNA

Demonstrating the effectiveness of natural attenuation processes will typically require obtaining additional site data (e.g. source mass, contaminant distribution, geochemical and hydrogeological data) to test and validate the conceptual model.

Multiple but converging lines of evidence are used to demonstrate natural attenuation in a groundwater plume. These lines of evidence are:

i. Primary lines of evidence using historical contaminant data to demonstrate a trend of reduced concentration down-gradient of the source and along the groundwater flow path. This particular line of evidence shows that attenuation is occurring, but fails to establish the biotic and/or abiotic mechanisms causing the reduction or removal of the identified contaminants;

ii. Secondary lines of evidence measure changes in chemical and geochemical conditions within the plume over a defined period. This data can be used to provide further supportive evidence that:

   (a) A decrease in concentration of the parent contaminant and/or electron acceptor can be directly correlated to an increase in intermediate products and/or metabolic by-products; and

   (b) Historical chemical data, complemented, if necessary, by biologically recalcitrant tracer testing, demonstrates the plume to be shrinking, stable or expanding at a rate slower than that predicted by conservative groundwater velocity calculations.

iii. Tertiary lines of evidence involve interpreting data from laboratory microbiological studies to show that the indigenous microbial consortia are capable of degrading the contaminants identified on site. This line of evidence should be used where the first two lines of evidence are inconclusive.

   In addition, analytical and numerical solute fate and transport models may complement these lines of evidence by:

   (a) Highlighting differences between observed and predicted contaminant concentrations that may be inferred to be attributable to attenuation processes;

   (b) Estimating the relative importance of various attenuation mechanisms; and

   (c) Testing the accuracy of model input data by comparing observed concentrations against those predicted by fate and transport modelling.

3. Performance monitoring of MNA

In the event that the lines of evidence indicate natural attenuation to be protective of the identified receptors, a long term monitoring programme must be put in place to provide assurance that the attenuating processes will continue to be effective in protecting the water environment and thereby achieve the standard of remediation. The objectives of the long-term monitoring programme are to:

- Demonstrate that natural attenuation is occurring according to expectations;
- Determine the status of the plume (e.g. shrinking, stable or expanding);
- Identify any changes in groundwater flow patterns;
- Identify any toxic breakdown products resulting from degradation;
- Detect new release of contaminants;
- Demonstrate that there is no impact on receptors down-gradient;
- Confirm compliance with the standard of remediation;
- Provide a basis for implementing a contingency plan, if necessary;
- Provide a basis for ceasing MNA.

The design and duration of performance monitoring will be site specific. For many sites, contaminant concentrations may take tens of years to achieve the standard of remediation. Contaminant fate and transport modelling should provide an indication of this time-scale.

EFFECTIVENESS OF NATURAL ATTENUATION

Contaminant types

MNA has previously been demonstrated to be effective for treating groundwater plumes containing one or more of the following:

- BTEX;
- Phenols;
- Chlorinated solvents (PCE, TCE, TCA, TCM, DCM, DCE);
- Polyaromatic hydrocarbons (e.g. lower ringed aromatic compounds such as napthalene and phenanthrene);
- Petroleum hydrocarbons (e.g. diesels, light lubicating oils, crude oil);
- Oxygenated hydrocarbons (e.g. MTBE, ethers, alcohols);
- Nitroaromatics (e.g. TNT, RDX);
- Pesticides (e.g. Lindane, Malathion, Diazinon, Isoproturon, Mecoprop);
- Heavy metals (e.g. Cr (VI) reduced to Cr (III));
- Anions (PO_4, NO_3, SO_4).

Biodegradation rates for organic contaminants vary according to their molecular weight and structure, and also with site specific conditions. The mobility, toxicity or bioavailability of heavy metals can in certain cases be reduced by redox reactions.

Contaminant chemical properties

Chemical properties of contaminants that should be considered when determining the suitability of this remedial treatment action include:

- Molecular structure of the contaminants and their potential biodegradability. Microbial mediated redox reactions may ultimately result in complete degradation of the contaminants;

- Partitioning from NAPL into groundwater. Dissolution of contaminants from NAPL represents the primary source of dissolved contamination in groundwater;

- Volatilization of contaminants dissolved in groundwater and the generation of soil gas;

- Sorption to the aquifer matrix tends to reduce apparent contaminant transport velocity in the groundwater.

