CIRIA W18 London, 2004

SAFEGROUNDS
Technical options for managing contaminated land

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Keywords

Contaminated land, environmental good practice, ground improvement, ground investigation and characterisation, health and safety, *in situ* testing and instrumentation, nuclear, site management, sustainable construction

Reader interest	**Classification**	
This guidance has been developed primarily for site owners, site operators and their contractors. It is also addressed to governmental and non-governmental organisations and other groups within the public	AVAILABILITY	Unrestricted
	CONTENT	Information paper
	STATUS	Author's review
	USER	Site owners, site operators, contractors, governmental departments, local authorities, regulators, NGOs and other groups within the public

Version control	
Document title:	SAFEGROUNDS *Technical Options for Managing Contaminated Land*
Version and date:	Version 2, April 2004
Primary author:	Hugh Mallett, Enviros Consulting Limited
Prepared for:	SAFEGROUNDS Learning Network
History:	Replaces Version 1, October 2002 The front pages were reformatted in February 2007 for consistency across the SAFEGROUNDS documents
Status:	Information paper in support of the SAFEGROUNDS Learning Network This is a live document, subject to revision. Freely available web publication

Published by CIRIA, Classic House, 174–180 Old Street, London EC1V 9BP, UK.

Contents

1 Introduction

This SAFEGROUNDS paper presents a summary of information about the technical options for managing contaminated land. The information is presented for both non-radioactive (Chapter 3) and radioactive contamination (Chapter 4). There is more experience for non-radioactive contamination so that section of the paper is longer. Options for the remediation of groundwater and soil-gas are described in Chapters 5 and 6 respectively.

The bibliography contains a number of web sites which summarise the various technologies and provide hyperlinks to sites with more information regarding each technology. Reference to some of the more informative pages is included in the sections on the individual technologies.

2 Categories of options

For the purposes of description, the technical options for managing contaminated land and contaminated water (both non-radioactive and radioactive) can be grouped into three main categories:

- partial or complete removal or destruction of the contamination
- immobilisation or stabilisation of the contamination
- isolation and containment of the contaminated ground.

These categories can be further sub divided into *in situ* and *ex situ* techniques. The following text briefly described each of the available options in turn. References are given as appropriate from which further more detailed information on each of the various options can be obtained.

The table overleaf summarises the main *in situ* and *ex situ* remedial techniques (sub divided into physical, chemical, biological and thermal techniques) and their suitability for different categories of contaminants. A more comprehensive listing is available on <www.frtr.gov/matrix2/section3/matrix.html> (although this reports US experience and may therefore report techniques which may not have been utilised in the UK or Europe).

Summary of remedial techniques and their applicability

Category	*In situ* techniques	Heavy metals	Organics	Radiological	*Ex situ* techniques	Heavy metals	Organics	Radiological
Physical	Electroremediation	M	M	E/M	Excavation and disposal	C	C	C
	Capping	C	C	M	Soil washing	C	C	E
	Barrier	C	C	M	Electroremediation	E	E	E/M
	Hydraulic containment	M	M	M	Soil vapour extraction	NA	C	NA
	Detector based segregation	NA	NA	C				
	Soil vapour/dual phase extraction	NA	C	NA				
Chemical	Soil flushing by chemical leaching	C	C	M	Soil washing by chemical treatment	C	C	E
	Solidification/ stabilisation	C	C	C	Chemical Treatment	C	C	E.M
	Surface amendment	M	M	M	Solidification/stabilisation	C	C	E/M
					Surface amendment	M	M	M
Biological	Phytoremediation	E	E	E/M	Bioremediation	NA	C	NA
	Monitored natural attenuation	C	C	M				
	Bioremediation	NA	C	NA				
Thermal	Vitrification	M	M	NA	Incineration/thermal desorption	C	C	NA
					Vitrification	M	M	E

Key

C Commonly used, well developed technology, effective

M Maybe suitable either in conjunction with the techniques, and/or following detailed consideration of site-specific characteristics

E Experimental/pilot scale

NA Not Applicable

Gases are not included in this table but are discussed in Chapter 6.

3 Options for non-radioactive contamination (soils)

3.1 *In situ* partial or complete removal or destruction of the contamination

3.1.1 *In situ* electroremediation

Electroremediation involves passing an electrical current through the contaminated material to remove the contaminants. A combination of electrokinetic and electrochemical processes result in the movement of contaminants to the electrodes. The contaminants contained in the soil are then removed from the electrodes for subsequent removal. This method is particularly suitable for inorganic contaminants and low concentrations of organic compounds. It is usually undertaken *in situ*, but its applicability for *ex situ* use is currently being investigated.

The advantages of this technique are that it reduces large quantity of contaminated material to small amounts that are capable of treatment. Finally contamination will also be removed from site. The disadvantages are that typically the technique requires substantial borehole construction when it is used *in situ* and to date it has not been demonstrated to be feasible on a large scale. There are currently no costs available for the field scale use of the technique. Timeframes are likely to involve medium term strategies and depend on the volume of material requiring treatment.

3.1.2 *In situ* phytoremediation

Phytoremediation involves the use of plants that accumulate contaminants. It can use metal accumulating species to decontaminate heavy metal contaminated soils. The plant type can be selected specific to the type of contaminant. More then one crop can be grown per annum. It is a low capital cost technique which produces no process residues. The treatment timescale can be relatively long-term and the process generates large volumes of secondary waste (contaminated vegetative matter). It has been successfully demonstrated at pilot scale but has not yet demonstrated on large scale. Costs are not currently available although projected costs are claimed to indicate cost savings over other techniques.

3.1.3 Monitored natural attenuation

Naturally occurring processes may act to reduce the concentration and environmental load of a pollutant. Physical, chemical and biological processes may act to restrict the movement of, disperse or degrade contaminants. For soils, examples of natural attenuation include volatilisation where compounds such as chlorinated solvents slowly vaporise, and the resulting concentration in the soil is reduced. Biodegradation occurs where organic compounds such as petroleum hydrocarbons are slowly degraded by organisms present in the soil mass. Monitored natural attenuation may be a viable remedial option for some sites, where the current risks from contamination are very low, and the pollutant linkages are unlikely to change.

