Soil Bioremediation (Naturally Aerated Processes)

(U.S.) Naval Energy and Environmental Support Activity
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Abstract: Bioremediation is an innovative technology being considered more frequently, and more positively, for the remediation of soil contaminated with organic compounds. The main advantages of soil bioremediation are that it can be done on site (possibly avoiding land disposal restrictions) at relatively low cost and involves destruction of contaminants without transferring them to another media. While many points discussed will be applicable to soil bioremediation in general, the Tech Data Sheet focuses on treatment of soil in the vadose zone (the unsaturated soil above the water table) by solid phase processes (in contrast to the use of liquid phase slurries) using natural aeration.

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(Naturally Aerated Processes)

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Introduction

Bioremediation is an innovative technology being considered more frequently, and more positively, for the remediation of soil contaminated with organic compounds. The main advantages of soil bioremediation are that it can be done on site (possibly avoiding land disposal restrictions) at relatively low cost and involves destruction of contaminants without transferring them to another media.

While many points discussed will be applicable to soil bioremediation in general, this Tech Data Sheet focuses on treatment of soil in the vadose zone (the unsaturated soil above the water table) by solid phase processes (in contrast to the use of liquid phase slurries) using natural aeration. Processes using forced aeration (mechanically pumping air through the soil as in heap piles and bioventing) will be covered in a separate Tech Data Sheet titled "Heap Pile Bioremediation."

Purpose and Audience

Tech Data Sheets are designed to:

- Disseminate practical, implementation-related information to minimize design and construction problems;
- Help Remedial Project Managers (RPMs) to evaluate a technology (one recommended in a Feasibility Study [FS], for example) and decide if it is practical and cost-effective;
- Aid RPMs in writing a Remedial Action (RA) Delivery Order;
- Help Engineering Field Division (EFD) Remedial Design personnel to write a Statement of Work (SOW) for, and RPMs to review, Remedial Design Plans; and
- Enable field personnel such as Project Superintendents, Engineers in Charge, On-Scene Coordinators (OSCs), and Resident Officers in Charge of Construction (ROICCs) to become familiar with a technology at a site they will be overseeing.

Description of Technology

Bioremediation uses microorganisms—typically, naturally occurring bacteria, fungi, and/or actinomycetes (metabolically advanced microorganisms)—to degrade and, desirably, detoxify contaminants. This degradation is the breaking down of contaminants into simpler compounds that may or may not be less toxic. These simpler intermediate compounds may themselves be degraded. If the process leaves only carbon dioxide and water as end products, degradation is complete, and mineralization is said to have occurred.

Aboveground bioremediation is an aerobic process. That is, the microorganisms need oxygen to live and metabolize contaminants. In contrast, anaerobic microorganisms propagate in the absence of oxygen.

There are two basic approaches to naturally aerated soil bioremediation: landfarming and prepared beds. With natural aeration, oxygen consumed by bacterial respiration can be replaced only by diffusion of air through the soil. This means both approaches operate on thin layers of soil (about one-foot thick).

Landfarming is defined in this Tech Data Sheet as the tilling and cultivating of soil in place (i.e., without excavation) to enhance the biodegradation of hydrocarbon compounds. Since most degradation takes place in the aerobic zone of soil, landfarming can be used only in cases of shallow, widespread contamination, where no downward migration into ground water can be expected. Landfarming historically has involved the application of liquid hydrocarbon sludges from refineries to initially uncontaminated land and plowing to mix the sludge into the soil. After a certain degree of degradation has occurred, more sludge is applied.

Using lined landfarming treatment beds known as "prepared beds" or "treatment cells" is the most common form of soil bioremediation because: 1) most contamination is too deep for a plowing device to reach; and 2) placing the soil on a liner guards against the spread of contamination. Soil is excavated and spread above ground on specially prepared beds, usually at the site in order to minimize the cost of transporting hazardous waste and to avoid triggering Land

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Disposal Restrictions (LDRs) (see **Regulatory Issues**). The sites are designed to prevent the migration of contaminants to ground or surface water. They are surrounded by berms to control runoff and may be lined with clay or polymeric liners. Ancillary features may include systems for leachate collection treatment and systems for water, nutrient, enzyme, and cultured bacteria delivery.

Soil conditions are often controlled to optimize the rate of contaminant degradation. Conditions normally controlled include:

- Moisture content (usually by irrigation or spraying);
- Oxygen level (by mixing the soil via tilling, etc.);
- Nutrients, primarily nitrogen and phosphorus (by fertilizing);
- pH (increased slightly by adding lime); and
- Soil clumping (by adding soil amendments and by mixing via tilling, etc.).

In landfarming and prepared beds, mixing of the soil and contaminant is important. Mixing aerates the soil while evenly distributing concentrations of soil, contaminant, moisture, nutrients, oxygen, and bacteria. It also maximizes the surface area of soil and contaminant available to the bacteria.

Standard agricultural practices and equipment are often used in both landfarming and prepared beds. Disk harrows, tillers, and other plowing devices are used for mixing, and normal fertilizing implements are often used to add nutrients and for liming.

