ELSEVIER

Journal of Environmental Management 71 (2004) 95–122

Journal of
Environmental
Management

www.elsevier.com/locate/jenvman

An overview and analysis of site remediation technologies

Faisal I. Khan*, Tahir Husain, Ramzi Hejazi[1]

Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St John's NL, Canada A1B 3X5

Received 22 June 2001; revised 19 January 2004; accepted 2 February 2004

Abstract

This paper presents an analysis of the site restoration techniques that may be employed in a variety of contaminated site cleanup programs. It is recognized that no single specific technology may be considered as a panacea for all contaminated site problems. An easy-to-use summary of the analysis of the important parameters that will help in the selection and implementation of one or more appropriate technologies in a defined set of site and contaminant characteristics is also included.

Keywords: Site remediation; Soil remediation; Groundwater cleanup; Soil vapor extraction; Natural attenuation

1. Introduction

Pollutants enter the environment directly as a result of accidents, spills during transportation, leakage from waste disposal or storage sites, or from industrial facilities (Riser-Roberts, 1992). Problems associated with the cleanup of petroleum-contaminated sites have demonstrated that there is a need to develop remediation technologies that are feasible, quick, and deployable in a wide range of physical settings. Government, industry, and the public now recognize the potential dangers that complex chemical mixtures such as total petroleum hydrocarbons (TPH), polychloro biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), heavy metals, and pesticides pose to human health and the environment. In response to a growing need to address environmental contamination, many remediation technologies have been developed to treat soil, leachate, wastewater, and groundwater contaminated by various pollutants, including in situ and ex situ methods (Riser-Roberts, 1998). A particular contaminated site may require a combination of procedures to allow the optimum remediation for the prevailing conditions. Biological, physical, and chemical technologies may be used in conjunction with one another to reduce the contamination to a safe and acceptable level (Reddy et al., 1999; RAAG, 2000).

This paper describes the biological, physical, and chemical technologies currently available for dealing with soil and groundwater contaminated by petroleum and related products. The process, applicability, advantages, limitations and concerns, site-specific parameters, and costs of each remediation alternative are evaluated and discussed. Even though many technologies are available for the treatment of contaminated sites, the selection depends on contaminant and site characteristics, regulatory requirements, costs, and time constraints (Riser-Roberts, 1998; Reddy et al., 1999). Since most remediation technologies are site-specific, the selection of appropriate technologies is often a difficult, but extremely important, step in the successful remediation of a contaminated site. Therefore, the successful treatment of a contaminated site depends on proper selection, design, and adjustment of the remediation technology's operations based on the properties of the contaminants and soils and on the performance of the system. Detailed descriptions of individual technologies can be found in Chareneau et al. (1995), API (1993), Alexander (1994), Demars et al. (1995), and Anderson (1995), USEPA reports (USEPA, 1995–1998), Federal Remediation Technologies Roundtable reports (FRTR, 1999a–q), Reddy et al. (1999), RAAG (2000), Feng et al. (2001), Hejazi (2002), Kao et al. (2001), Li et al. (2002), Abbott et al. (2002), Guerin et al. (2002), Barnes (2003), Chu (2003), Halmemies et al. (2003), Khan and Husain

---

* Corresponding author. Tel.: +1-709-737-8939; fax: +1-709-737-4042. *E-mail address:* fkhan@engr.mun.ca (F.I. Khan).

[1] Environmental Chemistry Unit, Saudi Aramco, Box 5487, Dhahran 31311, Saudi Arabia.

0301-4797/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2004.02.003

(2003), Juhasz et al. (2003), Liang et al. (2003), Wilk (2003) and Wait and Thomas (2003).

2. Soil remediation technologies

2.1. Soil washing

Soil washing uses liquids (usually water, occasionally combined with solvents) and mechanical processes to scrub soils. Solvents are selected on the basis of their ability to solubilize specific contaminants, and on their environmental and health effects (Asante-Duah, 1996; Feng et al., 2001; Chu and Chan, 2003; Urum et al., 2003). The soil washing process separates fine soil (clay and silt) from coarse soil (sand and gravel). Since hydrocarbon contaminants tend to bind and sorb to smaller soil particles (primarily clay and silt), separating the smaller soil particles from the larger ones reduces the volume of contaminated soil (Riser-Roberts, 1998). The smaller volume of soil, which contains the majority of clay and silt particles, can be further treated by other methods (such as incineration or bioremediation) or disposed in accordance with federal regulations. The clean, larger volume of soil is considered to be non-toxic and can be used as backfill (USEPA, 1996a; RAAG, 2000; Chu and Chan, 2003). Soil washing is often combined with other technologies. Chu (2003) has provided an update review of surfactant added soil washing technologies.

2.1.1. Discussion

The target contaminant groups for soil washing include semi-volatile organic compounds (SVOCs), petroleum and fuel residuals, heavy metals, PCBs, PAHs, and pesticides (Asante-Duah, 1996; Feng et al., 2001; Park et al., 2002; Juhasz et al., 2003; Lin et al., 2001). This technology permits the recovery of metals and it can clean a wide range of organic and inorganic contaminants from coarse-grained soils (Urum et al., 2003). Soil washing is cost-effective because it reduces the quantity of material that would require further treatment by another technology.

Important observations related to soil washing performance are:

- Complex waste mixtures require a combination of solvents.
- Pre-treatment is required for soils containing humic acids.
- Organics adsorbed onto clay particles are difficult to remove (CPEO, 1997).
- Since soil washing does not destroy or immobilize the contaminants, the resulting soil must be disposed of carefully.
- Wash water needs to be treated before its final disposal.
- Soil washing is most effective for soil that does not contain a large amount of silt and clay.

Soil washing is used extensively in Europe, but it has limited use in the United States. The average cost for this technology, including excavation, is approximately $170 US/t, depending on site-specific conditions and the target waste quantity and concentration (FRTR, 1999a).

2.2. Soil vapor extraction

Soil vapor extraction (SVE), also known as soil venting or vacuum extraction, is an accepted, recognized, and cost-effective technology for remediating unsaturated soils contaminated with VOCs and SVOCs (Suthersan, 1997; Zhan and Park, 2002; Halmemies et al., 2003). SVE involves the installation of vertical and/or horizontal wells in the area of soil contamination. Air 'blowers' are often used to aid the evaporation process (Fig. 1). Vacuums are applied through the wells near the source of contamination to evaporate the volatile constituents of the contaminated mass which are subsequently withdrawn through an extraction well. Extracted vapors are then treated (commonly with carbon adsorption) before being released into the atmosphere (USEPA, 1995a). The increased airflow through the subsurface provided by SVE also stimulates the biodegradation of contaminants, especially those that are less volatile (USEPA, 1996b, 1998a; Halmemies et al., 2003; Harper et al., 2003). This procedure is also used with groundwater pumping and air stripping for treating contaminated groundwater. A simplified schematic diagram of SVE is shown Fig. 1.

2.2.1. Discussion

SVE is typically more applicable in cases where the contaminated unsaturated zone is relatively permeable and homogeneous. Ideally the site should be covered with an impermeable surface layer to minimize the short-circuiting of airflow and infiltration (Suthersan, 1997; Zhan and Park, 2002; Halmemies et al., 2003; Barnes et al., 2002; Barnes, 2003). SVE is generally most successful when it is applied to lighter, more volatile petroleum products such as gasoline. Heavier fuels, such as diesel fuel, heating oils, and kerosene, are not readily removed by SVE. The injection of heated air enhances the volatility of these heavier petroleum products, but the large energy requirements make it economically prohibitive (USEPA, 1995a, 1998a; Zhan and Park, 2002). Benzene, toluene, xylene, naphthalene, biphenyl, perchloroethylene, trichloroethylene, trichloroethane, and gasoline are all effectively removed from contaminated soils by SVE systems (USEPA, 1996b; RAAG, 2000; Barnes et al., 2002).

Important observations related to the performance of SVE technology are:

- As SVE is an in situ technology, the site disturbance is minimal.
- SVE can treat large volumes of soil at reasonable costs.

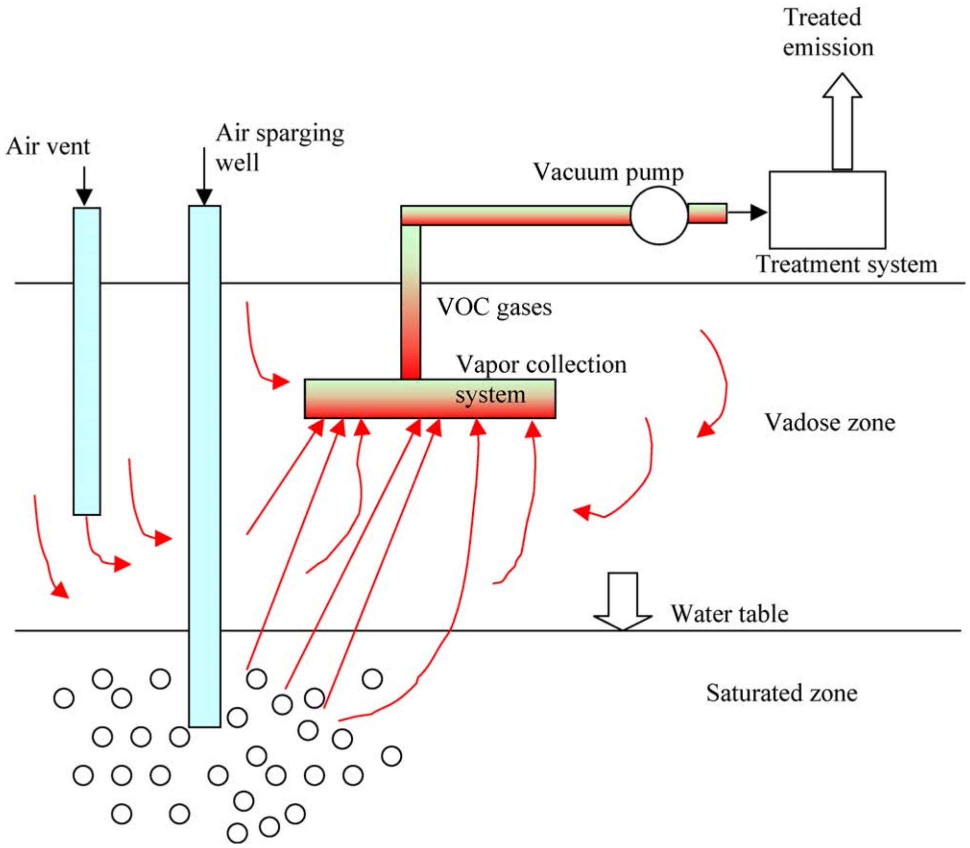

Fig. 1. Air spaging with soil vapor extraction process.

- It is effective at reducing VOCs in the vadose zone, thereby reducing the potential for further migration (USEPA, 1996b).
- It has a short treatment time (usually a few months to 2 years under optimal conditions) (USEPA, 1995a).
- Its applicability is limited to cases involving volatile compounds and sites with a low groundwater table.
- It is difficult, if not impossible, to develop models that permit an accurate prediction of SVE cleanup times from the data collected in short-term pilot studies (Riser-Roberts, 1998; Yeung and Hsu, 2002; Barnes et al., 2002). Barnes (2003) has discussed in detail the method to estimate SVE operation time.
- Concentration reductions greater than 90% are difficult to achieve (USEPA, 1996b; Zhan and Park, 2002).
- The permeability of the soil affects the rate of air and vapor movement through the soil. Therefore, the higher the permeability of the soil, the more effective will be the SVE system at removing contaminants from the soil (USEPA, 1995a, 1998a; Yeung and Hsu, 2002).
- Coarse-textured soils are best suited for SVE (USEPA, 1996b, 1998a).
- High moisture levels in the soil can reduce its permeability, and thus reduce the effectiveness of SVE by restricting the air flow through the soil pores.
- SVE is generally not appropriate for sites with a groundwater table located less than 0.9 m below the land surface.

According to the United States Environmental Protection Agency, SVE operational costs vary from \$20 to \$50 US/t of contaminated soil (USEPA, 1995a, 1998a).

2.3. Landfarming

Landfarming is an above-ground remediation technology that reduces the concentration of petroleum constituents present in soils through processes associated with bioremediation. This technology usually involves the spreading of excavated contaminated soils in a thin layer (no more than 1.5 m) on the ground surface of a treatment site and stimulating aerobic microbial activity within the soils through aeration and/or the addition of nutrients, minerals, and water/moisture (USEPA, 1998b; Hejazi, 2002). Bacteria, which have been selected for their success in breaking down hydrocarbons, are frequently added to the soil to achieve speedy degradation. The enhancement of microbial activity increases the degradation of adsorbed petroleum products (Riser-Roberts, 1998). The soil must be well mixed in order to increase the contact between the organics and microorganisms and to supply the oxygen required for aerobic biological degradation. Depending on the rate of degradation, soils which contain petroleum contaminants can be applied to the site at regular intervals. This helps to replenish the hydrocarbon supply, and more importantly, to maintain biological activity (Harmsen, 1991; RAAG, 2000; Hejazi, 2002).

2.3.1. Discussion

Landfarming is successful in treating petroleum hydrocarbons (FRTR, 1999b). It has been practiced worldwide for over 100 years and by the petroleum industry for more than 25 years (Riser-Roberts, 1998). Lighter petroleum hydrocarbons, including the constituents of gasoline, tend to be removed by evaporation during aeration processes and, to a lesser extent, degraded by microbial respiration (USEPA, 1998b; Hejazi, 2002; Hejazi et al., 2003). However, heavier petroleum hydrocarbons do not evaporate during aeration but are broken down by microorganisms present in the soil at the treatment site. These higher molecular weight petroleum constituents, such as those found in heating and lubricating oils and to a lesser extent in diesel fuel and kerosene, require long periods of time to degrade.

Important observations related to the performance of landfarming technology are:

- A large amount of land is required.
- Volatile contaminants must be pre-treated because they would volatilize into the atmosphere and cause air pollution (FRTR, 1999b).
- It is not efficient in degrading the heavy components of petroleum.
- There is a possibility for contaminant movement from the treatment site to a previously undisturbed site (Riser-Roberts, 1998; Hejazi, 2002).
- Concentration reductions greater than 95% and constituent concentrations less than 0.1 ppm are difficult to achieve.
- It may not be effective for sites of high constituent concentrations of greater than 50,000 ppm TPH (USEPA, 1998b).
- Due to reduced microbial growth and metabolic rates biodegradation tends to decline with a decline in temperature. The optimum temperature range is 25–40 °C.
- The optimum moisture content for the highest degradation rate, for landfarming is 18%. At 33% moisture (too wet) and 12% moisture (too dry), degradation rates tend to be low.
- Nutrients, especially nitrogen, within the soil zone allow biological processes to proceed efficiently. The most rapid biodegradation of refinery sludge occurs when added nitrogen reduces the C:N ratio to 9:1.
- Maintaining the soil pH within the 6.5–7.5 range provides optimum conditions for biodegradation.
- The availability of oxygen throughout the zone of incorporation is important for the biodegradation of petroleum products. This can be achieved by tilling or cultivating the zone of incorporation and by avoiding saturated soils.

