PUBLIC WORKS TECHNICAL BULLETIN 200-1-111
30 NOVEMBER 2011

BIODEGRADATION FOR TREATMENT OF POL-CONTAMINATED SOIL

Public Works Technical Bulletins are published by the US Army Corps of Engineers, Washington, DC. They are intended to provide information on specific topics in areas of Facilities Engineering and Public Works. They are not intended to establish new Department of Army policy.

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
441 G Street NW
Washington, DC 20314-1000

CECW-CE

Public Works Technical Bulletin 30 November 2011

No. 200-1-111

Facilities Engineering
Environmental

BIODEGRADATION FOR TREATMENT OF POL-CONTAMINATED SOIL

1. Purpose.

a. This Public Works Technical Bulletin (PWTB) provides information on using biodegradation, a form of bioremediation, for treatment of soil contaminated by petroleum, oil, and lubricant (POL). U.S. Army installations are increasingly asked to comply with more stringent regulations for disposal of POL-contaminated soils, grit, and sludge. Biodegradation is among the methods for treatment and disposal.

b. All PWTBs are available electronically at the National Institute of Building Sciences' Whole Building Design Guide webpage, which is accessible through this link:

http://www.wbdg.org/ccb/browse_cat.php?o=31&c=215

2. Applicability. This PWTB applies to all Department of the Army installations responsible for disposal of waste contaminated by POLs, consisting of soil, grit, or sludge.

3. References.

a. Army Regulation (AR) 200-1, Environmental Protection and Enhancement, 13 December 2007.

b. AR 420-49-02, Facilities Engineering Utility Services, 28 May 1997.

4. Discussion.

a. AR 200-1 implements federal, state, and local environmental laws and Department of Defense (DOD) policies for preserving, protecting, conserving, and restoring the quality of the environment. It specifies roles and responsibilities and reiterates the Army's commitment to environmental protection and stewardship.

b. AR 420-49-02 contains policy and criteria for the operation, maintenance, repair, and construction of facilities and systems, for efficient and economical management of non-hazardous solid waste. Such management of solid waste includes source reduction, reuse, recycling, composting, collection, transport, storage, and treatment. Chapter 3 of the regulation gives general guidance on all aspects of solid waste management, including composting (Section 3-3i).

c. Biodegradation is a form of bioremediation, which is the use of microorganisms to remove pollutants. More specifically, biodegradation is the use of applied or naturally occurring micro-organisms (with or without additional nutrients or other amendments) for the biological breakdown of carbon-based materials. The biodegradation of pollutants in the environment is a complex process, with the quality and quantity of the process dependent on three factors: (1) the nature and amount of pollutants present, (2) the actual surrounding environmental conditions, and (3) the composition of the native microbial community. Bioremediation can be applied to sites contaminated with a variety of chemical pollutants including monoaromatic hydrocarbons (e.g., benzene, xylene, and toluene) and alkanes and alkenes (e.g., fuel oil).

d. A discussion of the science and process of biodegradation is presented in Appendix A. Bioremediation can successfully treat soil from POL contaminated sites such as residues from Central Vehicle Wash Facilities (CVWFs), POL spill sites, or remedial action sites. The time for acceptable cleanup varies depending upon: type and concentration of contaminant, level of cleanup required or end use desired and environmental conditions. For example, remediation to a concentration level for landscape use has more stringent requirements than to use as intermediate landfill cover.

e. Appendix B gives a detailed explanation of biodegradation and gives examples of its implementation at Fort Hood, Texas, and Fort Riley, Kansas. Fort Hood, for example, found they could meet state requirement levels for soil use as landfill cover in less than six months by adjusting environmental parameters to optimal conditions and using a program of adjusting soil pH, adding fertilizer, aeration through tilling and watering to add supplemental moisture. Remediation costs were half that of the previous procedure of using proprietary inoculums to assist the process resulting in a cost of $3.48 per cubic yard. Inocula were found to be of limited use for treating hydrocarbon-contaminated soil because indigenous microorganisms are usually present and they include hydrocarbon degraders. Fort Riley also has a bioremediation site that achieves state cleanup requirements. Their soil is used as fill for construction projects or mixed in with soil at the installation’s green waste composting yard.

f. Appendix C presents a discussion of the concept of total petroleum hydrocarbons (TPH), a parameter used as an indicator for hydrocarbon contamination and remediation. It provides an inexpensive tool to evaluate and assess problem severity and to easily evaluate remediation progress.

g. Appendix D provides a literature review of biodegradation of POL in soil. While there are no federal regulations or guidelines for TPH in general, there are regulations addressing some of the TPH fractions and compounds.

h. Appendix E presents a regulatory review of several states with strong Army presences.

i. Further supporting documentation includes a bioremediation white paper (Appendix F), a discussion of biopiles as another method for treating POL contamination (Appendix G), a list of references cited throughout this PWTB (Appendix H), and a list of abbreviations used (Appendix I).

5. Points of Contact.

a. Headquarters, US Army Corps of Engineers (HQUSACE) is the proponent for this document. The point of contact (POC) at HQUSACE is Mr. Malcolm E. McLeod, CEMP-CEP, 202-761-5696, or e-mail: Malcolm.E.Mcleod@usace.army.mil.

b. Questions and/or comments regarding this subject should be directed to the technical POC:

U.S. Army Engineer Research and Development Center
Construction Engineering Research Laboratory
ATTN: CEERD-CN-E (Richard J. Scholze)

2902 Newmark Drive
Champaign, IL 61822-1072
Tel. (217) 398-5590
FAX: (217) 373-3430
e-mail: Richard.J.Scholze@usace.army.mil

FOR THE COMMANDER:

JAMES C. DALTON, P.E., SES
Chief, Engineering and
Construction Division
Directorate of Civil Works

APPENDIX A

BIOREMEDIATION

General

Bioremediation has gained considerable recognition in recent years as an innovative remedial technology to help reduce concentrations of petroleum hydrocarbons in soil. A major concern raised, when comparing bioremediation to other remedial techniques, is the time required for treatment to achieve the target level. It should be noted that significant strides have been made in optimizing systems to maximize the degradation rate. Optimization achieved through the use of supplements is known as bioaugmentation. Useful supplements include specialized bacterial cultures that claim to increase the rate of contaminant loss. However, implementing these enhancements can require significant effort and money. Therefore, most bioremediation users choose to carefully determine the cost/benefit ratio before including such supplements in full-scale bioremediation designs.

Army installations generate petroleum-contaminated soil from a variety of military operations. Examples include fuel spills, leaking underground storage tank (LUST) cleanups, and waste sludge from oil-water separators. Often, installations will store hydrocarbon-contaminated materials until sufficient quantities are generated to justify contracting for soil processing and/or disposal. Bioremediation has the capability to transform contaminated soil into a useful, recyclable material at a relatively low cost.

Science

Hydrocarbons

As a class, hydrocarbons have a wide range of physical and chemical characteristics. Their molecular weights range from very low to very high, as do their boiling points. They can be very fluid or very viscous, very volatile or relatively stable, and highly soluble or rather insoluble in water. Their solubility is dependent upon the number of carbon atoms in the compound; as the carbon chain increases, solubility decreases. This varying combination of characteristics also causes the behavior of individual hydrocarbons and mixtures to vary greatly (Reisinger 1995).

Microbiology

The organisms living in soil that are responsible for bioremediation include bacteria, fungi, and protozoans. Of these, bacteria appear to play the dominant role in hydrocarbon degradation. Of the total group of organisms in the soil, a dominant organism or group of organisms usually exists. Through natural selection, its dominance has developed because it thrives in that unique physical and chemical setting where it lives. Although the dominant organism or organisms generally predominates in terms of numbers and biomass, other organisms do exist within the environment. When that environment changes (for example, through the introduction of hydrocarbon contamination), the population of organisms likely changes in response. Those organisms that are best adapted to the new environment assume the position of dominance. Their dominance is a function of their capacity to use hydrocarbons as a primary source of carbon and energy.

The metabolic pathways used by hydrocarbon-degrading heterotrophs (organisms that cannot synthesize their own food) can be either aerobic (using oxygen as the primary electron acceptor) or anaerobic (using an alternative electron acceptor such as nitrate or sulfate). Although hydrocarbons can be degraded via both pathways, the aerobic pathway is generally considered more rapid and efficient, because aerobic reactions require less free energy to initiate a reaction and yield more energy per reaction. Authors Borden, Goney, and Becker (1995) have suggested that the aerobic process dominates in the presence of oxygen. When oxygen is depleted, however, denitrification processes will dominate.

Remediation Process

Indigenous organisms with the ability to biodegrade hydrocarbons are present in most subsurface systems. Thus, many researchers believe it is not necessary to introduce nonindigenous organisms in order to accomplish biodegradation.

Hydrocarbon bioremediation can be carried out either ex-situ (off-site) or in-situ (on-site). The primary advantage of in-situ bioremediation is that it is carried out without the need for removal of the hydrocarbon-impacted soil or groundwater. The ex-situ approach to hydrocarbon bioremediation is carried out above ground by physically removing the impacted medium. Soils are treated aboveground via landfarming, biopiling, and composting. The primary advantage to these ex-situ approaches is the degree of control that can be exerted over the processes being used to manipulate the system. The primary disadvantage is the expense and disruption associated with removal, treatment, and disposal or replacement of the impacted medium.