Technology Status

Naturally aerated soil bioremediation is one of the best-established and most cost-effective methods for treating soil contaminated with petroleum hydrocarbons. As of November 1990, the Environmental Protection Agency (EPA) had identified approximately 32 sites where soil bioremediation projects are either under consideration or are operational (1). Most of the sites involve bioremediation of nonvolatile, heavier petroleum hydrocarbons and polynuclear aromatic hydrocarbons (PAHs).

Landfarming involving sludge spreading has been practiced near refineries for more than 30 years, and prepared beds have been used for about 10 years (2). While the agricultural practices involved are conventional, bioremediation technology continues to evolve with respect to:

- Optimization of degradation rate and degree;
- Identification of intermediate products; and
- Combination with other processes such as soil venting.

Types of Applications

The most common applications of landfarming and prepared beds have been remediating soils contaminated by low-volatility petroleum products released from leaking underground storage tanks, spills, or past disposal practices (e.g., leaking drums).

Types of Contaminants

Soil bioremediation has been proven most successful in treating petroleum hydrocarbons. Since lighter, more volatile hydrocarbons such as gasoline are treated very successfully by processes that utilize their volatility (i.e., soil vapor [vacuum] extraction and bioventing), use of aboveground bioremediation is usually limited to heavier hydrocarbons—and products and wastes that include them. As a rule of thumb, the higher the molecular weight (and the more rings with a PAH), the slower the degradation rate. Also, the more chlorinated or nitrated the compound, the more difficult it is to degrade. (Note: Many mixed products and wastes include some volatile components that transfer to the atmosphere before they can be degraded.)

Contaminants that have been successfully treated include diesel fuel, #2 and #6 fuel oils, JP-5, oily sludge, wood-preserving wastes (creosote), coke wastes, and certain pesticides (3,4,5).

Despite demonstrated effectiveness with many compounds, there are too many site-specific considerations to extrapolate success in degrading a given compound from one site to another. Consequently, treatability studies must be conducted using a site's particular contaminant and soil characteristics.

Advantages

Natural aeration bioremediation in general has several advantages:

- It is easy to implement (since it uses conventional agricultural practices and equipment);
- The cost is low relative to other alternatives (such as incineration);
- Contaminants are not transferred to another media (so there is nothing else to treat);
- It is permanent (in that contaminants may be completely degraded to nontoxic gases and water); and
- It may not trigger LDRs—being *in situ*, landfarming definitely does not—but whether the use of on-site prepared beds does may be subject to interpretation.

Landfarming has the additional advantages of not requiring the expense of liners and leachate collection/treatment. Only rainfall run-off control is used.

The leachate collection/treatment systems, run-off collection/treatment systems, and liners (optional) used with prepared beds allow complete control of contaminant migration in a liquid phase. If necessary, volatile components can be controlled by enclosing the beds.

Disadvantages

Natural aeration bioremediation in general has several disadvantages:

- Technology is in the innovative stage for contaminants other than petroleum hydrocarbons (the process is still evolving; the exact cost to remediate a given compound is not known because of site variability, and results cannot be guaranteed);
- Treatment of some compounds, such as PAHs of four or more rings and chlorinated compounds like polychlorinated biphenyls (PCBs), is too slow to be practical (high molecular weight compounds, such as creosote, degrade slowly);
- Treatment may be long-term (some compounds may take months to degrade);
- Site conditions can make treatment impractical (e.g., biodegradation can be very slow in cold climates or during winter in northern latitudes); and
- Toxic intermediate compounds may be end products, although this is more likely with anaerobic than aerobic biodegradation.

Limiting Factors

The key to biodegradation at high rates is providing an environment that initially supports exponential growth of contaminant-degrading bacteria and then maintains that population. The main factors that affect achieving such an environment are presented in Figure 1. This figure also illustrates some of the considerations involved in rating the applicability of landfarming or prepared beds to a given site.

Interface with Other Technologies

At many sites, contamination goes below the water table. At these sites, some form of ground-water remediation technology may be integrated with soil bioremediation. Such ground-water treatment technologies may include pump and treat (where ground water is pumped to the surface and treated) or *in situ* biological treatment. When ground water is treated, remediation of the soil may be required, because contaminants held by the soil may recontaminate the ground water.

Design Criteria

The following activities are often done before preparing full-scale design plans and specifications:

- Site and contaminant characterization;
- Laboratory and field treatability studies; and
- Pilot testing and/or field demonstration.

Component	Factor	Potential Limitations
Contaminant	Biodegradability	Contaminant must be biodegradable at an acceptable rate
	Volatility	Volatile components are removed by volatilization rather than biodegradation; air quality regulations may restrict use of naturally aerated bioremediation
	Toxicity	Contaminant must be present in (or diluted to) a concentration not toxic to the degradation organisms
Soil	Physical characteristics	Presence of rock or debris may impact the use of agricultural equipment; clumping may limit exposed surface area and thus degradation
	Moisture content	Excessive water limits diffusion of oxygen
	Clay content	High clay content may affect physical characteristics and thus affect moisture control and exposed surface area
	Organic content	Low organic-material content may limit growth of degrading bacteria, but high content may cause bacteria to utilize that instead of the contaminant
Site	pH	Bacteria have an optimum range; pH may require adjustment
	Hydrological features	A high water table may dictate ground-water protection controls
	Geological features	Landfarming may be physically impeded
	Climate	Rainy climate may dictate special rainfall runoff and soil drainage controls; colder climates slow degradation and may prevent agricultural operations