Capital, installation, operation, and maintenance costs for landfarming operations are relatively inexpensive compared to other remediation technologies. The cost of landfarming for the remediation of petroleum-contaminated soils ranges from \$30 to \$60 US/t and can take from 6 months to 2 years (longer for heavier constituents of petroleum) (USEPA, 1998b; Hejazi, 2002).

2.4. Soil flushing

In situ soil flushing is an innovative remediation technology that ‘floods’ contaminated soils with a solution that moves the contaminants to an area where they can be removed (USEPA, 1996e; Otterpohl, 2002; Logsdon et al., 2002; Di Palma et al., 2003). Soil flushing is accomplished by passing an extraction fluid through in-place soils using an injection or infiltration process (Fig. 2). Contaminated groundwater and extraction fluids are captured and pumped to the surface using standard groundwater extraction wells. Recovered groundwater and extraction fluids with the adsorbed contaminants may need treatment to meet the appropriate discharge standards before being recycled or released to local, publicly owned, wastewater treatment works or receiving streams (FRTR, 1999h; RAAG, 2000; Otterpohl, 2002; Son et al., 2003). Soil flushing applies to all types of soil contaminants and is generally used in conjunction with other remediation technologies such as activated carbon, biodegradation, and pump-and-treat (Boulding, 1996). Since soil flushing is conducted in situ, it reduces the need for excavation, handling, or transportation of hazardous substances. Juhasz et al. (2003) has discussed in situ remediation of DDT-contaminated soil using a two-phase co-solvent flushing-fungal biosorption process. A line diagram of the process is shown in Fig. 2.

2.4.1. Discussion

The target contaminant group for this remediation technology is the inorganics which include radioactive contaminants. It can also be used to treat VOCs, SVOCs, fuels, and pesticides, but it may be less cost-effective than alternate technologies for these contaminant groups (FRTR, 1999h; Logsdon et al., 2002; Alter et al., 2003). Soil flushing tends to work best at sites with soils that have spaces that permit the movement of the flushing solution through it. High permeability soils with a hydraulic conductivity greater than 1.0×10^{-3} cm/s are favored over low permeability soils with a hydraulic conductivity less than 1.0×10^{-3} cm/s (Boulding, 1996; Johnston et al., 2002; Juhasz et al., 2003). If the soil has a high percentage of silt or clay, the flushing solution cannot move through the soil, and it cannot easily make contact with the contaminants; this reduces the effectiveness of the flushing process (USEPA, 1996e; Reddy and Saichek, 2003).

Important observations related to the performance of soil flushing technology are:

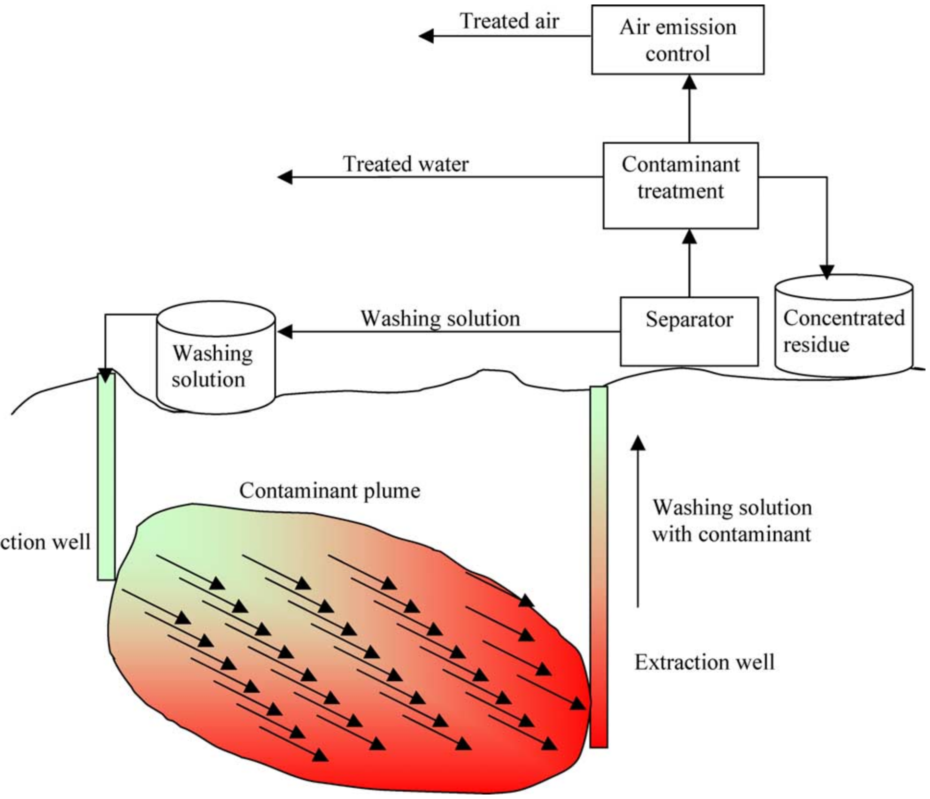

Fig. 2. In situ soil flushing process.

- Low permeability or heterogeneous soils are difficult to treat (FRTR, 1999h).
- Remediation times are usually lengthy because of the slowness of diffusion processes in the liquid phase.
- This technology requires hydraulic control to avoid the movement of contaminants off-site (Johnston et al., 2002).
- Hydrophobic contaminants require surfactants or organic solvents for their removal from the soil (Boulding, 1996; Juhasz et al., 2003).
- Recovered groundwater may require treatment to meet the appropriate discharge standards (Otterpohl, 2002).
- If soil flushing is used to extract VOCs, air emissions should also be treated (CPEO, 1998d).

The cost varies with site-specific conditions, specifically the size of the treatment area and the number of soil flushing cycles required. The cost of soil flushing also depends on the type and concentration of surfactants used. Rough estimates from \$25 to \$250 US per cubic yard have been reported (FRTR, 1999h).

2.5. Solidification/stabilization

Solidification/stabilization, also referred to as waste fixation, reduces the mobility of hazardous substances and contaminants in the environment through both physical and chemical means (FRTR, 1999e; Sherwood and Qualls, 2001). Stabilization generally refers to the process that reduces the risk posed by a waste by converting the contaminant into a less soluble, immobile, and less toxic form. Solidification refers to the process that encapsulates the waste materials in a monolithic solid of high structural integrity (Suthersan, 1997; Anderson and Mitchell, 2003). In situ stabilization and solidification involves three main components: (1) a means of mixing the contaminated soil in place; (2) a reagent storage, preparation, and feed system; and (3) a means to deliver the reagents to the soil mixing zone (Nyer, 1996). In situ and ex situ stabilization/solidification is usually applied to soils contaminated by heavy metals and other inorganic compounds. However, stabilization of soils that contain low levels of organic constituents is feasible, even for volatile organics (Riser-Roberts, 1998; Druss, 2003). Most stabilization/solidification technologies have limited effectiveness against organics and pesticides, except for asphalt batching and vitrification which destroys most organic contaminants (FRTR, 1999f; RAAG, 2000; Abbott et al., 2002; Wilk, 2003).

2.5.1. Asphalt batching

Asphalt batching, a stabilization/solidification method for treating hydrocarbon-contaminated soils, incorporates petroleum-laden soils into hot asphalt mixtures as a partial substitute for stone aggregate. This mixture can then be utilized for paving. This process involves excavation of the contaminated soils, which then undergo an initial thermal treatment, followed by incorporation of the treated soil into an aggregate for asphalt. During the incorporation process, heating of the mixture results in the volatilization of the more volatile hydrocarbon constituents (Asante-Duah, 1996). The remaining compounds are incorporated into an asphalt matrix during cooling, thereby limiting constituent migration. After it is given sufficient time to set and cure, the resulting solid asphalt now has the waste uniformly distributed throughout it and is impermeable to water (FRTR, 1999f; Abbott et al., 2002; Alpaslan and Yukselen, 2002).

2.5.2. Vitrification

Vitrification, or molten glass, is a method of stabilization/solidification that uses a powerful source of energy to ‘melt’ soil or other earthen materials at extremely high temperatures (1600–2000 °C), immobilizing most inorganics and destroying organic pollutants by pyrolysis (Acar and Alshawabkeh, 1993; FRTR, 1999e) (Fig. 3). During this process, the majority of contaminants initially present in the soil are volatilized, while the remainder are converted into a chemically inert, stable glass and crystalline product (Asante-Duah, 1996). The high temperatures destroy any organic constituents, resulting in few by-products. Inorganics, such as heavy metals and radionuclides, are actually incorporated into a glass structure which is generally strong, durable, and resistant to leaching (FRTR, 1999f; Dermatas and Meng, 2003).

There are three main types of vitrification processes:

- *Electrical processes*: in situ application of electrical energy through graphite electrodes inserted into the ground (Acar and Alshawabkeh, 1993) (Fig. 3).
- *Thermal processes*: require an external heat source and a typical reactor (refractory-lined rotary kit) (Wait and Thomas, 2003).
- *Plasma processes*: can achieve temperatures up to 5000 °C via electrical discharges (Suthersan, 1997).

2.5.3. Discussion

Important observations related to the performance of solidification/stabilization technology are:

- The depth of the contaminants may limit these processes.
- Long-term monitoring is often necessary to ensure that the contaminants are actually immobilized.
- Organic constituents are generally not immobilized, and unless very high temperatures are used to destroy them, they will most likely migrate (CPEO, 1998b).
- If not completed properly, these processes may result in a significant increase in contaminant volume.
- Certain wastes are incompatible with these processes (FRTR, 1999e).

The representative overall cost of ex situ solidification/stabilization from more than a dozen vendors indicates an approximate cost of under $110 US/t, including excavation (FRTR, 1999f). The cost of in situ solidification/stabilization ranges from $80 US per cubic meter for shallow applications to $330 US per cubic meter for deeper applications (FRTR, 1999e).

2.6. Thermal desorption

Thermal desorption is an innovative treatment technology where contaminated soil is excavated, screened, and

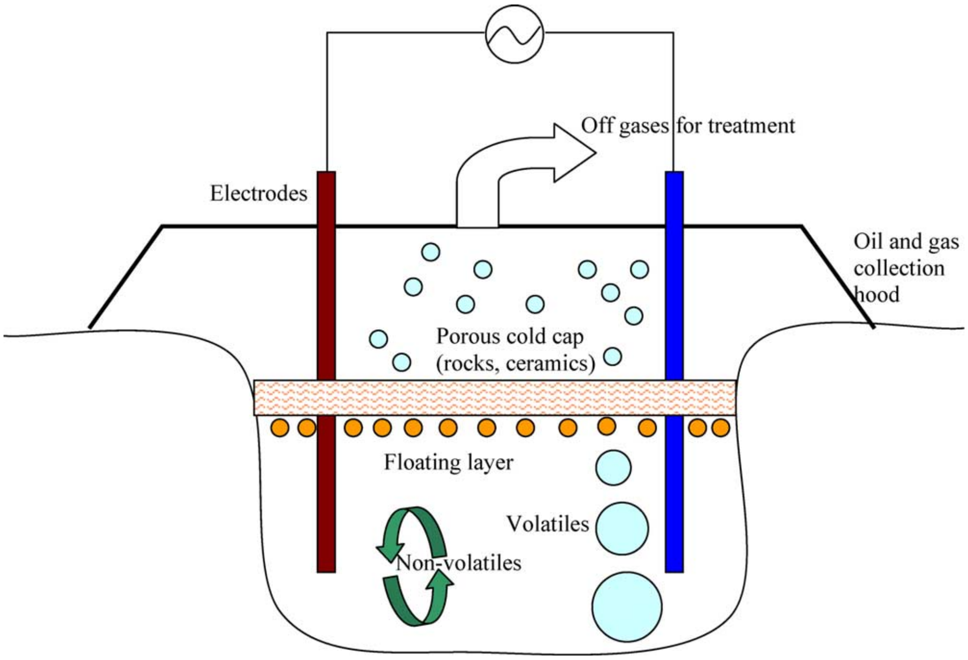

Fig. 3. In situ vitrification system.

heated to release petroleum from the soil (USEPA, 1995a). It involves heating soils to temperatures of 100–600 °C so that those contaminants with boiling points in this range will vaporize and separate from the soil. The vaporized contaminants are then collected and treated by other means (USEPA, 1996f; Dermatas and Meng, 2003). There is some confusion about the difference between thermal desorption and incineration: thermal desorption does not aim to destroy the organic but rather to change the form to a more treatable one, while incineration aims to destroy the contaminant (FRTR, 1999j; Alpaslan and Yukselen, 2002). The actual process of thermal desorption involves heating the soil in a chamber where organic contaminants and certain metals can be vaporized. From there, a gas or vacuum system transports the vaporized contaminants to an off-site treatment system. If oxidization occurs in place of vaporization, the process has become incineration. Based on the temperature in the operating chamber, thermal desorption can be divided into high and low temperature thermal desorption (CPEO, 1998e; Wait and Thomas, 2003).

2.6.1. Discussion

Thermal desorption works on most hydrocarbon-contaminated soils (USEPA, 1995a), but it may have varying effects on the full range of organics (FRTR, 1999j). With the exception of mercury, metals usually cannot be treated with this process. Other metals remaining in the soil require further treatment or vaporize and complicate the treatment process of the vaporized contaminants. Low temperature thermal desorption is usually used to treat VOCs and various fuels, while high temperature thermal desorption is mainly used for PAHs, PCBs, and pesticides (FRTR, 1999h; Alpaslan and Yukselen, 2002; Wait and Thomas, 2003).

There are several advantages of using thermal desorption as opposed to other technologies such as conventional solvent extraction. These include:

- The efficiency of desorption can be greater than 99%.
- It is insensitive to contaminant concentration levels in the soil.
- It is a fairly environment friendly technology.

Thermal desorption is not equally effective for all soil types. The presence of water reduces its effectiveness since more than the contaminant water is being vaporized. As well, a high clay or silt content hinders the process. The air generated from silt and clay interferes with the air emission equipment used to treat the chemicals. Tightly packed soil does not allow the penetration of heat through the soil (USEPA, 1996f; Wait and Thomas, 2003).

The cost of remediation petroleum-contaminated soils with thermal desorption can range from $50 US to 330 US per metric ton. Of this between $20 US to $35 US goes towards direct operating costs. These figures include initial setup and unit transportation costs as well as the cost of excavating the contaminated soil and replacing the treated soil (FRTR, 1999j).