APPENDIX B

ARMY INSTALLATION EXPERIENCES

Fort Hood Experience

Fort Hood has successfully demonstrated the use of bioremediation with (and more recently without) bioaugmentation for treatment of POL-contaminated sludges and soil. Fort Hood constructed a permanent bioremediation site with the capacity to handle 1,600 cu yd of soil in treatment, with another 250 cu yd in a staging area. Pilot projects provided an estimated treatment time of 6 months, giving Fort Hood an annual treatment capability of 3,200 cu yd. Remediation goals below 1,500 ppm were reached, allowing the soil to be used as intermediate cover at the installation's sanitary landfill. This reduced the need to purchase soil at $10 per cu yd.

Site Design

General: Fort Hood staff designed the bioremediation facility in-house. The facility then was constructed by contractors. For security, an 8-ft high chain-link fence was installed around the entire treatment site. A single access point is secured by lock and key. Signs deter entry by unauthorized personnel.

Staging Area: An area is marked and set aside on the concrete bioremediation pad away from all in-treatment materials. The area is open across the front, allowing for placement of contaminated soil and grit-trap material awaiting laboratory analysis, and for drainage of excess moisture.

Remediation Pad: The remediation pad was constructed of reinforced concrete 6-in. thick, with a surface treatment area of 130 x 80 ft. All seams and joints were sealed so that no contaminants could leak into the ground under the concrete. There is a sand base under the concrete pad and then an 80-mil impermeable plastic liner. Leach field pipes were installed as a leak detection system.

Drainage System: The entire remediation pad area is sloped at a 0.5 percent grade to a concrete settlement area along the west end of the pad. This settlement area works as a sand or grit interceptor. The area also enables easy access for front-end loaders removing these materials for further treatment. Water from the settlement system drains into an impoundment, after any residue that accumulates in the area has been separated.

Impoundment and Irrigation System: The bioremediation site uses water piped from an already-established Central Vehicle Wash Facility (CVWF). A separate pump station located at the impoundment serves the bioremediation site. The water is pumped by two irrigation pumps through a line system to the remediation pad, where it is applied by reciprocating sprinklers.

Grit Collection Chamber: The grit collection chamber (Figure B-1) holds the semi-solid slurry gathered by the suction trucks that are used to empty over 100 on-post oil water separators (maintenance site interceptors). The chamber also is designed to facilitate entry of equipment used for soil removal and cleaning. Soil removed from the chamber is classified as interceptor grit material and is placed in the staging area as newly arrived contaminated soil. The ramp that is connected to the grit collection chamber is also used as an equipment wash pad and collects any contaminated soil washed from vehicles and equipment. This minimizes cross-contamination of materials treated on the pad.

Operations Building: The building provides office space for site workers to document laboratory on-site soil testing and for storage of products used in the remediation process.

Figure B-1. Grit collection chamber.

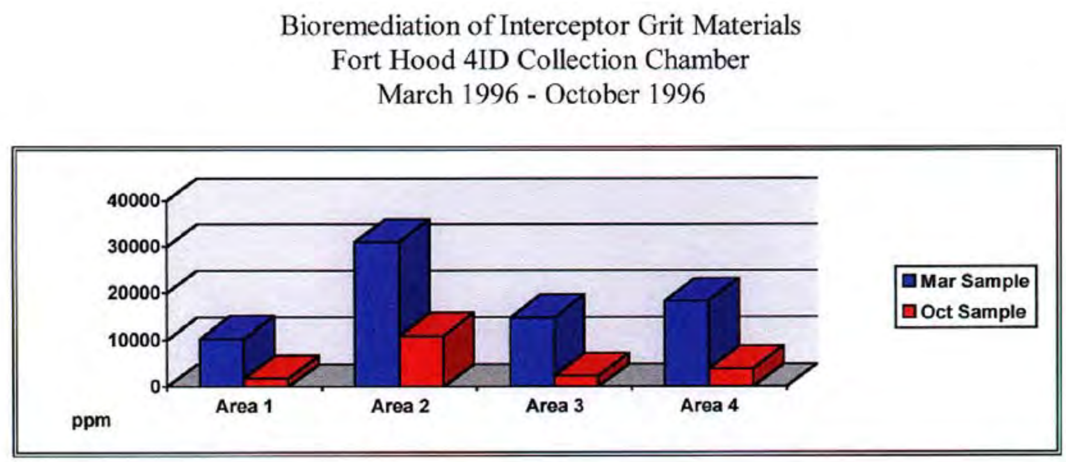
Pilot Project

The installation performed several pilot projects to evaluate the performance and cost-effectiveness of bioremediation for cleanup of petroleum-contaminated soils and interceptor grit. Figure B-2 shows a later treatability study at the biosite, using test plots of a few cubic yards of soil with different additives and conditions. A study of material from washrack interceptors (i.e., motor pool oil-water separators) is discussed here.

Fort Hood has more than 100 oil-sand interceptors at maintenance facility washracks that require periodic cleaning. The scheduled cleaning is done by vacuum trucks that clean out all grit material on a 14-day cycle and then, deposit the grit in a large interceptor at the 4th Infantry Division (4ID) Central Vehicle Wash Facility. Before development of the bioremediation process, the hydrocarbon levels in the 4ID facility were extremely high. Every 6 months, when the interceptor was emptied, costly thermal burning was required.

Figure B-2. Treatability study.

Initial samples were collected in March 1996, before start-up of the bioremediation process. These samples identified a high level of hydrocarbon contamination. The chamber was then emptied, cleaned, and returned to service as a collection container for grit materials whose bioremediation had already started. In October 1996, after 5 months of use, the content of the grit collection chamber was again sampled. Figure B-3 shows a comparison of the reductions. Initial results ranged from 10,300 ppm to 31,100 ppm of total petroleum hydrocarbons (TPH). Seven months later, results indicated a substantial decline to a range of 1,810 ppm to 11,000 ppm.



	Area 1	Area 2	Area 3	Area 4
Mar 1996	10300 ppm	31100 ppm	14800 ppm	18300 ppm
Oct 1996	1810 ppm	11000 ppm	2320 ppm	2870 ppm

Figure B-3. Test results from grit collection chamber.

The Fort Hood results from 2006 highlighted one particular field-scale experiment. POL-contaminated soil was taken to the staging area and thoroughly mixed. The soil was divided into two sections, spread at the biosite, and treated in different ways. Most notably, one section was treated with a proprietary microbial inoculum, and one was not.

Both sections were watered and tilled identically; the climate exposure was identical; and there was no pH adjustment. The inoculum section was fertilized with 21-0-0 fertilizer; the other section with 18-10-5. The sections were monitored for 199 days. At the end of the experiment, the soil section without the inoculum had a notably higher TPH removal, at a lower cost (see Table B-1). This has become the current operating protocol, and has resulted in substantially lower costs because it was proven unnecessary to add expensive microbial inoculum.

Table B-1. Fort Hood experimental results.

	Soil with proprietary inoculum	**Soil without inoculum**
Starting TPH concentration (ppm)	4,360	5,440
Ending TPH concentration (ppm)	1,470	452
Percent TPH reduction	66	92
Treatment cost ($/yd^3)	$6.29	$3.48

Some of the basic equipment recommended for operating both this site and a basic biosite is listed below, and examples are shown in Figure B-4,Figure B-5, and Figure B-6:

1 rubber tire tractor with bucket-loader attachment

1 rotary tiller that is 6-ft wide with three-point hitch and is PTO-driven

1 seeder/spreader that has 800-lb capacity, three-point hitch, and is PTO-driven

1 irrigation system

1 box blade that has three-point hitch and is 6-ft.wide

6 pH recorders for measuring and recording cell pH conditions

Figure B-4. Grader with blade.

Figure B-5. Front-end loader on rubber-tire tractor.

Figure B-6. Earth mover.

General Operating Procedures

Incoming contaminated soil is transported to the staging area. The staging area is divided into grids to accurately identify the source of each batch of contaminated soil received. Soil from underground storage tanks (USTs) is kept separate because it requires special reporting. After receipt on the staging area, soil samples are obtained for initial testing, which is conducted by an external analytical laboratory to determine extent and type of contamination. If the soil is classified non-hazardous (per the Code of Federal Regulation, 40CFR261), it is transferred to the nearby remediation pad within 90 days. If determined to be hazardous, the soil is transferred immediately from the staging site to the treatment pad.

After transfer to the treatment pad, the contaminated soil is spread to a depth of 1.0–1.5 ft and treated. Treatment consists of adding fertilizer and lime (if necessary to adjust soil pH), mixing well to aerate the soil, and watering. Mixing is done when needed, although in general, mixing every two weeks has been found to be beneficial. Watering is done to meet moisture demand of the soil.

Then, a second layer of soil of equal depth is added and similarly treated, if it is necessary to treat a large volume of soil. The depth of each layer is a function of the capability of the equipment used. Materials are worked using agricultural implements to both thoroughly mix additives (nutrients) and to aerate the soil (Figure B-7).

Figure B-7. Tilling operation.

