

226
National Cooperative Highway Research Program

NCHRP Synthesis 226

Remediation of
Petroleum-Contaminated Soils

A Synthesis of Highway Practice

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National Cooperative Highway Research Program

Synthesis of Highway Practice 226

Remediation of Petroleum-Contaminated Soils

DAVID J. FRIEND
Bedford, Massachusetts

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials (AASHTO) initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research need to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program, can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U. S. Department of Transportation.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in the daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

*By Staff
Transportation
Research Board*

This synthesis will be of interest to state transportation personnel involved with project planning and location (administrative and regulatory personnel), design staff (general civil, geotechnical, and environmental engineers), and project managers (construction and maintenance engineers and staff). It will also be of interest to federal and state environmental agencies and to environmental consultants and contractors as well as to trainers in the field of petroleum-contaminated soil remediation. This synthesis describes the remedial technologies that may be available to transportation agencies faced with the regulatory responsibility to clean or remediate petroleum-contaminated soils in the vadose zone (unsaturated soils above the groundwater table) at a particular site as well as the state of the practice within the agencies.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board describes the applicability and cost-effectiveness of alternate technologies to remediate petroleum-contaminated soil. Practices currently being used by state transportation agencies to remediate petroleum-contaminated soils, both on site and off site are also described. This summary of transportation agency practice complements the limited telephone survey of soil remedia-

tion techniques that was performed in preparing NCHRP Report 351, *Hazardous Wastes in Highway Rights-of-Way*.

Other areas germane to the topic but not covered by this synthesis include:

- Field investigation and laboratory testing to identify the types and characteristics of contaminated soils and limits of their existence (depth, length, and width);
- What tests are needed to evaluate the soils that were treated by the various techniques described in the synthesis;
- Acceptance criteria for the test results;
- Effects on construction materials such as geosynthetics, steels, concrete, and aggregate by contaminated soils and the soils after treatment; and
- Changes in soil characteristics (especially moisture content and plasticity) after treatment using various techniques.

Perhaps they could be the focus of future studies.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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Director, Geomechanics and Environmental Laboratory, GeoSyntec Consultants, Atlanta, Georgia; Mehmet T. Tumay, Director of Research and Professor of Civil Engineering, Louisiana Transportation Research Center; Thomas F. Zimmie, Professor, Civil Engineering Department, Rensselaer Polytechnic Institute.

The Principal Investigators responsible for the conduct of this synthesis were Sally D. Liff, Manager, Synthesis Studies, and Stephen F. Maher, Senior Program Officer. This synthesis was edited by Linda S. Mason:

Scott A. Sabol, Senior Program Officer, National Cooperative Highway Research Program, assisted the NCHRP 20-5 staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

REMEDIATION OF PETROLEUM-CONTAMINATED SOIL

SUMMARY

Millions of underground storage tanks (USTs) have been installed over the years at various locations and facilities. A significant percentage of these UST systems have leaked and released their stored contents, usually petroleum products, into the environment. To minimize the threat of groundwater contamination, strict federal, state, and local regulations require the owners and operators of these petroleum storage tanks to clean up the environmental damage that is caused by past leaks and spills.

A state transportation agency that has underground storage tanks containing petroleum products (e.g., gasoline, diesel fuel, heating oil) at its vehicle fueling sites or maintenance facilities may be affected by these requirements. Many transportation agencies have been found responsible for cleaning up the petroleum-contaminated soil and/or groundwater from past facility operations and practices that resulted in petroleum leaks or spillage. Many agencies have also become responsible for cleaning up the petroleum contamination from leaking storage tanks they encounter when acquiring the land for, or during the construction of, new transportation facilities.

This synthesis describes the technologies that may be available to transportation agencies faced with the regulatory responsibility to clean up or remediate petroleum-contaminated soils at a site. Some of these remediation technologies remove and destroy i.e., treat the petroleum contaminants that exist in the soil, while others are designed only to contain the movement or leaching of the contaminants. The technologies differ from one another by the type of process that is employed e.g., biological, physical, chemical, thermal, or containment to accomplish cleanup objectives. In addition, some remediation technologies can be applied in-situ, or while the soil is still in the ground; others are ex-situ technologies that require soil excavation before deployment. A total of 18 different soil remediation technologies are described: passive biodegradation, bioventing, in-situ biodegradation, biopiles, land treatment or landfarming, slurry biodegradation, soil venting, soil flushing, soil washing, coal tar agglomeration, solvent extraction, radio frequency heating, vitrification, thermal desorption, solidification/stabilization, capping, land disposal (landfilling), and incorporation in cold-mix asphalt.