If natural attenuation is selected as a remedial strategy then it will be necessary to demonstrate by monitoring that reductions of concentrations are occurring over time. This process is of low capital cost and does not disturb (and/ or mobilise) the contaminant source. However, the technique does not address any immediate or short term risks and should be considered on a long-term strategy. The requirements for monitoring are likely to be intensive. It is also important to note that degradation of a contaminant can produce more toxic by-products. The costs of monitoring typically range from £2–20k per borehole.

3.1.4 *In situ* bioremediation

Biological treatment methods rely on the natural metabolic processes of living organisms (eg bacteria, fungi and higher plants) to destroy contaminants or convert them to a less toxic or less available form. The processes usually involve metabolisation of carbon-bearing substrates by organisms to generate energy for growth and reproduction. Most biological treatments rely on respiration pathways and are therefore most useful for the treatment of organic contaminants. However, some species are capable of removing inorganic compounds from the soil or making them less available/mobile. Bioremediation is commonly more effective for water-soluble contaminants since most biological activity (but not all) takes place in this phase. For near surface soils, inorganic nutrients (such as nitrogen or phosphate) and/or organic materials (such as manure) are added to the soils. When the soils requiring treatment are at depth, the nutrients and other biological additives are allowed to percolate through the contaminated area using a water recirculation system (*in situ* soil flushing). *In situ* bioremediation techniques are suitable for many organic contaminants, but heavier weight organics such as larger PAHs, are more difficult to treat.

Bioremediation can be very effective provided conditions are optimised. Apart from not being able to create optimum conditions, other limitations to bioremediation include the production of intermediate products which may be more toxic, long timescales and difficulties in achieving stringent concentrations in soil. The advantages of the technique are that the technology is commercially available and has been used successfully on a number of sites in the UK. The cost of biological treatment is generally lower than other treatment methods and many biological treatment techniques do not give rise to process residues requiring further treatment or disposal. However, the effectiveness of *in situ* biological treatment is very dependent on the physical, chemical and biological properties of the material being treated. Space will be required for on-site treatment beds and in some conditions, achieving acceptable residual contamination levels can be difficult, although removal efficiencies of 95-98% have been recorded in some US trials. *In situ* bioremedation techniques typically costs between £5–170 per tonne.

3.1.5 Soil flushing by chemical leaching (*in situ* soil washing)

Soil flushing is a process which adds chemicals to the soil to transfer the contaminants to water . This water is then treated. This technique can transfer difficult material to a form more amenable to treatment. The disadvantage of the technique is that it requires the input of a chemical reagent which can be both expensive and hazardous. Successful implementation of the technique is usually difficult with mixed contamination and its effectiveness can be limited by high concentrations of contaminants in the soil. In addition, post treatment processing may be required. The products of treatment can be phytotoxic thus sterilising soils. Timeframes are likely to involve medium term strategies and depend on the volume of material requiring treatment. Typically, costs range from £25–85/t.

3.1.6 *In situ* physical treatment – soil vapour/free phase extraction

Soil vapour extraction (SVE) involves the use of vacuum wells used to draw air slowly through soil for separation and treatment of volatile contaminants. Dual phase extraction comprises the extraction of both free phase (LNAPL) and vapour by means of vacuum wells, for subsequent treatment. These techniques reduce a large quantity of contaminated material to small amounts capable of treatment.

The advantages of these extraction processes are that they remove contamination from site and they are capable of treating mixed organic contaminants. Disadvantages are that waste streams normally require additional treatment. Silt/clay size materials are difficult to treat and some treatment techniques render soils unsuitable for future use. Timeframes are likely to involve medium term strategies and depend on the volume of material requiring treatment. Costs of SVE are in the range £5–50/t. Costs of Dual Phase extraction systems typically lie in the range £400–£1000/bh.

3.2 *Ex situ* partial or complete removal or destruction of the contamination

3.2.1 Excavation and disposal

Following excavation of the contaminated material, a suitable disposal route needs to be identified. The three main options are off-site disposal; on-site disposal; or processing of the material to allow re-use or to reduce disposal requirements. It may also be feasible to combine excavation with disposal of the material on-site. Some of the technical aspects of on-site disposal options are also common to other engineering methods, for example, if the contaminated material is placed in a containment structure.

One advantage of excavation and removal is that it effectively removes the source of many environmental risks from the site once the remediation is successfully completed. Removal and re-deposition on-site transfers the contamination to an area of the site where the risks can be controlled and managed through the creation of a purpose-built disposal or containment facility. The technique is suitable for a wide range of contaminants and also on sites where there are different types of contamination. Excavation and removal can be undertaken over a relatively short timescale and in cases when there are physical constraints preventing other options.

The limitations of the technique are that the contaminated area needs to be adequately defined to ensure all contaminated material is removed and operational structures or services may constrain excavations. Some contaminants may be inaccessible because they are out of reach of excavation plant or beneath immovable structures. Excavation and disposal does not treat contaminated material, ie does not involve the destruction or transformation of contaminants into a less hazardous form. Transport movements may be onerous and problems may arise if groundwater is encountered

For off-site disposal, a disposal facility with an appropriate licence (ie that will accept the contamination) must be accessible from the site and material must be disposed of in accordance with Duty of Care Regulations. For on-site disposal there are increased regulatory requirements including the need for planning permission and a Waste Management Licence. As part of the licence application, a “competent person” will need to be identified, and restoration, monitoring and aftercare requirements defined for on-going arrangements once the facility is constructed. Financial provisions for this will need to be made at the time of application.