Some types of contaminated soil products contain wood chips, oil absorbents, or other materials that make the soil matrix more porous. This allows staff to form the soil into windrows, and still achieve adequate aeration (Figure B-8).

Figure B-8. Soil windrow.

The pH of the contaminated soil may need to be adjusted to neutral to ensure optimal degradation. Agricultural lime is typically used to raise pH levels. The initial amount to be added is based on soil testing. A soil slurry in distilled water is mixed with incremental additions of lime, and the resulting pH values are recorded. Adequate time (one week) between intervals of lime addition must be allowed for pH stabilization. Lime is added as necessary, according to field monitoring of pH drop during bioremediation. Care must be taken to avoid excess lime, since pH levels above 9.0 will hinder microbial growth. Less commonly, the existing soil pH may be higher than optimal, due to high carbonate concentration or presence of other wastes. In this case, the pH can be lowered towards 7 by adding elemental sulfur, iron sulfates, or other sulfur containing compounds (Dupont et al. 1988).

Nutrients to sustain a healthy microbial metabolism are an important additive. At Fort Hood, a standard agricultural fertilizer containing a nitrogen/phosphorous mixture with a ratio of three to one (3:1) is generally used. Fertilizers are applied in a dry form and are worked in by plowing, then tilling. The nutrient requirement is based on stoichiometric calculation (calculation of the quantities of elements involved in a chemical reaction), treatability studies, or the need to control a specific microbial response. Soil samples should be analyzed at intervals (at least monthly) to maintain optimum process parameters, and adjustments made as needed.

Micro-organisms and nutrients are added using a plow and power take off (PTO)-driven rototiller. After all additives have been applied, the contaminated soil is plowed, and then tilled soon after placement on the pad (as shown previously in Figure B-7 and below in Figure B-9). These soil mixing operations optimize degradation by redistributing nutrients, contaminants, and micro-organisms. Frequency of mixing varies, and is usually done only at the onset of the treatment and/or when soil or moisture sampling tests indicate it could be helpful. At Fort Hood, it was found to be beneficial to till every 2 weeks during the last month of the 6-month remediation process.

Figure B-9. Plowed and tilled soil.

Throughout the degradation process, watering, if required, is performed after tilling. The soil will need the addition of approximately 1.5 in. of water per week during months of little or no rainfall. Moisture is determined by a standard moisture content test. In compost type operations, microbial activity is maximized when soil moisture is between 40 percent and 50 percent of saturation. Water is pulled from the impoundment by an irrigation pump system, and then added to the soil by using common reciprocating sprinklers.

Samples are taken at the remediation pad at three intervals: (1) after the initial mixing of additives, (2) near the middle of the treatment, and (3) at the end of the degradation cycle. Samples are collected from evenly spaced grid areas of each soil group on the remediation pad, through use of a hand auger at a depth of 1 ft. Samples are analyzed by an external analytical laboratory for hydrocarbon content (Figure A-10). Leachate samples (samples of water that drains from the site) must be monitored. Contaminant loss should be measured to document the loss of contaminants by water transport vs. volatilization vs. true degradation.

Figure B-10. Extracting sample material.

The following tests are to be run at established intervals (suggested at least monthly) during the remediation process, unless initial testing results indicate specific tests are not needed.

- BTEX test (Benzene, Toluene, Ethylbenzene, and Xylene) to determine pollution levels for aromatics.
- TPH test to determine pollution levels in ppm for all hydrocarbons.
- TKN test (Total Kjeldahl Nitrogen) to determine levels in ppm of nitrogen.
- TP test (Total Phosphorous) to determine levels in ppm of phosphorous.
- pH test to determine acidity or alkalinity of soil.
- Bench test to determine potential for bacterial toxic shock.

Disposition of Treated Soil

Generally, treated soil is removed from the remediation pad only when both of the following conditions are met:

1. The contaminated soil has undergone degradation for a period of not less than 6 months; *and*
2. The soil meets the sanitary landfill reuse standards of less than 1,500 ppm TPH and/or meets the topsoil cover standard of

less than 500 ppm TPH. (These numbers are dependent upon the requirements of each state.)

In either event, the soil will be properly disposed, with final disposition (location) of soils documented for reference and closure reports.

Documentation

To meet state regulations, extensive documentation is needed during the soil treatment process. From the moment the soil enters the bioremediation treatment site, to its final destination as a recyclable cover material, full documentation is essential. The following information is to be collected and kept on file.

- location from which the contaminated soil was generated
- location (by grid) of material being treated on the bioremediation pad
- test results during the degradation process, as indicated from drops in TPH concentration from samples taken initially and other times during the time period, until finished soil is ready to be removed
- dates and quantities of additives, by type, introduced into the soil during the degradation process
- types and quantities of micro-organisms added
- plowing, tilling, and watering cycles
- final disposition of soil, identified by site locations and quantities delivered to each

Costs

Cost information calculated by the installation from pilot project studies indicates treatment using the commercially available micro-organisms was $41/cu yd treated. This total cost is broken out as: a)$35/lb for the micro-organisms (using 1 lb/ton of soil); b) $5/cu yd treated for support cost (equipment and manpower hours used for tilling, etc.); and c)$1/cu yd treated for added nutrients. The cost for construction of the bioremediation facility was approximately an additional

$300,000. Equipment is assigned zero value, as it is on loan from the Directorate of Public Works (DPW).

Summary

Bioremediation at Fort Hood has been successful in reducing hydrocarbon-contaminated soil to levels that allow it to be used for intermediate cover at the installation's sanitary landfill. Army personnel use a process that includes adding nutrients and moisture, along with appropriate tilling. The method routinely has produced satisfactory results within 6 months.

In summary, the scientific literature generally has found that inocula are of limited use for treating hydrocarbon-contaminated soil. They may speed up the initial rate of degradation, but indigenous micro-organisms usually present already include hydrocarbon degraders. At Ford Hood, a unique approach is the collection of interceptor grit in a vacuum truck that has been dosed with microbes and nutrients, which, during the course of collection, become thoroughly mixed before being drained into the holding tank, and then, moved into a soil treatment facility. Costs are estimated at $37–$41/cu yd for micro-organisms, nutrients, and labor and equipment operating costs. The bioremediation facility was constructed for $300,000. Equipment is on loan from the DPW.

Fort Riley Experience

Fort Riley has operated a bioremediation site for POL-contaminated soil since the 1990s. It is used to treat spills from off-site military operations. Similar to Fort Hood, the Fort Riley DPW uses a sloped, concrete pad which is surrounded by a security fence. Through bioremediation, they are able to achieve state-required cleanup levels. Thus, the soil can be used as fill for construction projects throughout the installation, or can be mixed in with soil in Ft. Riley's green (yard) waste composting yard, which is adjacent (See Figures 11 and 12, below).

The Kansas Department of Health and Environment employs “risk based” POL in soil action levels, broken down by chemical component, residential vs. commercial, and child vs. adult. See http://www.kdheks.gov/tanks/rbca_report_manual.html.

The Fort Riley POC is Dick Clement, 785-239-3515.

Figure B-11. Bioremediation pad at Fort Riley.

Figure B-12. Fort Riley green waste compost site.

APPENDIX C

DISCUSSION OF TOTAL PETROLEUM HYDROCARBONS (TPH)

The chemical composition of petroleum products is complex and may change over time, following release of the products into the environment. A wide range of past practices has resulted in a significant number of petroleum hydrocarbon-impacted sites at Army installations across the United States. Most site cleanup or disposal investigations involving petroleum hydrocarbons are regulated by individual states, which may each have differing requirements in methodologies, action levels, and cleanup criteria.

TPH is a parameter used to indicate the level of contamination present in the environment. Using TPH concentrations to establish target cleanup levels for soil or water is a common approach that has been implemented by U.S. regulatory agencies. Approximately 75 percent of the states use TPH-based cleanup criteria.

Because TPH values have become such key remediation criteria, it is essential that that everyone using TPH data understand the various analytical methods. Minor variations may be found between states. For example, some agencies distinguish between “gasoline range organics” (GRO) and “diesel range organics” (DRO). GRO is the lighter petroleum fraction and tends to be mobile in the environment. Each of these ranges have specific toxic compounds (e.g., benzene is one type of GRO), and there may be specific limits for each compound.

TPH concentration data cannot be used to quantitatively estimate human health risk. Under various circumstances, the same concentration of TPH may represent very different compositions and have very different risks to human health and the environment. For example, suppose two sites both have TPH measurements of 500 ppm. One site may include carcinogenic compounds, while the other site may include no carcinogens. Moreover, the risk at a specific site will change with time as contaminants evaporate, dissolve, biodegrade, and become sequestered.

Although the utility of TPH data for risk assessment is limited, it is still an inexpensive tool that can be used to:
(1) determine if there is a problem, (2) assess the severity of contamination, and (3) follow the progress of a remediation effort. A collection of reports has been developed by the Total

Petroleum Hydrocarbon Criteria Working Group (TPHCWG), which details the subject in its complexity. The TPHCWG is a working group, convened in 1993 to address the large disparity among cleanup requirements used by individual states with sites contaminated with hydrocarbon materials such as fuels, lubricating oils, and crude oils. As stated earlier, these requirements usually focus on TPH, but with widely ranging numerical standards. The Group is guided by a steering committee consisting of representatives from industry, government, and academia, with many sources of support (including DoD). The Group's goal is to develop scientifically defensible information for establishing soil cleanup levels that protect human health at petroleum-contaminated sites. Documents are available at http://www.aehs.com/publications/catalog/contents/tph.htm.