2.7. Biopiles

Synonyms for biopiles include biocells, bioheaps, biomounds, compost cells (USEPA, 1998e; Jorgensen et al., 2000), heap pile bioremediation, and static-pile composting (FRTR, 1999l). This treatment involves the piling of petroleum-contaminated soils into piles or heaps and then simulating aerobic microbial activity by aeration and the addition of minerals, nutrients, and moisture (USEPA, 1998e; Filler et al., 2001). Heat and pH can also be controlled to enhance biodegradation. Treatment areas are often covered with an impermeable liner to reduce the amount of leachate entering the uncontaminated soil. These piles, which have an underground system through which air passes, can be up to 6 m high (this height is not recommended) and may be covered to prevent runoff, evaporation and volatilization, and to promote solar heating. If VOCs are present in the soil, the air may need to be treated before being discharged into the atmosphere. This is a short-term technology and may last from a few weeks to a few months (FRTR, 1999l). Biopiles are similar to landfarming but in the latter the soil is aerated through tilling or plowing (USEPA, 1998e; Jorgensen et al., 2000; Filler et al., 2001; Li et al., 2002).

2.7.1. Discussion

Biopiles are effective in reducing most petroleum products (USEPA, 1998e) as well as other contaminants including non-halogenated VOCs, halogenated VOCs, SVOCs, and pesticides (FRTR, 1999l). Lighter petroleum products such as gasoline tend to be removed during aeration by evaporation since they contain VOCs. Mid-range products like diesel or kerosene contain lower amounts of volatile components, and their biodegradation is more effective. Heavier compounds like heating and lubricating oil do not evaporate, and biodegradation is needed to reduce them (Chaineau et al., 2003). The mid-weight and heavier compounds take much longer to biodegrade than the lighter ones (USEPA, 1998e; Li et al., 2002).

Important observations related to the performance of biopile technology are:

- Biopiles are easy to design and implement.
- Treatment time is usually short; under optimal conditions, the treatment time is from 6 months to 2 years.
- Biodegradation is effective on a range of organic constituents.
- A closed system can control vapor emissions.
- It can be engineered to fit a number of products and site conditions.
- Contaminant reductions of more than 95% are difficult to achieve.

- It may not be effective on petroleum concentrations greater than 50,000 ppm.
- The presence of a high concentration of heavy metals may inhibit microbial growth.
- Volatile components tend to evaporate rather than biodegrade.
- The vapor generated from evaporation may require treatment before being discharged.
- This technology may require large areas of land, although the area required is less than for landfarming.

Soil characteristics which play a major role in the success of biopiles include texture, permeability, moisture content, and bulk density. Soils with a low permeability are difficult to aerate but retain water better than soils with a high permeability. Low permeability soils often clump together, making the distribution of moisture, air, and nutrients difficult. Because of the non-uniform distribution of these characteristics in soils, turning or tilling may be required to promote optimal conditions for biodegradation. Microorganisms require moist conditions for proper growth, but excess moisture inhibits the movement of the air necessary for aerobic bacterial growth through the soil (USEPA, 1998e; Chaineau et al., 2003). Optimal biodegradation occurs between 20 and 40 °C.

The cost of biopiles is dependent on the contaminant, the procedure used, pre- or post-treatment, or the need for emission control equipment. It requires few personnel for operation and maintenance. The typical cost associated with this treatment can range from $130 to $260 US per cubic yard (FRTR, 1999l).

2.8. Phytoremediation

Phytoremediation uses plants to clean up contaminated soils and groundwater. This process takes advantage of the ability of plants to take up, accumulate, and/or degrade constituents that are present in soil and water environments (GWRTAC, 1996d). All plants extract necessary components, including nutrients and heavy metals, from these environments. Some plants are referred to as hyperaccumulators as they have the ability to store large amounts of these metals that do not appear to be used in their function. Plants have also been known to take up various organics and either degrade or process them for use in physiological processes (GWRTAC, 1996d; Erickson et al., 1999; Vouillamoz and Milke, 2001). Barter (1999) has presented a good overview of phytoremediation of contaminated soils. It mainly outlines the five basic phytoremediation techniques: rhizofiltration, phytoextraction, phytotransformation, phytostimulation, and phytostabilization. In another effort, Pulford and Watson (2003) have presented state-of-the-art review of phytoremediation of heavy metal-contaminated land using trees.

There are five basic types of phytoremediation: (1) rhizofiltration, a water remediation technique in which contaminants are taken up by the plant's roots; (2) phytoextraction, which involves the uptake of contaminant from the soil; (3) phytotransformation, which is applicable to both soil and water and involves the degradation of contaminants through plant metabolism; (4) phytostimulation or plant-assisted bioremediation, which involves the stimulation of microbial degradation through the activities of plants in the root zone; and (5) phytostabilization, which uses plants to reduce the migration of contaminants through the soil medium (GWRTAC, 1996d).

Small-scale experiments indicate that phytoremediation can clean up a number of different contaminants. Further research and development are needed to ascertain this fact and to broaden the use and acceptance of phytoremediation as a remediation technology option (USEPA, 1996g; RAAG, 2000; Rai and Singhal, 2003; Alkorta and Garbisu, 2001).

2.8.1. Discussion

Phytoremediation has been applied to a number of contaminants in small-scale field and/or laboratory studies. These contaminants include heavy metals, radionuclides, chlorinated solvents, petroleum hydrocarbons, PCBs, PAHs, organophosphate insecticides, explosives, and surfactants (Nedunuri et al., 2000).

Important observations related to the performance of phytoremediation technology are:

- Remediation is accomplished with minimal environmental disturbance.
- It is an aesthetically pleasing and passive, solar energy-driven technology.
- It can be used on a large range of contaminants.
- The generation of secondary wastes is minimal.
- Organic pollutants may be converted to CO_2 and H_2O instead of transferring toxicity.
- It is cost-effective for large contaminated sites (with a low concentration of contaminants).
- The topsoil is left in a usable condition and may be used in agriculture.
- The soil can remain at a site after the removal of the contaminant rather than being disposed of or isolated.
- The uptake of contaminated groundwater can prevent the migration of contaminants.
- Remediation usually requires more than one growing season.
- Treatment is limited to soils less than one meter from the surface and groundwater less than 3 m from the surface.
- Climate and hydrologic conditions such as flooding and drought may restrict plant growth and the type of plants that can be utilized.
- Contaminants may enter the food chain through animals which eat the plants used in these projects.
- Require special disposal of the used plants.

The cost of remediation of one acre of soil contaminated with lead to a depth of 50 cm is estimated to be from

$60,000 US to $100,000 US. In comparison, excavating and landfilling the same soil volume would cost from $400,000 US to $1,700,000 US (FRTR, 1999m).

2.9. Bioslurry systems

This ex situ biological treatment requires excavation of contaminated soil. It is accomplished by combining the excavated soil with water and other additives. In this system the bacteria selected for breaking down the contaminant is also added. The excavated soil is treated in a controlled bioreactor where the slurry is mixed to keep the solids suspended and the microorganisms in contact with the contaminants. In these reactors, biodegradation occurs at a rapid rate, with typical treatment times ranging from less than 1 month to more than 6 months (RAAG, 2000). After the process is completed, the slurry is dewatered and treated soil disposed (FRTR, 1999o; Zhang et al., 2001).

2.9.1. Discussion

Bioslurry/bioreactors are successful in treating non-halogenated SVOCs and VOCs in excavated soils or dredged sediments. Other contaminants include ordinance compounds, pesticides, and PCBs. Some of these compounds require the addition of specific bacteria or the use of anaerobic/aerobic reactors for biodegradation (FRTR, 1999o; Riser-Roberts, 1998; Zhang et al., 2001; Kuyukina et al., 2003).

Important observations related to the performance of bioslurry technology are:

- Bioslurry/bioreactors are technically simple, and pellet formation can be avoided during dry treatment.
- It works on most petroleum types.
- It is relatively simple and versatile.
- It is more effective than bioremediation.
- Closed systems allow the control of temperature, moisture, pH, oxygen, nutrients, addition of surfactants, supplementation of microorganisms, monitoring of reactions and conditions, and the control of VOC emissions.
- Excavation is required.
- Non-homogeneous and clayey soils can cause serious handling problems.
- In the case of free product, removal is necessary.
- Dewatering of fine soils after treatment can be expensive.
- A disposal method is needed for non-recycled wastewater.
- It may require extensive site and contaminant characterization (chemical reactivity, vapor pressure, biodegradability, etc.).

Treatment using bioslurry/bioreactors ranges from $130 US to $200 US per cubic meter. When further gas treatment is required because of the presence of volatile compounds, the cost increases (FRTR, 1999o). The price for capital, equipment, design, and construction of these systems ranges from $125,000 US to $2,000,000 US (Riser-Roberts, 1998; Zhang et al., 2001).

2.10. Bioventing

The bioventing process injects air into the contaminated media at a rate designed to maximize in situ biodegradation and minimize or eliminate the off-gassing of volatilized contaminants to the atmosphere. Unlike biosparging, which involves pumping air and nutrients into the saturated zone, bioventing pumps the air only into the unsaturated or vadose zone (USEPA, 1998d; Mihopoulos et al., 2001). Bioventing also degrades less volatile organic contaminants and, because a reduced volume of air is required, it allows for the treatment of less permeable soils (FRTR, 1999k). Baker and Moore (2000) have studied the optimized performance and effectiveness of in situ bioventing. Mihopoulos et al. (2002) and Diele et al. (2002) have discussed numerical models and their applications in bioventing system design and operation. A simplified sketch of the process is depicted in Fig. 4.

2.10.1. Discussion

Any aerobic degradable substance can be treated by bioventing and ultimately biodegradation. This technology is successful with a variety of petroleum products. Bioventing is most successful on mid-weight petroleum products like diesel since lighter products tend to volatilize quickly and can be treated better with SVE, while the heavier products generally take longer to biodegrade. If the contaminant has to be cleaned to a level lower than 0.1 ppm or if TPH has to be reduced to greater than 95%, a pilot study is needed to evaluate the appropriateness of bioventing at that site or another technology should be considered (USEPA, 1998d; Kao et al., 2001).

Important observations related to the performance of bioventing technology are:

- Equipment is readily available and easy to install.
- It requires short treatment times, from 6 months to 2 years.
- It is easy to combine with other technologies.
- It may not require off-gas treatment.
- High concentrations of contaminants may be toxic to organisms.
- It cannot be applied to certain site conditions (low permeability, high clay content, etc.).
- It cannot always reach low cleanup limits.
- It is effective only in unsaturated soils; other methods are needed for the saturated zone.

Bioventing is cost-competitive and ranges from $30 US to $90 US/t of contaminated soil (USEPA, 1995a; FRTR, 1999k).

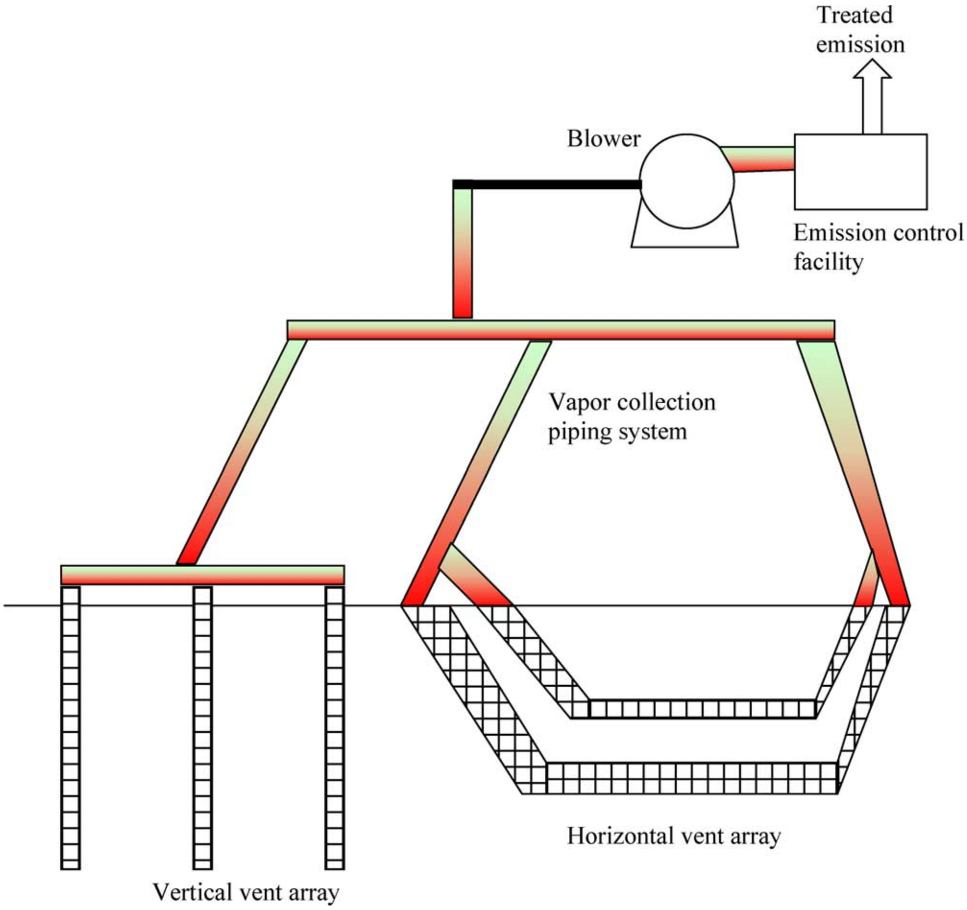

Fig. 4. Bioventing process.

2.11. Encapsulation

Encapsulation is a remedial alternative comprised of the physical isolation and containment of the contaminated material. In this technique, the impacted soils are isolated by low permeability caps, slurry walls, grout curtains, or cut-off walls. The contaminant source is covered with low permeability layers of synthetic textiles or clay caps designed to limit the infiltration of precipitation and thus prevent leaching and migration of contaminants away from the site and into the groundwater (Asante-Duah, 1996; Anderson and Mitchell, 2003; Robertson et al., 2003).

2.11.1. Discussion

An isolation and containment system can work adequately, but there is no guarantee as to the destruction of the encapsulated contaminant (Mitchell and Potter, 1999).

Important observations related to the performance of encapsulation technology are:

- The efficacy of encapsulation is highly dependent on the lithology of the site.
- The efficiency of encapsulation decreases with time and cannot be considered a permanent remedy.
- It is implemented only with shallow contaminated soils.

The cost of implementing this technology is dependent on the lithology of the site and the depth of the contaminant. As the depth of contamination increases, so does cost.

2.12. Aeration

This technology evaporates the volatile components of petroleum from the soil into the air. It is a well-developed process in which the area of contact between the water and the air is increased (FRTR, 1999n). The contaminated soil is spread thinly and tilled or turned to increase the rate of evaporation. The disadvantage of this method is that it should not be employed in urban areas or other locations where organic vapors could cause health, fire, or nuisance hazards. The collected vapors also require further treatment. Aeration is often placed lower on the hierarchy of treatment technologies than those that destroy the contaminants. In the groundwater, aeration brings about contact between the air and the water to promote biological degradation. It may be employed in activated sludge, rotating biological contactors, trickling filters and biological lagoons (FRTR, 1999n). Many configurations may promote aeration including jets to blow air into the water or mechanical aeration devices that propel water droplets through the air (Nakhla and Lugowski, 2003).