A survey found that approximately 90 percent of the petroleum-contaminated sites being cleaned up by state transportation agencies involve gasoline and/or diesel fuel-contaminated soils. Transportation agencies have also been responsible for remediating soils containing kerosene and heavier weight petroleum products, but at far fewer sites. It was also found that most of the petroleum-contaminated sites undergoing cleanup by transportation agencies contain relatively small volumes of contaminated soil. Approximately 62 percent of all the sites remediated by transportation agencies during the 2 years prior to a fall 1994 survey conducted for this synthesis have involved less than 380 cubic meters (m^3) (500 cubic yards, yd^3) of contaminated soil; 75 percent of the sites have involved less than 765 m^3 (1,000 yd^3) of soil.

Because most sites contain readily volatile petroleum contaminants in relatively small amounts, state transportation agencies have been able to select from and employ a broad range of alternative soil remediation technologies. The following conditions and practices were found to exist:

- Many state transportation agencies place petroleum-contaminated soils in landfills, particularly in states where such a practice is allowed by the environmental regulatory agency, and the cost of landfilling is not too high. The practice of landfilling occurs despite the long-term liability that may accompany this activity.
- Where landfilling is not allowed or is cost prohibitive, and air quality conditions are satisfactory, landfarming (including the use of biopiles) often becomes the most cost-effective soil remediation technology of choice to a transportation agency. This appears to be particularly true in the South and West where temperatures are suitable for biodegradation and sufficient land area is available.
- The thermal treatment of contaminated soil in modified hot-mix asphalt plants or low temperature strippers is also performed by many state transportation agencies. Thermal treatment technologies appear to be used most frequently by highway agencies in northern states with climates that are not conducive to landfarming. Although the cost of thermal treatment is typically greater than the cost of landfarming, environmental conditions in many states render landfarming either impractical or cost prohibitive because of the need to construct and maintain temperature-controlled enclosures.
- When allowed by state regulators, some transportation agencies use a number of biological treatment technologies other than landfarming to remove petroleum contaminants from soil. Natural biodegradation is allowed by some state environmental regulatory agencies. In general, however, biological treatment technologies are not used extensively by transportation agencies because: (a) low temperature and other conditions make biodegradation impractical in many geographic areas, (b) biotreatment is not yet widely accepted by many environmental regulatory agencies (although that is changing rapidly), (c) biological treatment is often costly due to the need for extensive site characterization studies and treatability tests, and (d) in-situ biotreatment is simply not very practical when there are small amounts of contaminated soil involved and insufficient land or time available because of project scheduling demands.
- Transportation agencies rely more on ex-situ technologies than they do on in-situ soil remediation techniques. Faced with project deadlines and the unavailability of suitable space for treatment within the right-of-way, there often remains no alternative but to excavate the soil and perform off-site treatment. The high rate of ex-situ treatment may also be a reflection of the fact that transportation agencies continue to discover some petroleum-contaminated sites late in the project development process. In addition, even with the cost of soil excavation and transport, ex-situ treatment is often the lowest cost option available to an agency when dealing with relatively small volumes of contaminated soil.

The cleanup practices of state transportation agencies at petroleum-contaminated sites were found to mirror closely those used by other responsible parties to remediate UST sites nationally. However, the cost and regulatory feasibility of soil remediation technologies cannot be considered static. In terms of cost, for example, it is unclear how much longer petroleum-contaminated soils will be welcome at many landfills. While relatively inexpensive now in many geographic areas, the cost of landfilling petroleum-contaminated soils will inevitably rise as landfill space becomes more scarce and landfill operators become more selective in what they accept. As the cost of landfilling escalates, many transportation agencies may find that land disposal no longer emerges as the most cost-effective technology at even small petroleum-contaminated sites.

The regulatory environment surrounding petroleum-contaminated sites is also changing.

