



Engineering Bulletin

In Situ Biodegradation Treatment

Purpose

Section 121(b) of the Comprehensive Environment Response, Compensation, and Liability Act (CERCLA) mandates the Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants and contaminants as a principal element." The Engineering Bulletins comprise a series of documents that summarize the latest information available on selected treatment and site remediation technologies and related issues. They provide summaries of and references for the latest information to help remedial project managers, on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site characteristics needed to evaluate a technology for potential applicability to their Superfund or other hazardous waste site. Those documents that describe individual treatment technologies focus on remedial investigation scoping needs. Addenda will be issued periodically to update the original bulletins.

Abstract

In situ biodegradation may be used to treat low-to-intermediate concentrations of organic contaminants in place without disturbing or displacing the contaminated media. Although this technology has been used to degrade a limited number of inorganics, specifically cyanide and nitrate, in situ biodegradation is not generally employed to degrade inorganics or to treat media contaminated with heavy metals.

During in situ biodegradation, electron acceptors (e.g., oxygen and nitrate), nutrients, and other amendments may be introduced into the soil and groundwater to encourage the growth of an indigenous population capable of degrading the contaminants of concern. These supplements are used to control or modify site-specific conditions that

impede microbial activity and, thus, the rate and extent of contaminant degradation. Depending on site-specific cleanup goals, in situ biodegradation can be used as the sole treatment technology or in conjunction with other biological, chemical, and physical technologies in a treatment train. In the past, in situ biodegradation has often been used to enhance traditional pump and treat technologies by reducing the time needed to achieve aquifer cleanup standards.

One of the advantages of employing an in situ technology is that media transport and excavation requirements are minimized, resulting in both reduced potential for volatile releases and minimized material handling costs. Biological technologies that require the physical displacement of media during treatment (e.g., "land treatment" applications involving excavation for treatment in lined beds or tilling of non-excavated soils) assume many of the risks and costs associated with ex situ technologies and cannot strictly be considered in situ applications.

As of Fall 1993, in situ biodegradation was being considered or implemented as a component of the remedy at 21 Superfund sites and 38 Resource Conservation and Recovery Act (RCRA), Underground Storage Tank (UST), Toxic Substances Control Act (TSCA), and Federal sites with soil, sludge, sediment, or groundwater contamination [1, p. 13][2][3]. This bulletin provides information on the technology's applicability, the types of residuals produced, the latest performance data, the site requirements, the status of the technology, and sources for further information.

Technology Applicability

In situ biodegradation has been shown to be potentially effective at degrading or transforming a large number of organic compounds to environmentally-acceptable or less mobile compounds [4, p. 54][5, p. 103][6][7][8][9]. Soluble organic contaminants are particularly amenable to biodegradation; however, relatively insoluble contaminants may be degraded if they are accessible to microbial degrad-

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ers. Classes of compounds considered amenable to biodegradation include petroleum hydrocarbons (e.g., gasoline and diesel fuel), nonchlorinated solvents (e.g., acetone, ketones, and alcohols), wood-treating wastes (e.g., creosote and pentachlorophenol), some chlorinated aromatic compounds (e.g., chlorobenzenes and biphenyls with fewer than five chlorines per molecule), and some chlorinated aliphatic compounds (e.g., trichloroethene and dichloroethene). As advances in anaerobic biodegradation continue, many compounds traditionally considered resistant to aerobic biodegradation may eventually be degraded, either wholly or partially, under anaerobic conditions. Although not normally used to treat inorganics (e.g., acids, bases, salts, heavy metals, etc.), *in situ* biodegradation has been used to treat water contaminated with nitrate, phosphate, and other inorganic compounds.

Although *in situ* biodegradation may be used to remediate a specific site, this does not ensure that it will be effective at all sites or that the treatment efficiency achieved will be acceptable at other sites. The complex contaminant mixtures found at many Superfund sites frequently result in chemical interactions or inhibitory effects that limit contaminant biodegradability. Elevated concentrations of pesticides, highly chlorinated organics, and some inorganic salts have been known to inhibit microbial activity and thus system performance during *in situ* biodegradation. Treatability studies should be performed to determine the effectiveness of a given *in situ* biological technology at each site. Experts based out of EPA's Risk Reduction Engineering Laboratory (RREL) in Cincinnati, Ohio and the Robert S. Kerr Environmental Research Laboratory (RSKERL) in Ada, Oklahoma may be able to provide useful guidance during the treatability study and design phases. Other sources of general observations and average removal efficiencies for different treatability groups are contained in the Superfund Land Disposal Restrictions (LDR) Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions," (OSWER Directive 9347.3-06FS, September 1990) [10] and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions," (OSWER Directive 9347.3-06BFS, September 1990) [11].

Limitations

Site- and contaminant-specific factors impacting contaminant availability, microbial activity, and chemical reaction rates may limit the application of *in situ* biodegradation. Variations in media composition and contaminant concentrations can lead to variations in biological activity and, ultimately, inconsistent degradation rates. Soil characteristics (e.g., non-uniform particle size, soil type, moisture content, hydraulic conductivity, and permeability) and the amount, location, and extent of contamination can also have a profound impact on bioremediation. The following text expands upon these factors.

The biological availability, or bioavailability, of a contaminant is a function of the contaminant's solubility in water and its tendency to sorb on the surface of the soil. Contaminants with low solubility are less likely to be distrib-

uted in an aqueous phase and may be more difficult to degrade biologically. Conversely, highly soluble compounds may leach from the soil before being degraded. In general, however, poor bioavailability can be attributed to contaminant sorption on the soil rather than a low or high contaminant solubility. The tendency of organic molecules to sorb on the soil is determined by the physical and chemical characteristics of the contaminant and soil. In general, the leaching potential of a chemical is proportional to the magnitude of its adsorption (partitioning) coefficient in the soil. Hydrophobic (i.e., "water fearing") contaminants, in particular, routinely partition from the soil water and concentrate in the soil organic matter, thus limiting bioavailability. Additionally, contaminant weathering may lead to binding in soil pores, which can limit availability even of soluble compounds. Important contaminant properties that affect sorption include: chemical structure, contaminant acidity or basicity (pK_a or pK_b), water solubility, permanent charge, polarity, and molecule size. In some situations surfactants (e.g., "surface acting agents") may be used to increase the bioavailability of "bound" or insoluble contaminants. However, it may be difficult to identify a surfactant that is both nontoxic and not a preferred substrate for microbial growth.

Soil solids, which are comprised of organic and inorganic components, may contain highly reactive charged surfaces that play an important role in immobilizing organic constituents, and thus limiting their bioavailability. Certain types of inorganic clays, possess especially high negative charges, thus exhibiting a high cation exchange capacity. Alternatively, clays may also contain positively charged surfaces, causing these particles to exhibit a high anion exchange capacity. Soil organic matter also has many highly reactive charged surfaces which can limit bioavailability [12].

Bioavailability is also a function of the biodegradability of the target chemical, i.e., whether it acts as a substrate, co-substrate, or is recalcitrant. When the target chemical cannot serve as a metabolic substrate (source of carbon and energy) for microorganisms, but is oxidized in the presence of a substrate already present or added to the subsurface, the process is referred to as co-oxidation and the target chemical is defined as the co-substrate [12][13, p.4]. Co-metabolism occurs when an enzyme produced by an organism to degrade a substrate that supports microbial growth also degrades another non-growth substrate that is neither essential for nor sufficient to support microbial growth. Co-oxidation processes are important for the biodegradation of high molecular weight polycyclic aromatic hydrocarbons (PAHs), and some chlorinated solvents, including trichloroethene (TCE). However, like surfactants, cometabolites (e.g., acetate and phenol) may be more readily mineralized by the indigenous microorganisms than the target organics [13, p. 4].