Figure 1. Limiting Factors

Source Arthur D. Little, Inc., and NEESA

Contaminant Considerations

- Types and concentrations of contaminants
- Depth, profile, and distribution of contaminants
- Presence of toxic contaminants
- Presence of volatile organic compounds (VOCs)
- Presence of inorganic contaminants (e.g., metals)

Site Considerations

- Surface geological features (e.g., topography, vegetative cover)
- Subsurface geological and hydrogeological features
- Temperature
- Precipitation
- Wind velocity and direction
- Water availability
- Surface water features

Soil Considerations

- Type and texture
- Moisture content
- Organic matter content
- Cation exchange capacity
- Water-holding capacity
- Nutrient content
- pH
- Temperature
- Electrical conductivity
- Permeability
- Microorganisms (degradative populations present at site)
- Soil respirometry (field and/or laboratory)

Source: Reference 7 and Arthur D. Little, Inc.

Figure 2. Site and Contaminant Characterization Parameters

Typical parameters to be considered in site and contaminant characterizations are shown in Figure 2. These characterizations are conducted to:

- Identify and quantify contaminants;
- Determine the level of productive microbial activity in the soil; and
- Identify factors that will affect biodegradability.

Laboratory studies are conducted to determine the biodegradability of the contaminant(s) in the type of soil at the site. In addition, results of these studies will be used to optimize process design and operating parameters.

Pilot tests and field demonstrations can be expensive and may not be necessary. For sites contaminated with materials that have been repeatedly proven treatable, experienced contractors are able to scale up for full-scale design based on laboratory study results (5). However, pilot and demonstration tests may be necessary if a site is complicated or there are many unknowns.

Design criteria for full-scale soil bioremediation will address elements including:

- Rate of degradation (or time required for treatment);
- Pretreatment requirements (dewatering, pH adjustment, soil screening);
- Soil moisture control;
- Aeration of soil (method and frequency of tilling or plowing);
- Requirements for monitoring and adjustment of pH during treatment operations;
- Addition of nutrients (type, quantity, frequency);
- Requirements for bioaugmentation (addition of microorganisms); and
- Requirements for support systems such as run-off control, liners, and leachate collection and treatment.

In addition, design criteria will address all the specifications, construction, and necessary installation procedures. Design criteria for prepared beds will address treatment bed size, bed slope, orientation, berm height, and installation procedures for liners.

Field Implementation Considerations

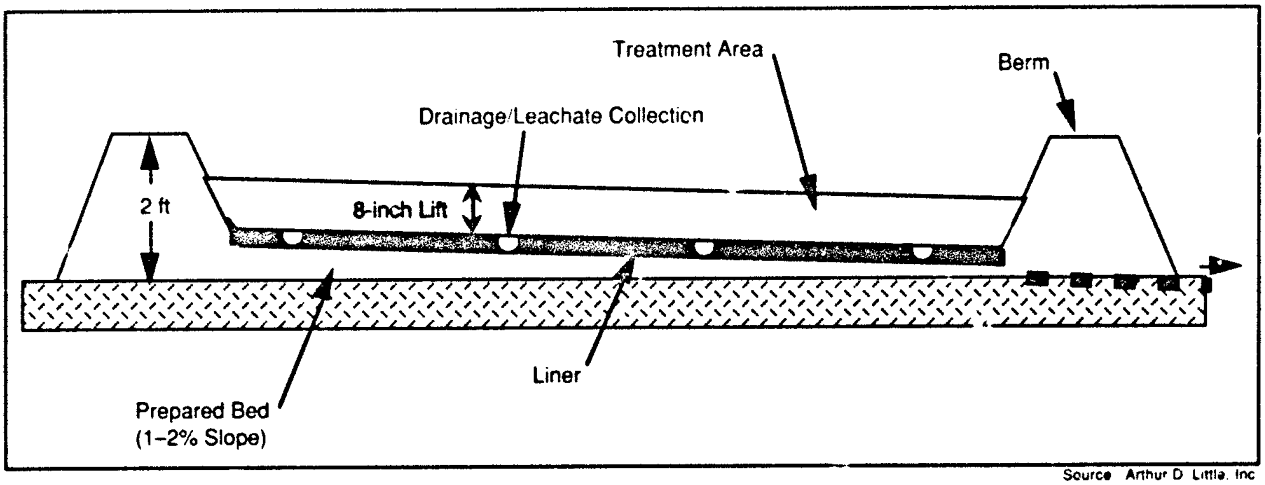
Field activities are much simpler in landfarming processes than in prepared bed processes. The following discussion primarily addresses the use of prepared beds while recognizing that some of the activities are common to landfarming.

Figure 3 shows a typical prepared bed. Actual dimensions can vary according to site conditions.

Typical prepared bed operations are conducted in cycles with successive lifts (or layers) of soil. As a general rule of thumb, a single treatment cycle of 1,000 cubic yards of soil can be conducted per acre, assuming a lift of approximately 8 inches (5).

Primary field activities of naturally aerated soil bioremediation include:

- Site preparation;
- Liner installation (prepared bed only);
- Excavation and screening of contaminated soil (prepared bed only);
- Material addition (e.g., nutrients, lime, amendments, additional microorganisms);
- Soil aeration; and
- Moisture control.