Site conditions that influence effectiveness

Site conditions that influence the effectiveness of MNA include:

- Presence of identified source term(s);

- Physical properties of the aquifer (e.g. hydraulic conductivity, porosity, hydraulic gradients, fissure flow, intergranular flow, multi-layer, shallow/deep);

- Geochemical conditions (e.g. redox, dissolved oxygen, Fe^{2+}, NO_3, SO_4, aquifer mineralogy);

- Presence and activity of indigenous microbial consortia to degrade contaminants;

- Fluctuations in the water table due to recharge may cause dilution of the contaminant plume and replenish electron acceptor concentrations;

- Changes in land use or site conditions.

Treatability studies for determining site specific effectiveness

Demonstrating the effectiveness of NA is likely to involve obtaining secondary and/or tertiary lines of evidence to test and calibrate the conceptual model. This process is iterative, whereby available data is used to refine the model and determine additional site characterisation requirements such as; source mass, contaminant phase distribution and aquifer hydrogeological properties. This chemical and geochemical data (2° lines of evidence) may be collated by further site investigations (SI) through an assessment action.

The objectives of the SI are twofold:

- To provide site specific input data to forecast the future behaviour of plume using fate and transport modelling; and
- To provide data to demonstrate and quantify NA.

Tertiary lines of evidence involve laboratory based microbiological studies to demonstrate that the indigenous microbial populations are capable of degrading the contaminants present. Biodegradation is the principle attenuating process for organic contaminants, which may be represented by:

Microbes + electron donor (e.g. BTEX) + electron acceptor (e.g. O_2, NO_3, Fe^{3+}) + nutrients
$\rightarrow$ Metabolic by-products + energy + microbes

Time-scales to achieve effective remediation

Time-scales for achieving the standard of remediation will vary depending upon the nature of the contamination and their respective concentrations, site specific conditions and the standard of remediation to be achieved. However, some indicative time-scales for the various stages are provided below:

Time factors	Timescales (years)
Screening Stage	0.1-0.5
Demonstration & Assessment	1-5
Performance Monitoring	2 –30

Factors influencing time-scales for achieving effective remediation

The effectiveness of MNA will be dependent largely on:

- Nature of the contaminants and their respective concentration;
- Presence of source term(s);
- Geochemical conditions on site (e.g. suitable electron acceptors and electron donors);
- Degradative activities of the indigenous microbial communities;
- Biotic and abiotic transformation rates of contaminants;
- Physical properties of the aquifer (e.g. groundwater flow, hydraulic conductivity, etc);
- Changes in site conditions or land.

DURABILITY

MNA may be an effective remedial treatment action for managing a contaminant plume, although in all cases the performance monitoring programme should be supported with a Contingency Plan to provide for additional action if MNA proves to be ineffective on its own.

Characteristics for long term performance

The design and duration of performance monitoring will be site specific. An example of a typical monitoring network is illustrated in Fig. 2. Minimum monitoring borehole requirements for a contaminant plume will be:

- One borehole located up-hydraulic gradient;
- At least two boreholes located down-gradient of the contaminant plume;
- At least one borehole located directly on the flow path between the source and each identified receptor to act as a sentinel or early warning.

Most MNA schemes will require a much denser monitoring network than these minimum requirements. The basic elements of the monitoring programme should include:

- Type, number and location of monitoring points (e.g. borehole, surface water, spring);
- Design of monitoring points (incl. borehole construction and depth of screen);
- Methodology to obtain representative samples;
- Number and type of samples;
- Range of determinants for analysis;
- Frequency and duration of sampling;
- Basis for ceasing monitoring or the trigger for implementing the contingency plan.