2.12.1. Discussion

The group of contaminants targeted by aeration includes SVOCs, pesticides, and fuels. VOCs may also be treated by aeration, followed by some off-gas treatments. Aeration may also be used for the reduction of odors (FRTR, 1999n; Fonade et al., 2000; Boyle, 2002).

There are several limitations associated with the use of aeration (FRTR, 1999n):

- It cannot be used with contaminants with a high VOC content without some off-gas treatment.
- Vapors may cause health, fire, and nuisance hazards.

Aeration costs depend on the volume of oil treated; for example, one US Navy spill cost about $14,000 US per cubic yard of soil (FRTR, 1999n).

3. Groundwater treatment technologies

3.1. Air sparging

In situ air sparging has been used for the past 15 years for the remediation of VOCs dissolved in groundwater, sorbed to the saturated zone soils, and trapped in the pores of the saturated zone (Suthersan, 1997; Benner et al., 2002; Adams and Reddy, 2003). It involves injecting atmospheric air, under pressure, into the saturated zone to volatilize groundwater contaminants and to promote biodegradation by increasing subsurface oxygen concentrations (GWRTAC, 1996a; Biorem, 1998; Benner et al., 2002). The injected air forms channels through the contaminated plume as it flows upwards through the saturated zone and into the vadose zone (Fig. 1). The injected air volatilizes the contaminants in the flow channels and transports them to the vadose zone where they are either biodegraded or removed by a SVE system (Kirtland and Aelion, 2000). Three contaminant removal mechanisms that occur during air sparging include: (1) in situ stripping of dissolved VOCs, (2) volatilization of trapped and sorbed contaminants present below the water table in the capillary fringe, and (3) aerobic biodegradation (Nyer, 1996). Air sparging offers a means of remediating contaminated soils and groundwater without the need for active groundwater pumping (Bass et al., 2000). This technology addresses a broad range of volatile and semi-volatile soil and groundwater contaminants including gasoline and other fuel components and chlorinated solvents (GWRTAC, 1996a).

3.1.1. Discussion

According to the sources reviewed, those sites with relatively permeable, homogeneous soil conditions due to greater effective contact between the injected air and the media being treated and the effective migration/extraction of volatilized vapors favor the use of air sparging (GWRTAC, 1996a; Bass et al., 2000; Benner et al., 2002; Adams and Reddy, 2003; Tomlinson et al., 2003). Other site factors that influence the applicability of air sparging include the thickness of the saturated zone and the depth of the groundwater. For example, if the thickness of the saturated zone is small and the depth of groundwater is shallow, the number of wells required for adequate coverage could become expensive for such a remediation project (Suthersan, 1997; Adams and Reddy, 2003; Tomlinson et al., 2003).

Important observations related to the performance of air sparging technology are:

- Silt and clay sediments are not appropriate for this technology (Kirtland and Aelion, 2000).
- Heterogeneous geologic conditions, with the presence of low permeability layers overlying zones of higher permeability, reduces the effectiveness of the system.
- This technology is ineffective in the case of non-strippable and non-biodegradable contaminants (Suthersan, 1997; Bass et al., 2000; Benner et al., 2002).
- This technology is inefficient if the vertical passage of air becomes hampered while the lateral movement is being increased.

The remediation costs for the treatment of petroleum-contaminated soil/groundwater using air sparging technologies ranges somewhere between $20 US and $50 US per cubic yard of soil (USEPA, 1995a).

3.2. Groundwater pump-and-treat technology

During the last decade, much attention has been focused on the remediation of contaminated aquifers. One of the most common technologies for the cleanup of a contaminated aquifer is pump-and-treat (Bear and Sun, 1998; Illangasekare and Reible, 2001; Theis et al., 2003), where extraction wells are introduced at various locations in a contaminated aquifer, and the contaminants are removed with the pumped water. Contaminants are subsequently removed from the pumped water by various treatment technologies (Mackay and Cherry, 1989; Zheng and Wang, 2002). Once treated, the groundwater is either re-injected into the aquifer or discharged into a surface water body, such as a lake or river, or into municipal sewage plants. Pump-and-treat systems can be designed to meet two different objectives: to prevent the contaminant from spreading, and to remove the contaminant mass (Suthersan, 1997; Illangasekare and Reible, 2001; Bayer et al., 2002). Today, pump-and-treat systems are no longer considered the best or most popular choice among groundwater remediation systems because of the time required to achieve cleanup goals and the ineffectiveness of the system. Although pump-and-treat systems are widely criticized for their inefficiencies, they are still useful, especially in areas with significant contamination (Moyers et al., 1997; Illangasekare and Reible, 2001; Bayer et al., 2002).

One or more recovery wells are installed in a contaminated plume of groundwater. Water is pumped from the aquifer to the surface where it is treated by standard water treatment operations (Pacific Northwest National Laboratory, 1994; Zheng and Wang, 2002). The network of recovery wells is generally designed to capture water from the center (high concentration area) of the plume for rapid mass removal, and from the leading edge of the plume to minimize the plume spread (National Research Council, 1994). The application of surfactants to the groundwater can facilitate the groundwater pumping process by increasing the mobility and solubility of the contaminants sorbed to the soil matrix. The implementation of surfactant-enhanced recovery requires the injection of surfactants into the contaminated aquifer (FRTR, 1999g; Theis et al., 2003).

3.2.1. Discussion

The first step in determining whether pump-and-treat technologies are appropriate for the remediation of contaminated groundwater is to conduct a site characterization investigation. Site characteristics include parameters such as hydraulic conductivity, transmissivity, and hydraulic gradient which are used to determine the number of wells required, their location, and the pumping rates (FRTR, 1999g). Pump-and-treat systems can be applied to sites that contain groundwater contaminated with a variety of dissolved materials including VOCs, SVOCs, fuels, and dissolved metals (CPEO, 1998c). It is important to note that pump-and-treat technologies are not applicable to fractured rock or clay sites, and it is a relatively poor choice for contaminants that adsorb to soils or those with low solubilities (Pacific Northwest National Laboratory, 1994; Zheng and Wang, 2002).

Important observations related to the performance of pump-and-treat technology are:

- It is simple to design and operate.
- Equipment is easily available.
- It treats all types of dissolved (mobile) contamination.
- Implementation is quick.
- It is compatible with other remediation technologies such as vacuum extraction, air sparging, and air stripping (Pacific Northwest National Laboratory, 1994).
- Site disturbance is minimal. It leaves a small 'footprint' upon the landscape compared to other remediation technologies.

Remediating contaminated groundwater with pump-and-treat technologies may not be the most efficient cleanup method, but it is the most common. Its chief limitations include (Illangasekare and Reible, 2001):

- It often takes a long time (e.g. 5–50 years) to meet the cleanup goals (CPEO, 1998c).
- It is not applicable to fractured rock or clay soils.
- In most cases drinking water standards are not reached.
- It is not effective for contaminants that adsorb to soils (Pacific Northwest National Laboratory, 1994).
- The cost of pump-and-treat projects tends to be high.
- It is very effective in hard water.

Cost data varies greatly from site to site. Typical system installation costs (site preparation, design, and equipment for a 100 gal/min system), based on full-scale field demonstrations and operations experience, are approximately \$200,000 US for design and installation of the system (assume three 200-foot-deep recovery, and the necessary support equipment and surface treatment). The most significant cost is the operating cost (energy, maintenance, etc.) for the surface treatment units, which traditionally ranges from \$1 US to \$100 US per 1000 gal of groundwater, depending on the site and the contaminant characteristics (Pacific Northwest National Laboratory, 1994). It is therefore important to investigate a site carefully before choosing pump-and-treat technologies as the major remediation alternative.

3.3. Passive/reactive treatment walls

The use of in situ treatment walls for remediation is an emerging technology that has been developed and implemented only within the last few years. Treatment walls are structures installed underground to treat the contaminated groundwater found at hazardous waste sites (Suthersan, 1997; Birke et al., 2003; Baciocchi et al., 2003). Treatment walls rely on the natural movement of water to carry the contaminants through the wall structure (Nyer, 1996). As contaminated groundwater passes through the treatment wall, the contaminants are either trapped by the treatment wall or transformed into harmless substances that flow out of the wall (USEPA, 1996d). Target contaminant groups for passive treatment walls are VOCs, SVOCs, and inorganics (FRTR, 1999c). The specific filling chosen for the wall is based on the contaminant found at the site (RAAG, 2000; Birke et al., 2003). Guerin et al. (2002) have discussed an interesting application of reactive barrier technology to petroleum hydrocarbon contaminated groundwater. Woinarski et al. (2003) have investigated the effects of cold temperature on copper ion exchange by natural zeolite for use in a permeable reactive barrier in Antarctica.

Wall fillings work through different chemical processes, of which the three most common are (USEPA, 1996d; Birke et al., 2003):

- *Sorption barriers* contain fillings that remove contaminants from the groundwater by physically removing contaminants from the groundwater and holding them on the barrier surface. Zeolites and activated carbon are two examples of sorption barriers (Woinarski et al., 2003).

- *Precipitation barriers* contain fillings that react with contaminants in the groundwater as they pass through the treatment wall. The reactions cause the contaminants dissolved in groundwater to become insoluble and to precipitate out. The barrier traps the insoluble products and clean groundwater flows out the other side.
- *Degradation barriers* cause reactions that break down the contaminants in the groundwater into harmless products. Filling walls with iron granules helps to degrade certain VOCs, and walls filled with a mixture of nutrients and oxygen sources can stimulate the activity of the microorganisms found in the groundwater (Guerin et al., 2002).

Two main types of treatment walls

- *Permeable reactive trench*: this is the simplest form of treatment walls and it consists of a trench that extends across the entire width of the plume. The system is installed by digging a trench and filling it with permeable material. As the contaminant plume moves through the wall, contaminants are removed by various mass transfer processes such as air stripping, SVE, and adsorption (Suthersan, 1997; Guerin et al., 2002; Birke et al., 2003; Baciocchi et al., 2003).
- *Funnel and gate systems*: Used primarily when contaminated plumes are too large or too deep to dig a trench across its width. To overcome this problem, a system consisting of low permeability cut-off walls are installed to funnel contaminated groundwater to a smaller reactive wall to treat the plume. When dealing with funnel and gate systems, the gate is used to pass contaminated groundwater through the reactive wall, and the funnel is integrated into the system to force water through its gates. Plumes which contain a mixture of contaminants are funneled through a gate with multiple reactive walls in series (Nyer, 1996).

3.3.1. Discussion

Treatments walls are often used for groundwater contaminated with VOCs, SVOCs, and inorganics. This technology is ineffective in treating other fuel hydrocarbons (FRTR, 1999c; Birke et al., 2003; Baciocchi et al., 2003).

Important observations related to the performance of passive/reactive treatment technology are:

- It is limited to a subsurface lithology that has a continuous aquitard at a depth that is within the vertical limits of the trenching equipment.
- Passive treatment walls have a tendency to lose their reactive capacity over time, and require replacement of the reactive medium.
- Large and deep plumes are more difficult to remediate than small and shallow plumes.

The complete cost of using treatment walls to remediate contaminated groundwater is not available. However, the cost is believed to be dependent on the reactive media and the contaminant concentration in the groundwater.

3.4. Bioslurping

Bioslurping is a new in situ remediation technology that combines elements of bioventing and vacuum-enhanced pumping to recover free product from the groundwater and soil while promoting the aerobic bioremediation of hydrocarbon contaminants (CPEO, 1998a; FRTR, 1999d). Vacuum extraction/recovery removes free product along with some groundwater; vapor extraction removes high volatility vapors from the vadose zone; and bioventing enhances biodegradation in both the vadose zone and the capillary fringe (GWRTAC, 1996a; Midwest Research Institute, 1998; Yen et al., 2003). The bioslurping system consists of well(s) into which an adjustable length ‘slurp tube’ is installed. The slurp tube is lowered into the light non-aqueous phase liquid (LNAPL) layer, connected to a vacuum pump, and removes free product along with some groundwater. When LNAPL levels decline slightly in response to pumping, the slurp tube extracts vapors (vapor extraction). The liquids (product and groundwater solution) removed from the slurp tube are sent to an oil/water separator, and the vapors to a liquid/vapor separator (GWRTAC, 1996a; Cresap, 1999). In addition, the extraction of vapors through the slurp tube promotes aeration of the unsaturated zone; it increases the oxygen content and therefore the rate of aerobic degradation (GWRTAC, 1996b; FRTR, 1999d; RAAG, 2000).

3.4.1. Discussion

Bioslurping, designed to address floating LNAPL layers, is used most often at sites with fine- to medium-grained overburden materials, but it is also used successfully at sites with medium- to coarse-grained materials and in fractured rock (GWRTAC, 1996b). It can be applied at sites with shallow groundwater as well as sites with the groundwater below 30 m (Midwest Research Institute, 1998; Cresap, 1999; Yen et al., 2003).

Important observations related to the performance of bioslurping technology are:

- Bioslurping recovers free product, thus speeding remediation (Midwest Research Institute, 1998; FRTR, 1998d; Yen et al., 2003).
- Bioslurping reduces aquifer ‘smearing’. Smearing can increase the vertical extent of contamination in the aquifer by introducing contaminants into saturated soils as LNAPL travels deeper into the aquifer on the lowered water table (GWRTAC, 1996b; Cresap, 1999).
- Bioslurping enhances natural in situ bioremediation of the vadose zone soils (Midwest Research Institute, 1998).

- Bioslurping is ineffective in low permeability soils.
- Too much soil moisture reduces the air permeability of soil and decreases its oxygen transfer capability; too little moisture inhibits microbial activity.
- Low temperatures slow remediation.
- Extracted groundwater and air emissions from the bioslurper may require treatment before discharge (CPEO, 1998a).

As compared to most other LNAPL remediation systems, bioslurping is considered to be cost-effective. The reduction in the amount of extracted groundwater and the ability to extract soil–gas at concentrations below the regulatory limits minimizes storage, treatment, and disposal costs, thus reducing project costs (GWRTAC, 1996b; FRTR, 1998d; Cresap, 1999).

3.5. Ultraviolet-oxidation treatment

Ultraviolet (UV)-oxidation treatment methods represent one of the most important technologies emerging as a viable treatment for groundwater remediation. These systems generally use an oxygen-based oxidant (e.g. ozone or hydrogen peroxide) in conjunction with UV light. In this process UV bulbs are placed in a reactor where the oxidant comes in contact with the contaminants in the groundwater (Asante-Duah, 1996; Brillas et al., 2003; Liang et al., 2003). UV-oxidation has two basic forms:

- *UV–peroxide systems*: High intensity UV lights catalyze the formation of hydroxyl radicals from hydrogen peroxide. Under controlled conditions, the hydroxyl radicals react with the contaminants and oxidize the chemicals into less harmful compounds. This reaction may be aided by the ability of UV light to loosen some of the bonds in the organic contaminants and make them easier to destroy. With sufficient exposure to light and oxidation, the final product will be water, carbon dioxide, and the appropriate inorganic salt (USEPA, 1995a; GWRTAC, 1996c; Asante-Duah, 1996; Brillas et al., 2003).
- *UV–ozone systems* utilize the strong oxidizing properties of UV light and ozone. UV light and ozone act synergistically to oxidize the contaminants.