Source Arthur D Little, Inc

Figure 3. Prepared Bed

For prepared beds, site preparation may include grading the site to provide adequate drainage for runoff and leachate collection. Typical bed slopes range from one to two percent. Berms are constructed to contain the contaminated soil. The height of the berm depends on the depth of the prepared bed, including foundation and liner, the depth of soil (or lift) to be treated, and potential rainfall amounts. Because of the costs and efforts associated with the construction of berms, their height is kept to a minimum while maintaining required controls. Typical berm heights may be 2 to 3 feet.

Liners are installed before placing the contaminated soil in prepared beds. Low-cost liners may be constructed of clay if locally available. Synthetic materials may also be used. Synthetic liners are placed over a prepared surface free of rocks and debris. Often, a layer of sand is placed over both clay and synthetic liners to protect the liners as well as accommodate leachate collection systems.

Methods used to excavate contaminated soil should be selected to minimize soil handling and time while maintaining worker safety. If large rocks or debris are present, the contaminated soil should be screened prior to placement. If multiple zones of contamination exist, the soil may be segregated according to contaminant type or concentration to optimize treatment. Usually, however, a uniform contaminant concentration is preferred.

Soil excavation may cause concern if VOCs are present. It has been observed that often soil excavation is responsible for the majority of VOC emissions during soil bioremediation (5). For this reason, if VOCs are present, air monitoring for worker protection should be performed during excavation.

Materials may be added to the soil to optimize the biodegradation processes. These materials may be added with power implements, tillers, and applicators (C). Types of added materials may include:

- Lime or acidifying materials for pH control;
- Nutrients;
- Soil amendments to improve soil quality; and
- Adapted, naturally occurring microorganisms (bioaugmentation).

A pH near neutral (pH 7) is usually desirable. As biodegradation occurs, acids may be generated that decrease pH. For this reason, pH should be monitored and controlled as necessary, usually by adding lime throughout the bioremediation.

Nutrients are added based on soil nutrient analyses. The most common nutrients required are nitrogen and phosphorus. Additional carbon sources may be required if the concentration of organic contaminants is insufficient to support an active microbial population or if treatability studies show improved degradation rates. A typical carbon-nitrogen-phosphorus ratio to be maintained is 100:10:2 (5). Nutrients are often supplied in the form of readily available agricultural fertilizers.

Amendments such as manures or plant materials (e.g., mulch) may be added to the soil to:

- Improve the soil structure;
- Enhance diffusion of oxygen;
- Provide for moisture control; and/or
- Stimulate microbial activity and populations (6).

Bioaugmentation with naturally occurring microorganisms is typically not required in most naturally aerated soil bioremediations (5,7,8). If bioaugmentation is required to achieve a desired rate or degree of biodegradation, the isolation and growth of acclimated microorganisms from the site (as opposed to the introduction of foreign microorganisms) is the most effective approach.

In naturally aerated bioremediations, tilling enhances oxygen diffusion into the soil. Available equipment and site and soil conditions will determine how and how often the soil should be tilled. Tilling frequency is generally dictated by soil type. The heavier or more claylike the soil, the more frequent the tilling. Sandier types of soil may require less frequent tilling. A weekly tilling frequency in soil of average texture is typical.

The depth of tilling is determined by the equipment used. Typical tractor/tiller combinations are operated to depths of approximately 8 inches.

Tilling operations may require special consideration due to:

- Increased susceptibility of the site to erosion;
- Increased potential for air emissions such as particulate (dust) and VOCs; and
- Compaction of wet, clayey soils.

Moisture is required to keep the microorganisms alive; however, too much moisture can saturate the soil and limit the diffusion of oxygen. Optimal moisture contents are typically 70 to 80 percent of the soil's water-holding capacity (5).

If local precipitation is insufficient to maintain proper soil moisture, irrigation may be necessary. Standard methods such as overhead or sprinkler irrigation are employed. Irrigation should be applied frequently in relatively small amounts to minimize the potential for leaching or to prevent saturation of the soil (6). In prepared beds, collected leachate may often be used to supplement irrigation.

If an overly high moisture content seems likely because of heavy rainfall, drainage systems should be built to remove excess water.

Naturally aerated soil bioremediation will generally be conducted during warmer weather periods. This limitation is due in part to a decrease in the rate of biodegradation as temperatures decrease, but also due to the physical operations involved. Usually, bioremediation operations will be initiated in the spring once the soil is dry enough and tilling or plowing is feasible. Field operations will usually be stopped at, or soon after, the first freeze when tilling becomes difficult or impossible.

If necessary, prepared beds can be covered with black plastic or mulches to insulate the bed, transmit heat in winter, and/or control moisture.

Quality Control

Regular monitoring of critical parameters during field operations will be required to provide for the most efficient operation. Among these parameters are:

- Nutrients (maintaining optimum levels of nutrients such as nitrogen and phosphorus);
- Soil pH (maintain within a 6.5 to 8.5 range);
- Soil moisture (maintain between 60 and 80 percent of moisture-holding capacity); and
- Oxygen (maintain at levels above which oxygen becomes a growth-limiting factor).

System performance can be rapidly assessed by measuring respiration rates. As organics degrade, oxygen is consumed and carbon dioxide is generated. Oxygen and carbon dioxide (respiration) measurements in soil gas from the site (compared to an adjacent, uncontaminated site) or through laboratory respirometric determinations can warn of potential problems beforehand or servo to determine aeration frequency. However, carbon dioxide may be converted to insoluble carbonates in alkaline soils (8).