Microbial activity can be reduced by nutrient, moisture, and oxygen deficiencies, significantly decreasing biodegradation rates. Extreme soil temperatures, soil alkalinity, or soil acidity can limit the diversity of the microbial population and may suppress specific contaminant degrad-

ers. Spatial variation of soil conditions (e.g., moisture, oxygen availability, pH, and nutrient levels) may result in inconsistent biodegradation due to variations in biological activity. While these conditions may be controlled to favor biodegradation, the success of in situ biodegradation depends in a large part on whether required supplements can be delivered to areas where they are needed. Low hydraulic conductivity can hinder the movement of water, nutrients, aqueous-phase electron acceptors (e.g., hydrogen peroxide and nitrate), and, to a lesser extent, free oxygen through the contamination zone [14, p. 155]. Restrictive layers (e.g., clay lenses), although more resistant to contamination, are also more difficult to remediate due to poor permeability and low rates of diffusion [13, p. 4]. Low percolation rates may cause amendments to be assimilated by soils immediately surrounding application points, preventing them from reaching areas that are more remote, either vertically or horizontally. During the simultaneous addition of electron acceptors and donors through injection wells, excessive microbial growth or high iron or manganese concentrations may cause clogging in the well screen or in the soil pores near the well screen [15]. Variable hydraulic conductivities in different soil strata within a contaminated area can also complicate the design of flow control; minor heterogeneities in lithology can, in some cases, impede the transfer of supplements to specific subsurface locations.

Microbial activity may also be influenced by contaminant concentrations. Each contaminant has a range of concentrations at which the potential for biodegradation is maximized. Below this range microbial activity may not occur without the addition of co-substrate. Above this range microbial activity may be inhibited and, once toxic concentrations are reached, eventually arrested. During inhibition, contaminant degradation generally occurs at a reduced rate. In contrast, at toxic concentrations, contaminant degradation does not occur. The concentrations at which microbial growth is either supported, inhibited, or arrested vary with the contaminant, medium, and microbial species. Given long-term exposure, microbes have been known to acclimate to very high contaminant concentrations and other conditions inhibiting microbial activity. However, if prompt treatment is a primary goal, as is the case during most remedial activities, toxic conditions may need to be addressed by pH control, metals control (e.g., immobilization), sequential treatment, or by introducing microbial strains resistant to toxicants.

Numerous biological and non-biological mechanisms (e.g., volatilization, sorption, chemical degradation, migration, and photodecomposition) occur during biological treatment. Since some amendments may react with the soil, site geochemistry can limit both the form and concentration of any supplements added to the soil. Thus, care must be employed when using amendments to "enhance" biological degradation. For example, ozone and hydrogen peroxide, which can be added to enhance dissolved oxygen levels in soil or groundwater systems, may react violently with other compounds present in the soil, reduce the sorptive capacity of the soil being treated, produce gas bubbles that block the pores in the soil matrix, or damage

the bacterial population in the soil [4, p. 43]. Nitrogen and phosphorus (phosphate) must also be applied cautiously to avoid excessive nitrate formation [4, p. 47] and the precipitation of calcium and iron phosphates, respectively. Excessive nitrate levels in the groundwater can cause health problems in humans, especially children. If calcium concentrations are high, the added phosphate can be tied up by the calcium and, therefore, may not be available to the microorganisms [16, p. 23]. Lime treatment for soil pH adjustment is dependent on several soil factors including soil texture, type of clay, organic matter content, and aluminum concentrations [4, p. 45]. Since changes in soil pH may also affect the dissolution or precipitation of materials within the soil and may increase the mobility of hazardous materials, pH amendments (acid or base) should be added cautiously and should be based on the soil's ability to resist changes in pH, otherwise known as the soil's "buffering capacity" [4, p. 46]. Since the buffering capacity varies between soils, lime and acidification requirements should be determined on a site-specific basis.

Finally, high concentrations of metals can have a detrimental effect on the biological treatment of organic contaminants in the same medium. A number of metals can be oxidized, reduced, methylated (i.e., mercury), demethylated, or otherwise transformed by various organisms to produce new contaminants. The solubility, volatility, and sorption potential of the original soil contaminants can be greatly changed in the process [17, p. 144], leading to potential significant toxicological effects, as is the case during the methylation of mercury. To avoid these complications, it is sometimes possible to pretreat or complex the metals into a less toxic or leachable form.

Technology Description

During in situ biodegradation, site-specific characteristics are modified to encourage the growth of a microbial population capable of biologically degrading the contaminants of concern. Presently, two major types of in situ systems are being employed to biodegrade organic compounds present in soils, sludges, sediments, and groundwater: bioventing systems and "traditional" in situ biodegradation systems, which usually employ infiltration galleries/wells and recovery wells to deliver required amendments to the subsurface. In general, bioventing has been used to treat contaminants present in the unsaturated zone. Traditional in situ biodegradation, on the other hand, has mostly been used to treat saturated soils and groundwater. The occasional treatment of unsaturated soil using traditional in situ biodegradation techniques has been generally limited to fairly shallow regions over groundwater that is already contaminated.

Traditional In Situ Biodegradation

Traditional in situ biodegradation is generally used in conjunction with groundwater-pumping and soil-flushing systems to circulate nutrients and oxygen through a contaminated aquifer and associated soil. The process usually

involves introducing aerated, nutrient-enriched water into the contaminated zone through a series of injection wells or infiltration trenches and recovering the water down-gradient. Depending upon local regulations and engineering concerns, the recovered water can then be treated and, if necessary, reintroduced to the soil onsite, discharged to the surface, or discharged to a publicly-owned treatment works (POTW). A permit may be required for the re-injection of treated water. Note that a variety of techniques can be used to introduce and distribute amendments in the subsurface. For example, a lower horizontal well is being used at the Savannah River Site near Aiken, North Carolina to deliver air and methane to the subsurface. A vacuum has been applied to an upper well (in the vadose zone) located at this site to encourage the distribution of air and methane within the upper saturated zone and lower vadose zone [18][19].

Figure 1 is a general schematic of a traditional in situ biodegradation system [20, p. 113][16, p. 13]. The first step in the treatment process involves pretreating the infiltration water, as needed, to remove metals (1). Treated or contaminated groundwater, drinking water, or alternative water sources (e.g., trucked water) may be used as the water source. If groundwater is used, iron dissolved in the groundwater may bind phosphates needed for biological growth. Excess phosphate may be added to the infiltration water at this point in the treatment process in order to complex the iron [20, p. 111]. The presence of iron will also cause a more rapid depletion of hydrogen peroxide, which is sometimes used as an oxygen source. Surface active agents may also be added at this point in the treatment process to increase the bioavailability of contaminants, especially hydrophobic or sorbed pollutants, while methane or other substances may be added to induce the cometabolic biodegradation of certain contaminants. In continuous recycle systems, toxic metals originally located in the contaminated medium may have to be removed from

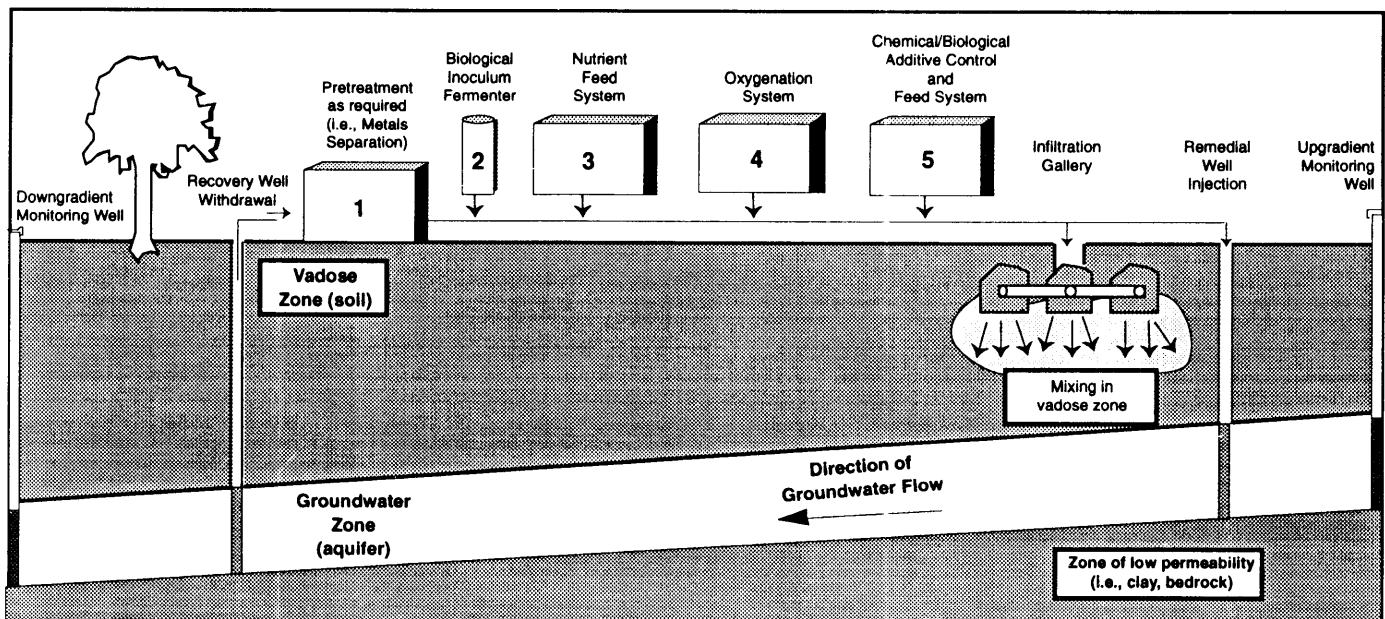
the recycled infiltration water to prevent inhibition of bacterial growth. The exact type of pretreatment will vary with the water source, contamination problem, and treatment system used.