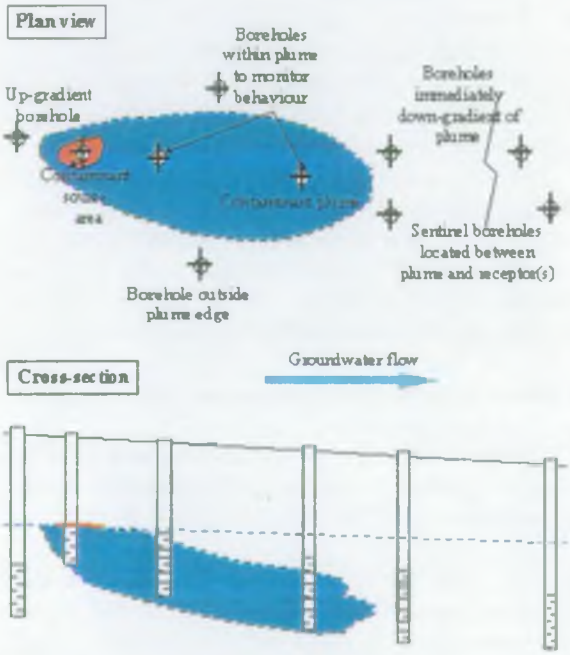

Fig. 2 Schematic location of monitoring boreholes around a groundwater contaminant plume.

For many sites, contaminant concentrations may take tens of years to reach the standard of remediation. The frequency of monitoring will be a function of:

- Groundwater contaminant plume behaviour;
- Rate of contaminant migration;
- Sensitivity of receptor(s);
- Natural variability of groundwater flow regime and contaminant concentrations.

Compliance with the standard of remediation should be based on the statistical validation of the analytical data collected (e.g. decreasing contaminant levels, concentration of intermediate products, electron acceptor levels, etc.). Monitoring should be continued until:

- Contaminant concentrations in the plume have reached background levels; or
- Standard of remediation has been met substantially (due to MNA or other remedial

treatment actions) and there is a high degree of confidence that natural attenuation can be effective in reducing further the contaminant levels.

PRACTICABILITY

Practical constraints

In determining the practicability of implementing this remedial treatment action, consideration should be given to:

- Long term access to monitoring wells located on site (incl. presence of existing buildings and services, together with land ownership, and the security of installations);
- Long-term access to monitoring wells located off-site where the contaminant plume has migrated, or is likely to migrate;
- Changes in site conditions and land use and their impact on a long term monitoring programme.

Wider environmental impacts of remediation

Potential adverse environmental impacts that may arise during this remedial treatment action include:

- Dominant attenuating mechanisms are ineffective in reducing or removing the contaminants over a period of time;
- Installation of monitoring boreholes may cause additional vertical migration of the contaminants;
- Generation and accumulation of toxic intermediate products;
- Migration of the contaminant plume will result in additional groundwater and/or surface water pollution;
- Re-mobilisation of inorganic contaminants such as heavy metals.

Regulatory requirements

Some activities associated with MNA may themselves be subject to regulatory control. These activities include drilling and construction of monitoring boreholes and borehole pumping tests on site. In addition, monitoring boreholes may need to be installed off-site.

Also, planning controls (e.g. Town & Country Planning Act s106) may be used to enable institutional control for the monitoring process if the site is subject to planning permission and monitoring needs to be continued for many years before the standard of remediation will be achieved.

Practical operational advice on good practice management

Long term performance monitoring plans should be developed on a site specific basis where it is agreed that the identified risks will be managed by MNA. Long-term performance monitoring will be required to:

- Demonstrate NA processes are occurring as expected, and at a rate that will achieve the standard of remediation;
- Determine plume status (ie. stable, expanding or shrinking);
- Identify any changes in groundwater flow;
- Identify any toxic breakdown products due to biodegradation;
- Detect new releases of contaminants;
- Identify any changes in geochemcial and biochemical conditions that would influence MNA;
- Demonstrate that there is no impact on down-gradient receptors;
- Provide a basis for implementing a contingency plan;
- Provides a basis for ceasing MNA.

Changing site conditions can result in unpredictable plume behaviour over a period of time. To mitigate any potential problems arising due to variable plume behaviour, contingency plans should be developed as a integral part of the performance monitoring plan. The contingency plan should include:

- The basis for its implementation;
- Remedial treatment actions that will be implemented and the time-scales in which this should be done.