Residuals Generated

Residuals generated during naturally aerated soil bioremediation should be minimal. Successful treatment should result in a product that can be maintained or replaced on site, with few contaminated residuals left to be transported off site.

Potential residuals that may result during soil bioremediation include:

- Liquid and solid residues resulting from personnel and equipment decontamination and cleaning; and
- Liquids accumulated as a result of leachate collection and/or run-off control.

Although the latter can be minimized if recycled during irrigation, there may be potential for this water to be contaminated. In most cases, management of these liquids (including treatment and disposal) will be a part of the action plan.

Regulatory Issues

A regulatory review should be the first step in planning the remedial action. Subsequent coordination with regulators is often accomplished through negotiations affecting various aspects of the remediation, including:

- Treatment criteria;
- Analytical methodology to be used;
- Monitoring requirements (during and after field operations);
- System design requirements;
- Management of water or treatment residues;
- Worker protection; and
- Site closure.

It is best that the most experienced personnel participate in regulatory negotiations to provide for the most practical and cost-effective remedial design.

The types of regulatory permits that may be required are site- and system-specific. In soil bioremediations involving leachate collection and run-off control, permits regarding the management of the collected liquids may be required. Air permits are often required for operations of any kind in environmentally sensitive areas (e.g., California).

At many U.S. Navy sites, selecting a site for soil bioremediation may be affected by on-site wetlands issues (9).

Because naturally aerated soil bioremediation is conducted on site, permitting under the Resource Conservation and Recovery Act (RCRA) is typically not required. However, parts of RCRA (such as LDRs) may apply as Applicable or Relevant and Appropriate Requirements (ARARs). Landfarming, since performed *in situ*, may not trigger LDRs. The applicability of LDRs to the use of on-site prepared beds may be subject to interpretation.

Specific regulatory coordination and documentation requirements will be affected by site-specific factors and local regulatory issues. Typically, an RPM should tell regulators what the proposed plan is. The RPM can then prepare a Corrective Action (or Remedial Action) Plan according to regulatory input. This plan, prepared after the final remedial design, will document what will be accomplished (7). Features of the plan may include:

- Description of process and procedures;
- Parameters to be measured and controlled;
- Sampling and analysis procedures and methodology;
- Quality assurance and quality control procedures to be employed;
- Treatment endpoint verification; and
- Post-treatment closure and monitoring requirements.

Feasibility Study (FS) Criteria Ranking

The use of naturally aerated soil bioremediation has been rated by remedial engineers with respect to certain performance and regulatory criteria. The results of this rating are presented in Figure 4. It should be noted that performance ratings may change with the contaminant being degraded.

Successful soil bioremediation will result in destruction or detoxification of contaminant(s) of concern. For this reason, long-term effectiveness and reduction of toxicity criteria are rated favorable.

Although relatively quick to implement, successful bioremediation may require months to achieve. As such, short-term effectiveness may be less favorable than other techniques such as incineration.

Experience has shown that naturally aerated soil bioremediation has the potential to be a lower-cost remedy for soil treatment.

Key Cost Factors

Costs associated with naturally aerated soil bioremediation include the costs of:

- Pretreatment tasks, including site characterization, treatability study, and pilot-scale testing or field demonstration (often optional for petroleum products); and

- Actual field implementation, including site and soil preparation, prepared bed construction, establishment and operation of rainfall runoff and leachate controls, irrigation, nutrient addition, pH control, sampling and analyses, and site cleanup and closure.

As with any RA, total costs are site- and application-specific. Costs often heavily depend on the time required to achieve specified treatment levels. Thus, the more concentrated the contaminant or the slower the rate of degradation, the longer and therefore more costly is the required treatment time. Other issues that may affect total cost include:

- Excavation of contaminated soil;
- Liner use;
- Rainfall runoff and leachate treatment; and
- Additives needed for nutrient enhancement and pH control.

Criteria	Ranking
Effect of reducing the overall threat to human health and the environment	◐
Compliance with ARARs	○
Long-term effectiveness and permanence	⊜
Reduction of toxicity, mobility, or volume	◐
Short-term effectiveness	○
Implementability	◐
Cost	⊜
State and community acceptance	○

⊜ ◐ ○ ◑ ●

Favorable ◄——► Unfavorable

Figure 4. FS Criteria Ranking

Ranges of costs likely to be encountered are:

- ***Costs prior to treatment (assumed to be independent of volume to be treated)***: $25,000 to $50,000 for laboratory studies; $100,000 to $500,000 for pilot tests or field demonstrations;

- ***Cost of landfarming (in situ treatment requiring no excavation of soil)***: $25 to $50 per cubic yard; and

- ***Cost of prepared bed (with liner)***: $100 to $200 per cubic yard.

Treatment costs are exclusive of sampling/analysis and monitoring costs.

Points to Remember

The following points to remember reflect issues identified by those experienced in bioremediation.