Following infiltration water pretreatment, a biological inoculum can be added to the infiltration water to enhance the natural microbial population (2). A site-specific inoculum enriched from site samples may be used; commercially available cultures reported to degrade the contaminants of concern can also be used (e.g., during the remediation of "effectively sterile soils"). Project managers are cautioned against employing microbial supplements without first assessing the relative advantages associated with their use and potential competition that may occur between the indigenous and introduced organisms. The ability of microbes to survive in a foreign and possibly hostile (i.e., toxic) environment, as well as the ability to metabolize a wide range of substrates should be evaluated. The health effects of commercial inocula must also be carefully evaluated, since many products on the market are not carefully screened or processed for pathogens. It is essential that independently-reviewed data be examined before employing a commercially-marketed microbial supplement [21].

Nutrient addition can then be employed to provide nitrogen and phosphorus, two elements essential to the biological activity of both indigenous and introduced organisms (3). Optimum nutrient conditions are site-specific. Trace elements may be added at this stage, but are normally available in adequate supply in the soil or groundwater.

During contaminant oxidation, energy is released as electrons are removed. Since oxygen acts as the terminal electron acceptor during aerobic biodegradation, oxygen concentrations in the subsurface may become depleted. To avoid this complication, air, oxygen, and other oxygen


Figure 1.
Schematic Diagram of Traditional In Situ Biodegradation of Soil and Groundwater





sources (hydrogen peroxide and ozone) can be added to the infiltration water (4). To prevent gas binding in the subsurface, and a subsequent reduction in the effective soil permeability, oxygen amendment/supplementation methods must be carefully selected. During anaerobic degradation, alternative electron acceptors (nitrate, carbonate, or sulfate) may be added to the infiltration water in place of oxygen. Alternatively, during the co-oxidation of a target substrate, a co-substrate (methanol or acetate) may be added to the infiltration water [22].


Just before the water is added to the soil or groundwater, chemical additives may be used to adjust the pH (neutral is recommended for most systems) and other parameters that impact biodegradation (5). Care should be taken when making adjustments to the pH, since contaminant mobility (especially of metals) can be increased by changing the pH [4, p. 45]. Site managers are also cautioned against employing chemical additives that are persistent in the environment. The potential toxicity of additives and any synergistic effects on contaminant toxicity should also be evaluated.



During in situ bioremediation, amendment concentrations and application frequencies can be adjusted to compensate for physical/chemical depletion and high microbial demand. If these modifications fail to compensate for microbial demand, remediation may occur by a sequential deepening and widening of the active treatment layer (e.g., as the contaminant is degraded in areas near the amendment addition points, and microbial activity decreases due to the reduced substrate, the amendments move farther, increasing microbial activity in those areas). Additionally, hydraulic fracturing may be employed to improve amendment circulation within the subsurface.

The importance of using a well-designed hydraulic delivery system and thoroughly evaluating the compatibility of chemical supplements was demonstrated at sites in Park City, Kansas; Kelly AFB, Texas; and Eglin AFB, Florida. Air entrainment and iron precipitation resulted in a continued loss of injection capacity during treatment at the Park City site [23][24] and calcium phosphate and iron precipitation resulted in the failure of the two field tests at Kelly and Eglin AFBs, respectively [25].

Bioventing



Bioventing uses relatively low-flow soil aeration techniques to enhance the biodegradation of soils contaminated with organic contaminants. Although bioventing is predominantly used to treat unsaturated soils, applications involving the remediation of saturated soils and groundwater (e.g., using air sparging techniques) are becoming more common [26][27]. Aeration systems similar to those employed during soil vapor extraction are used to supply oxygen to the soil (Figure 2). Typically a vacuum extraction, air injection, or combination vacuum extraction and air injection system is employed [28]. An air pump, one or more air injection or vacuum extraction probes, and emissions monitors at the ground surface are commonly used. Although some systems utilize higher air flow rates, thereby

combining bioventing with soil vapor extraction, low air pressures and low air flow rates are generally used to maximize vapor retention times in the soil while minimizing contaminant volatilization. An interesting modification to traditional aeration techniques has been proposed at the Picatinny Arsenal in New Jersey. Here researchers and project managers have proposed collecting TCE vapors at the surface, amending them with degradable hydrocarbons (methane, propane, or natural gas) capable of stimulating the cometabolic degradation of vapor-phase TCE, and then re-injecting the amended vapors into the unsaturated zone in an attempt to encourage the in situ bioremediation of the TCE remaining in the subsurface [29][30][31][32][27].

Off-gas treatment (e.g., through biofiltration or carbon adsorption) will be needed during most bioventing applications to ensure compliance with emission standards and to control fugitive emissions. Off-gas treatment systems similar to those employed during soil vapor extraction may be used. These systems must be capable of effectively collecting and treating a vapor stream consisting of the original contaminants and/or any volatile degradation products generated during treatment. Although similar vapor treatment systems may be employed during soil vapor extraction and bioventing, less concentrated off-gases would be expected from a bioventing system than from a soil vapor extraction system employed at the same site. This difference in concentration is attributed to enhanced biological degradation within the subsurface.

Nutrient addition may be employed during bioventing to enhance biodegradation. Nutrient addition can be accomplished by surface application, incorporation by tilling into surface soil, and transport to deeper layers through applied irrigation water. However, in some field applications to date, nutrient additions have been found to provide no additional benefits [33]. Increasing the soil temperature may also enhance bioremediation, although in general high temperatures should be avoided since they can decrease microbial population and activity. Heated air, heated water, and low-level radio-frequency heating are some of the techniques which can be used to modify soil temperature. Soil core analyses can be performed periodically to assess system performance as determined by contaminant removal. A control plot located near the bioventing system, but not biovented, may also be used to obtain additional information to assess system performance.

Process Residuals

During in situ biodegradation, limited but potentially significant process residuals may be generated. Although the majority of wastes requiring disposal are generated as part of pre- and post-treatment activities, process residuals directly arising from in situ biological activities may also be generated. These process residuals may include: 1) partially degraded metabolic by-products, 2) residual contamination, 3) wastes produced during groundwater pre- and post-treatment activities, and 4) volatile contaminants that are either directly released into the atmosphere or

collected within add-on emission control/treatment systems. The following text expands upon the specific types of process residuals, their control, and their impact on disposal requirements.

Ultimately biological technologies seek to mineralize hazardous contaminants into relatively innocuous by-products, specifically carbon dioxide, water, and inorganic salts. However, a number of site- and contaminant-specific factors may cause the partial degradation or "biotransformation" of a contaminant and the generation of an intermediate by-product. These metabolic by-products may be located in either the saturated or unsaturated zones. The identity, toxicity, and mobility of these partially degraded compounds should be determined since intermediate degradation products can be as toxic or more toxic than the parent compound. Since metabolic by-products can accumulate in the soil and groundwater, future remedial actions may be necessary.