Biological treatment technologies are becoming more widely accepted by many environmental agencies as the risks of petroleum contamination are better understood. State environmental regulations and policies that have hindered or prohibited the use of certain soil remediation techniques are being re-evaluated. In addition, many states are now adopting approaches to the establishment of site cleanup levels that are site-specific, risk-based, and do not use total petroleum hydrocarbons (TPH) as the indicator parameter. As more state environmental agencies embrace such chemical-specific risk-based cleanup guidelines, the use of biological treatment methods (including natural attenuation) by transportation agencies at many of their sites may be viewed more favorably. This change in regulatory attitude may provide transportation agencies with increased opportunity to argue for the controlled "re-use" of lightly contaminated soils as suitable subbase or other construction material within the limits of their projects.

The regulatory and technology related information that is needed to select the most cost-effective soil remediation technology for a site is constantly changing. The relative cost-effectiveness of alternative technologies differs not only from site to site, but also over time as the cost of existing treatment and disposal options change and new options (e.g., permitting of local asphalt plants to accept petroleum-contaminated soils) become commercially available in a particular geographic area. Transportation agencies and their consultants are encouraged to assemble and use the most up-to-date cost and other information available as they undertake the technology evaluation and selection process at each petroleum-contaminated site they encounter.

INTRODUCTION

BACKGROUND

Millions of underground storage tanks (USTs) exist at facilities owned by large petroleum companies and mid-size marketers, at small “Mom and Pop” gasoline service stations, convenience stores, airports, and residences, and at government facilities, including transportation agencies. Many of these tanks were installed with little attention given to their design, installation, or maintenance. As a result, a significant number of existing UST systems have leaked and released their stored contents into the environment. Until recently, confirmed releases of petroleum hydrocarbons from leaking USTs were being reported to state regulatory agencies at the rate of approximately 1,000 per week. Each leaking tank typically results in between 23 to 38 m³ (30 to 50 yd³) of contaminated soil (1).

In areas that depend on ground and surface water sources for their drinking water supply, and especially in areas with shallow aquifers, leaking USTs present a serious threat. When tanks or other sources containing petroleum leak, the products they release can contaminate nearby surface and ground water. Serious safety problems can also arise if gasoline accumulates in sewer lines and other confined spaces, allowing vapors to spread into homes and businesses. These vapors are poisonous and can present a fire or explosion hazard. Human exposure to petroleum hydrocarbons, which include such chemicals as benzene, can produce adverse health effects.

To minimize the threat of groundwater contamination, strict federal, state, and often local regulations exist to require owners and operators of petroleum storage tanks to (a) replace or upgrade their tanks to meet minimum design standards, (b) test their tanks regularly for leaks and establish controls for spills, and (c) clean up any environmental damage that past leaks and spills may have caused. Every transportation agency that has multiple USTs containing petroleum products (e.g., gasoline, diesel fuel, heating oil) at their vehicle fueling sites and maintenance facilities are affected by these regulations and requirements. Most state transportation agencies have responded to these federal and state tank requirements by developing tank management programs that address the operational, replacement, or tank closure requirements that apply to them.

As a result of these regulations, many state transportation agencies have shouldered the responsibility to clean up the petroleum-contaminated soil and groundwater that may have resulted from improper transportation facility operations and practices. Agencies have also been found responsible for cleaning up the petroleum contamination from leaking storage tanks they encounter when acquiring the land for, or during the construction of, new transportation facilities.

Petroleum-contaminated soils are more frequently encountered in highway rights-of-way than any other type of contamination (2,3,4).

Many transportation agencies were able to comply initially with applicable regulations by landfilling the petroleum-contaminated soil. However, the excavation of petroleum-contaminated soil and its disposal in landfills is not a risk-free option. Although petroleum-contaminated materials and debris from underground and aboveground sources are currently (or will soon be) exempt from regulation as hazardous wastes under Subtitle C of the Resource Conservation and Recovery Act (RCRA)(5), its “nonhazardous” status does not shield a transportation agency completely from future liability should the contamination leach from the landfill and impact human health or the environment. The treatment and removal of harmful constituents in a contaminated soil is always preferred to disposal without treatment. In addition, the availability and cost of landfilling petroleum-contaminated soils is constantly changing as many landfills close, refuse to accept the soils, increase their dumping fees, or place tighter restrictions on the soils they will accept (6). It is essential that transportation agencies carefully review and select the most cost-effective technology from among the full range of alternative soil remediation technologies when complying with environmental cleanup regulations.