- Regulatory review and coordination should be initiated as soon as possible in the technology selection and planning process;
- Remedial personnel should enter into regulatory negotiations with specific goals and objectives in mind. They should be prepared to negotiate to develop realistic and practical criteria and operational requirements;
- Making use of contractors with experience and proven capabilities provides for the best assurance that success will be achieved with a minimum of unforeseen problems;
- If prepared bed treatment is to be used, site selection should be carefully considered with respect to space requirements, moisture control, and the potential impact of natural or cultural resources;
- Laboratory treatability studies are required in order to define the factors affecting biodegradation and to allow for necessary process optimization; and
- Site climate (particularly with respect to temperature) may dictate the timing of naturally aerated soil bioremediation.

Application Examples

Examples of recent applications of naturally aerated soil bioremediation actions are summarized in Figure 5. The first six examples were selected as representative of a variety of treatment conditions that may be encountered. Examples 7, 8, and 9 represent U.S. Navy applications. The U.S. Navy examples are described below in greater detail.

Example 1—Petroleum Products Terminal

Naturally aerated bioremediation was used in the cleanup of a decommissioned petroleum products terminal proposed for residential development. The first stage of the bioremediation was a thorough subsurface site characterization to define areas of mixed contamination and areas contaminated by a single product. Soils were then segregated by contaminant, and laboratory treatability studies were performed with each soil type to demonstrate applicability and optimize treatment parameters. In the full-scale remediation, soils were treated separately.

Example 2—Fuel Oil Spill

Soil contaminated as a result of a 20,000-gallon fuel oil spill was excavated and treated. The soil was a heavy clay, and amendments were required to improve the soil consistency for bioremediation.

Example 3—California Industrial Site

Naturally aerated bioremediation was conducted at a California industrial site contaminated with a variety of petroleum products, including waste oil, crude oil, and diesel fuel. Prior to treatment, the contaminated soil was excavated and screened to remove trash and debris. Because of different action levels established for refined and crude oil contaminants (100 and 1,000 ppm, respectively), the contaminated soil was segregated by contaminant for separate treatment.

Example 4—Creosote Waste Impoundments

Two creosote waste impoundments at a Superfund site in Minnesota were treated by naturally aerated bioremediation. These impoundments contained approximately 10,000 cubic yards of sludge and contaminated soils at an average concentration of 4,000 ppm of total PAHs. A three-acre lined facility was constructed and operated to treat these wastes. Cleanup levels were based on visual criteria; treatment was considered complete when the contaminated sludges and soils were no longer black and agglomerated. Corresponding analyses indicated that this occurred at levels of approximately 1,000 ppm of total PAHs.

Example 5—Pesticide Storage Facility

This example represents an application of naturally aerated bioremediation in which prepared beds were used to successfully reduce concentrations of pesticides to limits at or below regulatory cleanup guidelines.

Example 6—Contaminated Soil from Leaking Underground Storage Tanks (USTs)

Soil at a site in Marina del Rey, California, was contaminated with gasoline, diesel fuel, transmission fluid, lube oil, kerosene, and trichloroethylene. The "Safesoil Biotreatment System" was used by ENSITE, Inc., to remediate the site (10,11).

Since soil particles greater than 3 inches in diameter cannot be treated in this system, the contaminated soil is first screened to remove rocks and debris. The soil is then conveyed to a horizontal shaft ribbon blender, where it is mixed with various organic and inorganic nutrients, naturally occurring surfactants, soil conditioners, and water. Ten gallons of this additive/nutrient mix and five gallons of water are typically added per each cubic yard of soil. During the final mixing phase, air is injected and entrained in the soil matrix.

The mixed soil is placed into piles (roughly 3.5-ft square and 2.5-ft high) and left undisturbed while curing. Curing results in a honeycomblike structure through which air can passively diffuse. According to the vendor, a crust forms on the surface of the soil that prevents volatile contaminants from escaping but allows for natural infusion of air.

The "Safesoil Biotreatment System" is best suited for soil contaminated with an average of less than 2,000 ppm of Total Petroleum Hydrocarbons (TPH). At higher concentrations, especially where longer-chain, weathered petroleum residuals are present, the soil may have to be processed a second time. Indigenous, acclimated microorganisms capable of degrading the contaminants must be present.

Treatability studies are required to optimize process conditions for this system. Typically, ambient temperatures of greater than 75°F are optimal. No biodegradation will occur if ambient temperatures drop below 40°F or rise above 100°F (10).