In addition to intermediate degradation by-products, residual contamination may persist in the soil following treatment. Microbes are capable of degrading only that fraction of the contamination that is readily available for microbial incorporation. As a result, biologically resistant contaminants and contaminants that remain sorbed to the soil and sediment during the remedial action cannot be degraded. Depending on the nature of the contaminants and media, the "bound" fraction may slowly desorb over long periods of times (months to years), potentially recontaminating "treated" media near the residual contamination [34][35]. Additionally, fluctuations in the water table may result in the recontamination of previously remediated soils if groundwater contamination, specifically

contamination associated with the presence of a light non-aqueous phase layer (LNAPL), has not been effectively addressed.

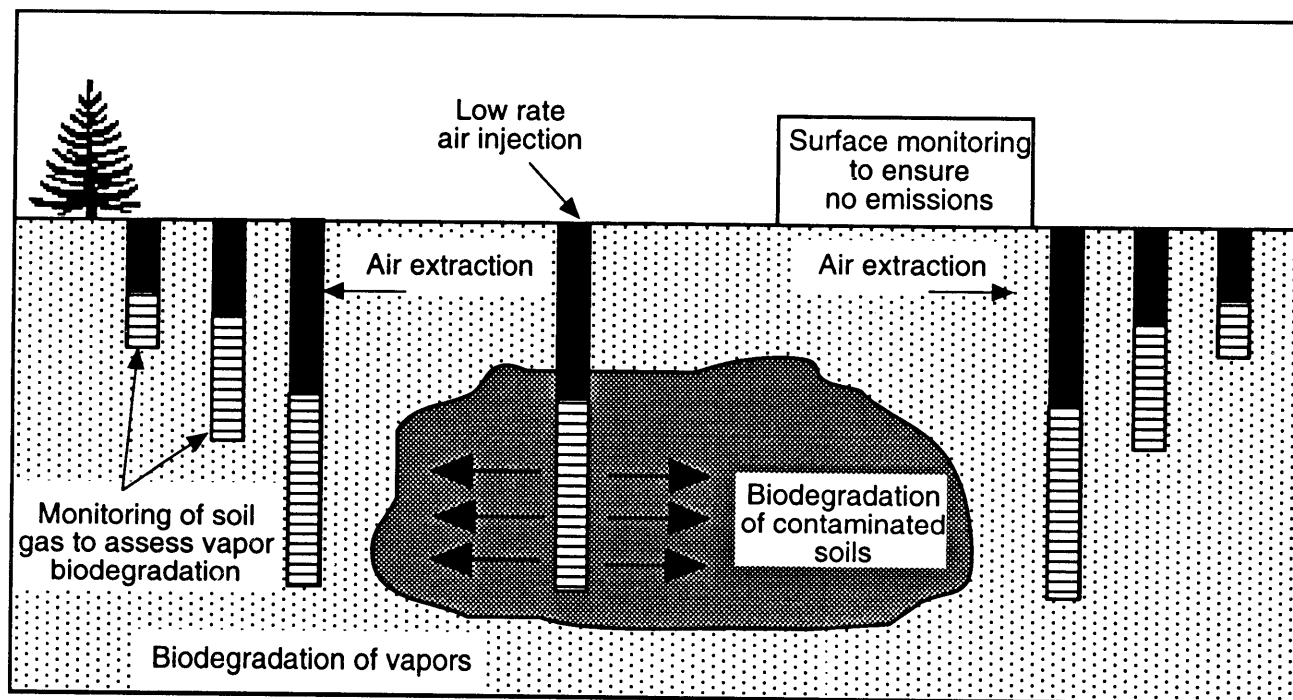
Above-ground activities taken to ensure that the remedial action complies with regulatory requirements and adequately guards against cross-contamination and uncontrolled releases may result in the generation of a significant volume of waste requiring disposal. For example, when groundwater is used to deliver amendments to the subsurface, it may be necessary to pre-treat the water before it can be re-introduced to the subsurface. Additionally, in order to protect water quality outside of the treatment zone from contaminant or amendment migration, a down-gradient groundwater recovery and treatment system designed to collect and treat amendment- and contaminant-laden groundwater may be needed. The residuals produced by these add-on treatment processes will eventually require disposal.


Significant volatile emissions may also be produced during in situ biodegradation (e.g., bioventing). Depending on their concentration, toxicity, and total volume, these emissions, which may consist of the original contaminant or any volatile degradation products produced during treatment, may need to be controlled, collected, or treated. Ultimately, the by-products of an emissions treatment/control system will require disposal.

Site Requirements

In situ biodegradation normally requires the installation of wells or infiltration trenches; therefore, adequate

Figure 2. Bioventing





access roads are required for heavy equipment such as well-drilling rigs and backhoes. Soil-bearing capacity, traction, and soil stickiness can limit vehicular traffic [17, p. 61].

In general, the area required to set up mixing equipment is not significant. However, space requirements increase as the complexity of the various pre- and post-treatment systems increases. During the installation of infiltration galleries and wells, several hundred up to several thousand square feet of clear surface area will be required. Climate can also influence site requirements. If periods of heavy rainfall or extremely cold conditions are expected, a cover may be required.

Electrical requirements will depend on the type of technology employed. Standard 220V, three-phase electrical service may be used to supply power to pumps and mixing equipment. Since water is used for a variety of purposes during biological treatment, a readily available water supply will be needed at most sites. Municipal water or clean groundwater may be used. Contaminated groundwater may be used if permitted by the appropriate regulatory agency. The quantity of water needed is site- and process-specific. Waste storage is not normally required for in situ biodegradation.

Onsite analytical equipment for conducting pH and nutrient analyses will help improve operation efficiency and provide better information for process control. During bioventing applications, air emissions monitors at the ground surface are commonly used.



Regulatory Considerations and Response Actions

Federal mandates can have a significant impact on the application of in situ biodegradation. RCRA LDRs that require treatment of wastes to best demonstrated available technology (BDAT) levels prior to land disposal may sometimes be determined to be applicable or relevant and appropriate requirements (ARARs) for CERCLA response actions. The in situ biodegradation technology can produce a treated waste that meets treatment levels set by BDAT, but may not reach these treatment levels in all cases. The ability to meet required treatment levels is dependent upon the specific waste constituents and the waste matrix. In cases where in situ biodegradation does not meet these levels, it still may, in certain situations, be selected for use at the site if a treatability variance establishing alternative treatment levels is obtained. Treatability variances are justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.06FS, September 1990) [10], and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.06BFS, September 1990) [11]. Another approach could be to use other treatment techniques with in situ biodegradation to obtain desired treatment levels,

for example, carbon treatment of recovered groundwater prior to re-infiltration into the subsurface.

When determining performance relative to ARARs and BDATs, emphasis should be placed on assessing the risk presented by a bioremediation technology. As part of this effort, risk assessment schemes, major metabolic pathways of selected hazardous pollutants, human health protocols for metabolite and pathogenicity tests, and fate protocols and issues for microorganisms and metabolites must be assessed [36]. A detailed summary of the findings of the June 17-18, 1993 EPA/Environment Canada Workshop in Duluth, Minnesota addressing Bioremediation Risk Assessment should be available in early 1994.

Performance Data

Performance data for Superfund sites are limited. The first record of decision (ROD) selecting in situ biodegradation as a component of the remedy was in FY87. Since then, in situ biodegradation of soil or groundwater contaminants has either been considered or selected at 22 Superfund sites and 30 RCRA, UST, TSCA, and Federal sites [1][2][3]. The following two subsections address traditional in situ and bioventing applications, respectively; a third subsection has been included to briefly address information sources and data concerns related to remedial efforts performed in the private sector.