One TPHCWG document, listed in the reference section of this report, contains an appendix with a detailed breakdown of common fuel chemical compounds (Gustafson 1997).

APPENDIX D

LITERATURE REVIEW

This section summarizes several research journal articles that directly pertain to biodegradation of POL in soil. See this report's reference section for full citations of the following:

Compeau 1991

Compared two different, commercially available cultures to uninoculated and sterilized inocula, for petroleum degradation in soil. When compared to indigenous micro-organisms, neither of the cultures led to an increase in petroleum hydrocarbon degradation, even though the microbial density was higher.

Venosa 1991

Describes USEPA screening of commercial inocula for its ability to stimulate oil biodegradation in closed laboratory systems. The USEPA issued a public solicitation for commercial microbial products for testing degradation of weathered Alaska crude oil. After submission of 40 proposals, 10 were selected for laboratory testing. Laboratory testing consisted of electrolytic respirometers set to measure oxygen uptake over time, and shake flasks to measure oil degradation and microbial growth. The conclusions after laboratory testing and following evidence supplied through microbiology, respirometry, and oil chemistry, were that only two products should be continued to the next stage for field testing. Evidence showed that the indigenous Alaskan micro-organisms were primarily responsible for the biodegradation in the closed flasks and respirometer vessels. Any enhancement provided by the two products selected for further testing might have been due simply to metabolites, nutrients, or co-substrates present in the products.

Pritchard 1992

Reviews several attempts at inoculation of oil-contaminated soil, but that have had little success. He indicates the work of Jobson et al. (1974) showed that inoculation had no more effect than simple nutrient addition. Also, tilling or mechanical re-working of the soil is often needed to get oxygen to the microbes. Mueller et al. (1992) states that sustained stimulatory effect of inoculation was no greater than that observed with the addition of inorganic nutrients alone.

The biological removal of petroleum products using landfarming[*] has been applied on a large scale with relative success. The technology has been widely used, due to its simplicity and cost-effectiveness. However, together with these advantages, there are physical, chemical, and biological aspects of the technology that can hamper the remediation process. The dominant pollutant-removal mechanisms involved in landfarming are volatilization of low molecular weight volatile compounds during the early days of contamination or treatment, biodegradation, and adsorption. However, volatilization, leaching of the petroleum products, and the remaining 'recalcitrant' hydrocarbon residues present both health and environmental challenges to landfarming practitioners. Landfarming involves two promising bioremediation approaches – bioaugmentation and biostimulation. However, due to inherent problems such as the poor survival rate of augmented strains, biostimulation should be preferred in contaminated sites with indigenous pollutant-degrading bacteria.

In 1992, the USEPA established treatment standards under the land disposal restrictions program for various hazardous wastes that included petroleum products. As a result, landfarm sites had to either operate their facilities to treat the waste below the EPA-specified contaminant levels (referred to as a treatment standard), or submit a petition demonstrating that there was no migration of hazardous components into the injection zone (the soil immediately below the waste site). That change in standards effectively closed most North American landfarms. Although there have been some restrictions on the application of the technology, it is still being used with added measures (i.e., capturing off-gases to maintain air quality or capture and treatment of leachate) for minimizing or treating volatiles and leachates. Landfarming is still an option for low-level POL-contaminated soils in areas of low-density population.

Soil moisture can also impact the efficiency of removing petroleum compounds from the soil. The level of moisture in most landfarms is kept between 30–40 percent of the field's moisture capacity. An adequate moisture level ensures the survival of the pollutant-degrading bacteria, and assists with dust control which would otherwise carry bacteria or pollutants to surrounding areas.

---

[*] Landfarming is a bioremediation technology in which contaminated soils are mixed with soil amendments such as bulking agents and nutrients through farm tillage practices until decontamination occurs.

Landfarming has been used to treat volatile and biodegradable pollutants with relative success. However, the technology has not been greatly used to treat persistent organic pollutants like the high molecular weight polyaromatic hydrocarbons.

Leavitt and Brown 1994

Presents case studies that examine biostimulation versus bioaugmentation. The first case was a 2-month pilot study in 1991 at the USEPA Test and Evaluation Facility in Cincinnati, OH. The objective was to demonstrate biodegradation of sludges generated during crude oil storage. The project used two slurry reactors, each with a capacity of 64 L. The first slurry reactor(R1) was augmented with nutrients and the pH adjusted to 7.0. The second reactor(R2) was bioaugmented with a naturally isolated, petroleum-degrading bacteria culture. In both reactors, low-molecular-weight hydrocarbons degraded readily. However, the R2 reactor did not perform as well with longer chains. The poor performance in R2 prompted the conclusion that bioaugmentation did not benefit this bioreactor system.

The authors presented another study designed to demonstrate accelerated biodegradation of weathered crude oil in drilling mud, using pilot-scale soil volume and equipment. The demonstration was intended to compare the extent of biodegradation with conventional treatment, with additional bulking agents, and with bioaugmentation. Three plots were constructed at the site, each containing approximately 500 cu yd of waste soil. Plot 1 received fertilizer, mixing, and irrigation, each as needed. Plot 2 received the same treatment, but initially was mixed with 7 percent straw by volume. Plot 3 was augmented with a proprietary culture and nutrient blend, and treated as recommended by the blend's vendor. Mixing and irrigation in Plot 3 were the same as for Plots 1 and 2. The inoculation rate was 1 gal for every 2 cu yd. Additional nutrients were also added to Plot 3. The demonstration was maintained for 6 months.

Oil and grease, as well as total recoverable petroleum hydrocarbon (TRPH) analyses were conducted on samples before and after slurrying. Considering oil and grease results, Plot 3 was the best performer, with a loss of 86 percent at the end of the study. Plot 2 exhibited an 82 percent loss in oil and grease, whereas Plot 1 exhibited only a 32 percent loss. TRPH analyses in slurried samples proved Plot 2 to be the best performer (55 percent loss), followed by Plot 1 (45 percent loss) and then Plot 3 (27 percent loss). TRPH results in samples that were not slurried had a 62 percent loss in Plot 3, 59 percent in Plot 2, and 59 percent in Plot 1. When all analyses were averaged for each plot, Plot 2 showed the highest percentage loss at 65 percent. Plot 3 averaged a 58 percent loss, and Plot 1 a 45 percent loss.

Recommendations drawn from this study were applied theoretically to a full-scale system. Considering the increased scale, nutrients became a significant cost factor. Nutrient costs for Plots 1 and 2 were $0.35/lb. At the time of the study, the cost for bacteria was $1,700 per drum and $3.00/lb for the proprietary nutrient blend. Following the vendor's recommendations would have resulted in more than a $1 million cost for bacteria alone. Considering the cost and marginal benefit in TRPH reduction, bioaugmentation was not recommended for the full-scale treatment. The bulking agent (straw) was recommended, because it did render the soils more workable and was relatively inexpensive.

Reynolds et al. 1994

Discusses the application of field-expedient bioreactors and landfarming in Alaskan climates. Study authors found that landfarming can be used to treat less-contaminated soil, which often comprises the bulk of contaminated-soil volume. Highly contaminated soils can be readily contained and treated on-site, using re-circulating leach beds. In field evaluations, the spatial average of TPH concentration in diesel fuel-contaminated soil decreased in approximately 7 weeks from 6,200 mg/kg dry soil to 280 mg/kg. At another site, a re-circulating leach bed was used to treat diesel-contaminated soil. In a 5-week period, the TPH concentration was decreased from a range of 300 mg/kg to 47,000 mg/kg, to a range of 240 mg/kg to 570 mg/kg.

Landfarming is a frequently chosen treatment for contaminated soil because it has advantages such as containment, relatively low cost, and high potential for success. Lining and leachate recovery systems often are used to assure that soluble fractions or high concentrations do not leach, but their use essentially doubles the landfarm's construction cost. To maximizing cost-effectiveness of landfarms in situations where the volume of contaminated soil is large, one possibility is to use centrally located, lined landfarms to treat multiple batches of contaminated soil. The Alaskan landfarm site studied by the authors occupied about one acre. Nutrient amendments were 270 lb of nitrogen, 34 lb of phosphorous, and 26 lb of potassium. Nutrients were added 1 month apart and were periodically tilled to approximately an 8-in. depth. About 1,200 cu yd of soil were treated.

Quinn 1997

Researchers at the Kennedy Space Center evaluated ex-situ biopiles[†] as an alternative to thermal treatment for 500 m^3 of diesel-contaminated soil. Static piles with forced aeration were employed. A commercial liquid fertilizer was used to create a carbon, nitrogen, phosphorous ratio of 30:1:0.1. A liquid fertilizer was selected to enable better distribution of fertilizer throughout the piles. The TPH concentration dropped from 3000 mg/kg to less than 10 mg/kg over 12 weeks. The total remediation cost was about $\$50/m^3$.