3.5.1. Discussion

This technology is applicable to all types of petroleum products. It also works on VOCs, SVOCs, aromatics, alcohols, ketones, aldehydes, phenols, ethers, pthalates, glycols, pesticides, ordinance compounds, dioxins, PCBs, PAHs COD, BOD, TOC and various other forms of organic carbons (GWRTAC, 1996c).

There are two advantages to use this technology: (1) the chemicals used do not add to the system's pollutant load; and (2) it is successful with substances such as ferricyanides on which other methods have failed (GWRTAC, 1996c; Liang et al., 2003).

Limitations to this technology include (GWRTAC, 1996c):

- When using H_2O_2, the process is only efficient at low wavelengths.
- Low turbidity and suspended solids are necessary for good light transmission.
- The presence of free radical scavengers may interfere with the reactions.
- The water may have to be treated for heavy metals, insoluble oil and grease, high alkalinity and carbonates to reduce fouling of the UV quartz sleeves.
- Ongoing treatment may be necessary to reduce future cleaning of the sleeves.
- The storage and handling of oxidizers may require special precautions.
- There may be potential air emission problems associated with the use of ozone.

Several factors affect the cost of this treatment: the degree of contaminant destruction required, the flow rate of the groundwater system, the type and concentration of the contaminants, and the requirement for pre- and post-treatment. The estimated cost of using this technology ranges from \$10 US-\$50 US per 1000 gal of water treated.

3.6. Biosparging

The rationale behind biosparging is that air and nutrients are injected into the soil below the water table where it will enhance the degradation of contaminants by naturally occurring organisms (USEPA, 1995a; Muehlberger et al., 1997; Brown et al., 1999). This in situ technology generally uses microorganisms that are indigenous to the area. It can be used on petroleum products dissolved in groundwater, or adsorbed to the soil below the water table and within the capillary fringe. It has often been used in conjunction with SVE, especially when volatiles are present (USEPA, 1998c; Muehlberger et al., 1997; RAAG, 2000).

3.6.1. Discussion

Biosparging can be used at most types of petroleum-contaminated sites, but it is least effective on heavy petroleum because of the length of time required (USEPA, 1995a). It is used most often at sites with mid-weight and lighter petroleum. Heavier products such as lubricating oils tend to take longer, but this does not mean that this technology cannot be employed for them (USEPA, 1998c; Muehlberger et al., 1997; Brown et al., 1999).

Important observations related to the performance of biosparging technology are:

- The equipment is readily available and easy to install.
- It is implemented with little disturbance to site operations.

- Treatment times are short, often from 6 months to 2 years.
- It often enhances the effectiveness of air sparging.
- It requires no removal, treatment, storage or discharge of groundwater.
- Low injection rates reduce the need for vapor capture and treatment.
- It can only be used in areas where air sparging is suitable, for example, with uniform permeable soils, unconfined aquifers, and no free phase hydrocarbons.
- Some interactions between complex chemical, physical and biological processes are not well understood.
- There is a shortage of field and laboratory data to support design considerations.
- There is some potential for the migration of contaminants.

Bioparging cannot be applied to areas where free product is present since it creates groundwater mounding which could lead to contamination migration. There are limitations to the use of biosparging if basements, sewers, or other confined subsurface spaces are present. Dangerous vapors, which may accumulate in these basements, can be remediated with vapor extraction systems. Biosparging cannot be used when the contaminant is in a confined aquifer since the confining layer traps the air (USEPA, 1998c; Brown et al., 1999). The cost of biosparging is defined as ‘cost-competitive’ (USEPA, 1998c).

3.7. Groundwater circulation wells

Groundwater circulation wells is a new and developing technology used for removing contaminants from groundwater and saturated soils (USEPA, 1998f). It is relatively simple in design and has low maintenance requirements. Synonyms for groundwater circulation wells include in-well vapor stripping, in-well air stripping, in situ vapor stripping, in situ air stripping, and vacuum vapor extraction. The process of groundwater circulation continuously removes VOCs from the groundwater without bringing it to the surface. This circulation pattern is created in an aquifer by drawing water into and pumping it through a well and then reintroducing it without reaching the surface. The well is double cased with upper and lower screening intervals. The most common configuration of these wells involves the injection of air through the inner casing, thereby decreasing the density of the groundwater and allowing it to rise. In the rising process, the groundwater passes through the lower screening interval and is partially stripped of volatile compounds. The groundwater then moves upward in the inner casing. It is eventually moved to the outer casing by passing through the upper screening interval to the vadose zone. Once in the subsurface, the de-contaminated groundwater flows down to the lower portion of the aquifer and replaces the water which has risen due to the density gradient. This creates a hydraulic circulation pattern which allows the remediation of contaminated groundwater.

3.7.1. Discussion

The target contaminant groups for this technology are halogenated VOCs, SVOCs, and fuels. Little modifications in the conventional circulation well technology can make it available for other contaminants as well (FRTR, 1999p). A more complete list of contaminants to which circulation wells may be applied include: non-halogenated VOCs; petroleum products and their constituents such as benzene, toluene, ethylbenzene and xylene; halogenated VOCs; SVOCs; pesticides; and other inorganics (FRTR, 1999p).

Important observations related to the performance of circulation wells technology are:

- This technology is successful in most soil types (USEPA, 1998f).
- It is inefficient in areas with strong natural flow patterns.
- It is ineffective in areas with hydraulic conductivities less than 10^{-5} cm/s.
- Shallow aquifers may limit the effectiveness of this technology.
- Infiltrating precipitation with oxidizing constituents may foul the system.
- It requires a well-defined contaminant plume to prevent spreading or smearing of the contaminant.
- It is inapplicable for sites containing NAPLs.

3.8. Horizontal well technology

Horizontal well technology was originally developed for use in petroleum production and underground utility installation, but it has recently been adapted for environmental remediation application. This technology is currently used in environmental remediation applications such as in situ bioremediation, air sparging, vacuum extraction, soil flushing, and free product recovery. Two general types of horizontal wells have been applied to remediation activities: trenched and directionally-drilled. The drilling of trenched horizontal wells involves the excavation of a relatively large diameter borehole, with simultaneous installation of well materials and backfill. Directional drilling of a horizontal well produces a smaller diameter borehole and is more similar to vertical well installation (GWRTAC, 1996e).

3.8.1. Discussion

The ‘steering’ capability associated with some horizontal well drilling technologies allows for installation in areas containing underground utilities, vertical wells, and other subsurface obstructions. Horizontal wells can be installed beneath buildings and other surface structures, allowing access for treatment of areas generally inaccessible to vertical wells.

Important observations related to the performance of horizontal well technology are:

- It can be adopted to many in situ remediation technologies.
- There is a five fold increase in contaminant removal rate compared to the use of vertical wells.
- It requires fewer wells to achieve similar remediation goals due to the greater surface area of contact between the screen and the contaminated media.
- It is more efficient because the configuration of these wells is more consistent with natural conditions, since groundwater transmissivity is generally greater in the horizontal rather than vertical direction.
- There is minimum disturbance to the site.
- The application of this technology is reported only to the limited depth; as the contaminant depth increase, the efficacy of the technology decreases.
- It is unable to recover free product in the areas of large water table fluctuations

The cost of horizontal well installation varies with site-specific factors, with estimates from $5000 US to $850,000 US per well. The price per foot estimate ranges from $25 US to $85 US, and per day from $1500 US to $15,000 US (GWRTAC, 1996e).

3.9. Natural attenuation

Natural attenuation, also known as passive remediation, in situ bioremediation, intrinsic remediation, bioattenuation, and intrinsic bioremediation, is an in situ treatment method that uses natural processes to contain the spread of contamination from chemical spills and to reduce that concentration and amount of pollutants at contaminated sites. This means the environmental contaminants are undisturbed while natural attenuation works on them. Natural attenuation processes are often categorized as destructive or non-destructive. Destructive processes destroy the contaminant, while non-destructive processes cause a reduction in contaminant concentrations (USEPA, 1996c). This remediation technology is often mislabeled as the ‘do nothing’ or ‘walk away’ approach to site cleanup. Natural attenuation is a proactive approach that focuses on the verification and monitoring of natural remediation processes rather than relying totally on ‘engineered’ processes (DENIX, 1995; Wiedemeier et al., 1999; Khan and Husain, 2002; 2003). Before natural attenuation can be proposed for a site, soil and groundwater samples must be collected and analyzed to document that natural attenuation is occurring and to estimate the effectiveness of natural processes in reducing contaminant concentrations over time.

Natural attenuation processes may reduce contaminant mass (through processes such as biodegradation); reduce concentrations (through simple dilution or dispersion); or bind contaminants to soil particles to prevent contaminant migration (adsorption) (USEPA, 1996c; Khan and Husain, 2003).

- *Dilution/dispersion*: As contaminants mix with soil and groundwater over time, their concentrations are reduced (DENIX, 1995). As mentioned above, this process does not destroy the contaminants.
- *Adsorption*: occurs when contaminants attach or sorb to underground soil particles. Fuel hydrocarbons are hydrophobic and when they are given the opportunity to escape from the groundwater by attaching to organic matter and clay minerals that also repel water, they tend to do so. This prevents the contaminants from migrating into an area where they might pose a threat to human health and the environment (USEPA, 1996c).
- *Biodegradation/bioremediation*: is a process in which naturally occurring microorganisms (i.e. yeast, fungi, or bacteria) break down or degrade hazardous substances into less toxic or non-toxic substances. Many organic contaminants such as petroleum can be biodegraded by microorganisms in the underground environment (USEPA, 1996c). Natural bacteria in soil and groundwater will use petroleum compounds as their primary source of energy, thus biodegrading the compounds during the process (DENIX, 1995). There are three processes by which microorganisms aid in the breakdown of hydrocarbons: fermentation, aerobic respiration, and anaerobic respiration (Canter and Knox, 1985). During fermentation, carbon, the energy source, is broken down by a series of enzyme-mediated reactions that do not involve an electron transport chain. In fermentation, organic compounds can act as both electron donors and acceptors (Riser-Roberts, 1992). During aerobic respiration, microorganisms use available oxygen in order to function (USEPA, 1996h). In aerobic respiration, carbon, the energy source, is broken down by a series of enzyme-mediated reactions, in which oxygen serves as an external electron acceptor (Riser-Roberts, 1992). Anaerobic conditions support microbial activity without oxygen present, so the microorganisms break down chemical compounds in the soil to release the energy it needs (USEPA, 1996h). In anaerobic respiration, carbon, the energy source, is broken down by a series of enzyme-mediated reactions in which nitrates, sulfates, carbon dioxide, and other oxidized compounds (excluding oxygen) serve as electron acceptors (Riser-Roberts, 1992; Wiedemeier et al., 1999; Khan and Husain, 2002; 2003).

3.9.1. Discussion

In situ bioremediation technologies are potentially effective in degrading or transforming a large number of organic compounds to environmentally acceptable or less mobile compounds (USEPA, 1990). The classes of compounds considered to be amenable to biodegradation include petroleum hydrocarbons (e.g. gasoline and diesel

Table 1
A brief review of recent soil remediation case studies

Site	Contaminant	Highlights
Landfarming		
Brown Wood Preserving Superfund Site, FL	PAH	About 8100 yd^3 soil treated Six carcinogenic PAHs reduced from 100–280 to 23–92 mg/kg Estimated cost \$70 yd^3 Project completed in 8 months
Lowry Air Force Base, CO	BTEX and TPH	TPH reduced from 11,000 to 100 mg/kg On target with \$104,257 capital cost and \$18,460 annual operating cost
Scott Lumber Company Superfund Site, MO	PAH	15,916 t soil treated in about 22 months Sixteen PAHs reduced from 560–700 to 135–155 mg/kg Operating cost estimated as \$81/t of soil treated
Bioventing		
Eielson Air Force Base, AK	BTEX and TPH	Various soil warming techniques used for demonstration purposes Site still operative \$758,077 capital cost incurred Annual operating cost \$177,160
Hill Air Force Base, Site 280, UT	BTEX and TPH	Optimized air flow rates maximize bioremediation while minimizing volatilization Only one injection well \$115,000 capital cost incurred Annual operating cost \$24,000 Presently maintained for natural attenuation
Hill Air Force Base, Site 914, UT	BTEX and TPH	Two years for site remediation System converted from SVE to bioventing after 1 year Four injection wells, relatively high concentration of contaminant Operational cost estimated as \$120/yd^3
Lowry Air Force Base, CO	BTEX and TPH	Excavated soil used for treatment Relatively shallow bioventing system Still on target with \$115,000 capital cost and \$24,000 annual operating cost
Soil vapor extraction with subsequent treatment		
Commencement Bay, South Tacoma channel well 12 A Superfund Site, WA	Chlorinated aliphatic	Demonstration project On target with 22 extraction wells and annual operating cost \$100,000
Fairchild Semiconductor Corporation Superfund Site, CA	Chlorinated and non-chlorinated aliphatic	Complex hydrology required pre-treatment of site About 42,000 yd^3 decontaminated 16,000 lbs contaminant removed in 16 months Operating cost \$93/yd^3 soil treated and \$240/lbof contaminant removed
Hasting Groundwater Contamination Superfund Site, NE	Chlorinated aliphatic	About 185,000 cubic yard soil treated in 12 months Ten extraction wells 600 lbs carbon tetrachloride removed, operating cost \$2/yd^3 soil treated
Hill Air Force Base, Site 914, UT	BTEX and/or TPH	SVE used for initial period, bioventing later used for remediation In 2 years of operation 5000 yd^3 soil treated and 211,000 lbs TPH removed Operating cost \$120/yd^3 soil treated

(*continued on next page*)

Table 1 (*continued*)

Site	Contaminant	Highlights
Luke Air Force Base, North Fire Training Area, AZ	BTEX and non-chlorinated aliphatic	With two extraction wells, cleanup operation completed in 14 months 12,000 lbs contaminant removed and about 14,200 lbs contaminant destroyed using thermal oxidation Operating cost estimated as $42/lb contaminant removed
Rocky Mountain Arsenal Superfund Site, CA	Chlorinated aliphatic	Pilot scale unit demonstrated in 6 months about 34,000 yd^3 soil decontaminated with two extraction wells 70 lbs contaminant removed, operating cost $2.20/yd^3 soil treated
Sacramento Army Depot Superfund Site, CO	BTEX and TPH	Eight extraction wells operated in complex hydrogeology with low permeability soil 650 yd^3 soil treated and 500 lbs VOC removed Operating cost estimated as $450/yd^3 soil treated
Verona Well Field Superfund Site, MI	Chlorinated and non-chlorinated aliphatic	First superfund application of SVE Twenty three extraction wells completed cleanup in 4 years 26,700 yd^3 soil treated and 45,000 lbs VOC removed, operating cost $60/yd^3 soil treated
Thermal desorption		
Anderson Development Company Superfund Site, MI	Chlorinated aliphatic and PAH	High moisture content in soil affected cleanup process About 5100 t soil treated in 18 months Project cost $230–$340/t soil treated
Mckin Superfund Site, ME	Chlorinated aliphatic, BTEX and PAH	Early full-scale application of thermal desorption 11,500 yd^3 soil treated Details of cost not available
Outboard Marine Corporation Superfund Site, OH	PCBs	Achieved PCB removal efficiency of 99.98% in 6 months (much higher than required) 12,755 tons soil and sediment treated at $190/t
Pristine, Inc, Superfund Site	Chlorinated aliphatic, pesticides, and PAHs	Decontamination of about 12,800 tons soil achieved in 14 months Contaminated soil exhibited wide range of pH, moisture and other parameters
T.H. Agriculture and Nutrition Company Superfund Site, GA	Pesticides	About 4300 t soil decontaminated in 4 months Operating cost estimated as $200/t soil treated
Wide Beach Development Superfund Site, NY	PCBs	Thermal desorption combined with APEG dechlorination Lack of structural integrity of treated soil required off-site disposal
Soil washing		
King of Prussia Technical Corporation Superfund Site, NJ	Chlorinated aliphatic and PAH	Early full-scale soil washing application About 19,200 t soil washed in 4 months Operation cost estimated as $75/t soil treated
In situ vitrification		
Parsons Chemical/ETM Enterprises, MI	Pesticides, metals and PAHs	First application at superfund site Required about 1 year to cool 3000 yd^3 soil treated with operating cost $270/yd^3 of soil treated
Bioslurping		
NAS Fallon, NV	BTEX	Removed 24 gal contaminant/day during operation with maximum removal rates 60 gal/day

fuel), non-chlorinated solvents, wood treating wastes, some chlorinated aromatic compounds, and some chlorinated aliphatic compounds (Boulding, 1996; Hejazi, 2002).