Traditional In Situ Bioremediation

Methane and phenol were employed during a series of stimulus-response studies investigating the co-metabolic degradation of TCE, cis-dichloroethene (c-DCE), trans-dichloroethene (t-DCE), and vinyl chloride (VC) at the Moffet Field site in California. Both sets of experiments used indigenous bacteria and were performed under the induced gradient conditions of injection and extraction. During the first set of experiments, methane, oxygen, and TCE (from 50 to 100 µg/L), c-DCE, t-DCE, and VC were added to the soil to stimulate methanotrophic degradation of the injected chlorinated aliphatic compounds. Approximately 20 percent of the TCE added to the system was degraded within the 2-meter hydraulically-controlled biostimulated zone. Approximately 50 percent of the c-DCE, 90 percent of the t-DCE, and 95 percent of the VC were also degraded. During the second set of tests, methane was replaced with phenol in order to stimulate growth of an indigenous phenol-utilizing population. During 4 weeks of testing, the concentration of TCE injected into the subsurface was raised from an initial concentration of 62 µg/L to a final concentration of 1000 µg/L. A bromide tracer was used to determine transformation extent. Up to 90 percent of the TCE in the 2-meter biostimulated zone was degraded, demonstrating that even at relatively high TCE concentrations significant removal efficiencies can be achieved in situ through phenol and dissolved oxygen (DO) addition. During the course of the project, transformation yields (i.e., grams of TCE per grams of phenol) ranging from 0.0044 to 0.062 were obtained for varying concentrations

of phenol and TCE. Future studies at the site will determine whether a compound more environmentally acceptable than methane or phenol can be used to induce an indigenous population that effectively degrades TCE [37][7][8].

A 40- by 120-foot test zone in an aquifer that receives leachate from an industrial landfill at the Du Pont Plant near Victoria, Texas was used to demonstrate the in situ biotransformation of tetrachloroethene (PCE), TCE, DCE, chloroethane, and VC to ethane and ethylene using microbial reductive dehalogenation under sulfate-reducing conditions. Groundwater from this zone was alternately amended with either benzoate or sulfate and circulated through the aquifer. Initially PCE and TCE concentrations were approximately 10 and 1 micro-mole (μM), respectively. After a year of treatment the halogenated compounds were reduced to concentrations near or below 0.1 μM . PCE and TCE degraded to DCE rapidly following the introduction of benzoate. A decrease in sulfate concentrations led to increases in the vinyl chloride concentrations. Therefore, sulfate concentrations were kept above 10 mg/L until the DCE was further biodegraded. After approximately 6 months of treatment, most of the DCE, chloroethane, and VC biodegraded to produce ethane and ethylene [38].

A field-scale in situ bioremediation system, consisting of down-gradient groundwater extraction wells and an up-gradient infiltration system, was installed at a gasoline-contaminated site owned by the San Diego Gas and Electric Company. [Note: extracted groundwater was amended with nutrients (nitrate and phosphate) prior to re-infiltration into the subsurface]. Due to the relatively low rate of groundwater extraction (approximately 800 to 900 gallons per day) and the low hydraulic gradient at the site (0.004), it took nearly 2 years (until June/July 1991) for the added nitrate to reach the down-gradient well and overtake the xylene (BTX) plume. BTX concentrations, which ranged from 25 to 50 mg/L for the preceding 2-year period, dropped markedly as nitrate levels in the groundwater increased. By late August 1991, benzene and toluene concentrations had dropped below the detection limit (0.01 mg/L), and total xylene concentrations had dropped to 0.02 mg/L. The coincident occurrence of nitrate appearance and BTX loss in the aquifer, as well as an eight-fold increase in the percentage of denitrifiers present in the groundwater (from 1 to 8 percent), points to a potential stimulatory effect nitrate may have on BTX loss in situ [5].

An in situ bioremediation system consisting of four injection and three recovery wells was employed to treat gasoline contamination present in the saturated zone at a former service station in Southern California. During treatment, recovered groundwater was amended with hydrogen peroxide (from 500 to 1,000 mg/L) and nutrients and re-injected into the aquifer. Prior to treatment, total fuel hydrocarbons in the saturated clay soils ranged from below detection limits to 32 mg/kg as BTX. Maximum groundwater concentrations were 2,700 $\mu\text{g/L}$ for benzene; 6,600 $\mu\text{g/L}$ for toluene; 4,100 $\mu\text{g/L}$ for xylene; and 45,000 $\mu\text{g/L}$ for TPH [4]. After 10 months, BTX and TPH levels in the groundwater and saturated soils had dropped below the

detection limits. Roughly 1,350 kilograms of hydrogen peroxide were introduced to the aquifer over 10 months, roughly two times the estimated requirements based on the estimated mass of hydrocarbon in the saturated zone (i.e., 110 kg of fuel hydrocarbon and 2 to 3 kg of dissolved hydrocarbons). After 34 months of treatment, soil hydrocarbon concentrations ranged from below the detection limit to 321 ppm as TPH; benzene was not detected in any samples [39].

Following successful laboratory treatability testing, General Electric performed a 10 $\frac{1}{2}$ -week field study to investigate the biodegradation of polychlorinated biphenyls (PCBs) in the Hudson River sediment. Initial PCB concentrations in the sediment ranged between 20 and 40 ppm. The study attempted to enhance the aerobic bacteria native to the upper Hudson River. Six caissons were installed at the Hudson River Research Station (HRRS) to isolate sections of the river bottom for this field study. Because of extensive, naturally occurring dechlorination, approximately 80 percent of the total PCBs encountered in the sediments were mono-, di-, and trichlorobiphenyls. Biodegradation was stimulated using oxygen and nutrient addition. Mixing was employed to enhance the dispersal of oxygen and nutrients within the sediment. Between 38 and 55 percent of the PCBs present in the sediment were removed by aerobic degradation during the study. This corresponds to the percentage biologically available PCBs [9].

Bioventing

In May 1992, the U.S. Air Force began a Bioventing Initiative to examine bioventing as a remedial technique at contaminated sites across the country. The Air Force's decision to examine bioventing on such a large scale was prompted by a successful demonstration of the technology at Tyndall AFB, Florida, where bioventing coupled with moisture addition removed one-third of the TPH and nearly all of the BTEX in JP-4 contaminated soils during 7 months of treatment. The Bioventing Initiative targets 138 sites with diesel fuel, jet fuel, or fuel oil in soil. In selecting sites for the initiative, the Air Force looked for characteristics appropriate for bioventing, such as deep vadose soil, heavy hydrocarbon contamination, and high air permeability. The chosen sites represent a wide range of depths to groundwater, hydrocarbon concentrations, and soil textures. Preliminary testing has been completed and 33 systems have been installed at Battle Creek Air National Guard Base and the following AFBs: Beale, Eglin, Eielson, F.E. Warren, Galena, Hanscom, Hill, K.I. Sawyer, McGuire, Newark, Offutt, Plattsburgh, Robins, Vandenberg, and Westover. According to the Air Force, initial results are very promising with degradation rates measured as high as 5,000 mg/kg per year [40][41].

The EPA RREL, in collaboration with the U.S. Air Force, initiated two 3-year pilot-scale bioventing field studies in mid-1991 at JP-4 contaminated fuel sites located at Eielson AFB near Fairbanks, Alaska and at Hill AFB near Salt Lake City, Utah. Four soil plots are being used to evaluate passive, active, and buried heat tape soil-warming methods

during the Eielson study. The fourth plot was vented with injected air but not artificially heated. Roughly 1 acre of soil is contaminated from a depth of 2 feet to the water table at 6 to 7 feet. At the Hill site, a series of soil gas cluster wells capable of obtaining samples up to 90 feet deep is being used with a single air injection well and two groundwater wells to remediate JP-4 contamination found at depths ranging from 35 feet to perched water at approximately 95 feet. Inert gas tracer studies, regular soil gas measurements at several locations and depths, and periodic in situ respirometry tests to measure in situ oxygen uptake rates are being performed. Final soil hydrocarbon analyses will be conducted at both sites in mid-1994 and compared with the initial soil data. In situ respirometry data from the Hill site (Table 1) indicate that petroleum hydrocarbons are being removed at a significant rate. Intermediate respirometry data from the test and control plots at the Eielson site indicate that higher biodegradation rates are being obtained at higher soil temperatures.[42][43].