Technology track record

MNA is being increasingly considered as a viable remedial treatment action for managing the risks associated with contaminated groundwater in the UK. At present in the UK, it has been accepted as an agreed remediation strategy for hydrocarbon/chlorinated solvent plumes.

Potential for integration with other remedial treatment actions

MNA may be one of a number of remedial treatment actions considered within a remediation package or remediation scheme that also considers other remedial measures such as source removal using soil vapour extraction.

COSTS

Factors influencing the cost of natural attenuation

Factors that most influence the cost of this remedial treatment action are represented qualitatively below as three ticks, whilst those that least influence costs are represented as a single tick.

Cost factors	Relevance
Screening Stage (incl. desk study, site investigation)	✓✓✓
Demonstration and assessment	✓✓
Long term monitoring	✓✓✓
Process management	✓
Contingency plan	✓

Costs of implementing this remedial treatment action

Costs of implementing this remedial treatment action will vary from site to site depending upon factors such as:

- Nature of the contaminants and their respective concentrations;
- Number of wells to be monitored;
- Standard of remediation to be achieved; and
- Time-scales necessary for achieving this standard of remediation.

In determining the costs of MNA, it is worth considering the number of wells to be monitored and the sampling and analytical requirements per monitoring well. Costs vary considerably depending upon the analytical requirements, although £400-700 is estimated for sampling a monitoring well once, conducting the necessary laboratory analysis (e.g. organic contaminants, intermediate products, geochemical parameters, etc.), and then reporting the results.

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Further Information

Further details on the application of this, and other remedial treatment actions can be obtained from the National Groundwater and Contaminated Land Centre, Olton Court, Solihull B92 7HX. Tel 0121 711 5885.

Acknowledgements

The National Groundwater & Contaminated Land Centre would like to thank colleagues and remedial technology vendors for their comments when developing this data sheet.

ENVIRONMENT AGENCY

Remedial Treatment Action Data Sheet on Bioventing

Data Sheet No. DS-05

BASIC PROCESS DESCRIPTION

Bioventing processes effectively couple the principles of soil vapour extraction (SVE, DS-07) with those of bioremediation. Before being recognised as a technique in its own right, bioventing was investigated for the purpose of reducing the cost of treating vapour emissions from SVE systems. The difference between the two techniques is one of emphasis. For SVE, the aim is to optimise the removal of contaminants through volatilisation. For bioventing, the focus of the treatment is on biodegradation.

Bioventing is an *in situ* process whereby active aeration of the contaminated area within the unsaturated zone provides a means of stimulating and enhancing the biological transformation of volatile and semi-volatile organic compounds (VOCs and SVOCs). Air flow within the unsaturated zone is enhanced by air injection, air extraction or a combination of the two through a network of injection and/or extraction wells, pipes or trenches which provides an enhanced flux and distribution of oxygen rich air through the zone of contamination (Fig. 1). These enhanced levels of oxygen stimulate indigenous microbial populations to transform and biodegrade contaminants to less toxic compounds.

The main principles to consider when undertaking bioventing within the unsaturated zone include:

1. Stimulation of microbial degradative processes;
2. Chemical characteristics of the contaminants;
3. Geological conditions influencing air flow within the unsaturated zone;
4. Controlled application of bioventing; and
5. Treatment of process emissions.

1. Stimulation of microbial degradation

Bioremediation processes use naturally occurring micro-organisms (e.g. bacteria and fungi) for the elimination, attenuation or transformation of contaminating substances. During bioventing, the activities of indigenous microbial populations present in contaminated soils are stimulated and consequently *in situ* biological transformations of organic contaminants are enhanced. Biodegradation of hydrocarbons under aerobic conditions normally gives rise to an increase in microbial biomass, formation of intermediate products, carbon dioxide and water.