The costs associated with disposing of contaminated material, if a suitable licensed facility can be found, vary from about £20 per tonne to about £50 per tonne depending on the contaminant concentrations, plus excavation costs which are commonly up to £5 per tonne and transport costs. Typically transport can cost £1 per tonne per mile and can therefore be a substantial cost element of any disposal scheme if an appropriately licensed landfill is not located in the vicinity of the site. In addition, it will be necessary to pay Landfill Tax, which is currently £15 per tonne for contaminated material and which will increase. Landfill Tax exemption may be granted by Customs & Excise for some sites.

3.2.2 *Ex situ* soil washing by particle separation

Soil washing is a volume reduction/waste minimisation process in which the particles which contain the contamination are removed from the remaining relatively clean soil. To be economic the "clean" fraction should be the bulk of the soil, which can then be used as fill material from excavation. The relatively small proportion of contaminated soil separated during washing can be either disposed to an appropriate hazardous waste facility or further treated (at a considerably lesser volume than the original soil). Cost effectiveness is achieved by being able to significantly offset the cost of soil washing treatment and limited disposal against the disposal of the whole soil. An advantage of this technique is that it can treat mixed organic/ inorganic contaminants. However, waste streams normally require additional treatment and silt/clay materials are more difficult to treat. Some treatment techniques render soils unsuitable for future use. This is a Relatively short timeframe option. Typical costs of this technique are £20–160/t.

3.2.3 *Ex situ* soil washing by chemical treatement

Soil washing by chemical treatment is a process which adds chemicals to excavated soil to transfer the contaminants to a leachate. This leachate is then treated. This technique can transfer difficult material to a form more amenable to treatment. It can result in the contamination being destroyed and for some contaminants (eg dioxins/ PCBs) it is one of the very few viable methods for removal/ treatment. The disadvantage of the technique is that it requires the input of a chemical reagent which can be both expensive and hazardous. Successful implementation of the technique is usually difficult with mixed contamination. Its effectiveness can be limited by high concentrations of contaminants in the soil. Post treatment processing may be required. The products of treatment can be phytotoxic thus sterilising soils. It is typically a long-term strategy. Typically, costs range from £25–85/t.

3.2.4 *Ex situ* bioremediation

The general principles of bio remediation are as described above for which there are a number of specific techniques.

(i) The construction of bio-piles involves the excavation of soils and the introduction of nutrients, moisture and aeration via pipework to promote bio-degradation. Costs are typically £10–65/t.

(ii) Land farming comprises the excavation and spreading of the contaminated soils in a thin layer, which is then ploughed and tilled to improve aeration. Costs are typically £10–100/t.

(iii) Windrow turning involves the excavation of the contaminated soils which are then formed into windrows of between 1m to 2m in height which are turned over using agricultural machinery. Costs are typically £15–50/t.

(iv) Bio remediation in the slurry phase involves mixing of the contaminated soils with water to a slurry, to which nutrients and/or oxygen is added (with pH control) followed by dewatering. Costs are typically £50–80/t.

Generally these techniques have a beneficial effect on the soil structure (not slurry treatment) and are suitable for organic and cyanide contamination in granular soils. The technology is available and can be cost efficient although it is not effective for some contaminants (eg metals) or with clay/silt soils where there is a high groundwater table. Some of the techniques require large process areas and long time periods to achieve acceptable concentrations.

3.2.5 *Ex situ* chemical treatment

Three main techniques fall under this category all of which transfer difficult material to a form that is more amenable to treatment:

1. Chemical dehalogenation comprises adding a chemical reagent to the contaminated soils to split off the chlorine/fluorine from the halogenated molecule to a less toxic form. Costs typically range from £150–430/t.
2. Solvent extraction involves that additions of a solvent to transfer soil contaminant to a fluid for further processing/ disposal. Costs typically range from £75–600/t.
3. Physico-chemical washing mobilises soil contaminants into an aqueous solution for treatment /disposal. Costs typically range from £54–170/t.

For some contaminants (eg dioxins/ PCBs) it is one of the very few viable methods for destruction. The techniques require the input of chemical reagents, which can be expensive and hazardous and difficulties can be encountered with mixed contamination. The effectiveness of chemical treatment techniques can be limited by high concentrations and post treatment processing may be required. The products of treatment can be phytotoxic thus sterilising soils. It is typically a long-term strategy.

3.2.6 *Ex situ* soil vapour extraction

Ex situ soil vapour extraction (SVE) involves the excavation of soil which is then placed over a network of above ground piping to which a vacuum is applied to encourage volatilisation of organics. Soil piles are generally covered with a geomembrane to prevent volatile emissions and to prevent the soil from becoming saturated by rain. The process includes a system for handling off-gases. Advantages over its *in situ* counterpart include that the excavation process forms an increased number of passageways, shallow ground water no longer limits the process, leachate collection is possible, and treatment is more uniform and easily monitored. The major disadvantage over *in situ* SVE is the excavation cost. The length of operations and maintenance for *ex situ* SVE process is medium- to long-term.

Disadvantages of the process include: the potential for air emissions possibly requiring treatment; volatilisation is inhibited by high moisture content, high humic content, or dense soil; residual liquid/ spent activated carbon will require treatment and a large amount of space is required. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

Cost for *ex situ* SVE is under $110/t, including the cost of excavation but excluding treatment of off-gases and collected ground water.

3.2.7 *Ex situ* incineration/thermal desorption

Remediation by incineration involves the destruction of contaminants by thermal oxidation at very high temperature. Thermal desorption is the transfer of contaminants to a vapour phase by volatilisation and treatment or destruction of off-gases. Following volatilisation the contaminants can be condensed for further treatment (in concentrated form) or the off-gases can be treated to destroy the contaminants. The advantages of these thermal techniques are that contaminants are removed from soil relatively quickly and destroyed. They are one of the few feasible disposal routes for some contaminants (eg explosives). The disadvantages are that incineration involves a high energy input. The techniques are difficult with clay soils. Emission control procedures are required and there is a risk of explosion with some contaminants. Acidic soils can corrode plant and the process destroys the soil structure. There is also a public concern with incineration technology. Costs of incineration technologies range from £150–£750/t. Thermal desorption costs typically range from £30–£225/t.