Jorgensen 2000

Authors conducted a series of field-scale, ex-situ biopile tests, using bark chips as a bulking agent. By volume, the ratio of soil to chips was 1:3. Soil contaminated with diesel and mineral oil was used. Two types of commercially available mixed microbial inocula were tested, soil nutrients were adjusted, and soil pH was adjusted to neutral.

Over 5 months, concentrations of both diesel and mineral oil decreased by about 70 percent. The researchers analyzed total hydrocarbons and mineral oil content, using an in-house method based on the Finnish standard, SFS 3010 (1980).[‡] There was no observed particular effect from added inocula. Naturally occurring microbial community in soil is usually able to degrade oil hydrocarbons. Rather than inoculation for TPH reduction, it is more important to optimize conditions for existing bacteria (nutrients, aeration).

Thomassin-Lacroix 2002

The authors conducted experiments with small-scale biopiles on Ellesmere Island in the Canadian Arctic region. Some biopiles were inoculated with a culture of indigenous soil bacteria and soil nutrients were optimized. Bacteria populations in both inoculated and un-inoculated piles increased by more than 100

[†] A biopile is a bioremediation technology in which excavated soils are mixed with soil amendments and formed into compost piles and enclosed for treatment.

[‡] SFS 3010 (1980). Determination of Oil and Grease in Water. Infared Spectophotometric Method. Finnish Standards Association, Helsinki (in Finnish).

times, reaching the same end concentration. In this case, there appeared to be no benefit for TPH reduction by adding additional microbes to the biopiles.

Chaîneau 2003

The authors evaluated biodegradation of crude oil contamination in a clayey soil. Clean soil was spiked with 18,000 mg/kg of hydrocarbons. Windrows were built, each containing 5 m^3 of soil. The first windrow had no additives. The second was treated with agricultural fertilizer to achieve a carbon/nitrogen/phosphorous (C/N/P) ratio of 100:10:1. Other windrows had the same nutrients added, as well as straw for a bulk agent (at 15 percent by volume). Forced-air biopiles were also evaluated. Crude oil degradation of 70 percent to 81 percent was achieved in the treated windrows, in comparison to 56 percent reduction in the untreated windrow (meant to mirror natural reduction).

Benyahia 2005

Authors of this study conducted laboratory scale biopile experiments with soil contaminated by crude oil. They found no difference in microbial respiration rates between piles with naturally occurring soil bacteria and those with commercial microbial additives. However, they did find that adding fertilizer (soil nutrients) dramatically reduced time required for biodegradation to occur, to 118 days from 1 year, for a 75 percent concentration reduction. Biopile technology (ex-situ) was found to be a desirable remediation strategy because it allows safe operation, process control, and management of soils and additives.

Rojas-Avelizapa 2007

Drilling mud generated by the petroleum industry has a very high TPH concentration. The authors of this study performed a field-scale study by constructing four, one-ton biopiles. Three biopiles had the same treatment, and the fourth was not treated. Amendments included:

- fertilizer to achieve a C/N/P ratio of 100:3:0.5
- straw as a bulking agent, at 3 percent of volume
- moisture content at 30 to 35 percent

Results were that after 180 days, TPH concentration in the amended piles decreased by an average of 94 percent. The reduction in the unamended pile was 77 percent. The highest bacteria counts occurred within the first 30 days of the test, which corresponded with the highest rate of TPH degradation.

Kogbara 2008

Many previous studies have demonstrated that efficient microbial activity and biodegradation depends on availability of soil nutrients, soil moisture, and oxygen exposure. This study attempts to measure the relative contribution of each of these factors. Authors found that frequent tilling to promote oxygen exposure was the single most important factor in promoting biodegradation. However, there is a synergistic effect, and all three factors must be controlled to optimize degradation.

APPENDIX E

REGULATORY REVIEW

There are no federal regulations or guidelines for TPH in general. However, there are regulations for some of the TPH fractions and compounds. Nearly all states have clean-up standards for TPH, as well as some individual TPH compounds. State environmental agencies usually regulate POL soil contamination in terms of action limits, allowable uses, and varying concentrations. These agencies internally divide their responsibilities by environmental “medium,” (e.g., air, water, waste). There may not be a section, department, regulation, or guidance document that specifically addresses cleanup levels for soil bioremediation. However, one can make inferences from related guidance, such as leaking underground storage tank guidance, since it will address contaminated soil. Of course, any Army installation considering a soil remediation program should consult their own state's regulators for advice. Permits may be required, depending on the specific activity planned.

Setting “risk-based” soil cleanup concentrations is a difficult task, because many factors must be taken into account. These factors include specific contaminant, exposure pathways, and material end-use. Kostecki and Calabrese (1992) developed a “reasonable maximum exposure” as a soil cleanup guideline of 1,166 mg/kg for diesel fuel in soil, based on a lifetime cancer risk of 1×10^{-5}.

Included in this section are reviews of soil cleanup regulations for a few states with a notable Army presence. Responsible state environmental agencies regulate POL soil contamination in terms of action levels, allowable uses, and varying concentrations. Many states also divide responsibility by medium: air, water, soil, and waste.

A summary table of the regulations is given below (Table E-1) and details by state follow.

Table E-1. Summary of state soil cleanup regulations for those states with a notable presence of Army installations.

State	Summary Soil Cleanup Regulations
Georgia	Regulate soil action level in relation to groundwater and surface water supplies and pollution susceptibility areas
Kansas	Risk-based soil action levels determined by chemical component; residential versus commercial; child versus adult exposure
Kentucky	Site-specific, risk-based limit for TPH in surface soils, use health risk-based concentrations of contaminants with different values for different exposure paths
North Carolina	Several state-mandated requirements
Texas	Risk-based cleanup program, site-specific criteria and cumulative exposure, variety of protective concentration limits for individual contaminants of concern

Georgia

The Department of Natural Resources, Environmental Protection Division (EPD) is the state's compliance agent. See http://www.georgiaepd.org/Documents/index_land.html. EPD regulates and sets cleanup limits for soil from underground petroleum storage tank excavations. In this situation, EPD requires soil sampling for BTEX, TPH, and Gasoline Range Organics and/or Diesel Range Organics (TPH-GRO and/or TPH-DRO), as appropriate.
Two different sets of action levels are prescribed for BTEX and Polynuclear Aromatic Hydrocarbon (PAH) compounds, in relation to public groundwater and surface water supplies (refer to Table E-2 and

Table E-3, taken from UST Closure Report Guidance Document by Georgia Department of Natural Resources, Environmental Protection Division, Underground Storage Tank Management Program, available online at www.gaepd.org/Files_DOC/techguide/lpb/clsrptguid.doc).

Table E-2. Georgia's soil constituent threshold levels, where public water supplies are closer[a] (Georgia DNR 2010).

CONSTITUENT	AVERAGE OR HIGHER GROUNDWATER POLLUTION SUSCEPTIBILITY AREA[b] (Where public water supplies exist within 2.0 miles or non-public supplies exist within 0.5 miles)		LOWER GROUNDWATER POLLUTION SUSCEPTIBILITY AREA[c] (Where public water supplies exist within 1.0 mile or non-public supplies exist within 0.25 miles)	
VOLATILE ORGANIC COMPOUNDS	≤500 feet to withdrawal point	>500 feet to withdrawal point	≤500 feet to withdrawal point	>500 feet to withdrawal point
Benzene	0.005 mg/kg[d]	0.008 mg/kg	0.005 mg/kg[d]	0.71 mg/kg
Toluene	0.400 mg/kg	6.00 mg/kg	0.400 mg/kg	500.00 mg/kg
Ethylbenzene	0.370 mg/kg	10.00 mg/kg	0.500 mg/kg	140.00 mg/kg
Xylenes	20.00 mg/kg	700.00 mg/kg	27.00 mg/kg	700.00 mg/kg
POLYNUCLEAR AROMATIC HYDROCARBONS	≤500 feet to withdrawal point	>500 feet to withdrawal point	≤500 feet to withdrawal point	>500 feet to withdrawal point
Acenaphthene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Anthracene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Benz(a)anthracene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Benzo(a)pyrene	0.660 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Benzo(b)fluoranthene	0.820 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Benzo(g.h.i)perylene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Benzo(k)fluoranthene	1.60 mg/kg	N/A[e]	N/A[e]	N/A[e]
Chrysene	0.660 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Dibenz(a,h)anthracene	1.50 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Fluoranthene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Fluorene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Indeno(1,2,3-c,d)pyrene	0.660 mg/kg[d]	N/A[e]	0.660 mg/kg[d]	N/A[e]
Naphthalene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Phenanthrene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Pyrene	N/A[e]	N/A[e]	N/A[e]	N/A[e]

a - Based on worst-case assumptions for one-dimensional vadose zone and groundwater contaminant fate and transport models.; b - Based on an assumed distance of 0.5 feet between contaminated soils and the water table; c - Based on an assumed distance of 5.0 feet between contaminated soils and the water table. d - Estimated Quantitation Limit; the health-based threshold level is less than the laboratory method limit of detection. e - Not applicable; the health-based threshold level exceeds the expected soil concentration.

Table E-3. Georgia soil constituent threshold levels, where public water supply locations are not as close[a] (Georgia DNR 2010).