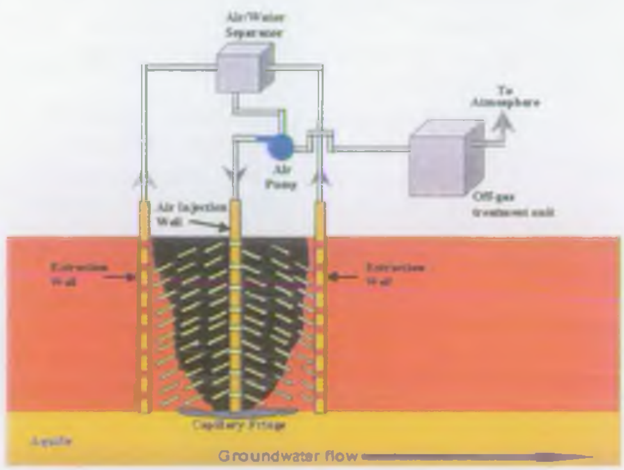

Fig.1. Schematic of a bioventing process

The key elements to consider when determining the feasibility of a bioventing operation are:

- Biodegradability of the contaminants under enhanced aerobic conditions within the unsaturated zone; and
- Biodegradation rates of the contaminants and whether they are likely to exceed the rates of volatilisation at a specified air flow.

In the event that the rate of volatilization greatly exceeds the rate of biodegradation for the identified contaminants over the operational air flow range, then bioventing will be considerably less effective than a system optimised for SVE. However, bioventing and SVE may work together for a complex mixture of contaminants (e.g. SVE being applied to highly volatile contaminants with bioventing being applied to the semi-volatile contaminants).

2. Geological conditions influencing air flow in the subsurface

In the event, that it has been established that the contaminants present are amenable to bioventing, then the geological conditions pertaining to the site are likely to be the most important site characteristic influencing successful implementation of this remedial treatment action. In particular, soils must be sufficiently permeable for effective delivery of air streams to the area of contamination. The primary physical parameters that are most likely to influence bioventing processes are:

i. Soil gas permeability which is a function of soil structure, particle size and soil moisture content. Soils must be sufficiently permeable to allow movement of the soil gas (0.25 to 0.5 pore volumes of soil gas per day) such that an adequate supply of oxygen is available to promote and enhance aerobic biodegradative processes. Typically soil gas permeability in excess of 0.1 Darcy is adequate to enable sufficient air exchange.

ii. Soil moisture content has a direct effect on soil gas permeability and the solubilisation of the contaminant and other nutrient supplies. Generally, soil moisture content should be maintained between 40-60% of field capacity throughout the treatment period. Soil moisture levels in excess of this, are likely to cause shrinkage of the pores for movement of air through the soil, and thereby decrease air permeability and flow through the unsaturated zone.

iii. Oxygen radius of influence is defined as the radius to which oxygen has to be supplied to promote and sustain aerobic biodegradation. It is a function of both airflow rate and oxygen utilisation rate, and therefore depends on site geology, well design, extraction/injection flow rates and microbial activity. This radius of influence differs to that typically used in SVE (DS-07).

iv. Depth of contamination and its heterogeneity both laterally and vertically. Generally bioventing is not suitable for treating contaminated soils within 0.6m of the ground surface due to the potential impact of VOCs migrating to the surface.

v. Fluctuating water table is likely to cause difficulties when treating significant quantities of contamination in the capillary fringe. In such circumstances, dewatering may be considered an appropriate means of enhancing aeration processes, alternatively a combination of air sparging and bioventing may be employed to treat soils in the unsaturated and saturated zones.

3. Controlled application of bioventing

Biodegradation of contaminants by indigenous microbial consortia is enhanced by optimising and controlling a number of key environmental parameters, in which oxygen levels, are the most critical. Other environmental parameters important to process performance include; nutrient levels, pH and temperature.

Oxygen is the terminal electron acceptor during aerobic biodegradation, and for many contaminants in soil (e.g. petroleum hydrocarbons) it has been found to be the rate limiting parameter. It is therefore crucial that aeration of the unsaturated zone is sufficient to enhance microbial degradation, but low enough to minimise volatilisation of volatile organic compounds (e.g. BTEX).

Aeration of the unsaturated zone may be accomplished through air injection, air extraction or a combination of the two. Typically, most bioventing systems are operated using a combination of air injection and air extraction systems (Fig. 1). However, the extraction rates are normally much lower than those used in SVE systems.