3.2.8 *Ex situ* electro remediation

Electro remediation is the process in which contaminants are desorbed from an excavated soil and migrate to electrodes, where they are removed. The process reduces large quantities of contaminated material to small amounts capable of treatment and contamination is removed from site. Considered to be a medium term strategy. The technique has not been demonstrated to be feasible on large scale. No costs are currently available.

3.3 *In situ/ex situ* immobilisation or stabilisation

3.3.1 Solidification/stabilisation

Cement stabilisation involves the mixing of soils with cement *in situ* by means of mixing blades with the injection of a solidification agent. The process can also take place *ex situ* by excavating and mixing soil with a stabilising agent either in plant (eg concrete mixer) or by being spread on the ground in layers. The processes are applicable to a wide range of mixed contaminants in a range of soils. It can transfer difficult materials to a more manageable form. Disadvantages of the process are that it can result in an increase in the volume for treatment. Its effectiveness depends on good mixing, relatively quick technique. Organic contaminants can be problematic in a cement system. Costs range from £17–£85/t.

3.3.2 Surface amendment to stabilise (immobilise) contaminants

The addition of chemical to soils to stabilise contaminants can transfer difficult material to a form more amenable to treatment. The process requires the input of a chemical reagent which in itself can be can be expensive and hazardous. The process can be difficult with mixed contamination and its effectiveness and Timeframe can be limited by high concentrations. Post treatment processing may be required and the products of treatment can be phytotoxic thus sterilising soils. Costs typically range from £12–£35/t.

3.3.3 Vitrification

Vitrification involves the application of very high temperatures to melt contaminated soils to form a glassy product. This results in the immobilisation of the contaminant within a glassy matrix. Organic contaminants are volatilised or destroyed by pyrolysis. The process is applicable to a wide range of mixed contaminants in range of soils. It can transfer difficult materials to more manageable form and forms a very immobile residual product. Operational problems have been reported and no full field implementation has been achieved. Off gases may be created. Costs in the US are quoted as approximately $330–$440/tonne inclusive of all labour, materials, energy, plant and contractor profit.

3.4 *In situ* isolation and containment of the contaminated ground

3.4.1 Capping

Containment Cover and barrier systems are constructed to encapsulate contamination. Cover systems comprises one or more layers of inert material to prevent the potential for contact by people/fauna/buildings and structures with the underlying contamination. The infiltration of rainfall is inhibited (by low permeability capping systems, which then also retards the lateral and/ or downward migration of any contamination. The technique is applicable to a wide range of soil types/sites and has the advantage that it minimises/avoids disturbance of the contaminant source. The engineering is well understood, straightforward and available and can deal with very large contaminant volume in relatively short time frame. The principle disadvantage is that the contamination is not removed. The long-term performance of such capping systems is unproven) and monitoring may be required. Future uses of the land may be constrained by such cover systems. Costs typically range from £15-30/m^2.

3.4.2 Vertical and horizontal in-ground barriers

Vertical barriers can also be placed around contaminated material to prevent lateral migration. The barriers can be classified as either displacement barriers (eg sheet piling), excavated systems (eg concrete diaphragm walls or jet grouting) or injection systems (eg chemical or jet grouting).

Horizontal barriers comprise barriers installed beneath contaminated material to prevent downward migration of contaminated solids and liquids. The barriers can be formed from natural low permeability layers (such as clay), through jet grouting (formation of a void space, followed by infilling with cement-bentonite) or through other grouting techniques. They may also include synthetic membranes or natural materials used as liners. Encapsulation comprises a combination of a cover system vertical barriers and a horizontal barrier in such a way that the contaminated material is encased.

Active containment is a special case which aims to treat migrating contaminants, usually dissolved in the groundwater or vapour phase. The barrier in such an active system is “reactive” in that it treats/ removes the contaminant as it passes through the barrier. This can address some of the perceived limitations of passive containment measures, such as doubts around the long-term integrity of barriers, and the lack of treatment of contamination by passive barrier systems.

The advantages of such systems are that they can be widely applied to different contaminants and they do not disturb the contamination source. This can be an important issue for surface water/groundwater protection. For some sites, containment may be the only option (eg for very large volumes of contamination or if contamination is beneath buildings which are to remain).

The limitations of these techniques are that normally the contamination is not removed (except for active barriers). Cover systems when used in isolation may be ineffective at controlling the lateral migration of contaminants. Soils containing viscous materials such as tars or oils present specific problems for cover systems since under high loading pressures (such as the movement of heavy vehicles across the surface), tars may be forced upwards into the cover layer, thereby significantly reducing the effectiveness of the cover system. Long-term monitoring and maintenance of the systems (which can be relatively quick to install) are likely to be required to ensure the on-going effectiveness of this solution. In addition, a Waste Management Licence and planning permission may be required and future change in use may be constrained.

The cost of vertical barriers varies widely depending on the techniques used. Approximate vertical barrier costs are £80/m^2 for sheet piling, £200–300/m^2 for concrete diaphragm walls, £280/m^3 for jet grouting and £250-300/m^3 for chemical grouting. Horizontal barrier costs are difficult to predict due to the substantial variation in site conditions, but indicative costs for jet grouting as a basal seal are £400–500/m^2 and for soil mixing £200–250/m^2.

3.4.3 Hydraulic containment

Hydraulic measures can be used in isolation or in conjunction with other measures for source control/treatment specifically to address contaminants in the liquid phase. These techniques are described in Section 4.5.1 of this appendix.