CONSTITUENT	AVERAGE OR HIGHER GROUNDWATER POLLUTION SUSCEPTIBILITY AREA[b] (where public water supplies do not exist within 2.0 miles or non-public supplies exist within 0.5 miles)		LOWER GROUNDWATER POLLUTION SUSCEPTIBILITY AREA[c] (where public water supplies do not exist within 1.0 mile or non-public supplies exist within 0.25 miles)	
VOLATILE ORGANIC COMPOUNDS	≤500 feet to withdrawal point	>500 feet to withdrawal point	≤500 feet to withdrawal point	>500 feet to withdrawal point
Benzene	0.017 mg/kg	0.120 mg/kg	0.020 mg/kg	11.30 mg/kg
Toluene	115.00 mg/kg	500.00 mg/kg	135.00 mg/kg	500.00 mg/kg
Ethylbenzene	18.00 mg/kg	140.00 mg/kg	28.00 mg/kg	140.00 mg/kg
Xylenes	700.00 mg/kg	700.00 mg/kg	700.00 mg/kg	700.00 mg/kg
POLYNUCLEAR AROMATIC HYDROCARBONS	≤500 feet to withdrawal point	>500 feet to withdrawal point	≤500 feet to withdrawal point	>500 feet to withdrawal point
Acenaphthene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Anthracene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Benz(a)anthracene	0.660 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Benzo(a)pyrene	0.660 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Benzo(b)fluoranthene	0.660 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Benzo(g.h.i)perylene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Benzo(k)fluoranthene	0.660 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Chrysene	0.660 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Dibenz(a,h)anthracene	0.660 mg/kg[d]	N/A[e]	N/A[e]	N/A[e]
Fluoranthene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Fluorene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Indeno(1,2,3-c,d)pyrene	0.660 mg/kg[d]	N/A[e]	0.660 mg/kg[d]	N/A[e]
Naphthalene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Phenanthrene	N/A[e]	N/A[e]	N/A[e]	N/A[e]
Pyrene	N/A[e]	N/A[e]	N/A[e]	N/A[e]

a - Based on worst-case assumptions for one-dimensional vadose zone and groundwater contaminant fate and transport models.; b - Based on an assumed distance of 0.5 feet between contaminated soils and the water table; c - Based on an assumed distance of 5.0 feet between contaminated soils and the water table. d - Estimated Quantitation Limit; the health-based threshold level is less than the laboratory method limit of detection. e - Not applicable; the health-based threshold level exceeds the expected soil concentration.

Kansas

The Kansas Department of Health and Environment employs "risk based" POL in soil actions levels, broken down by chemical component, residential vs. commercial, and child vs. adult. See http://www.kdheks.gov/tanks/rbca_report_manual.html for more information.

The TPH cleanup levels are broken down by residential vs. non-residential applications and GRO vs. DRO compounds. These soil limits are shown in Table E-4.

Table E-4. Kansas soil TPH limits.

TPH type	Residential soil concentration limit (mg/kg)	Non-residential soil concentration limit (mg/kg)
GRO	220	450
DRO	2,000	20,000

Kentucky

The Kentucky Division of Waste Management, Superfund Branch, Petroleum Cleanup Section (Kentucky 2005) addresses sites that have had releases of petroleum and/or petroleum products, except for soil contamination resulting from leaking underground storage tanks (see http://www.waste.ky.gov/branches/sf/).

Kentucky utilizes the Preliminary Remediation Goals (PRG) from the USEPA Region 9 Superfund office as its initial screening levels in soil for BTEX and PAH. They use a site-specific, risk-based limit for TPH in surface soils. PRGs are health risk-based concentrations for specific contaminants, with different values for different exposure pathways. They are often used as preliminary cleanup goals, but are subject to change, and may not accurately reflect site-specific conditions. See http://www.epa.gov/region09/waste/sfund/prg/ for a full list of the most current values.

North Carolina

POL soil activities in North Carolina (NC) are regulated by the NC Department of Environment and Natural Resources, Division of Waste Management (see http://wastenot.enr.state.nc.us/). Any soil remediation facility in North Carolina must meet several requirements per state regulations (Source: 15A NCAC 2T.1501 and 2T.1503):

Storage of POL-contaminated soil:

- POL soil may be stored for a maximum of 45 days
- storage is on 10 mil or thicker plastic
- provisions are made for containing potential leachate and runoff
- setbacks required (see Table E-5)
- approval of the activity has been received from the appropriate Regional Supervisor or his designee

Land application of POL soil:

- setbacks required
- approval of the activity has been received from the appropriate Regional Supervisor or his designee
- if contaminated with substances other than POL, must be analyzed to demonstrate they are not a hazardous waste

Permits are required for soil remediation sites, and must contain the following [Source: 15A NCAC 2T.1504(a)]:

- chemical analysis of the soil to be treated, including TPH, volatile organic compound (VOC), semi volatile organic compound (SVOC), pH, and heavy metals
- determination of “hazardous” status via the USEPA Toxicity Characteristic Leaching Procedure (TCLP) analysis
- site map
- an erosion control plan, submitted to the Division of Land Quality, if the remediation site exceeds one acre
- the volume of soil to be remediated
- a landowner agreement

Operating requirements for a landfarm system [Source: 15A NCAC 2T.1505(a), (b), and (c)]:

- contaminated soils must be incorporated into native soils immediately

- there must be an 18-month gap between applications at the same site

Bioremediation site requirements, that would apply to ex-situ treatment, such as biopiles (15A NCAC 2T.1505(d)):

- must have either a synthetic liner at least 30-mils thick, or a 1-ft-thick liner with low permeability

- the bottom of the containment structure is at least 3 ft above seasonal-high water table or bedrock

- control runoff either with a leachate control system or other means to avoid stormwater accumulation and contaminant migration

Table E-5. North Carolina setbacks for soil remediation.

Structure or feature	Minimum setback required (ft)
Any habitable residence or place of public assembly under separate ownership or not to be maintained as part of the project site	100
Any well with the exception of a Division approved groundwater monitoring well	100
Surface waters (streams - intermittent and perennial, perennial waterbodies, and wetlands)	100
Surface water diversions (ephemeral streams, waterways ditches)	25
Groundwater lowering ditches (where the bottom of the ditch intersects the SHWT)	25
Subsurface groundwater lowering drainage systems	25
Any building foundation except treatment facilities	15
Any basement	15

Structure or feature	**Minimum setback required (ft)**
Any property line	50
Any water line	10
Any swimming pool	100
Rock outcrops	25
Public right-of-way	50

(Source: 15A NCAC 2T.1506)

Texas

The Texas Commission on Environmental Quality (TCEQ) has a risk-based cleanup program that promotes cleanup concentrations based on site-specific criteria (and cumulative exposure, if multiple contaminants are involved). The program is called the Texas Risk Reduction Program (TRRP) (see http://www.tceq.state.tx.us/remediation/trrp/trrp.html).

Remediation goals are described as protective concentration levels (PCL). Tier 1 PCLs are the default cleanup standards within the TRRP. Tier 2 PCLs are derived through more thorough, site-specific calculations. A web page explaining this further, with links to PCL tables, and separate sheet for TPH calculations, is located at: http://www.tceq.state.tx.us/remediation/trrp/trrppcls.html.

Table E-6 gives the Tier 1 PCL levels for BTEX in industrial soil. There are several different PCLs for each contaminant of concern (COC) based on media, site geometry, and a cancer or non-cancer health end point. Only the lowest value is shown here, as an example.

Table E-6. Texas protective concentration for BTEX.

Chemical of Concern	**Protective Concentration Limit (mg/kg)**
Benzene	110
Toluene	33,000

Chemical of Concern	Protective Concentration Limit (mg/kg)
Ethyl benzene	10,000
Xylene	1,100

The state regulations define “petroleum substance waste” and “petroleum substance waste storage and treatment facility classification” (source: 30 TAC 334.481). However the definitions seem to limit the applicability of associated regulations to material from petroleum storage tanks, not from other sources such as a spill or grit. In any case, pursuant regulations (30 TAC 334.482) give worthwhile guidance on manifesting and record-keeping.

APPENDIX F

BIOREMEDIATION WHITE PAPER

(NOTE: The following paragraphs are condensed and adapted from Atlas and Bartha 1997.)

Background

Bioremediation involves the use of microorganisms to remove pollutants. The biodegradation of pollutants in the environment is a complex process whose quantitative and qualitative aspects depend on the nature and amount of the pollutant present, the ambient and seasonal environmental conditions, and the composition of the indigenous microbial community. Bioremediation can be applied to sites contaminated with a variety of chemical pollutants including monoaromatic hydrocarbons (e.g., benzene, xylene and toluene) and alkanes and alkenes (e.g., fuel oil).

The two general approaches to bioremediation are environmental modification, such as through nutrient application and aeration, and the addition of appropriate xenobiotic[§] degraders by seeding. The end products of effective bioremediation, such as water and carbon dioxide, are nontoxic and can be accommodated without harm to the environment and living organisms. Using bioremediation to remove pollutants is inexpensive, compared to physical methods for decontaminating the environment, which can be extraordinarily expensive. Bioremediation, though, is not the solution for all environmental pollution problems. Like other technologies, it is limited by the materials it can treat, conditions at the treatment site, and time available for treatment. Petroleum and creosote have been the most common pollutants of concern comprising about 60 percent of the sites where bioremediation is being used for field demonstrations or full-scale operations.