Table 1.
Rates of Biodegradation, Averaged Over Depth, at Three Wells at Hill AFB

Well	Depths (ft)	Rate (mg/kg/day)	
		September 1991	September 1992 ¹
CW-1	20-90	0.97	0.30
CW-2	60-90	0.59	0.36
CW-3	10-90	0.56	0.32

1 Since bioventing is being performed on a sandy soil, with little to no naturally occurring organic matter, a biodegradation rate approaching zero would indicate that biodegradation had finished.

In November 1991, a pilot-scale bioventing system originally used to treat gasoline-contaminated vadose soils at the U.S. Coast Guard Air Station in Traverse City, Michigan was converted into a groundwater biosparging process. Eight 2-inch diameter sparge wells were installed to a depth of 10 feet below the water table. A control plot located in the vicinity of the contaminated plume, but not biosparged, was established to help assess the system's performance. After 12 months of biosparging, one-third of the oily phase residue below the water table, as well as almost all the BTEX initially present within the groundwater plume, was removed. (See Table 2 for groundwater quality data after 7 months of biosparging.) The globular nature of the oily residue limited the surface area in contact with the introduced air, thus restricting the biodegradation and vaporization of the oily-phase contaminants [44][45].

Non-Superfund Sites

In situ biodegradation has been applied at many sites in the private sector. Those interested in accessing informa-

Table 2.
Groundwater Quality After Seven Months of Biosparging at the U.S. Coast Guard Air Station in Traverse City, Michigan

Well Depth (ft)	Benzene (µg/L)	Xylenes (µg/L)	Total Fuel Carbon(µg/L)
Control			
16	9.9	19	2,880
17.5	228	992	4,490
20.5	70	38	956
22	57	7.7	783
Sparge Plot			
15	1.9	5.3	559
18	<1	5.0	<6
19.5	<1	<1	<6
21	<1	<1	<6

tion generated in the private sector may want to refer to the following EPA Publications:

- U.S. Environmental Protection Agency. Bioremediation Case Studies: Abstracts. EPA/600/R-92/044, March 1992.
- U.S. Environmental Protection Agency. Bioremediation Case Studies: An Analysis of Vendor Supplied Data. EPA/600/9-92/043, March 1992.

Most of the data contained in these resources were directly supplied by the vendor and have not been technically reviewed by EPA. Since independently-reviewed data are not always available from privately sponsored remedial efforts, in part due to proprietary issues [46, p. 1-1], readers should use these data cautiously. Often the quality of the data used to determine system effectiveness has not been substantiated by the scientific community. Thus, many vendor claims of effectiveness, specifically regarding introduced organisms and surface-active agents, are not supported within the scientific literature. Furthermore, many bioremediation firms have only limited experience working with the complex wastes normally associated with Superfund sites. Typically these firms deal only with gasoline and petroleum product leaks and spills. Additionally, many of the systems currently on the market involve the use of in situ biodegradation in combination with other above-ground treatment technologies such as carbon adsorption, air stripping, and biological reactors. In situ biodegradation is believed to enhance the total removal efficiency of the system. However, in many cases, it is unclear how much of the degradation occurred as a result of biological or non-biological mechanisms (volatilization, chemical destruction, etc.). How much biodegradation actually takes place in the soil or groundwater, in contrast to ex situ biodegradation, is not always clear.

Technology Status

In situ biodegradation either has been considered or selected as the remedial technology at 21 Superfund sites, as well as 38 RCRA, UST, TSCA, and Federal sites [1][2][3]. Table 3 lists the location, primary contaminants, treatment employed, and status of these sites. Information has also been included on three in situ biotechnology demonstrations presently being performed under the U.S. EPA Superfund Innovative Technology Evaluation (SITE) Program and seven sites selected for performance evaluations under the U.S. EPA Bioremediation Field Initiative. The data obtained during the SITE demonstrations and Bioremediation Field Initiative performance evaluations will be used to develop reliable cost and performance information on biotreatment technologies and applications.

The majority of the information found in Table 3 was obtained from the August 1993 version of "Bioremediation in the Field" [1]. These sites have been sorted numerically by Region and then alphabetically by site name. Sites employing "in situ land treatment" were not included in this list since these applications typically involve a significant amount of material handling. Additionally, some of the information was modified based on phone calls made to the various site project managers. This resulted in the removal of the American Creosote Works site in Florida and four pesticides sites (i.e., the Joliet Weed Control District site in the Joliet, Montana; the Lake County Weed Control site in Ronan, Montana; the Miles Airport site in Miles City, Montana; and the Richey Airport site in Richey, Montana) [47], which are no longer considering in situ treatment. Quarterly updates of this information can be obtained from subsequent versions of "Bioremediation in the Field".

Most of the hardware components of in situ biodegradation systems are available off-the-shelf and present no significant availability problems. Selected cultures, nutrients, and chemical/biological additives are also readily obtainable.

Bioremediation, particularly in situ applications, which avoid excavation and emissions control costs, are generally considered cost effective. This can be attributed in part to low operation and maintenance requirements. During set up and operation, material handling requirements are minimal, resulting in lowered worker exposures and reduced health impacts. Although in situ technologies are generally slow and somewhat difficult to control, a large volume of soil may be treated at one time.

It is difficult to generalize about treatment costs since site-specific characteristics can significantly impact costs. Typically, the greater the number of variables requiring control during biological treatment, the more problematic the implementation and the higher the cost. For example, it is less problematic to implement a technology in which only one parameter (e.g., oxygen availability) requires modification than to implement a remedy that requires modification of multiple factors (e.g., pH, oxygen levels, nutrients, microbes, buffering agents, etc.). Initial concentrations and volumes, pre- and post-treatment requirements, and air emissions and control systems will impact

final treatment costs. The types of amendments employed (e.g., hydrogen peroxide) can also impact capital cost and costs associated with equipment and manpower required during their application.

In general, however, in situ bioremediation is considered to be a relatively low-cost technology, with costs as low as 10 percent of excavation or pump and treat costs [7, p. 6-16]. The cost of soil venting using a field-scale system has been reported to be approximately \$50 per ton as compared to incineration, which was estimated to be more than ten times this amount. A cost estimate of about \$15 per cubic yard for bioventing sandy soil at a JP-4 jet fuel contaminated site has been reported by Vogel [48]. Exclusive of site characterization, the biological remediation of JP-4 contaminated soils at the Kelly Air Force Base site was estimated to be \$160 to \$230 per gallon of residual fuel removed from the aquifer [9]. At the French Limited site in Texas, the cost of bioremediation is projected to be almost three times less expensive than incineration. Because of the large amount of material requiring treatment at this site, it has been projected that cleanup goals will be achieved in less time by using bioremediation rather than incineration.

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Table 3. Superfund, RCRA, UST, TSCA, and Federal Sites