OBJECTIVE OF SYNTHESIS

When petroleum products are released from a source they move downward under the influence of gravity and, to a lesser extent, horizontally under the influence of capillary forces. Where the characteristics of the subsurface allow it, the petroleum contaminants will migrate downward through an unsaturated or vadose zone of soils until they reach an impermeable layer (e.g., clays), a level of residual saturation, or the water table. Residual saturation is the maximum volume of water that can be held within soil pores by adsorption and capillary forces. The petroleum product cannot flow further downward when the moisture content exceeds the residual saturation level.

Petroleum contamination that lies within this unsaturated zone of soils may exist in the form of petroleum vapors in the soil pore space, as residual petroleum trapped between or adsorbed onto soil particles, or as petroleum dispersed in soil moisture. This synthesis describes the remedial options that may be available to a transportation agency for the treatment of soils in this unsaturated zone that have become contaminated with petroleum products. Cleanup technologies that can be applied to the contaminated soils without physically removing it from the ground are described, as well as reme-

diation approaches that require excavation of the contaminated soils and treatment at another location either on the site or off-site.

This synthesis does not describe the remediation techniques that may be applied to recover petroleum products that exist in the saturated zone of the subsurface either resting on the water table or emulsified in the groundwater. The removal of petroleum constituents from groundwater is a relatively difficult and expensive process that often involves combinations of cleanup methods or more complex technologies than those required for the treatment of contaminated soils only. Some of the remediation techniques effective for removing petroleum from the unsaturated soils can, to varying extents, also remove contaminants from the saturated zone and achieve groundwater cleanup objectives. However, additional resource documents should be consulted when either the recovery of free product resting on the water table or the removal of petroleum contaminants from groundwater is required. This synthesis also does not review and evaluate alternative remediation technologies for soils containing wastes that are listed or test characteristic under the U.S. Environmental Protection Agency's (EPA) RCRA hazardous waste rules.

For each of the alternative soil remediation technologies identified to be effective in treating petroleum contaminants, written and tabular summaries are provided to describe:

- The components of the technology;
- The types of petroleum the technique is effective in treating;
- The site, soil, and contaminant parameters that will affect the performance of the technology;
- The advantages and limitations of the technology;
- The relative costs of implementing the technology; and
- Regulatory and other considerations important to its use (e.g., need for emissions control equipment and permits, need for post-cleanup monitoring, and health and safety requirements).

There are numerous books, technical reports, professional journal articles, technical publications, electronic bulletin boards, and computer databases containing vast amounts of information on one or more of the soil remediation technologies identified. Existing and ongoing sources of important technical and cost information relevant to each of the technologies are identified throughout the synthesis.

This synthesis also describes the technologies currently being used by state transportation agencies to remediate petroleum-contaminated soil both on-site and off-site. This state of the practice profiles (a) the types of petroleum-contaminated sites most frequently encountered by transportation agencies, (b) the types of petroleum contamination (e.g., gasoline, diesel, fuel oil) most frequently encountered; (c) the average size of the contaminated area and site conditions; (d) the nature and costs of remediation techniques being applied at these sites, and (e) the factors that are most influ-

ential in a transportation agency's selection of a particular soil remediation technique for a particular site. This summary of transportation agency practice complements the limited telephone survey of soil remediation techniques that was performed in preparing *NCHRP Report 351 (2)*.

It is intended that this synthesis will be a reference document for transportation agency staff who have varying responsibilities during the transportation project development process. However, it is not intended to be a definitive guideline. Staff with responsibilities for project planning and location might use the information provided to identify the applicable cleanup method and approximate the cost to remedy the type of petroleum contamination released from underground storage sites found within the right-of-way targeted for acquisition. Design staff might find the information describing a particular cleanup method useful during the preparation of design documents. Project managers may find the synthesis useful in understanding the applicability of different remediation techniques to different types of petroleum contamination and sites, and in evaluating the appropriateness of consultant recommendations.