4 Options for radioactive contamination (soils)

4.1 *In situ* partial or complete removal of the contamination

4.1.1 Electroremediation

In situ or *ex situ* process in which contaminants are desorbed from soil and migrate to electrodes where they are removed. The process reduces large quantity of contaminated material to small amounts capable of treatment. It removes contamination from site. Waste streams normally require additional treatment and intermediate level waste can be created which cannot be disposed of. Some treatment techniques render soils unsuitable for future use. It is reported to be most effective in clays, because of the negative surface charge of clay particles, and where moisture content is between 14–18 per cent. It requires substantial borehole construction when used *in situ*. The technique is not suitable for all radionuclides and has not been demonstrated to be feasible on a large scale. Timeframes are likely to involve medium term strategies and depend on the volume of material requiring treatment. Costs are in the range of £20–£170/t, plus waste treatment and storage/disposal costs.

4.1.2 Phytoremediation

Phytoremediation involves the use of plants that accumulate radionuclides. The process is of low capital cost and there are no process residues. The timescale for treatment can be prolonged and the technique may generate large volumes of secondary waste (contaminated vegetative matter). There is a potential for radioactively contaminated pollen/seeds to migrate off-site. It has not been demonstrated on large scale and costs are not currently available.

4.1.3 Monitored natural attenuation

This technique involves utilising and monitoring natural radioactive decay. It is of low capital cost and does not disturb (mobilise) contaminant source. However, it does not address immediate/ short term risks. Monitoring is likely to be intensive and the success of the technique is dependant on the area and depth of contamination and the particular radioactive isotope concerned.

4.1.4 Cryogenic barriers

This technique involves the formation of a frozen barrier encapsulting the contaminated material. The technique reduces the mobility of contaminants by confining materials and reducing groundwater flow through contamination. Effective delineation of the contaminated area is required. Sound understanding of hydrogeology and soil properties is essential to ensure optimum freezing of the contaminated area. Disadvantages of the technique are in the precision required to establish the underground freezing network and the on going requirement for refrigeration. High level radioactive waste can require higher energy consumption for on-going refrigeration. Monitoring can be undertaken at ground level and within the frozen mass using readily available methods and technologies.

4.2 *Ex situ* partial or complete removal of the contamination

4.2.1 Excavation and disposal

This option comprises the excavation of contaminated soils and their subsequent disposal to landfill or Drigg, or their transport to passively safe storage on a nuclear licensed site. In-filling of the void by clean inert fill then takes place as required. The technique is applicable to a wide variety of soil types and/ or mixed contaminants and can be undertaken relatively quickly. The distinct advantage of this solution is the certainty of the creation of an uncontaminated site if all the contaminants are removed. The works are often straightforward and utilise readily available engineering. The definition of the contaminated area is required prior to excavation. The availability of a disposal or storage facility can limit applicability and Regulatory approval can be difficult/ time consuming to obtain. If segregation is too efficient intermediate level waste level waste can be created which cannot be disposed of. There is often a coincidental environmental impact (transport/noise/dust etc).

Costs associated with excavation and disposal of radioactive materials are very much dependent on the nuclides present, the applicability of the exemption orders, view of the environment agency inspector concerned, market conditions, and distance from a suitable landfill. Where material has been identified to be exempt material (with respect to the RSA 93) the raw excavation costs are not dissimilar to those associated with chemically contaminated material. However, additional safety factors are required, and potentially more costly analysis is required. Taking typical costs for exempt material to around £75–£80/t, for budget purposes a rough cost estimate can be obtained for excavation, removal and disposal by applying a rate of £200/m^3.

If material has been identified as LLW, or ILW, costs are very much higher than this. These costs are related to volume, activity, and nuclide present. Disposal of LLW or ILW requires additional analysis, additional administration, higher transport costs, handling costs, and disposal costs. This can increase the cost of disposal to figures up to £3000–£4000/t. Landfill tax exemption can be obtained but must be applied for and granted by Customs and Excise prior to disposal.

4.2.2 Detector based segregation (Instrument based excavation and disposal)

Detector based remediation technologies rely on accurate investigation and survey data. It is paramount that the investigation identifies the radioactive contaminants present. Specific laboratory analysis, combined with field measurements needs to identify a fingerprint for the gamma emitters. In addition to the contaminants present the investigation needs to identify how and where the contamination occurs. It is important to identify if the activity detected is limited to discrete artefacts or materials, or spread more uniformly within a soil matrix, and identify depths to which the contamination may have spread.

This information allows for a better characterisation of the contamination present, and allows a more structured approach to its removal, and where possible identify areas of Low Level Waste which can be distinguished/ separated from the bulk exempt fraction. The ability to use a detector- based system is best suited to contaminants which emit gamma radiation at sufficient energy to be detectable by standard health physics monitoring equipment.

Following a rigorous calibration, backed up with suitable laboratory analysis it is possible to set course limits to allow segregation to take place with some confidence. However, this segregated material needs to be checked prior to sentencing with Quality Assured analysis to allow correct waste route sentencing.

Areas of contamination may be identified in a soil mass through either direct probe measurements by trained Health Physics monitors and removed by standard civil engineering techniques, or through a more automated system. Automated systems applied in the US have achieved greater than 90 per cent reduction of radionuclides in field trials. Where radioactive contamination exists, on a sufficient scale, with suitable material it is possible to use an automated conveyor system. This system allows large volumes of material to be screened and monitored, and where areas of material are identified as containing activity above the threshold levels it can be removed, pending further segregation if required. For the most part these systems can only be used on large scale remediation projects, and are not commercially viable on smaller projects.

4.2.3 Soil washing by particle separation

Soil washing is a process which involves the mechanical and chemical separation of contaminants from "clean" soil particles exploiting differences in size, density or magnetic properties. It reduces large quantity of contaminated material to small amounts capable of treatment and ultimately removes contamination from site. Waste streams normally require additional treatment and silt/clay materials are more difficult to treat. Some treatment techniques render soils unsuitable for future use. Transfer of contaminated soils to soil washing facilities may result in fugitive dust and gases. Application of this technique in the US has demonstrated consistent levels of separation.