Organic contaminants (e.g. toluene) and natural organic compounds in soils typically provide an adequate supply of carbon for indigenous microbial populations. However, the availability of inorganic nutrients such as nitrogen and potassium may be insufficient for optimum treatment. Requirements for additional nutrients should be evaluated through treatability studies. Typically soils may be amended with nutrients in a granulated or dissolved form.

4. Treatment of process emissions

Volatile organic emissions present a potential risk to human receptors in buildings located within the radius of influence. In general, the optimal air input within the contaminated area, is equivalent to the minimum extraction rate that satisfies the oxygen demand to support enhanced *in situ* bioremediation.

Bioventing systems configured to extract air from the zone of contamination should be designed to include an off-gas treatment system. Extracted air streams are passed through an air/ water separator, that needs to be periodically drained, and the collected condensate treated. Downstream from the air/ water separator, off-gases (e.g. VOCs) should be monitored prior to, and after passing through the off-gas treatment system (e.g. activated carbon filters).

EFFECTIVENESS OF BIOVENTING

Contaminant types

Bioventing processes are reported to have been effective for treating soils contaminated with one or more of the following contaminants:

- BTEX;
- Phenols;
- Petroleum hydrocarbons (e.g. diesels, light lubricating oils, crude oil);
- Chlorinated solvents (e.g. TCE, DCE, TCA);
- Polyaromatic hydrocarbons (e.g. lower ringed aromatic compounds such as napthalene and phenanthrene).

Microbial degradation of hydrocarbons varies with molecular weight and structure. Biodegradation rates are generally highest for saturates (e.g. alkanes) followed by monoaromatic (e.g. BTEX, phenols) and the lighter polyaromatic hydrocarbons (e.g. 2, 3 and 4 ringed PAHs). In practical terms this means that during bioventing, low vapour pressure compounds (<1mm Hg, e.g. phenanthrene) need not biodegrade as rapidly as high vapour compounds (>760mm Hg – e.g. butane) for the treatment to be successful. Bioventing is less suitable for treating high molecular weight PAHs (e.g. 5 or 6 ringed aromatic compounds).

Contaminant chemical properties

Chemical properties of contaminants that should be considered when determining the suitability of this remedial treatment action include:

- Contaminants with vapour pressures in the range of 1 - 760 mmHg may be amenable to volatilization (e.g. benzene, xylene, octane). Generally highly volatile compounds (e.g. butane, propylene) are gaseous at ambient temperatures and volatilise for effective treatment. Typically these compounds constitute only a small fraction in any mixture of petroleum hydrocarbons. Compounds with low vapour pressures (e.g. phenanthrene) tend to be non-volatile but are biodegradable;

- Soluble contaminants are more effectively biodegradable than those volatilised in the air stream or those adsorbed onto the surface of soil particles;

- The nature of contaminants and their respective concentrations will vary considerably from site to site. The effectiveness of this remedial treatment action should be demonstrated for the contaminated soils on a site specific basis through treatability studies prior to implementation; and

- Presence of toxicants (e.g. heavy metals, cyanides or organic contaminants (e.g. free product) may inhibit microbial degradation.

Site conditions that influence effectiveness

The following site conditions should be considered:

- Site geology and soil gas permeability. Clay soils with low permeability are not amenable to bioventing;

- Location of the contaminated area within the unsaturated zone. Bioventing is not suitable for treating contaminated areas soils less than 0.6m from the surface;

- Heterogeneity of the contaminated area;

- Oxygen radius of influence within the contaminated area, and consequently the number and spacing of air injection wells;

- Suitable environmental conditions on site:
  - temperature on site during treatment should ideally be in the range of 10-25°C;
  - soil pH typically in the range of 6 to 8; and
  - depending upon the site geology and the size of the contaminated area, covers may be needed during periods of heavy rainfall.

Treatability studies for determining site specific effectiveness

Treatability studies may be required for collecting information prior to selecting this remedial treatment action for the identified SPL(s). They are effective in collecting information on the biodegradative activities of indigenous microbial populations and for configuring and designing an effective bioventing treatment that can achieve the necessary standard of remediation. Such treatability studies should involve field testing and/or pilot studies.