USEPA recognizes natural attenuation as a viable method of remediation for soil and groundwater, and its selection is often based on its ability to achieve remediation goals in a reasonable time frame and to be protective of human health and the environment (DENIX, 1995). In addition to USEPA acceptance, many state underground storage tank (UST) programs now accept natural attenuation as a valid approach to remediating petroleum-contaminated sites. Natural attenuation processes can effectively cleanse soil and groundwater of hydrocarbon fuels, such as gasoline and BTEX compounds (benzene, toluene, ethylbenzene, and xylene) (USEPA, 1996c; Hejazi, 2002). For example, in 1992, the Air Force initiated natural attenuation demonstrations at over 50 major fuel-contaminated sites. Four years later, the Air Force Center for Environment Excellence evaluated natural attenuation as a remedial option at the majority of its petroleum-contaminated sites (DENIX, 1995; Khan and Husain, 2002).

Important observations related to the performance of natural attenuation technology are:

- It is a relatively simple technology compared to other remediation technologies.
- It can be carried out with little or no site disruption.
- It often requires more time to achieve cleanup goals than other conventional remediation methods.
- It requires a long-term monitoring program; program duration affects the cost.
- If natural attenuation rates are too slow, the plume could migrate.
- It is difficult to predict with high reliability the performance of natural attenuation.

Sites must meet one or more of the following criteria:

- It must be located in an area with little risk to human health or to the environment.
- The contaminated soil or groundwater must be located an adequate distance from potential receptors (DENIX, 1995).
- There must be evidence that natural attenuation is actually occurring at the site.
- High permeability speeds contaminant spread, low permeability slows the breakdown. Ideally, natural attenuation works best in soils whose permeability ranks somewhere between high and low (USEPA, 1995a).

Natural attenuation is a cost-effective remediation technology. Its cost is primarily related to the costs of site evaluation and monitoring.

Table 1 (*continued*)

Site	Contaminant	Highlights
		About 6500 gal contaminant removed Cost details not available
Soil flushing		
Ninth Avenue Dump, MI	BTEX	Effectively completed Operating cost estimated as $65/yd^3 soil treated
Biopiles		
Umatilla Army Depot Activity Site, OR	Explosives	Field demonstration unit, about 20,000 t soil treated Operational cost estimated as $92/t soil treated, based on 5 years of treatment and compliance with RCRA
Bioslurry system		
French Ltd. Superfund Site, TX	Chlorinated aliphatic and PAHs	Large-scale treatment, about 300,000 t soil treated in 20 months Operational cost estimated as $90/t soil or sludge treated

Information derived from USEPA (1995b), NRMRL (1995), Bass et al. (2000), Kirtland and Aelion (2000), Lin et al. (2001), Johnston et al. (2002), and Anderson and Mitchell. (2003), and Filler et al. (2003).

Table 2
A brief review of recent groundwater remediation case studies

Site	Contaminant	Highlights
Air sparging with SVE		
Service Station, FL	BTEX	Six sparge wells Operated for about 47 months Concentration reduced from 24,000 to 10 μg/l Negligible rebound
AST Source, AK	BTEX	Twenty eight sparge wells operated for about 37 months Contaminant concentration reduced from 34,000 to 68 μg/l Little rebound observed
Fueling Station, NH	BTEX	Seven sparge wells operated for 13 months Contaminant reduced from 3270 to <5 μg/l No rebound observed
Amcor Precast, UT	BTEX and TPH	Air sparging combined with aerobic biodegradation Cleanup completed in about 18 months Total cost of project $219,700
Groundwater extraction followed by further treatment (pump-and-treat technology)		
Ft. Drum Dispensing Area 1595, NY	BTEX and TPH	Free product recovery On target with $958,780 capital cost and $129,440 annual operating cost
McClellan Air Force Base, Operational Unit B/C, CA	Chlorinated aliphatic	Large-scale cleanup Ten extraction wells 660 million gal groundwater treated in 7 years Approximately 44,000 lbs VOCs removed in 7 years Ongoing full-scale operation with $80/lb VOC removed
McClellan Air Force Base, Operational Unit D, CA	Chlorinated aliphatic	Large-scale cleanup Ten extraction wells 660 million gal groundwater treated in 7 years Approximately 44,000 lbs VOCs removed in 7 years On-going full-scale operation with $80/lb VOC removed
Twin City Army Ammunition Plant, MN	Chlorinated aliphatic	Large-scale cleanup efforts required Complex hydrogeology and wide range of hydraulic conductivity at site May take 50–70 years for complete remediation Ongoing full-scale cleanup with $0.12/1000 gal water treated
US Department of Energy Kansas City Plant, MO	BTEX, TPH, chlorinated aliphatic, and PAHs	Extracted groundwater treated using UV, ozone, and peroxide Presence of NPLs suspected Ongoing full-scale cleanup with operating cost $13.80/1000 gal water treated
US Department of Energy Savannah River Site, A/M area, SC	Chlorinated aliphatic	Contaminated groundwater covers 1200 acres at thickness of 150 ft with NPL 198 million gal water treated/year 273,000 lbs VOC removed 1985–1993 Ongoing full-scale operation at $0.75/1000 gal water treated
Groundwater circulation wells		
Keeseler Air Force Base, MS	BTEX and TPH	System operated for about 18 months, removed about 3449 lbs TPH Average concentration in monitoring well of TPH reduced by 87%, for BTEX reduced by 91% Total cost of project ~$360,000 ($100,000 for pilot study)

(continued on next page)

Table 2 (*continued*)

Site	Contaminant	Highlights
Port Hueneme Naval Exchange Site, CA	BTEX	Four circulation wells used for about 18 months for cleanup Concentration of BTEX in groundwater from deep wells reduced from 118 to <1 μg/l Total cost of project $184,000, excluding research and development cost
Tyndall Air Force Base, FL	TPH	Project operated about 12 months TPH concentration reduced from 15 mg/l to non-detectable Total project cost $80,000
Westinghouse Savannah river site, Aiken, SC	Chlorinated aliphatic	Two 8 in. diameter circulation wells installed In 14 months of operation, concentration of TCE reduced ~30–80% in zone of influence Total project cost ~$200,000
Top Stop Store, Park City, UT	TPH	Operation just above 2 years with six wells Concentration of contaminant in plume reduced more than 99% $99,000 for equipment installation, $34,000 for first-year operation and maintenance, and $12,000 for second-year operation and maintenance
Horizontal wells		
Savannah River Site, SC	Chlorinated aliphatic	Five-fold increase in contaminant removal rate compared to vertical wells 16,000 lbs chlorinated solvents removed over 20-week period 40% overall cost saving predicted compared to pump-and-treat methods
SMS Instruments Superfund Site, NY	Chlorinated and non-chlorinated aliphatic	1250 yd^3 soil treated using two extraction wells Cleanup completed in 17 months Operational cost estimated as $360/$\mathrm{yd}^3$ soil treated
Natural attenuation		
William Air Force Base, Site ST-12, AZ	TPH and BTEX	Natural biodegradation of dissolved hydrocarbons prevents migration of dissolved BTEX plume Anaerobic dominant mode of degradation Sulfate reduction predominant biodegradation pathway Analysis of recent data revealed stationary and stable BTEX plume
Keesler Air Force Base, Biloxi MI	BTEX and TPH	70 × 70 ft area delineated as affected area Natural attenuation effective at site 22% decrease in total BTEX concentration 1991–1995 indicates shrinking plume Based on monitoring data, groundwater contains significant biodegradation capacity (about 16.5 mg/l) associated mostly with sulfate reduction and methanogenesis
Cape Canaveral, FT-17, FL	Chlorinated aromatic hydrocarbons	Site characteristics demonstrate good potential for natural attenuation Two scenarios simulated: removal and non-removal of source With first model simulation, target concentration reached in 20 years; with second scenario, 46–53 years
Plattsburgh Air Force Base, NY	BTEX, and chlorinated aliphatic	Site demonstrates good potential for natural attenuation Depleted concentration of electron acceptors in source zone reflect natural attenuation in progress Site exhibits two major types of behavior: Type 1 (anaerobic) in area extending about 1500 ft down gradient from source area; Type 2 (aerobic) in area extending 1500–2000 ft down gradient from source area

Table 3
A comparative evaluation of soil remediation technologies

Technique	Development status	Contaminant	Soil type	Cost	Efficiency	Duration
Soil washing	F	B–F	F–I	A–B	A	A
Soil vapor extraction	F	A–B	F–I	C	A	B–C
Landfarming	F	B–C	A–I	C–D	B	B–C
Soil flushing	F	A–F	F–I	C–F	B–C	A–B
Solidification/stabilization	F	C, E–F	A–I	A–B	A	B
Thermal desorption	F	A–F, except C	A–I	C–E	A	A–B
Biopiles	F	A–D	C–I	E–F	A–B	A–B
Bioventing	F	B–D	D–I	C–E	A	A–B
Phytoremediation	P	A–F	Independent	D–E	C–D	D–E
Bioslurry system	F	A–D	D–I	A–C	A	A
Encapsulation	F	C–F	A–I	B–D	B	B–C
Aeration	F	A–B,D	C–I	E	B	C–D

Contaminant		Soil type		Cost		Efficiency		Duration	
Type	Rank	Type	Rank	Range, US$/t of water treated	Rank	Range	Rank	Range	Rank
VOCs	A	Fine clay	A	>150	A	>90%	A	1–6 months	A
SVOCs	B	Medium clay	B	75–150	B	75–90%	B	6–12 months	B
Medium to heavy hydrocarbons	C	Silty clay	C	50–75	C	50–75%	C	1–2 years	C
Insecticides	D	Clay loam	D	25–50	D	<50%	D	2–5 years	D
Inorganic	E	Silt loam	E	10–25	E			>5 years	E
Heavy metals	F	Silt	F	<10	F				
		Sandy clay	G						
		Sandy loam	H						
		Sand	I						

F, full scale; technology used in real site remediation; P, pilot scale; studies conducted in the field or laboratory to fine-tune the design of the technology.

Table 4
A comparative evaluation of groundwater remediation technologies

Techniques	Development status	Contaminant	Groundwater level	Cost	Efficiency	Duration	Reliability
Air sparging	F	A and B	C–H	C	B	A	B
Groundwater pump-and-treat	F	A–F	C–H	D–F	B–C	E	C–D
Passive/reactive walls	P	A–C,E	A–H	Not available	B	E	C
Bioslurping	F	B–C	A–H	C–D	A–B	B–C	B–C
Ultraviolet oxidation	F	A–E	A–H	D–F	A	A–B	A
Biosparging	F	A–C	A–F	C–E	A–B	B–C	B–C
Groundwater circulation wells	P	A–C	C–G	E	A–B	B–C	B–C
Horizontal well technology	P	A–F	A–D	D–E	A–B	–	–
Natural attenuation	F	A,B–D	A–H	Variable	A–B	E	B–C

Contaminant		Groundwater table		Cost		Efficiency		Duration		Reliability	
Type	Rank	Below ground surface	Rank	Range, US$ per gal of water	Rank	Range	Rank	Range	Rank	Rebounding of contaminant concentration	Rank
VOCs	A	<15 ft	A	>150	A	>90%	A	1–6 months	A	One out of 10 sites	A
SVOCs	B	15–30 ft	B	75–150	B	75–90%	B	6–12 months	B	Three out of 10 sites	B
Medium/heavy hydrocarbons	C	30–50 ft	C	50–75	C	50%–75%	C	1–2 years	C	Five out of 10 sites	C
Insecticides	D	50–75 ft	D	25–50	D	<50%	D	2–5 years	D	Seven out of 10 sites	D
Inorganic	E	75–100 ft	E	10–25	E			>5 years	E	>7 out of 10 sites	E
Heavy metals	F	100–150 ft	F	<10	F						
		150–200 ft	G								
		>200 ft	H								

F, full scale; technology used in real site remediation. P, pilot scale; studies conducted in the field or laboratory to fine-tune the design of the technology.

4. Summary and conclusion

A brief summary of real life applications of soil remediation technologies is presented in Table 1. This table has been compiled using USEPA (1995b), NRMRL (1995), Bass et al. (2000), Kirtland and Aelion (2000), and Khan and Husain (2002, 2003). An attempt has been made to present applications of the above discussed technologies. It is evident from the available information and also from Table 1 that SVE is emerging as the most frequently used technology. SVE not only promises good results in a short time, but it is also cost-effective. In certain cases (for example, Hasting Superfund site and the Rocky Mountain arsenal Superfund site), the cost of remediation is estimated at just above $2 US per cubic yard. Landfarming, a conventional technology, is also an efficient and cost-effective technology in the treatment of TPH. Bioventing, an emerging technology, has been tested in few places and is now considered a full scale working technology. At least six Superfund sites use this technology for decontamination. Thermal desorption, an option for dealing with a wide range of contaminants in difficult soil environments (clay and silty soil), has shown encouraging results. It is cost-effective and efficient in removing contaminants that otherwise are difficult to treat. On average, $200 US/t of soil treated is the operational cost calculated for this technology. Soil washing an ex situ treatment technology effective only for limited soil quantities, is efficient and fast. In situ vitrification is effective in complex hydrogeologic settings. This technology is capable of dealing with a wide range of contaminants, and its testing has shown satisfactory results. Although bioslurping, biopiles, and bioslurry systems are promising, few applications have been reported. Phytoremediation is under a pilot study, but insufficient details are available at present.