SOURCES OF INFORMATION

An extensive review of pertinent literature and ongoing research concerning the remediation of petroleum-contaminated soils was conducted. A keyword search on petroleum-contaminated soil cleanup methods was conducted using the Transportation Research Information Service (TRIS) computerized information file. To supplement the abstracts from the TRIS search, the following information sources were also tapped for up-to-date information: U.S. EPA and national trade associations, professional journals and other publications, environmental research institutes, environmental databases, Canadian sources. These sources are identified in the reference list.

A comprehensive questionnaire was also developed and sent to transportation agencies in each of the 50 states, the District of Columbia, and Puerto Rico. Due to the nature of the topic, and the substantial amount of information being sought, transportation agencies were asked to provide information on the soil remediation technologies that had been employed at agency sites during the 2-year period previous to the survey conducted during the fall of 1994. Specific site and other information describing the application of an individual remediation technique at a single representative site was then requested. A copy of the state questionnaire is provided in Appendix A.

Thirty-seven states responded to the questionnaire. Several transportation agencies also forwarded general guidance manuals used to screen and evaluate alternative soil remediation options, as well as technical support documentation on the activities that occurred at a specific site. The findings of the state survey are discussed in Chapter 7. A glossary of terms and acronyms useful in understanding the material in this synthesis appears at the end of the document.

SOIL REMEDIATION ALTERNATIVES

OVERVIEW OF PETROLEUM-CONTAMINATED SOIL TREATMENT TECHNOLOGIES

Petroleum hydrocarbon contaminants are typically present at the site of a release in more than one phase—vapor, liquid, dissolved and/or adsorbed—and may be in more than one medium—soil and/or groundwater. Furthermore, soil heterogeneity and other differences in the subsurface make every site different. Remedial technologies that are effective for removing petroleum hydrocarbons that exist in one phase may not work well for another phase. And remediation systems that work at one site may not work at a different site. Effective remediation, therefore, is determined on a site-by-site basis and is designed to address the contamination present in all phases and media affected at that location. No one technology is presently available to singularly remediate contaminants present in all phases and media (7). In addition, some remediation techniques are well-established and commonly accepted by regulators and the public; others are known to be

effective, but not always accepted by the community; still others have been tested in the laboratory only (8).

During the period of study, a substantial volume of information was produced describing alternative treatment technologies for removing petroleum contaminants from soil. EPA and others presently offer many information resources to aid consultants and transportation agency staff in identifying and screening innovative technologies for petroleum and other waste site remediation (9). Resources exist in the form of:

- publication listings (10-15);
- general guidance documents (16-28); and,
- computer databases containing the results of specific field applications and information on technology vendors (29,30).

The technologies available for the treatment of petroleum-contaminated soils described in these materials have been grouped in a number of ways by different researchers. Table 1 categorizes the alternative soil treatment technologies that

TABLE 1
ALTERNATIVE PETROLEUM-CONTAMINATED SOIL TREATMENT TECHNOLOGIES

General Category	Type of Process	Technologies Applied In-Situ	Technologies Applied Ex-Situ
Treatment	Biological	<ul style="list-style-type: none"> • Passive biodegradation • Bioventing • In-situ biodegradation 	<ul style="list-style-type: none"> • Biopiles • Land treatment or landfarming • Slurry biodegradation
	Physical	<ul style="list-style-type: none"> • Soil venting <ul style="list-style-type: none"> - conventional - hot air or steam stripping • Soil flushing 	<ul style="list-style-type: none"> • Soil washing • Coal tar agglomeration
	Chemical	<ul style="list-style-type: none"> • Chemical oxidation/reduction 	<ul style="list-style-type: none"> • Chemical oxidation/reduction • Solvent extraction
	Thermal	<ul style="list-style-type: none"> • Radio frequency (RF) heating • Vitrification 	<ul style="list-style-type: none"> • Thermal desorption by: <ul style="list-style-type: none"> - low and high temperature thermal strippers - hot-mix asphalt plants • Vitrification
Containment	Other	<ul style="list-style-type: none"> • Solidification/stabilization • Capping 	<ul style="list-style-type: none"> • Solidification/stabilization • Microcontainment by cold-mix asphalt • Capping or Re-Use • Land disposal or landfilling