The most direct measure of bioremediation efficacy is the monitoring of disappearance rates of the

§ A xenobiotic is a chemical found in an organism which is not normally produced or expected to be present. It can also refer to substances which are present in much higher concentrations than are usual.

pollutant. Note that the “disappearance” of pollutants may occur not only by biodegradation but also by evaporation, photodegradation, and leaching.

Environmental Modification for Bioremediation

Some common environmental limitations to biodegradation of hazardous chemical wastes are excessively high waste concentrations, lack of oxygen, unfavorable pH, lack of mineral nutrients, lack of moisture, and unfavorable temperature. Once the limitations by environmental conditions are corrected, the ubiquitous distribution of microorganisms, in most cases, allows for a spontaneous enrichment of the appropriate microorganisms. In the great majority of cases, an inoculation with specific microorganisms is neither necessary nor useful. Exceptions exist when the biodegrading microorganisms are poor competitors and fail to maintain themselves in the environment, or when chemical waste is only co-metabolized and thus fails to provide a selective advantage to the catabolic organism(s). A massive accidental spill of a toxic chemical in a previously unexposed environment constitutes another situation where inoculation with pre-adapted microbial cultures may hasten biodegradative cleanup. However, inoculation should always be combined with efforts to provide the inoculum with reasonable growth conditions in the polluted environment. As a minimum, conditions need to be ensured for such factors as suitable growth temperature, adequate water potential, suitable pH, suitable nutrient balance, and — for aerobic processes – adequate oxygen supply. If the pollutant to be eliminated does not support microbial growth, the addition of a suitable growth substrate and/or repeated massive inoculations is necessary. Inoculation in the absence of the appropriate ecological considerations rarely attains the desired improvement in biodegradation.

The availability of oxygen in soils, sediments, and aquifers is often limiting, and is dependent on the type of soil and whether the soil is waterlogged. The microbial degradation of petroleum contaminants in some groundwater and soil environments is severely limited by oxygen availability. In surface soil and in on-site bioremediation, oxygenation is best ensured by providing adequate drainage. Air-filled porous spaces in the soil facilitate diffusion of oxygen to hydrocarbon-utilizing microorganisms, whereas in waterlogged soil, oxygen diffusion is extremely slow and cannot keep up with the demand of heterotrophic** decomposition processes. Substantial concentrations of decomposable hydrocarbons create a high oxygen demand in soil, and the rate of diffusion is inadequate to satisfy it, even in well-drained and light-textured soils. Cultivation (e.g., plowing and rotary tilling) has been used to turn the soil, ensuring its maximal access to atmospheric oxygen.

Besides oxygen availability and redox†† potential, biodegradation rates can be limited by the available concentrations of various nutrients. Several major oil spills have focused attention on the problem of hydrocarbon contamination in marine and estuarine‡‡ environments, and the potential use of bioremediation through nutrient addition to remove petroleum pollutants. Because microorganisms require nitrogen and phosphorous for incorporation into biomass, it is critical for these nutrients to be available within the same area as the hydrocarbons. Under conditions where nutrient deficiencies limit the rate of petroleum biodegradation, the beneficial effect of fertilization with nitrogen and phosphorous has been conclusively demonstrated and offers great promise as a countermeasure for combating oil spills.

For the bioremediation of pollutants in surface soils, it is generally easy to add nutrients via agricultural fertilizers. However, getting nutrients to subsurface soil and groundwater populations is more complex.

Bioaugmentation

Because bioremediation relies on the biodegradation capacity of microorganisms in contact with the pollutants, some have proposed seeding with pollutant-degrading bacteria. This approach is called bioaugmentation because it augments the metabolic capabilities of the indigenous microbial populations.

** Meaning capable of utilizing only organic materials as a source of food.

†† Also known as oxygen reduction, when there is a chemical reaction between two substances in which one substance is oxidized and the other is reduced.

‡‡ Referring to that part of the mouth or lower course of a river in which the river's current meets the sea's tide.

Bioaugmentation involves the introduction of microorganisms into the natural environment, for the purpose of increasing the rate or extent (or both) of biodegradation of pollutants. The rationale for this approach is that indigenous microbial populations may not be capable of degrading either xenobiotics or the wide range of potential substrates present in complex pollutant mixtures. However, as found by many of the studies described earlier in this report, indigenous soil bacteria are sufficient (under most conditions) for biodegradation of most common POL types.

Soil Bioremediation

Soil bioremediation is the most economical treatment of oily wastes from refineries and petrochemical plants. The process is called “landtreatment” or “landfarming” and constitutes a deliberate disposal process in which place, time, and rates can be controlled. Rates of biodegradation may be slower, using on-site landfarming than using bioreactor treatment, but it is much more cost effective. In land treatment, the chosen site has to meet certain criteria and needs to undergo preparation to assure that floods, runoff, and leaching will not spread the hydrocarbon contamination in an uncontrolled manner. Oily sludges are applied at rates to achieve approximately 5 percent hydrocarbon concentration (mass hydrocarbon/mass soil or sludge), because concentrations above 10 percent definitely inhibit the biodegradation process. With acidic soils, the soil pH is adjusted (through the use of agricultural limestone) to a value between 7 and 8, or to the nearest practical value, based on location and cost. Fertilizers are applied in a ratio of hydrocarbon to nitrogen equal to 200:1, and a ratio of hydrocarbon to P of 800:1. Adequate drainage is essential, but irrigation is necessary only in very arid and hot climates. Some volatile hydrocarbons are inevitably lost to the atmosphere in this type of treatment. Typically, a portion of the waste organic chemical is mineralized during treatment, and another portion (after partial biodegradation) is incorporated into soil humus, bringing about a high degree of detoxification and immobilization of the hydrocarbons.

APPENDIX G

BIOPILES

Biopiles are another method for treatment of POL-contaminated soils. Biopile treatment is a full-scale technology in which excavated soils are mixed with soil amendments, placed on a treatment area, and bioremediated using forced aeration or turning the windrows with a tractor-drawn implement. A basic biopile system includes a treatment bed, an aeration system, an irrigation/nutrient system and a leachate collection system. Moisture, heat, nutrients, oxygen and pH are controlled to enhance biodegradation. The irrigation/nutrient system is buried under the soil to pass air and nutrients either by vacuum or positive pressure. Under extreme conditions, the piles may be covered with plastic to control runoff, evaporation, and volatilization, and to promote solar heating. If volatile organic compounds (VOCs) in the soil volatilize into the air stream, the air leaving the soil may be treated to remove or destroy the VOCs before they are discharged into the atmosphere.

Benefits and Limitations

Benefits of bioremediation with biopiles include:

- contaminants are reduced to carbon dioxide and water
- applicable to all POLs, including heavy-chain hydrocarbons such as JP-5 and diesel fuel
- application of water, nitrogen and phosphorous accelerates the process
- treatability study averages $20,000
- treatment usually takes 3–6 months
- cost ranges from $25 to $70 per ton of contaminated soil (Cost depends on contaminants, cleanup procedure, need for additional pretreatment and post-treatment, and need for air emission control equipment.)
- relatively simple operation and maintenance, requiring few personnel

Factors that may limit the applicability and effectiveness of biopiles include:

- requires excavation of contaminated soil
- not economical for smaller areas of contamination (e.g., off-site disposal may be more economical for less than 250 cu yd)
- large amount of relatively flat space is required to build a system

Minimum Design Requirements

To develop an ex-situ bioremediation site, the following parameters and site conditions are reasonable:

- soil contaminant is biodegradable
- TPH concentration of less than 50,000 mg/kg in soil
- heterotrophic bacteria greater than or equal to 1,000 CFU/1g dry soil
- soil pH between 6 and 9
- water at 70 to 95 percent of field capacity
- low clay or silt content (defined as less than or equal to 25 percent of the soil volume).
- soil contamination greater than 250 cu yd
- availability of electricity and water
- relatively flat ground, outside of a 100-year flood plain
- location secured; away from residential areas
- space for system pads, soil storage and handling (11,000 sq ft for 500 cu yd biopile)

Treatability Study Objectives

1. Conduct treatability testing to determine the biodegradability of contaminants in soils specific to the site and to produce appropriate oxygenation and nutrient loading rates.

2. Determine if contamination can be degraded to acceptable cleanup levels, depending on state requirements and desired end use of the soil.

3. Establish soil conditions in the laboratory that will enhance on-site biodegradation rates. Such conditions include the soil's pH, temperature, nitrogen and phosphorous counts, moisture content, salinity, and particle-degrading microorganism population density (if there is some concern that that soil has been sterilized due to some toxic material.

APPENDIX H

REFERENCES

Atlas, R.M., and R. Bartha. 1998. Microbial ecology: fundamentals and applications. 4th edition. Menlo Park, Calif.: Benjamin/Cummings.

Benyahia, F., M. Abdulkarim, A. Zekri, O. Chaalal, and H. Hasanain. 2005. Bioremediation of crude oil contaminated soils: a black art or an engineering challenge? *Trans IchemE, PartB, Process Safety and Environmental Protection* 83(B4):364-370.