Magnetic separation is used to extract slightly magnetic radioactive particles from host materials such as water, soil or air. All uranium and plutonium compounds are slightly magnetic while most host materials are nonmagnetic. The process operates by passing contaminated fluid or slurry through a magnetised volume. The magnetised volume contains a magnetic matrix such as steel wool that extracts the slightly magnetic contamination particles from the slurry. Magnetic separation is a promising new technique used to remove radioactive contaminants from soils. It has recently been tested at the bench-scale level at USDOE sites although costs are currently not available. Considered a relatively quick technique.

4.2.4 Soil washing by chemical treatment

Soil washing by chemical treatment is a process which adds chemicals to the soil to transfer the contaminants to a leachate. This process removes the radionuclides to a leachate, addressing the principal threat. This leachate is then treated. This technique can transfer difficult material to a form more amenable to treatment. The disadvantage of the technique is that it requires the input of a chemical reagent which can be both expensive and hazardous. Disposal and treatment of residual leachates can be an issue. Successful implementation of the technique is usually difficult with mixed contamination.

Its effectiveness can be limited by high concentrations of contaminants in the soil. In addition, post treatment processing may be required. The products of treatment can be phytotoxic thus sterilising soils. The technique has demonstrated applicability for radioactive materials. Typically, costs range from £25–85/t, costs for radioactive materials are likely to be at the higher end of this range.

4.2.5 *Ex situ* electro remediation

See D.4.4.1 (*in situ* electro remediation).

4.2.6 Flotation

This is a separation technique, separating contaminated particulates from a slurry through the addition of a water repellant floatation agent. The effectiveness of the technique has not been proven, although bench-scale tests indicate consistent and successful reductions in contamination up to 70 per cent are achievable. The technique effectively concentrate radionuclides in a waste stream that may require additional treatment. Handling of the contaminated soils is essential potentially resulting in fugitive dust and gases.

4.3 *In situ* and *ex situ* immobilisation or stabilisation of the contamination

4.3.1 Solidification/stabilisation

Stabilisation involves the mixing of soils with cement and or chemicals *in situ* by means of mixing blades with the injection of a solidification agent. The process can also take place *ex situ* by excavating and mixing soil with a stabilising agent either in plant (eg concrete mixer) or by being spread on the ground in layers. The processes are applicable to a wide range of mixed contaminants in a range of soils and are relatively quick. The principal is to reduce to mobility of contaminants therefore transferring difficult materials to a more manageable form. Disadvantages of the process are that it can result in an increase in the volume for treatment. The technique does not shield from external radiation and may require continued access restrictions. Its effectiveness depends on good mixing and availability of mixing reagents. *Ex situ* mixing may give rise to fugitive dust and gases. USDOE has demonstrated the Polyethylene Encapsulation of Radionuclides and Heavy metals (PERM) process at the bench scale. The process is a waste treatment and stabilisation technology for high-level mixed waste, specific targeted radionuclides include caesium, strontium, and cobalt. Scale-up from bench-scale tests has demonstrated the feasibility to process waste at approximately 2000 lb/hr. The scale-up feasibility tests have successfully demonstrated the potential to encapsulate at least 6- wt% nitrate salt in polyethylene. Polyethylene waste forms have been demonstrated to exceed Nuclear Regulatory Commission, EPA, and Department of Transportation waste form criteria. Costs range from £17–£85/t, costs for radioactive materials are likely to be at the higher end of this range.

4.3.2 Vitrification

Vitrification involves the application of very high temperatures to melt contaminated soils to form a glassy product. This results in the immobilisation of the contaminant within a glassy matrix. The process is applicable to a wide range of mixed contaminants in range of soils. It can transfer difficult materials to more manageable form and forms a very immobile residual product stable for thousands of years. The technique does not reduce the radioactivity of the material, therefore shielding may be required. Operational problems have been reported and no full field implementation has been achieved. Off gases may be created. Costs in the USA have been quoted as $330–$440/tonne (inclusive of labour, materials, energy, plant and contractor profit). Costs for radioactive materials are likely to be at the higher end of this range.

4.4 *In situ* isolation and containment of the contaminated ground

4.4.1 Barrier systems

Containment cover and barrier systems are constructed to encapsulate contamination. Cover systems comprises one or more layers of inert material to prevent the potential for contact of the contamination by people, fauna, flora, buildings and structures. Cover systems also reduce the potential for external irradiation. The infiltration of rainfall is inhibited by low permeability capping systems, which then also retard the lateral and/or downward migration of any contamination. The technique is applicable to a wide range of soil types/sites and has the advantage that it minimises/avoids disturbance of the contaminant source. The engineering is well understood, straightforward and available and can deal with very large contaminant volume relatively quickly. The principle disadvantage is that the contamination is not removed. The long-term performance of such capping systems is unproven and monitoring/maintenance may be required. Future uses of the land may be constrained by such cover systems. Construction workers and neighbouring communities may be exposed during construction of capping systems. Costs typically range from £15–30/m^2.

Vertical barriers can also be placed around contaminated material to prevent lateral migration. The barriers can be classified as either displacement barriers (eg sheet piling), excavated systems (eg concrete diaphragm walls or jet grouting) or injection systems (eg chemical or jet grouting). Active barriers/porous barriers which permit the transmission of groundwater/liquids but which retain radioactive contamination are in use in the USA. Horizontal barriers comprise barriers installed beneath contaminated material to prevent downward migration of contaminated solids and liquids. The barriers can be formed from natural low permeability layers (such as clay), through jet grouting (formation of a void space, followed by infilling with cement-bentonite) or through other grouting techniques. They may also include synthetic membranes or natural materials used as liners. These techniques are more fully described and referenced in Section 3.4.2 above.

5 Options for contaminated groundwaters

5.1 Hydraulic barriers

When remediating land contamination, it is necessary to consider whether hydraulic measures are also necessary. Engineering-based measures can be used to isolate or contain the contaminant plume, to treat or dispose of contaminated groundwater or to support the physical/engineering methods being undertaken to address the contaminant source.