A brief description of the application of different technologies for groundwater remediation is presented in Table 2. This information has been compiled using USEPA (1995b, 1998f), NRMRL (1995), Wiedemeier et al. (1999), Bass et al. (2000), Kirtland and Aelion (2000), and Khan and Husain (2002, 2003). An attempt has been made to discuss at least one application of each technology. Conventional pump-and-treat is the groundwater remediation technology most frequently used in the past. However, due to excessive costs and the non-reliability of remediation with pump-and-treat systems, the newer technologies, particularly air sparging with SVE and subsequent treatment, now dominate. Four case studies of air sparging (see Table 2) demonstrate its capability of reducing contaminant concentrations in large proportions in a short span of time. The cleanup costs of a full scale application of pump-and-treat at many sites is less than $1 US per 1000 gal of water treated; however, at many sites it is near and above $100 US per 1000 gal of water treated. This clearly indicates that treatment cost is a strong function of site and contaminant characteristics. The success of the upcoming technology of groundwater circulation wells has been demonstrated in pilot studies, and has had full scale application at a few sites for demonstration purposes. The new horizontal well technology has been adopted by many remediation technologies and its use in SVE and other remediation technologies has shown encouraging results. As seen in Table 2, there is a five-fold increase in the removal of contaminants by using horizontal well technology compared to vertical well technology. This technology is being adopted at an increasing rate. According to GWRTAC (1996e), from 1987 to 1993 more than 100 horizontal wells have been installed, and this number will soon be more than doubled. Out of these, 25% of the wells are used for SVE, 25% for groundwater extraction, and 50% for other applications such as air injection, bioventing, and petroleum recovery.

As discussed above, a variety of remediation technologies are available for site remediation. However, no single technology is appropriate for all contaminant types and the variety of site-specific conditions that exist at different contaminated sites. Site conditions, contaminant types, contaminant source, source control measures, and the potential impact of the possible remedial measure determine the choice of a remediation strategy and technology. Often more than one remediation technology is needed to effectively address most contaminated site problems. Treatment processes can be, and usually are, combined into process trains for the more effective removal of contaminants and hazardous materials present at contaminated sites. For example, whereas biological treatment (with or without enhancement technologies) could result in the most desirable treatment scenario for petroleum-contaminated sites, the hot spot at such sites might be best handled by physical removal and thermal treatment of the removed materials rather than by biological methods. Consequently, several technologies that can provide both efficient and cost-effective remediation should normally be reviewed and explored as possible candidates in a remedy selection process.

The selection of one or more particular remediation technologies for a contaminated site is crucial in decision making. Many important parameters that conflict in nature play a crucial role in this decision making. To aid the analyst, important details of the available technologies are summarized in an easy-to-use format in Tables 3 and 4. These tables can be used for initial screening purposes. Once the user has access to the site and contaminant characterization report, these tables can aid in short-listing the most applicable technology(s) in the defined conditions. The short-listed technology(s) can be further studied in detail for real life applications in the situation of interest.

References

Abbott, E.H., Bell, J.T., Fjeld, R.A., Peterson, J.R., Sivavec, T.M., 2002. In situ Treatment of Mercury Contaminated Soils, Center for Research and

Technology Development, (Publication) CRTD, American Society of Mechanical Engineers, vol. 64., pp. 769–773.

Acar, Y.B., Alshawabkeh, A., 1993. Principle of electrokinetic remediation. Journal of Environmental Science and Technology 27(13), 2638–2647.

Adams, J.A., Reddy, K.R., 2003. Extent of benzene biodegradation in saturated soil column during air sparging. Ground Water Monitoring and Remediation 23(3), 85–94.

Alexander, M., 1994. Biodegradation and Bioremediation, Academic Press, San Diego, CA.

Alkorta, I., Garbisu, C., 2001. Phytoremediation of organic contaminants in soils. Bioresource Technology 79(3), 273–276.

Alpaslan, B., Yukselen, M.A., 2002. Remediation of lead contaminated soils by stabilization/solidification. Water, Air, and Soil Pollution 133(1–4), 253–263.

Alter, S.R., Brusseau, M.L., Piatt, J.J., Ray-M, A., Wang, J.-M., Cain, R.B., 2003. Use of tracer tests to evaluate the impact of enhanced-solubilization flushing on in-situ biodegradation. Journal of Contaminant Hydrology 64(3–4), 191–202.

Anderson, W.C., 1995. Innovative Site Remediation Technologies, vol. 1–8. American Academy of Environmental Engineers, Annapolis, ML.

Anderson, A., Mitchell, P., 2003. Treatment of mercury-contaminated soil, mine waste and sludge using silica micro-encapsulation. TMS Annual Meeting, Extraction and Processing Division, Mar 2–6 2003, San Diego, CA, pp. 265–274.

API, 1993. Guide for Assessing and Remediating Petroleum Hydrocarbons in Soils, American Petroleum Institute, API publication number 1629, Washington, DC.

Asante-Duah, D.K., 1996. Managing Contaminated Sites: Problem Diagnosis and Development of Site Restoration, Wiley, New York, NY.

Baciocchi, R., Boni, M.R., D'Aprile, L., 2003. Characterization and performance of granular iron as reactive media for TCE degradation by permeable reactive barriers. Water, Air, and Soil Pollution 149(1–4), 211–226.

Baker, R.S., Moore, A.T., 2000. Optimizing the effectiveness of in situ bioventing. Pollution Engineering 32(7), 44–47.

Barnes, D.L., 2003. Estimation of operation time for soil vapor extraction systems. Journal of Environmental Engineering 129(9), 873–878.

Barnes, D.L., Cosden, E., Johnson, B., Johnson, K., Stjarnstrom, S., Johansson, K., Filler, D., 2002. Operation of Soil Vapor Extraction in Cold Climates, Cold Regions Engineering Cold Regions Impacts on Transportation and Infrastructure, Proceedings of the Eleventh International Conference, May 20–22 2002, Anchorage, AK, pp. 956–967.

Barter, M.A., 1999. Phytoremediation—an overview. Journal of New England Water Environment Association 33(2), 158–164.

Bass, D.H., Hastings, N.A., Brown, R.A., 2000. Performance of air sparging systems: a review of case studies. Journal of Hazardous Materials 72, 101–119.

Bayer, P., Finkel, M., Teutsch, G., 2002. Reliability of Hydraulic Performance and Cost Estimates of Barrier-Supported Pump-and-Treat Systems in Heterogeneous Aquifers, IAHS-AISH Publication, vol. 277., pp. 331–338.

Bear, J., Sun, Y., 1998. Optimization of pump-treat-injection (PTI) design for the remediation of a contaminated aquifer: multi-stage design with chance constraints. Journal of Contaminant Hydrology 29, 225–244.

Benner, M.L., Mohtar, R.H., Lee, L.S., 2002. Factors affecting air sparging remediation systems using field data and numerical simulations. Journal of Hazardous Materials 95(3), 305–329.

Biorem, 1998. Air Sparging Bioremediation of Petroleum Hydrocarbon Contaminated Soils, Biorem Technologies Inc, Waterloo, ON, http://www.bioremtechnologies.com/assets/field_study_air_sparging.html.

Birke, V., Burmeier, H., Rosenau, D., 2003. Design, construction, and operation of tailored permeable reactive barrier. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management 7(4), 264–280.

Boulding, J.R., 1996. USEPA Environmental Engineering Sourcebook, Ann Arbor Press, Chelsea, MI.

Boyle, W.C., 2002. A Brief History of Aeration of Wastewater, Proceedings of the Environmental and Water Resources History, Nov 3–7 2002, Washington, DC, pp. 13–21.

Brillas, E., Calpe, J.C., Cabot, P.L., 2003. Degradation of the herbicide 2,4-dichlorophenoxyacetic acid by ozonation catalyzed with Fe^{2+} and UVA light. Applied Catalysis B: Environmental 46(2), 381–391.

Brown, R., Leahy, M.C., Molnaa, B., 1999. Bioremediation-a powerful and resilient companion technology. Pollution Engineering 31(10), 26–29.

Canter, L.W., Knox, R.C., 1985. Groundwater Pollution Control, Lewis Publishers, Chelsea, MI.

Chaineau, C.H., Yepremian, C., Vidalie, J.F., Ducreux, J., Ballerini, D., 2003. Bioremediation of a crude oil-polluted soil: biodegradation, leaching and toxicity assessments. Water, Air, and Soil Pollution 144(1–4), 419–440.

Chareneau, R.J., Bedient, P.B., Loehr, R.C., 1995. Groundwater Remediation, vol. 8. Technomic Publication Company, Lancaster, PA.

Chu, W., 2003. Remediation of contaminated soils by surfactant-aided soil washing. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management 7(1), 19–24.

Chu, W., Chan, K.H., 2003. The mechanism of the surfactant-aided soil washing system for hydrophobic and partial hydrophobic organics. Science of the Total Environment 307(1–3), 83–92.

CPEO, 1997. Soil washing. Center for Public Environmental Oversight. 425 Market Street, San Francisco, CA, http://thecity.sfsu/~cpeo/techtree/ttdescript/soilwash.html

CPEO, 1998a. Bioslurping. Center for Public Environmental Oversight. 425 Market Street, San Francisco, CA, http://thecity.www.sfsu.edu/~cpeo/techtree/ttdescript/bislurp.html

CPEO, 1998b. Solidification/stabilization. Center for Public Environmental Oversight. 425 Market Street, San Francisco, CA, http://www.cpeo.org/techtree/ttdescript/solidsta.htm

CPEO, 1998c. Pump and treat technology. Center for Public Environmental Oversight. 425 Market Street, San Francisco, CA, http://www.cpeo.org/techtree/ttdescript/pumptre.htm

CPEO, 1998d. Soil flushing. Center for Public Environmental Oversight. 425 Market Street, San Francisco, CA, http://www.cpeo.org/techtree/ttdescript/soilflus.htm

CPEO, 1998e. Thermal desorption. Center for Public Environmental Oversight. 425 Market Street, San Francisco, CA, http://www.cpeo.org/techtree/ttdescript/thedesop.htm

Cresap, G.H., 1999. Case study: application of short-duration, periodic bioslurping at a petroleum hydrocarbon release site, Hazardous and Industrial Wastes. Proceedings of the Mid-Atlantic Industrial Waste Conference, pp. 159–168.

Demars, K.R., Richardson, G.N., Yond, R.N., Chaney R.C., 1995. Dredging, remediation, and containment of contaminated sediments. ASTM Publication No. STP 1293, American Society of Testing Materials, Philadelphia, PA.

DENIX, 1995. Natural attenuation for petroleum-contaminated sites at federal facilities. Defense Environmental Network and Information exchange, http://www.denix.osd.mil/denix/Public/Library/Attenuation/attenuation.html

Dermatas, D., Meng, X., 2003. Utilization of fly ash for stabilization/solidification of heavy metal contaminated soils. Engineering Geology 70(3–4), 377–394.

Di Palma, L., Ferrantelli, P., Merli, C., Biancifiori, F., 2003. Recovery of EDTA and metal precipitation from soil flushing solutions. Journal of Hazardous Materials 103(1–2), 153–168.

Diele, F., Notarnicola, F., Sgura, I., 2002. Uniform air velocity field for a bioventing system design: some numerical results. International Journal of Engineering Science 40(11), 1199–1210.

Druss, D.L., 2003. Guidelines for Design and Installation of Soil–Cement Stabilization, Geotechnical Special Publication, Feb 10–12 2003, New Orleans, LA, Number 120, pp. 527–539.

Erickson, L.E., Banks, M.K., Davis, L.C., Schwab, A.P., Muralidharan, N., Reilley, K., Tracy, J.C., 1999. Using Vegetation to Enhance In Situ

Bioremediation, Center for Hazardous Substances Research, Kansas University, Manhattan, KA.

Feng, D., Lorenzen, L., Aldrich, C., Mare, P.W., 2001. Ex-situ diesel contaminated soil washing with mechanical methods. Minerals Engineering 14(9), 1093–1100.

Filler, D.M., Lindstrom, J.E., Braddock, J.F., Johnson, R.A., Nickalaski, R., 2001. Integral biopile components for successful bioremediation in the Arctic. Cold Regions Science and Technology 32(2–3), 143–156.

Fonade, C., Rols, J.L., Goma, G., Doubrovine, N., Bermejo, M., Grasa, J.P., 2000. Improvement of industrial wastewater treatment by aerated lagoon: case studies. Water Science and Technology 42(5), 193–200.

FRTR, 1999a. Soil washing. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W. Washington, DC, http://www.frtr.gov/matrix2/section4/4_21.html

FRTR, 1999b. Landfarming. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_15.html

FRTR, 1999c. Passive/reactive treatment walls. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_46.html

FRTR, 1999d. Bioslurping. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_39.html

FRTR, 1999e. In situ solidification/stabilization. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_10.html

FRTR, 1999f. In and ex situ solidification/stabilization. Federal Remediation Technologies Roundtable USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_24.html

FRTR, 1999g. Ground water pumping. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_58.html

FRTR, 1999h. Soil flushing. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_8.html

FRTR, 1999i. UV oxidation. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_56.html

FRTR, 1999j. Thermal desorption. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_29.html

FRTR, 1999k. Bioventing. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_1.html

FRTR, 1999l. Biopiles. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_12.html

FRTR, 1999m. Phytoremediation. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_5.html

FRTR, 1999n. Aeration. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_37.html

FRTR, 1999o. Slurry phase biological treatment. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_16.html

FRTR, 1999p. In-well air stripping. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_45.html

FRTR, 1999q. Incineration. Federal Remediation Technologies Roundtable. USEPA, 401 M Street, S.W., Washington, DC, http://www.frtr.gov/matrix2/section4/4_26.html

Guerin, T.F., Horner, S., McGovern, T., Davey, B., 2002. An application of permeable reactive barrier technology to petroleum hydrocarbon contaminated groundwater. Water Research 36(1), 15–24.

GWRTAC, 1996a. Technical documents-technical overview reports. Groundwater Remediation Technologies Analysis Center. 425 Sixth Avenue, Regional Enterprise Tower, Pittsburgh, PA, http://gwrtac.org/html/tech_over.html

GWRTAC, 1996b. Bioslurping. Groundwater Remediation Technologies Analysis Center. Publication # GWRTAC-TO-96-05. 425 Sixth Avenue, Regional Enterprise Tower, Pittsburgh, PA.