Berkey E., J.M. Cogen, V.J. Kelmeckis, L.T. McGeeham, and A.T. Merski. 1991. Evaluation process for the selection of bioremediation technologies for the Exxon Valdez oil spill, in *Environmental biotechnology for waste treatment*, ed. G.S. Sayler, R. Fox, and J.W. Blackburn, 85-90. New York: Plenum Press.

Borden, R.C., C.A. Goney, and M.J. Becker. 1995. Geochemical indications of intrinsic bioremediation. *Ground-Water*, 33(2):180-189.

Chaîneau, C.H., C. Yepremian, J.F. Vidalie, and J. Ducreux. 2003. Bioremediation of a crude oil-polluted soil: biodegradation, leaching, and toxicity assessments. *Water, Air, and Soil Pollution* 144:419-440.

Compeau, G.C., W.D. Mahaffey, and L. Patras. 1991. Full-scale bioremediation of contaminated soil and water, in *Environmental biotechnology for waste treatment,* eds. G.S. Sayler, R. Fox, and J.W. Blackburn, pp 91–110. New York: Plenum Press.

Dupont, R.R., R.C. Sims, J.L. Sims, and D.L. Sorensen. In site biological treatment of hazardous waste-contaminated soils. In *Biotreatment systems,* vol. II, ed. Donald L. Wise. Boca Raton, FL: CRC Press, Inc.

Eweis, J.B., S.J. Ergas, D.P.Y. Chang, and E.D. Schroeder. 1998. *Bioremediation principles*. Boston: WCB/McGraw-Hill.

Georgia Department of Natural Resources (DNR), Environmental Protection Division. 2010. “UST closure report guidance document” from Underground Storage Tank Management Program. Available online at www.gaepd.org/Files_DOC/techguide/lpb/clsrptguid.doc.

Gustafson, J.B., J.G. Tell, and D. Orem. 1997. *Selection of representative TPH fractions based on fate and transport considerations*. Total Petroleum Hydrocarbon Criteria Working Group series, v. 3. Amherst, Mass: Amherst Scientific Publishers.

Jobson, A., M. McLaughlin, F.D. Cook, and D.W.S. Westlake. 1974. Effects of amendments on the microbial utilization of oil applied to soil. *Applied Microbiology* 27:166-171.

Jorgensen, K.S., J. Puustinen, and A.M. Surortti. 2000. Bioremediation of petroleum hydrocarbon-contaminated soil by composting biopiles. *Environmental Pollution* 107:245-254.

Kansas Bureau of Environmental Remediation (BER) Policy. 2000. Clean-up levels for total petroleum hydrocarbons. BER Policy # BER-RS-041. Topeka, KS: Kansas Department of Health and Environment.

Kentucky Division of Waste Management, Superfund Branch - Petroleum Cleanup Section. 2005. Closure report for petroleum released and exempt petroleum tank systems. DEP 7097C.Frankfort, KY.: Department of Environmental Protection.

Klinger, F.W. 1997. Guidelines for bioremediation treatment of petroleum-contaminated soil and interceptor grit material at Fort Hood, Texas. Unpublished paper prepared for Fort Hood, TX: Army Directorate of Public Works.

Kogbara, R.B. 2008. Ranking agro-technical methods and environmental parameters in the biodegradation of petroleum-contaminated soils in Nigeria. *Electronic Journal of Biotechnology* (online) 11:1.Available from: http://www.ejbiotechnology.info/content/vol11/issue1/full/4/reprint.html ISSN 0717-3458.

Kostecki, P.T., and E.J. Calabrese. 1992. *Contaminated soils: diesel fuel contamination*. Boca Raton, FL: Lewis Publishers.

Leavitt, M.E., and K.L. Brown. 1994. Biostimulation versus bioaugmentation - three case studies. In *Hydrocarbon bioremediation*, ed. Battelle Memorial Institute, R.E. Hinchee, R.N. Miller, and R.E. Hoeppel,72-79. Boca Raton: Lewis Publishers. Available from CRC Press Online.

Mueller, J.G., S.M. Resnick, M.E. Shelton, and P.H. Pritchard. 1992. Effect of inoculation on the biodegradation of weathered Prudhoe Bay crude oil. *Journal of Industrial Microbiology and Biotechnology* 10:95-102.

Prince, R. C., J. R. Clark, J. E. Lindstrom, E. L. Butler, E. J. Brown, G. Winter, M. J. Grossman, P. R. Parrish, R. E. Bare, J. F. Braddock, W. G. Steinhauer, G. S. Douglas, J. M. Kennedy, P.J. Barter, J.R. Bragg, E. J. Harner, and R. M. Atlas. 1994. Bioremediation of the Exxon Valdez oil spill: monitoring safety and efficacy. In *Hydrocarbon bioremediation*, ed. Battelle Memorial Institute, R.E. Hinchee, R.N. Miller, and R.E. Hoeppel, 107-124. Boca Raton: Lewis Publishers. Available from CRC Press Online.

Pritchard, P.H. 1992. Use of inoculation in bioremediation. *Current Opinion in Biotechnology* 3:3:232-243.

Quinn, J.W., and D.R. Reinhart. 1997. Bioremediation of diesel contaminated soil using biopiles. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*. 1:1: 18-25.

Reisinger, H.J. 1995. Hydrocarbon remediation - an overview. In *Applied bioremediation of petroleum hydrocarbons*, ed. R.E. Hinchee, J.A. Kittel, and H.J. Reisinger, 148-162. Columbus, OH: Battelle Press.

Reynolds, C.M., M.D. Travis, W.A. Braley, and R.J. Scholze. 1994. “Applying field-expedient bioreactors and landfarming in Alaskan climates.” In *Hydrocarbon bioremediation*, ed. Battelle Memorial Institute, R.E. Hinchee, R.N. Miller, and R.E. Hoeppel, 100-106. Boca Raton: Lewis Publishers. Available from CRC Press Online.

Rojas-Avelizapa, N.G., T. Roldán-Carrillo, H. Zerarra-Martínez, A.M. Muñoz-Colunga, and L.C. Fernández-Linares. 2007. A field trial for an ex-situ bioremediation of a drilling mud-polluted site. *Chemosphere* 66:1595-1600.

Thomassin-Lacroix, E.J.M., M. Eriksson, K.J. Reimer, and W.W. Mohn. 2002. Biostimulation and bioaugmentation for on-site treatment of weathered diesel fuel in Arctic soil. *Applied Microbiology and Biotechnology* 59:551-556.

Venosa, A.D., J.R. Haines, W. Nisamaneepong, R. Govind, S. Pradhan, and B. Siddique. 1991. Screening of commercial inocula for efficacy in stimulating oil biodegradation in closed laboratory system. *Journal of Hazardous Materials* 28:131-144.

——— 1992. Efficacy of commercial products in enhancing oil biodegradation in closed laboratory reactors. *Journal of Industrial Microbiology and Biotechnology* 10(1):13-23.

Weisman, Wade. 1998. *Analysis of petroleum hydrocarbons in environmental media*. Total Petroleum Hydrocarbon Criteria Working Group series, v. 1. Amherst, Mass: Amherst Scientific Publishers.

APPENDIX I

ABBREVIATIONS

Term	**Spellout**
AR	Army Regulations
BER	Bureau of Environmental Remediation (Kansas)
BTEX	benzene, toluene, ethylbenzene, xylene
C/N	carbon/nitrogen
CEERD	U.S. Army Corps of Engineers, Engineer Research and Development Center
CEERD-CN	U.S. Army Corps of Engineers, Engineer Research and Development Center
CFU	colony farming unit
CN	Installations Division
COC	containment of concern
DA	Department of the Army
DEP	Department of Environmental Protection (Kentucky)
DoD	Department of Defense
DPW	Directorate of Public Works
DRO	diesel range organics
EPA	Environmental Protection Agency
EPD	Environmental Protection Division (Georgia
GRO	gasoline range organics
HQUSACE	Headquarters, U.S. Army Corps of Engineers
JP	jet propellant
LUST	leaking underground storage tank
N/A	not applicable
NCAC	North Carolina Administrative Code
PAH	polynuclear aromatic hydrocarbon
PCL	protective concentration levels
PDF	portable document format
POC	point of contact
POL	petroleum, oil, and lubricants
PRG	preliminary remediation goals (USEPA)
PTO	power take-off
PWTB	Public Works Technical Bulletin
SHWT	Seasonal High Water Table
SVOC	semi-volatile organic compounds
TAC	Texas Administrative Code
TCEQ	Texas Commission on Environmental Quality
TCLP	toxicity characteristic leaching procedure
TKN	total kjeldahl nitrogen
TP	total phosphorous
TPH	total petroleum hydrocarbons
TPHCWG	Total Petroleum Hydrocarbons Criteria Working Group
TPH-DRO	total petroleum hydrocarbons-diesel range organics

Term	**Spellout**
TPH-GRO	total petroleum hydrocarbons- gasoline range organics
TRPH	total recoverable petroleum hydrocarbons
TRRP	Texas Risk Reduction Program
URL	universal resource locator
U.S.	United States
USEPA	U.S. Environmental Protection Agency
UST	underground storage tank
VOC	volatile organic compound
WWW	World Wide Web