Isolation or containment of a groundwater contaminant plume is normally only considered as a remedial treatment when removal and treatment of the contaminated groundwater is not immediately feasible. This method can be implemented by: extracting the water and discharging elsewhere; extracting, treating and re-injecting the water; or extracting, treating and recharge through seepage basins.

Hydraulic measures can also be used for removing the groundwater for treatment of the contaminants. For these purposes, contaminated groundwater is abstracted through specially-designed wells. Pump to treat technologies are usually used where large quantities of contaminated groundwater have been identified. Alternatively groundwater or contaminated liquids can be removed by pumping for disposal elsewhere.

Hydraulic techniques can also be used in conjunction with other physical measures. For example, the groundwater regime may be altered to produce an inward flow into a vertical barrier containment system. Such techniques can be considered either as a long-term or short-term treatment method. These methods are essential in some remedial projects to control groundwater flow and are necessary for the *ex situ* treatment of groundwater. The technology is widely available.

The hydrogeological regime at the site needs to be carefully characterised in order to ensure the method can be successfully realised. The general performance of hydraulic measures are difficult to predict, particularly for sites with complex subsurface geology and hydrogeology. The effectiveness of pump and treat systems is reduced where contaminants have low mobility (such as some PAHs or PCBs), or where spatially discontinuous non-aqueous phase liquids are present. Costs for hydraulic barriers range from £1–6/m^3 of groundwater.

5.2 Physical treatment of contaminated groundwater

The physical techniques available for treatment of contaminated liquids includes such techniques as air stripping, carbon adsorption and coagulation and flocculation.

Air stripping is primarily used to remove volatile organics from contaminated liquids. Several different devices are available for the implementation of this technique including aeration tanks and packed towers. Packed towers have been shown to be more efficient at removing some contaminants (trichloroethene) than the other techniques. A packed tower process involves water entering at the top and flowing downwards through the tower while an air stream flows upwards stripping volatile substances.

Air sparging is a related technique which involves the injection of air into contaminated groundwater, as the air rises through the groundwater, there is a transfer of volatile contaminants to the vapour phase. The contaminated vapours are collected at the surface for treatment.

Carbon adsorption is a technique which is widely used by the water supply industry for removing trace organics from drinking water. This technique is suitable for removing a wide range of synthetic organic compounds from the liquids. The process involves physical adsorption of the molecules of the gas or liquid onto the surface of the carbon.

Coagulation and flocculation are used to remove suspended solids following other treatment to reduce levels of inorganic contaminants. Coagulation is the most commonly used method and involves changing the particle charge using a coagulant. Flocculation involves agglomerating particles that are too small to settle under gravitational force. Sedimentation is frequently used in conjunction with other processes and involves allowing particles suspended in the liquid to settle, generally in some form of treatment tank.

Some of these processes are well established and use relatively simple equipment. The hydrogeological regime at the site needs to be carefully characterised. For airstripping and air sparging, the heterogeneous nature of the subsurface at some sites can make monitoring and verification difficult. A Waste Management Licence may be required for projects involving these processes. Feasibility testing is required for all process-based methods. Air stripping and air sparging are both commercially available in the UK and overseas. Other treatments are available but have limited application to contamination in the UK. Coagulation and flocculation technology has been used for radionuclides in the US. Costs for air sparging range from £10–60/m^3.

5.3 Chemical treatment of groundwater

Chemical processes available for treating contaminated liquids include precipitation, oxidation, reduction and neutralisation. Precipitation is a well established method of treating industrial effluents containing heavy metals (such as cadmium, chromium and copper). It relies on chemical reactions to produce insoluble compounds usually by adjustment of the pH.

Oxidation is used to convert the contaminants into more stable or less toxic forms. Examples include destruction of cyanide by chlorine. Reagents used for the oxidation process include chlorine, hydrogen peroxide and ozone. Some organics can be oxidised to compounds which are more vulnerable to biological attack.

Reduction has only limited application for the treatment of organics, but can be used as a means of removing inorganics by converting them to a less toxic form. Sulphur dioxide for example can be used to convert more toxic hexavalent chromium into a less toxic trivalent form.

Neutralisation involves changing the pH of the liquid to approximately 7.0. This is often used as a pre-treatment prior to final discharge of the liquid. Neutralisation commonly uses strong mineral acids such as sulphuric acid.

These chemical treatment methods all utilise readily available equipment are relatively low cost and large volumes of liquid can be treated at any one time. The contamination is destroyed in the chemical process and chemical treatment can be very successful for some organic compounds and metals such as chromium. The limitations of the techniques are that they require an input of chemical reagent which can be costly and potentially hazardous. Chemical treatment may be difficult where mixtures of contaminants are present and a Waste Management Licence may be required. Feasibility testing is required for all process-based methods. Some techniques are available in the UK, although they have a limited proven field application. The costs for commercial applications are not currently available for treatment of contaminated groundwater.

5.4 Biological treatment for groundwater

Groundwaters contaminated with organics are often treated using biological techniques. Biological processes are generally either aerobic (requiring oxygen) or anaerobic. However, some biological processes operate under both conditions. *Ex situ* treatment is generally undertaken in a bioreactor, where contaminated groundwater or effluent is mixed with growth systems for microbial population. The main purpose of the reactors is to produce a large growth area for microbes which is in contact with the liquid being treated. Using oxygen instead of air can increase the efficiency of these systems.

In situ bioremedation of groundwaters, such as the degradation of chlorinated hydrocarbons have been piloted but are not yet commercially available. Not all organics can be readily treated by biological processes and some are toxic to microbial systems. Complex polyaromatics are either not amenable to biological action or degrade very slowly. However, aliphatic, aromatic and simple polyaromatic compounds can be treated biologically.