Site	Amount Treated	Contaminants	Results	Comments	Ref.
1 Petroleum Products Terminal	100,000 yd³	Petroleum hydrocarbons	TPH reduced from 1,000 ppm to 100 ppm. Treatment complete in 3 years of seasonal operation.	Soils segregated for treatment by contaminant type. 30-acre treatment area.	5
2 Fuel Oil Spill Site	4,000 yd³	Fuel oil	TPH reduced from 4,000–6,000 ppm to less than 100 ppm in 120 on-site treatment days.	Clay soil required amendments to improve soil texture.	7
3 Industrial Dump Site	6,000 yd³	Waste oil, diesel fuel, and crude oil	TPH reduced from 4,000 ppm to less than 100 ppm in 140 treatment days for one action level. TPH reduced from 2,000 ppm to less than 1,000 ppm in 100 treatment days for the other action level.	Soil screened prior to treatment to remove trash and debris. Two action levels established for different contaminants.	7
4 Creosote Waste Impoundments	10,000 yd³	Creosote (PAHs)	TPAH reduced from 4,000 ppm to 1,000 ppm. Ongoing seasonal treatment operation.	Superfund site. Visual criteria established.	5
5 Pesticide Storage Facility	10,000 yd³	Pesticides (2,4-D and MCPA)	Pesticide concentrations reduced from 86 ppm to 5 ppm in 5 months	12-inch clay liner with drainage employed.	3
6 Leaking USTs	35,000 yd³	Petroleum hydrocarbons	70% of soil reduced to <50 ppm TPH from 100–10,000 ppm in 14 days. Nine of 14 samples were nondetect for TPH and BTXE in less than 30 days.	California emission standards met. No further treatment required; soil backfilled on site. See text for further details.	10,11
7 Craney Island Fuel Terminal	20,000 yd³	Petroleum hydrocarbons	Target is to reduce TRPH from 2,000–5,000 ppm to 1,000 ppm.	Planned remediation. See text for details.	9
8 Marine Corps Base Camp Pendleton	50 tons (pilot study) and 1,000 tons (spill cleanup)	Petroleum hydrocarbons	Pilot study reduced TPH from 34,000–51,000 ppm to 88 ppm. Spill cleanup action reduced TPH from about 34,000 ppm to nondetect.	Two applications at Camp Pendleton. See text for details.	12,13, 14
9 NCBC Port Hueneme	1,250 yd³ - additional volumes from UST removal	Gasoline, diesel fuel, fuel oil, and waste oil	Target treatment levels not yet established; background TPH (100 ppm) levels assumed.	Planned remediation under U.S. Navy Remedial Action Contract. See text for details.	15,16, 17

TPH - Total Petroleum Hydrocarbons
TRPH - Total Recoverable Petroleum Hydrocarbons
TPAH - Total PAH
UST - Underground Storage Tanks

Figure 5. Application Examples (Summary)

Reported costs for mobilization, setup, excavation, treatment, backfill, compaction, and demobilization range from approximately $40/cubic yard for the treatment of 5,000 cubic yards to $60/cubic yard for the treatment of 1,000 cubic yards. Treatability study costs necessary for process optimization range from approximately $2,000 to $15,000 (10). All reported costs are exclusive of sampling and analytical costs.

Example 7—Craney Island Fuel Terminal

At Craney Island Fuel Terminal, soil has been contaminated with fuel oil and other petroleum hydrocarbons from tank bottom sludges and tank cleaning wastes over roughly the last 40 years. Thus, bacteria in the soil are well-acclimated and primed to degrade the petroleum compounds when supplied with air, water, and fertilizer. A risk assessment conducted using volatiles, semivolatiles, and metals data from a soil sample location with a TRPH (Total Recoverable Petroleum Hydrocarbon) level of 3,690 ppm yielded a conclusion of no significant risk to site workers. As a result, a safe cleanup level of 1,000 ppm TRPH was chosen. (Starting TRPH concentrations range from 2,000 to 5,000 ppm.) A Corrective Action Plan will be reviewed by the Virginia State Water Control Board once the remedial design is finalized.

Since 10 percent of the 23 acres of the tank construction site at Craney Island is classified as wetlands, and 0.4 acres of the wetlands area is located on the biocell treatment site, the U.S. Navy has applied for Wetlands Permits. The Army Corps of Engineers routes the permit applications through other environmental agencies for approval. These permits, which may be granted by June 1992, are needed before the contract can be advertised. Another hurdle has been a soil stabilization study that caused the design firm to question whether the soil on the treatment cell site is too soft to support construction equipment or the treatment cells. A preliminary examination of the soil boring data showed that the soil can be stabilized. Using a geotextile will probably ensure stability The question remaining is whether it will be too expensive to stabilize the soil versus downsizing the present biocell construction site.

The treatment cell will be about 16 acres. The base sand layer will be up to one-foot thick. Excess water will be collected by PVC pipe in a ditch and recycled. Optimistically, construction could begin in mid-October 1992, and the cells could be constructed by December 1992. Approximately 120 days of biodegradation would be needed to reduce the TPH level to below 1,000 ppm. Since the ambient temperature must be 50 F for efficient bioremediation to occur, the earliest the treatment could begin is mid-March 1993. After verification sampling and analysis of the soil in June, it could be backfilled (on site) in July 1993.

Example 8—Marine Corps Base Camp Pendleton

A pilot study was done under RCRA to demonstrate InPlant BioRemedial Services' prepared bed (or biocell) treatment process in March and April 1991 at Marine Corps Base Camp Pendleton, with 50 tons of petroleum-contaminated soil that had been stockpiled for about 90 days before remediation began (Example 7). Half the soil was contaminated with #2 heating fuel that had leaked into the ground; the other half was contaminated with diesel fuel, hydraulic oils, and glycols from sandy oil/water separator grit chamber waste, which was dewatered before it was stockpiled. Four samples were taken one foot below the surface of the stockpiled soil, which was divided into four quarters and analyzed for benzene, toluene, xylene (BTXE) and TPH. After treatment, the soil was again divided into four quarters and analyzed using EPA test 8015. Starting TPH concentrations ranged from 34,000 to 51,000 ppm.