The most important parameter in bioventing systems that influence its design is the radius of influence of oxygen (ROI) within the contaminated area (min. concentration of 5% O_2). The objective of field testing (approx. 20m x 20m) and/or pilot studies on site should be to:

- Determine the ROI; and
- Determine the biodegradative rates of the identified contaminants as estimated from the rate of oxygen decay.

In addition, pilot studies on site may be necessary for optimising the injection/extraction rates such that a suitable network of injection wells within the contaminated area can be designed and installed.

Time-scales to achieve effective remediation

Time-scales for achieving the standard of remediation will vary greatly depending on a range of factors including; the nature of the contaminants and their respective concentration, soil type, volume of material to be treated and the standard of remediation to be achieved. However, some indicative time-scales are provide below:

Time factors	Typical time-scales
Regulatory permits / consents	≤ 3 months
Treatability Studies (pilot test)	1-4 weeks
Site visit and design full-scale remedial treatment action	1-4 weeks
Drilling and installation of injection/extraction/monitoring wells	1-4 weeks
Process Operation	12 – 30 months
Process Monitoring	12 – 30 months

Factors influencing time-scales for achieving effective remediation

The effectiveness of this remedial treatment action is dependent largely on:

- Type of contaminants and their respective concentration;
- Soil Type;
- Soil conditions (e.g. soil gas permeability, heterogeneity of contamination, etc.);
- Biodegradative activities of indigenous microbial communities to degrade contaminants under aerobic conditions;
- Environmental conditions that prevail within the contaminated area (e.g. oxygen levels, moisture levels, pH, temperature);
- Presence of toxic inhibitors (e.g. heavy metals); and
- Climatic factors (e.g. level of rainfall and impact on the water table).

DURABILITY OF BIOVENTING

Bioventing contaminated soils within the unsaturated zone can be effective in breaking the significant pollutant linkage (SPL) by source treatment such that the level of contamination is no longer significant.

Characteristics for long term performance

Time-scales for completing this remedial treatment action generally range from 1-2 years, and during this period, an appropriate monitoring programme should be in place to ensure that the performance of the remediation is maintained over the required time-scale.

Monitoring data collected during remediation will demonstrate the progress of this treatment and the final compliance with the standard of remediation. However, compliance with the standard of remediation should be based on the statistical validation of the analytical data collected (e.g. reduction of contaminant mass, rates of O_2 decay, etc.). This data should continue to be collected until the standard of remediation for the soil has been verified over a specified period of time, that is, after achieving the standard of remediation, treatment may be continued for a period to ensure that this is indeed so.

Verification of this remedial treatment action should be in accordance with appropriate Agency guidance.

PRACTICABILITY

Practical constraints

In determining the practicability of implementing this remedial treatment action, consideration should be given to the factors listed below:

Practical constraint	Explanation
Space requirements	Identify the likely configuration (incl. nos. of wells/compressors, off gas treatment system) of the bioventing treatment
Location	Not suitable for areas prone to flooding or areas with a high water table.
Above ground structures	May influence the location of the off-gas treatment unit, wells and other above ground pipe work
Below ground structures	May influence the location of injection/extraction/monitoring wells
Access	Access to injection/extraction /monitoring wells and the off-gas treatment unit for maintenance
Provision of utilities	Identify those utilities (e.g. water supply and electricity) essential during remediation.
Site security	Prevent public access to the treatment equipment located above ground.

Wider environmental impacts of remediation

The potential for uncontrolled emissions (e.g. VOCs) arising during installation of the underground structures (e.g. injection wells), or during its operation needs to be considered on a site specific basis taking into account the nature of contamination and conditions of the site. Potential adverse environmental impacts that may arise during this remedial treatment action include:

- Emission of VOCs during installation and remediation;
- Emission of VOCs due to ineffective off-gas treatment systems;
- Enhanced mobilisation of contaminants during installation of injection/extraction wells and monitoring wells;
- Leakage or accidental release of concentrated nutrient solutions (e.g. conc. nitrate solutions);
- Accumulation of contaminated leachate in the air/water separator;
- Generation of dusts during excavation of holes for installing wells;
- Contaminants identified earlier in this data sheet are unlikely to generate any toxic intermediates under aerobic conditions in the unsaturated zone. However, contaminated soils containing additional contaminants such as chlorinated solvents (e.g. PCE, TCE) may generate toxic intermediates where anaerobic conditions are present; and
- Further migration of contamination within the sub-surface.