The cost of biological treatment is generally lower than other treatment method and large volumes of liquid can be treated at any one time. There is currently a limited track record other than for *ex situ* techniques which require extraction of groundwater from the ground. There is the potential for formation of intermediate compounds which are more toxic than the original contaminant and a Waste Management Licence may be required for mobile plant. Feasibility testing is required for all process-based methods. Costs for commercial applications not currently available.

5.5 Monitored natural attenuation

There are several processes which can be utilised in monitored natural attenuation schemes for groundwater. Biodegradation takes place in circumstances where organic compounds such as petroleum hydrocarbons are slowly degraded by organisms present. Sorption is the process where contaminants such as heavy metals contained within a liquid become attached to soil particles, thereby reducing the concentration in the liquid Dilution applies where the concentration of compounds is lowered through mixing of the contaminated liquid with a lesser or non-contaminated liquid. This process relies on the infiltration of rainfall or clean groundwater flowing through the contaminated zone as opposed to deliberate flushing of the zone. Volatilisation is utilised where compounds such as chlorinated solvents slowly vaporise and the resulting concentration is reduced.

The potential for natural attenuation is dependent upon the pollutant and the environment in which it exists. The advantages of these processes are that low capital costs are incurred compared with treatment plants. They do not disturb the contamination source, which can be an important issue for surface water/groundwater protection. However, such systems are only likely to be acceptable where there is not an unacceptable risk to receptors. The costs for investigation and monitoring may be greater than other schemes and the degradation of contaminants may produce more toxic breakdown products. Costs for site investigation will vary depending on site-specific circumstances, however could range from £50–500k. Monitoring costs could vary from £2–20k per borehole per annum.

5.6 Treatment for radioactive waters

There are two primary principals for the treatment of radioactively contaminated waters: chemical separation and physical separation. In both cases the aim is to separate and concentrate the contaminants resulting in clean water and a contaminate concentrated residual, suitable for further treatment and/or disposal.

Chemical separation technologies suitable for radioactively contaminated waters are typically applied *ex situ*. These include ion exchange, and chemical precipitation using carbonates, sulphates, sulphides, lime or other hydroxides. Up to a 99 per cent reduction in contamination is achievable under favourable conditions. The performance of this technology is dependant on the properties of the contaminated waters, in particular, pH, temperature and flow rate. Ion exchange only works on ionic wastewater. Non-ionic wastewaters require pre-treatment.

Chemical precipitation converts soluble contaminants to an insoluble form through chemical reaction. The technique involves the addition of a chemical precipitate and separation through settling. The success of this technique is dependant on the precipitate used, concentration of radionuclides, and pH of the wastewater. Proven technologies applied in the US are capable of treating 50 000 gallons a day. Up to 95 per cent removal of radioactive contaminants has been achieved.

Physical separation technologies include Membrane filtration (reverse osmosis, micro-filtration), carbon adsorption and aeration. All rely on the exploitation of physical properties of target contaminants. All have been pilot tested for radionuclide-contaminated media, although further testing is required to assess effectiveness.

The technologies do not reduce radioactivity, but do transfer contaminants to a more manageable form suitable for further treatment/disposal. Pre-treatment may be necessary to maintain the integrity of separation technologies.

6 Remedial options for soil gases

These techniques could be applicable to all gases including explosive (ie methane), asphyxiant (eg. carbon dioxide), toxic (eg benzene, toluene, ethyl-benzene, xylene) and radioactive (eg radon) gases.

6.1 Passive systems

Passive systems for control of soil gas migration rely on a combination of a low permeability gas barrier (to control gas movement to a sensitive receptor) and a high permeability venting layer (to encourage gas to dissipate in areas where it will not cause a problem). Passive systems can be installed vertically to control lateral migration through the ground (eg gas migrating from a landfill) or horizontally to control vertical movement (eg to prevent gas entering a building).

The advantages of passive systems are that no power systems are required. They provide a long-term solution with low maintenance costs. Barrier systems cannot "clog" with soil gases, such systems are generally robust and tamper-proof and utilise proven materials and installation methodologies. Venting media can act as biological filters, oxidising hydrocarbons to carbon dioxide, thus reducing atmospheric heating potential and odours.

The limitations of such systems are that venting zones can block with time and there is a limited depth of installation for vertical membrane barriers. Horizontal barriers (eg floor slab membranes) can be breached inadvertently.

A wide range of membrane barriers are available and in use. Barriers generally comprise aluminium and bitumen reinforced polyethylene liners. Typical costs (1999) are in the range £8–£10/m^2. Vent trenches typically cost £20–£25/m^3 stone fill, £5/m^2 geo-membrane and lining, £2/m^3 excavation (disposal costs extra).

6.2 Active systems

Active systems rely on mechanical systems to extract gases from the ground and prevent accumulation under and within buildings and structures. An alternative approach is to apply positive pressure to the interior of a building to ensure gas cannot enter from outside. Gas can be extracted from vertical wells (to control horizontal migration) and from horizontal pipework/venting zones (to control vertical movement). Fan systems can be installed in sub-floor voids to withdraw gas and introduce clean air.

The advantages of these active systems are that they utilise proven, well established technology, the necessary equipment is readily available and widely used. Control can be exercised over the rate of extraction of gas. Fans and pumps can be set to activate when pre-set trigger level gas concentrations are reached thus reducing energy requirements. The extracted gas can be flared, reducing climate warming potential of gas emissions and destroying odorous and toxic compounds. Where high volumes of flammable gas are extracted, energy recovery is feasible (eg from landfills).

The disadvantages of such systems are that they require on-going management and incur maintenance costs. Wells will clog and need regular cleaning or replacement and active systems can be prone to tampering and vandalism. Condensation can be a problem in pipework, reducing efficiency and flare stacks can be visually intrusive. There are increasingly stringent emission criteria imposed for the permanent flares.

The costs of vertical well drilling and installation costs are dependant on depth and diameter. Typical costs are £1500–3000 per well. The costs of gas extraction and flare units are typically £30 000 to £50 000.

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