GWRTAC, 1996c. Ultraviolet/Oxidation treatment. Groundwater Remediation Technologies Analysis Center. Publication # GWRTAC-TO-96-06. 425 Sixth Avenue, Regional Enterprise Tower, Pittsburgh, PA.

GWRTAC, 1996d. Phytoremediation. Groundwater Remediation Technologies Analysis Center. Publication # GWRTAC-TO-96-03. 425 Sixth Avenue, Regional Enterprise Tower, Pittsburgh, PA.

GWRTAC, 1996e. Horizontal wells. Groundwater Remediation Technologies Analysis Center. 425 Sixth Avenue, Regional Enterprise Tower, Pittsburgh, PA, http://gwrtac.org/html/tech_over.html

Halmemies, S., Grondahl, S., Arffman, M., Nenonen, K., Tuhkanen, T., 2003. Vacuum extraction based response equipment for recovery of fresh fuel spills from soil. Journal of Hazardous Materials 97(1–4), 127–143.

Harmsen, J., 1991. Possibilities and limitations of landfarming for cleaning contaminated sites. In: Hinchee, R.E., Olfenbuttel, R.F. (Eds.), On-Site Bioreclamation: Processes for Xenobiotic and Hydrocarbon Treatment, Butterworth-Heinemann, London.

Harper, B.M., Stiver, W.H., Zytner, R.G., 2003. Non-equilibrium nonaqueous phase liquid mass transfer model for soil vapor extraction systems. Journal of Environmental Engineering 129(8), 745–754.

Hejazi, R., Husain, T., Khan, F.I., 2003. Landfarming operation in arid region-human health risk assessment. Journal of Hazardous Materials B99, 287–302.

Hejazi, R.F., 2002. Oily Sludge Degradation Study Under Arid Conditions Using a Combination of Landfarm and Bioreactor Technologies. PhD thesis, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St John's, Canada.

Illangasekare, T.H., Reible, D.D., 2001. Pump-and-Treat for Remediation and Plume Containment: Applications, Limitations, and Relevant Processes, Manuals and Reports on Engineering Practice, American Society of Civil Engineers, vol. 100., pp. 79–119.

Johnston, C.D., Fisher, S., Rayner, J.L., 2002. Removal of Petroleum Hydrocarbons from the Vadose Zone During Multi-Phase Extraction at a Contaminated Industrial Site, IAHS-AISH Publication, number 275.

Jorgensen, K.S., Puustinen, J., Suortti, A.M., 2000. Bioremediation of petroleum hydrocarbon-contaminated soil by composting in biopiles. Environmental Pollution 107(2), 245–254.

Juhasz, A.L., Smith, E., Smith, J., Naidu, R., 2003b. In situ remediation of DDT-contaminated soil using a two-phase co-solvent flushing-fungal biosorption process. Water, Air, and Soil Pollution 147(1–4), 263–274.

Kao, C.M., Chen, S.C., Liu, J.K., Wu, M.J., 2001. Evaluation of TCDD biodegradability under different redox conditions. Chemosphere 44(6), 1447–1454.

Khan, F.I., Husain, T., 2002. Evaluation of Contaminated Sites Using Risk Based Monitored Natural Attenuation, Chemical Engineering Progress-AIChE, USA, January 34–44.

Khan, F.I., Husain, T., 2003. Evaluation of a petroleum hydrocarbon contaminated site for natural attenuation using 'RBMNA' methodology. Environmental Modeling and Software 18, 179–194.

Kirtland, B.C., Aelion, C.M., 2000. Petroleum mass removal from low permeability sediment using air sparging/soil vapor extraction: impact of continuous or pulsed operation. Journal of Contaminant Hydrology 41, 367–383.

Kuyukina, M.S., Ivshina, I.B., Ritchkova, M.I., Philp, J.C., Cunningham, C.J., Christofi, N., 2003. Bioremediation of crude oil-contaminated soil using slurry-phase biological treatment and land farming techniques. Soil and Sediment Contamination 12(1), 85–99.

Li, P., Sun, T., Stagnitti, F., Zhang, C., Zhang, H., Xiong, X., Allinson, G., Ma, X., Allinson, M., 2002. Field-scale bioremediation of soil contaminated with crude oil. Environmental Engineering Science 19(5), 277–289.

Liang, S., Min, J.H., Davis, M.K., Green, J.F., Remer, D.S., 2003. Use of pulsed-UV processes to destroy NDMA. American Water Works Association 95(9), 121–131.

Lin, H.K., Man, X.D., Walsh, D.E., 2001. Lead removal via soil washing and leaching. JOM 53(12), 22–25.

Logsdon, S.D., Keller, K.E., Moorman, T.B., 2002. Measured and predicted solute leaching from multiple undisturbed soil columns. Soil Science Society of America Journal 66(3), 686–695.

Mackay, D.M., Cherry, J.A., 1989. Groundwater contamination: pump-and-treat remediation. Environmental Science and Technology 23, 630–636.

Midwest Research Institute, 1998. Petroleum hydrocarbon remediation. 425 Volker Boulevard, Kansas City, MI, http://www.mriresearch.org/ae/phc-tech.html

Mihopoulos, P.G., Suidan, M.T., Sayles, G.D., 2001. Complete remediation of PCE contaminated unsaturated soils by sequential anaerobic–aerobic bioventing. Water Science and Technology 43(5), 365–372.

Mihopoulos, P.G., Suidan, M.T., Sayles, G.D., Kaskassian, S., 2002. Numerical modeling of oxygen exclusion experiments of anaerobic bioventing. Journal of Contaminant Hydrology 58(3–4), 209–220.

Mitchell, P., Potter, C., 1999. The Future of Waste Treatment in the Mining Industry, Proceedings of Global Symposium on Recycling, Waste Treatment and Clean Technology, Sep 5–91999, San Sebastian, Spain.

Moyers, J.R., Nichols, J.D., Whitlock, I., 1997. Disadvantages of Pump-and-Treat Remediation, Groundwater Pollution Primer, Virginia Tech University.

Muehlberger, E.W., Harris, K., Hicks, P., 1997. In Situ Biosparging of a Large Scale Dissolved Petroleum Hydrocarbon Plume at a Southwest Lumber mill, TAPPI Proceedings—Environmental Conference and Exhibition, vol. 1.

Nakhla, G., Lugowski, A., 2003. Control of filamentous organisms in food-processing wastewater treatment by intermittent aeration and selectors. Journal of Chemical Technology and Biotechnology 78(4), 420–430.

National Research Council, 1994. Alternatives for Groundwater Cleanup, National Academy Press, Washington, DC.

Nedunuri, K.V., Govindaraju, R.S., Banks, M.K., Schwab, A.P., Chen, Z., 2000. Evaluation of phytoremediation for field-scale degradation of total petroleum hydrocarbons. Journal of Environmental Engineering 126(6), 483–490.

NRMRL, 1995. Superfund innovative technology evaluation program, technology profiles, National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH.

Nyer, E.K., 1996. In situ Treatment Technology, Lewis Publishers, Boca Raton, FL.

Otterpohl, R., 2002. Options for alternative types of sewerage and treatment systems directed to improvement of the overall performance. Water Science and Technology 45(3), 149–158.

Pacific Northwest National Laboratory. 1994. Groundwater pump-and-treat, http://www.pnl.gov/WEBTECH/nonvoc/pmptreat.html

Park, J., Jung, Y., Han, M., Lee, S., 2002. Simultaneous removal of cadmium and turbidity in contaminated soil-washing water by DAF and electroflotation. Water Science and Technology 46(11–12), 225–230.

Pulford, I.D., Watson, C., 2003. Phytoremediation of heavy metal-contaminated land by trees—a review. Environment International 29(4), 529–540.

RAAG, 2000. Evaluation of Risk Based Corrective Action Model, Remediation Alternative Assessment Group, Memorial University of Newfoundland, St John's, NF, Canada.

Rai, J.P.N., Singhal, V., 2003. Biogas production from water hyacinth and channel grass used for phytoremediation of industrial effluents. Bioresource Technology 86(3), 221–225.

Reddy, K.R., Saichek, R.E., 2003. Effect of soil type on electrokinetic removal of phenanthrene using surfactants and co-solvents. Journal of Environmental Engineering 129(4), 336–346.

Reddy, K.R., Admas, J.F., Richardson, C., 1999. Potential technologies for remediation of Brownfield. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management 3(2), 61–68.

Riser-Roberts, E., 1992. Bioremediation of Petroleum Contaminated Sites, CRC Press, Boca Raton, FL.

Riser-Roberts, E., 1998. Remediation of Petroleum Contaminated Soil: Biological, Physical, and Chemical Processes, Lewis Publishers, Boca Raton, FL.

Robertson, D., Burnley, S., Barratt, R., 2003. The Immobilization of Flue Gas Treatment Residues through the Use of a Single Staged Wash and Crystalline Matrix Encapsulation (CME) treatment process, Proceedings of the 11th Annual North American Waste to Energy Conferences (NAWTEC11), Apr 28–30 2003, Tampa, FL, pp. 135–143.

Sherwood, L.J., Qualls, R.G., 2001. Stability of phosphorus within a wetland soil following ferric chloride treatment to control eutrophication. Environmental Science and Technology 35(20), 4126–4131.

Son, A.J., Shin, K.H., Lee, J.U., Kim, K.W., 2003. Chemical and ecotoxicity assessment of PAH-contaminated soils remediated by enhanced soil flushing. Environmental Engineering Science 20(3), 197–206.

Suthersan, S.S., 1997. Remediation Engineering: Design Concepts, Lewis Publishers, Boca Raton, FL.

Theis, T.L., O'Carroll, D.M., Vogel, D.C., Lane, A.B., Collins, K., 2003. Systems analysis of pump-and-treat groundwater remediation. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management 7(3), 177–181.

Tomlinson, D.W., Thomson, N.R., Johnson, R.L., Redman, J.D., 2003. Air distribution in the Borden aquifer during in situ air sparging. Journal of Contaminant Hydrology 67(1–4), 113–132.

Urum, K., Pekdemir, T., Gopur, M., 2003. Optimum conditions for washing of crude oil-contaminated soil with biosurfactant solutions. Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers, Part B 81(3), 203–209.

USEPA, 1990. Handbook of in situ treatment of hazardous waste-contaminated soils. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication # EPA 540-2-90-002, Washington, DC.

USEPA, 1995a. How to Evaluate alternative cleanup technologies for underground storage tank sites. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication # EPA 510-B-95-007, Washington, DC.

USEPA, 1995b. Abstracts of remediation case studies. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication number EPA-542-R-95-001, Washington, DC.

USEPA, 1996a. A citizen's guide to soil washing. Office of Solid Waste and Emergency Response, US Environmental Protection Agency Publication # EPA 542-F-96-002, Washington, DC.

USEPA, 1996b. In situ soil vapor extraction. Office of Solid Waste and Emergency Response, US Environmental Protection Agency, Washington, DC, http://www.epa.gov/techinfo/case/comm/soilvape.hml

USEPA, 1996c. A citizen's guide to natural attenuation. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication # EPA 542-F-96-015, Washington, DC.

USEPA, 1996d. A citizen's guide to treatment walls. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication # EPA 542-F-96-016, Washington, DC.

USEPA, 1996e. A citizen's guide to in situ soil flushing. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication # EPA 542-F-96-006, Washington, DC.

USEPA, 1996f. A citizen's guide to in situ thermal desorption. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication # EPA 542-F-96-005, Washington, DC.

USEPA, 1996g. A citizen's guide to phytoremediation. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication # EPA 542-F-96-014, Washington, DC.

USEPA, 1996h. A citizen's guide to bioremediation. Office of Solid Waste and Emergency Response, US Environmental Protection Agency. Publication # EPA 542-F-96-007, Washington, DC.

USEPA, 1998a. Soil vapor extraction (SVE). Office of the Underground Storage Tank, US Environmental Protection Agency. Publication # EPA 510-B-95-007, http://www.epa.gov/swerust1/cat/sve1.htm

USEPA, 1998b. Landfarming. Office of the Underground Storage Tank, US Environmental Protection Agency. Publication # EPA 510-B-95-007. http://www.epa.gov/swerust/cat/landfarm.htm

USEPA, 1998c. Biosparging. Office of the Underground Storage Tank, US Environmental Protection Agency. Publication # EPA 510-B-95-007, http://www.epa.gov/oust/cat/biosparg.htm

USEPA, 1998d. Bioventing. Office of the Underground Storage Tank, US Environmental Protection Agency. Publication # EPA 510-B-95-007, http://www.epa.gov/OUST/cat/biovent.htm

USEPA, 1998e. Biopiles. Office of the Underground Storage Tank, US Environmental Protection Agency. Publication # EPA 510-B-95-007, http://www.epa.gov/swerust1/cat/biopiles.htm

USEPA, 1998f. Field Application of in situ remediation technologies: ground-water circulation wells. US Environmental Protection Agency. Publication # EPA 542-R-98-009, Washington, DC.

Vouillamoz, J., Milke, M.W., 2001. Effect of compost in phytoremediation of diesel-contaminated soils. Water Science and Technology 43(2), 291–295.

Wait, S.T., Thomas, D., 2003. The Characterization of Base Oil Recovered From the Low Temperature Thermal Desorption of Drill Cuttings, SPE/EPA Exploration and Production Environmental Conference, Mar 10–12, San Antonio, TX, pp. 151–158.

Wiedemeier, T.H., Newell, C.J., Rifai, H.S., Wilson, J.T., 1999. Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface, Wiley, New York.

Wilk, C.M., 2003. Solidification/stabilization treatment: principles and practice. Air and Waste Management Association's Magazine for Environmental Managers July, 31–37.

Woinarski, A.Z., Snape, I., Stevens, G.W., Stark, S.C., 2003. The effects of cold temperature on copper ion exchange by natural zeolite for use in a permeable reactive barrier in Antarctica. Cold Regions Science and Technology 37(2), 159–168.

Yen, H.K., Chang, N.B., Lin, T.F., 2003. Bioslurping model for assessing light hydrocarbon recovery in contaminated unconfined aquifer. I: Simulation analysis. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management 7(2), 114–130.

Yeung, A.T., Hsu, H.T., 2002. Semi-analytical simulation of soil vapor extraction. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management 6(1), 14–22.

Zhan, H., Park, E., 2002. Vapor flow to horizontal wells in unsaturated zones. Soil Science Society of America Journal 66(3), 710–721.

Zhang, C., Daprato, R.C., Nishino, S.F., Spain, J.C., Hughes, J.B., 2001. Remediation of dinitrotoluene contaminated soils from former ammunition plants: Soil washing efficiency and effective process monitoring in bioslurry reactors. Journal of Hazardous Materials 87(1–3), 139–154.

Zheng, C., Wang, P.P., 2002. A field demonstration of the simulation optimization approach for remediation system design. Ground Water 40(3), 258–265.