Regulatory requirements

Treatment of contaminated soils by bioventing will normally need to be licensed under Part II of the Environmental Protection Act 1990 (EPA 1990).

Bioventing is regulated through the use of Mobile Plant Licences (MPL). The legislation (Waste Management Licensing Regulations 1994) requires such licences to be issued to the operators of the remedial process. Licensed processes can be moved from one site to another, but in doing so, the operator needs to agree a new site-specific working plan for each site. The working plan should ensure that an appropriate level of environmental control is in place given the circumstances of the site.

Further information on the regulation of remediation technologies under Part IIA of EPA 1990 is provided in: *Guidance on the Application of Waste Management Licensing to Remediation (Environment Agency, 2001).*

Excavation of pipe trenches may be subject to the Construction (Design and Management) Regulations 1994 (CDM), depending on the duration of the excavation works and the number of people involved.

In addition, bioventing operations may also require:

- Discharge consent for discharges to controlled waters;
- Authorisation under the Groundwater Regulations for discharge into or onto the land;
- Abstraction licence for abstraction of controlled waters (e.g. groundwater); and /or
- Trade effluent consent for discharge to sewer.

Finally, all other relevant regulatory bodies relevant to this particular remedial treatment action should be contacted (e.g. the local Petroleum Officer where a bioventing system is installed at a petrol station). Such requirements should be determined on a site-specific basis.

Practical operational advice on good practice management

Performance of bioventing systems should be monitored on a regular basis for the purpose of evaluating the ability of this remedial treatment action to achieve the standard of remediation within the given time-scale. During remediation this can be evaluated by monitoring:

1. Operational parameters such as injection/extraction flow rates;

2. Radius of influence of oxygen such that it is sufficient for treating the contaminated area;

3. Reduction of contaminant mass in the unsaturated zone, and its mass balance during remediation;

4. *In situ* oxygen decay rates as an indicator of *in situ* biodegradation;

5. Environmental parameters in the unsaturated zone (e.g. dissolved oxygen levels, soil moisture, nutrient levels, temperature, pH, etc.) necessary for effective degradation of the contaminants; and

6. Maintenance requirements during treatment (e.g. soil moisture levels, air pumps, vacuum extraction pumps, etc.).

Technology track record

Remediation of contaminated soils using bioventing has been practised in the UK in recent years. It has been used largely for treating small areas of contamination in the vicinity of petroleum distribution forecourts.

Potential for integration with other remedial treatment actions

Bioventing may be one of a number of remedial treatment actions within a remediation package or remediation scheme with the purpose of:

- Treating the source of contamination; or
- Treating the source in combination with other remedial measures for controlled waters.

For example, it may be that identified hot spots are excavated and disposed at a licensed landfill, while less contaminated material is treated *in situ* by bioventing. Alternatively, bioventing may be used to treat petroleum contaminated soils in combination with air sparging within the saturated zone.

COSTS

Factors that influence cost of remediation

Factors that most influence the cost of remediation are represented qualitatively below as three ticks, whilst those that least influence costs are represented as a single tick.

Cost Factors	Relevance
Regulatory licence (MPL)	✓
Treatability studies	✓✓
Site visit and design of full-scale treatment	✓
Drilling / Sampling	✓✓
Installation / Commissioning	✓✓
Operational costs	✓
Monitoring and analysis	✓✓✓
Process validation	✓✓
Decommissioning	✓
Process management	✓

Costs of implementing this remedial treatment action

Costs of implementing this remedial treatment action will vary from site to site depending upon factors such as:

- Nature of the contaminants and their respective concentrations;
- Soil type;
- Area of contamination to be treated;
- Standard of remediation to be achieved; and
- Time-scales necessary for achieving the standard of remediation.

Indicative treatment costs range from £10-50/m^3 with the costs per metre being highest for small sites.

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Further Information

Further details on the application of this, and other remedial treatment actions can be obtained from the National Groundwater and Contaminated Land Centre, Olton Court, Solihull B92 7HX. Tel 0121 711 5885.

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