Site Location (Regions)	Primary Contaminants	Status/Cost	Treatment
Charlestown Navy Yard Boston, MA (1)	Sediments: wood preserving (PAHs).	Design: pilot scale TS underway.	In situ treatment. Ex situ treatment. Aerobic and anaerobic.
General Electric - Woods Pond Pittsfield, MA (1)	Sediments: PCBs. Volume: 250 gallons.	Design: lab scale TS underway.	Anaerobic treatment, confined treatment facility, nutrient addition.
FAA Technical Center - Area D Atlanta County, NJ (2)	Soil (saturated sand)/groundwater: petroleum (jet fuel, NAPLs). Volume: 33K cubic yards.	Design: pilot scale TS completed 8/92. Expected cost: capital, \$286K; O&M, \$200K	Nutrient addition (soil, water). Groundwater re-injection.
General Electric - Hudson River, NY (2)	Sediments: PCBs, cadmium, chromium, lead. Volume: 150 cubic feet.	Predesign: lab scale TS completed. Incurred cost: \$2.6M.	Aerobic treatment. Less than 1% of site underwent bioremediation.
Knispel Construction Site Horsehead, NJ (2)	Soil/groundwater: petroleum.	Completed: full scale 10/89 Start date: 01/89. Incurred cost: O&M, \$25K.	Aerobic treatment, hydrogen peroxide, nutrient addition (water). 100% of site underwent bioremediation [25].
Picatinny Arsenal NJ (2)	Soil (vadose)/soil vapors: solvents (TCE).	Design: lab scale studies completed.	Aerobic treatment, bioventing. Co-metabolic degradation (methane, propane, or natural gas) [27].
Plattsburgh AFB Plattsburgh, NY (2)	Groundwater: petroleum.	Design: pilot scale. Start date (est.): 3/94.	Aerobic treatment, bioventing.
ARC Gainesville, VA (3)	Soil: solvent (chlorobenzene). Volume: 2,000 cubic yards.	Completed: full scale 6/91. Start date: 10/89.	Aerobic treatment, bioventing. Exogenous organisms. 5% of the site underwent bioremediation.
Dover AFB Dover, DE (3)	Soil (vadose sand and silt)/groundwater: petroleum, PAHs, TCE, solvents, metals (lead, iron, manganese). Volume: 365K cubic yards.	Four separate processes are planned. Field and lab TS results are expected 2/94 and 11/94.	Aerobic treatment, bioventing, air sparging. Ex situ land treatment.
L.A. Clarke & Son Fredericksburg, VA (3)	Sediments/soil: wood preserving. Volume: 119K cubic yards.	Design: pilot scale TS started 7/92. Expected cost: \$23M.	In situ treatment, creosote recovery. 25% of site will undergo bioremediation.
Charleston AFB Charleston, SC (4)	Soil (vadose sand): petroleum (jet fuel), solvents (1,1-DCE; 1,1,1-TCA; TCE; VC; trans-1,2-DCE; PCE; and dichloromethane), lead. Volume: 25 cubic yards.	Pilot scale TS started 11/92. Expected completion 12/93.	Aerobic treatment, bioventing. Less than 10% of the site under bioremediation.
Eglin AFB FL (4)	Soil (vadose): petroleum (jet fuel).	Completed field scale study.	Aerobic treatment, bioventing. Nutrient and hydrogen peroxide addition [27].
Savannah River Site Aiken, NC (4)	Soil (vadose)/groundwater/sediments: chlorinated solvents (TCE and PCE).	Operational: pilot scale research study.	Aerobic treatment, horizontal wells, methane addition [18][19].
Stallworth Timber Beatrice, AL (4)	Soil (sand, silt)/groundwater: wood preserving (PCP).	Predesign.	In situ aerobic treatment, nutrient addition. Ex situ treatment, activated sludge, continuous flow. Exogenous and indigenous organisms. 100% of site will undergo bioremediation.
Allied Chemical Ironton, OH (5)	Sediments (coal and coke fines): PAHs, arsenic. Volume: 500K cubic yards.	Design: pilot scale TS study completed. Expected cost: \$26M	Aerobic treatment. 50% of site will undergo bioremediation.
Amoco Production Co. Kalaska, MI (5)	Soil (saturated)/groundwater: BTEX.	Pilot scale TS completed.	Aerobic treatment, air sparging [49].
B&F Trucking Company Rochester, MN (5)	Soil (vadose and saturated)/groundwater: petroleum (lube oil). Volume: 700 cubic yards.	Operational: full scale. Start Date: 4/91. Incurred cost: \$341K.	In situ treatment. Ex situ treatment, sequencing batch reactor, continuous flow. Aerobic conditions. 75% of site under bioremediation.
BendixCorp./Allied ¹ Automotive Site St. Joseph, MI (5)	Groundwater: solvents (TCE, DCE, DCA, VC).	Predesign: lab scale TS underway.	Aerobic and anaerobic treatment.

Table 3. Superfund, RCRA, UST, TSCA, and Federal Sites (continued)

Site Location (Regions)	Primary Contaminants	Status/Cost	Treatment
Un-named site ² Buchanan, MI (5)	Groundwater: BTEX, PCE, TCE, DCE.	Pilot field study started 3/93. Expected completion 3/94.	Aerobic treatment.
Galesburg/Kopper Galesburg, IL (5)	Soil: phenols, chlorophenol, PNAs, PCP, PAHs.	Predesign. Start date (est): 12/92.	Nutrient addition. 100% of site under bioremediation.
Hentchells Traverse City, MI (5)	Soil/groundwater: petroleum.	Operational: full scale. Start date: 9/85.	Aerobic treatment, biosparging.
Kenworth Truck Company Chillicothe, OH (5)	Soil (vadose)/groundwater: solvents (BTEX, acetone, TPH).	Design: lab scale TS completed. Full scale system being installed.	In situ aerobic treatment, hydrogen peroxide, nutrient addition (nitrogen, phosphorus). Ex situ treatment, GAC bioreactor. 100% of site will undergo bioremediation.
K.I. Sawyer AFB Marquette, MI (5)	Soil (vadose sand): petroleum.	Field TS report expected 10/93.	Aerobic treatment, bioventing.
Mayville Fire Department Mayville, MI (5)	Groundwater: petroleum.	Operational: full scale since 5/90. Completion date (est): 1/94.	Aerobic treatment, air sparging. 100% of site will undergo bioremediation.
Michigan Air National Guard Battle Creek, MI (5)	Soil (vadose: sand, silt): petroleum, heavy metals.	Design: pilot scale TS started 9/92. Start date (est): 9/93 Expected cost: capital, \$3,000; O&M, \$1,268.	Aerobic treatment, bioventing. 100% of site will undergo bioremediation.
Newark AFB Newark, OH (5)	Soil (vadose: silt, clay): petroleum (gasoline). Volume: 60 cubic yards.	Design: pilot scale TS started 8/92. Expected completion 8/94. Expected cost: capital, \$35K; O&M, \$2K.	Aerobic treatment, bioventing. 40% of site under bioremediation.
Onalaska Municipal Landfill Lacrosse County, WI (5)	Soil (vadose and saturated sand): solvents (TCE), petroleum (total hydro-carbons), wood preserving (naphthalene). Volume: 5,000 cubic yards.	Design: lab scale TS completed 3/92. Expected cost: capital, \$400K; O&M, \$20K.	Aerobic treatment, bioventing. 20% of site will undergo bioremediation.
Parke-Davis Holland, MI (5)	Soil/groundwater: petroleum, solvents, arsenic, chloride, zinc.	Predesign.	In situ treatment. Ex situ treatment, fixed film.
Reilly Tar & Chemical 1,2 St. Louis Park, MN (5)	Soil (vadose loam): wood preserving (PAHs).	Design: pilot scale TS started 11/92. Expected completion 11/95. Incurred cost: \$25K. Expected cost: \$70K.	Aerobic treatment, bioventing, nutrient addition [50].
Sheboygan River and Harbor Sheboygan, IL (5)	Sediments (sand, silt, clay): PCBs. Volume: 2,500 cubic yards.	Lab and pilot scale TS are being conducted.	In situ treatment, capping of sediments. Ex situ treatment, confined treatment facility (tank). Aerobic and anaerobic conditions.
West K&L Avenue e Landfill 1 Kalamazoo, MI (5)	Groundwater: solvents (acetone; TCE; trans-1,2-DCE; 1,2-DCA; 1,1-DCA; BTEX; VC; methyl isobutyl ketone; MEK.	Design: pilot and lab scale TS ongoing.	Anaerobic treatment under sulfate reducing conditions.
Wright-Patterson AFB Dayton, Ohio (5)	Soil (vadose: sand, silt, clay): petroleum (jet fuel). Volume: 7.5K cubic yards.	Predesign: pilot scale studies planned. Expected completion 3/94.	Aerobic treatment, bioventing. 100% of site will undergo bioremediation.
Dow Chemical Company Plaquemine, LA (6)	Groundwater: solvents (1,1-DCA; 1,2-DCA; 1,1,1-TCA; 1,1-DCE, chloroethane). Volume: 90K cubic yards.	Design: pilot scale started 3/93. Expected cost: capital, \$1M; O&M, \$50K. Incurred cost: capital, \$250K; O&M, \$10K.	Anaerobic treatment, nutrient addition. Less than 1% of site under bioremediation. Experiencing nutrient dispersion problems [46].
French Limited Crosby, TX (6)	Sediments (sand, silt)/sludge/soil (sand, silt, clay)/groundwater: PCBs, arsenic, roleum (BAP, VOCs), arsenic.	Operational: full scale since 1/92. Expected cost: \$90M.	Aerobic treatment, pure oxygen dissolution system, nutrient addition (soil, water, sediments). 100% of site under bioremediation.
Kelly AFB San Antonio, TX (6)	Soil (vadose clay): petroleum (jet fuel), solvents (PCE, TCE, VC, DCE).	Operational: full scale since 2/93. Completion data (est): 9/94.	Aerobic treatment, bioventing.