A 60-foot by 120-foot prepared bed was constructed by placing hay bales as berms on the concrete slab of an old washrack facility. The slab's 1 percent downslope funneled any runoff into a drainage ditch connected to an oil/water separator. Visqueen® was used as a liner for the beds. A six-inch base layer of decomposed granite (a porous, sandy material) was placed on the Visqueen®. Next, 50 tons of the contaminated soil was placed in a 1.5-foot (approximately) layer on the decomposed granite. A surfactant was then sprayed on the soil to reduce air emissions. Bacteria had meanwhile been extracted from the contaminated soil and cultured in InPlant's lab. Using a 30-day treatment process, this cultured bacteria was sprayed onto the soil every other week. On successive days, a mixture of enzymes and nutrients was also applied biweekly. A "polyphasic suspension agent" was sprayed onto the soil five times, three to four days apart. The soil was rototilled using a 28-hp garden tractor after each product application and also once a week. On one day out of the 30-day period, it rained lightly and the treatment site was covered with Visqueen®. The average temperature during the period was about 63°F. Total TPH concentration was reduced to an average of 88 ppm TPH (which is below San Diego County's treatment level of 100 ppm) in 30 days, while all except toluene out of BTXE were reduced to "nondetect" (using EPA test 8020). After the 30 days, the soil was left in place (without treatment) an additional 60 days. Four additional samples were taken and analyzed using EPA test 8020. Toluene levels were reduced to nondetect in all samples. The treated soil was used as a final cover in the Box Canyon Landfill in San Diego. The total cost of treatment was $13,930: $250 per ton of contaminated soil and $1,430 for soil sampling.

In June 1991, about 10,000 gallons of #2 heating fuel leaked from an underground pipe near the Navy Regional Medical Center at Camp Pendleton. About 1,000 tons of soil was contaminated at an average of about 34,000 ppm. Because the contaminated soil was adjacent to a watershed, the San Diego County Department of Health Services and Regional Water Quality Control Board authorized the use of InPlant's prepared bed treatment to clean up the soil under emergency response guidelines. Camp Pendleton contracted InPlant under an emergency sole-source justification. The procedure used was the same as that described above, except the bed was lined with 20-mil polyethylene; rocks were screened from the soil and washed; the base layer consisted of only four inches of decomposed granite; the contaminated soil layer was 20- to 24-inches deep; bacteria and additives were applied with a 1,200-gallon water truck and pump; and the prepared bed, whose dimensions were 110 feet by 220 feet, was constructed on an asphalt parking lot. Thirty-two soil samples were taken immediately before remediation began and on the 30th day of treatment. All samples were analyzed for TPH, and two or three were analyzed for BTXE. Mainly because treatment conditions were optimized in the pilot study, all samples were reduced to nondetect for all analytes. The total cost of treatment, including analytical and design costs, was about $125 per cubic yard of contaminated soil.

Example 9—Naval Construction Battalion Center (NCBC) Port Hueneme

The U.S. Navy CLEAN (Comprehensive Long-Term Environmental Action, Navy) contractor will conduct a treatability study to determine how effective prepared bed biodegradation will be on contaminated soil from leaking USTs at the NCBC in Port Hueneme, California. The treatability study results will also support the establishment of target treatment levels. Primary soil contaminants are gasoline and diesel fuels.

Sixty to 70 USTs will be removed from July 1992 to August 1993. Construction of a 3.9-acre biocell (or prepared bed) with an asphalt slab base should be completed in August 1992. Although the Corrective Action Plan has not been finalized, it has been proposed that soil be sampled, excavated, and segregated into stockpiles in a staging area according to primary contaminant type (gasoline or diesel fuels). The stockpiles will be covered and monitored throughout the project.

Soil in which the primary contaminant is gasoline will first be aerated to remove volatile hydrocarbons. This volatilization step will be conducted by spreading the contaminated soil over the asphalt in layers one- to two-feet thick and disking the soil periodically. If resulting TPH levels indicate additional treatment is necessary, water and nutrients can then be added to stimulate biodegradation. A soil aeration permit from the local air pollution control district will be necessary for these activities if soils are contaminated with gasoline from 50 to 5,000 ppm. At concentrations above 5,000 ppm, volatilization is not allowed.

Diesel-contaminated soil will be placed on the asphalt and bioremediated by adding water and nutrients and disking.

Treatment of gasoline- and diesel-contaminated soils is expected to take place from January 1993 to September 1994. Treated soils will be backfilled in designated areas at NCBC Port Hueneme. If soils are found to be contaminated with inorganics such as lead, chromium IV, and other metals, they will be disposed of off site.

This remediation, classified as an UST removal action, will be funded under the Defense Environmental Restoration Account (DERA) and implemented by one of NEESA's Remedial Action Contractors (RACs).

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There are additional bibliographical references that pertain to naturally aerated bioremediation. For additional references, contact Mr. Hoeppel (see **Points of Contact**).

Points of Contact

Additional information regarding technical, regulatory, and practical aspects of naturally aerated bioremediation may be obtained from:

- Ronald E. Hoeppel, Naval Civil Engineering Laboratory, Code L71, Port Hueneme, CA. (805)982-1655.
- Scott Park, Naval Facilities Command, Atlantic Division, Norfolk, VA. (804)445-4803.
- John Fringer, NEESA, Code 112E4, Port Hueneme, CA. (805)982-4856.
- Don Cunningham, NEESA, Code 112E3, Port Hueneme, CA. (805)982-3684.

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