Table 3. Superfund, RCRA, UST, TSCA, and Federal Sites (continued)

Site Location (Regions)	Primary Contaminants	Status/Cost	Treatment
Fairfield Coal & Gas Fairfield, IA (7)	Soil (saturated: sand, silt, clay)/groundwater: coal tar (BTEX, PAHs).	Design: pilot scale TS started 12/91. Expected completion 12/93. Expected cost: \$1.6M.	Aerobic treatment, injection and extraction wells, hydrogen peroxide, nitrate addition.
Offutt AFB LaPlatte, NE (7)	Soil (vadose: sand, silt): petroleum (TRPH), arsenic, barium, lead, zinc. Volume: 700 cubic yards.	Design: pilot scale TS started 8/92.	Aerobic treatment, bioventing. 10% of site under bioremediation.
Park City ¹ Park City, KS (7)	Groundwater: petroleum (lube oil), benzene. Volume: 700K cubic feet.	Design: pilot scale TS completed. Incurred cost: \$275K. Expected cost: \$650K.	Groundwater: in situ treatment. Possible bioventing for soils. Anaerobic and aerobic conditions [23][24].
Burlington Northern Tie Plant Somers, MT (8)	Soil/groundwater: wood preserving (PAHs). Volume: 82K cubic yards.	Installed: full scale. Start date (est.): 7/92. Expected cost: \$11M.	In situ treatment. Ex situ land treatment. Aerobic conditions. 80% of site will undergo bioremediation.
Geraldine Airport Geraldine, MT (8)	Soil (vadose: sand, silt, loam, clay): pesticides (aldrin; dieldrin; endrin; chlordane; toxaphene; b-BHC; 4,4'-DDE; 4,4'-DDT; 4,4'-DDD); herbicides (2,4-D).	Predesign.	In situ treatment. Ex situ treatment. Aerobic and anaerobic conditions.
Idaho Pole Company Bozeman, MT (8)	Sediments/soils/groundwater: PCP, PAHs, dioxins/furans.	Predesign.	In situ treatment, oxygen enhancement, nutrient addition. Ex situ treatment, fixed film, slurry reactor. Aerobic conditions.
Hill AFB ¹ Salt Lake City, UT (8)	Soil: petroleum (JP-4 jet fuel).	Operational: full scale since 9/91. Completion date (est): 9/94.	Aerobic treatment, bioventing. 100% of site under bioremediation [40].
Libby Groundwater Site ¹ Libby, MT (8)	Soil (vadose and saturated)/groundwater: wood preserving (PAHs, pyrene, PCP, dioxin, naphthalene, phenanthrene, benzene, arsenic). Volume: 45K cubic yards.	Operational: three pilot scale efforts ongoing. Incurred cost: \$4M. TS results available (est): 8/93 and 4/94.	In situ treatment (groundwater), ex situ land treatment (soil), nutrient addition (soil, water). Also, treatment of groundwater in bioreactor. Aerobic conditions. 75% of site under bioremediation.
Public Service Company ¹ Denver, CO (8)	Groundwater: petroleum. Volume: 12M gallon.	Completed: full scale 3/92. Start date: 06/89. Incurred cost: \$500K.	Aerobic treatment, hydrogen peroxide, nutrient addition, combined bioprocess.
Beale AFB Marysville, CA (9)	Soil (vadose silty clay): petroleum (gasoline, diesel), solvents (TCE), lead. Volume: 163K cubic yards.	Seven processes are planned. 4 are in design (pilot scale), 2 are in predesign (full scale), and 1 is presently operating (completion date 7/95). Expected cost: capital \$500K; O&M, 136K.	In situ aerobic treatment, bioventing. Ex situ aerobic treatment, pile. Results of 4 bioventing TS expected 2/94.
Converse/Montabello Corporation Yard Montabello, CA (9)	Soil (vadose silt): petroleum (gas, diesel).	Design: pilot scale TS started 5/93. Expected completion 12/93.	Aerobic treatment, bioventing, nutrient addition. 10% of site under bioremediation.
Former Service Station Los Angeles, CA (9)	Soil/groundwater: petroleum. Volume: 3,000 cubic yards.	Completed: full scale 3/91. Start date: 11/88. Incurred cost: \$1.6M.	Aerobic treatment, hydrogen peroxide, nutrient addition (water), closed loop system. 65% of site underwent bioremediation.
Koppers Company, Inc. Orville, CA (9)	Soil (vadose: sand, clay, gravel, cobbles): wood preserving (PCP, PAHs, dioxins/furans), arsenic, chromium. Volume: 110K cubic yards.	Predesign: pilot scale TS planned. Expected completion 11/94. Expected cost: capital, \$4.5M; O&M, \$7.7M.	Aerobic treatment, nutrient addition. 30% of site will undergo bioremediation. (20 year remedial effort)
Marine Corps Air/ Ground Combat Center Twenty-Nine Palms, CA (9)	Soil: petroleum (jet fuel, gasoline, diesel, aviation fluid, transmission fluid).	Design: full scale.	Aerobic treatment, bioventing.
Naval Air Station Fallon Fallon, NV (9)	Soil (vadose and saturated silt)/groundwater: petroleum (jet fuel, p-xylene, naphthalene, 1-methyl naphthalene, n-butylbenzene), arsenic.	Design: pilot scale TS started 10/92.	Aerobic treatment, bioventing, nutrient addition (soil), oil/water separation.
Naval Weapons Station Seal Beach, CA (9)	Groundwater: petroleum.	TS conducted or in progress: laboratory scale.	Aerobic and anaerobic treatment.
Oakland Chinatown Oakland, CA (9)	Soil (saturated sand): groundwater: petroleum.	Volume: 10K cubic yards. Completed: full scale 8/90. Start date: 3/89.	Aerobic treatment, hydrogen peroxide and nutrient addition.

Table 3. Superfund, RCRA, UST, TSCA, and Federal Sites (continued)

Site Location (Regions)	Primary Contaminants	Status/Cost	Treatment
San Diego Gas and Electric San Diego, CA (9)	Soil (sand): petroleum (gasoline). Volume: 1,200 cubic yards.	Completed: full scale 4/93. Start date: 10/89.	Aerobic treatment. 100% of site underwent bioremediation [5].
Williams AFB ² Phoenix, AZ (9)	Soil (vadose): petroleum (JP-4 jet fuel).	Pilot field testing started 5/92. Test completed 6/93.	In situ treatment, bacterial supplementation (non-indigenous micro aerophilic bacteria).
East 15th Street Service Station Anchorage, AK (10)	Soil: petroleum (TPH diesel). Volume: 1,500 cubic yards.	Operational: full scale since 6/92. Incurred cost: \$75K. Expected cost: \$200K.	Aerobic treatment, bioventing. 20% of site under bioremediation.
Eielson AFB ¹ Fairbanks, Alaska (10)	Soil (sand/silt): petroleum (JP-4 jet fuel).	Operational: pilot full scale. Start date: 9/91. Completion date (est): 9/94.	Aerobic treatment, bioventing, soil warming [42]
Fairchild AFB Spokane, WA (10)	Soil (vadose and saturated silt)/groundwater: petroleum, solvents (TCE).	3 separate processes are planned. The first process is in pre-design; a pilot scale TS should start 1/95. The remaining two started pilot scale TSs in 4/93.	Aerobic treatment, bioventing, nutrient addition.

TS - Treatability Study

¹ Bioremediation Field Initiative

² Superfund Innovative Technology Evaluation (SITE) Demonstration

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