TABLE 2
DESCRIPTIONS OF PETROLEUM-CONTAMINATED SOIL TREATMENT TECHNOLOGIES

Type of Process	Alternate Technologies	Location of Application	General Description
Biological	Passive biodegradation (Natural attenuation)	In-situ	Passive biodegradation relies on naturally occurring microorganisms to slowly degrade the biodegradable petroleum contaminants in the soil. Microbes metabolize contaminants, leaving behind harmless by-products. Unlike other biological techniques, the biodegradation process is not enhanced by adding nutrients, some form of oxygen, and/or cultured microbes. Soils may be covered with plastic, however, to raise temperature and microbial activity.
	Bioventing	In-situ	In bioventing, oxygen is delivered to the subsurface to stimulate the biodegradation, but not volatilization, of contaminants by microbial activity. If necessary, the activity of indigenous microbes is also enhanced by adding nutrients. Like passive biodegradation, successful bioventing requires that suitable soil and contaminant conditions exist at a site.
	In-situ biodegradation	In-situ	In-situ biodegradation stimulates microbial activity and biodegradation by circulating water-based solutions through the contaminated soils.
	Biopiles	Ex-situ	Biomounding involves the excavation of contaminated soil and its placement in mounds (called biomounds) or piles (called biopiles) to which nutrients and/or other biological enhancements are added to stimulate contaminant degradation by microorganisms. Aeration pipes are usually installed in the mounds or piles to deliver oxygen and promote biodegradation of the hydrocarbons in the soil. Composting is a form of biomounding.
	Land treatment (Landfarming)	Ex-situ	Similar to biomounding, land treatment involves excavating contaminated soils and spreading them over a lined treatment area, or biocell. Volatilization and natural biodegradation is then enhanced by tilling, aerating, or watering, or by adding nutrients or microorganisms to the soil.
	Slurry biodegradation	Ex-situ	Petroleum-contaminated soils are excavated and treated in an aqueous or slurry solution within a bioreactor vessel that provides the nutrients or microbes necessary for successful biodegradation.
Physical	Soil venting	In-situ	Soil venting refers to the technique of removing residual hydrocarbons from the unsaturated zone by passing air through the contaminated area, volatilizing the hydrocarbons, and then capturing them for treatment. Hot air or steam may be injected under pressure or vacuum conditions into the subsurface in place of ambient air to accelerate the stripping of the volatile contaminants from the soil.
	Soil flushing	In-situ	Soil flushing refers to the process in which chemical surfactants or leaching agents are flushed through the contaminated area to separate contaminants from the soil. The aqueous solution is then recovered and treated.
	Soil washing	Ex-situ	Ex-situ soil washing involves the use of chemical surfactants or leaching agents combined with mechanical agitation to separate contaminants from the soil.
	Coal tar agglomeration	Ex-situ	The coal tar agglomeration process is an extraction process that uses a solid sorbent rather than a liquid sorbent to remove contaminants. The process operates on the principle that oily waste constituents are strongly adsorbed on the surface of fine coal particles and that the coal-organic agglomeration that is formed can be separated from the soil in an aqueous slurry.
Chemical	Solvent extraction	Ex-situ	This technology involves the blending of a leaching agent (proprietary solvent or chemical reagents) with the contaminated soil to extract contaminants. The extraction fluid is then reclaimed for recycling, and the contaminant waste stream treated or otherwise disposed. Used primarily by the petroleum refining industry to treat refinery sludges and wastes.

TABLE 2 (continued)

Type of Process	Alternate Technologies	Location of Application	General Description
Thermal	Radio frequency heating	In-situ	Radio frequency heating uses electromagnetic energy much like a microwave oven would to heat the subsurface soils and volatilize petroleum contaminants trapped there.
	Vitrification	In-situ or Ex-situ	In in-situ vitrification, electrodes or plasma torches are placed in the soil, the soil is heated, and some contaminants are volatilized while others are encased in glass. Effective for treating inorganic as well as organics. Problems with the off-gases, high energy and capital costs, and permitting issues have affected the widespread application of this technology.
	Thermal desorption	Ex-situ	Thermal desorption systems rely on the application of heat to the contaminated soil to promote the volatilization of VOCs and SVOCs. As the contaminants vaporize, they are desorbed and separated from the soil matrix. Depending on the specific technology employed, the volatile contaminants are either destroyed in a specific treatment chamber or captured, condensed and recovered, or incinerated.
Other	Stabilization/solidification	In-situ or Ex-situ	Stabilization and solidification technologies typically use lime, fly ash, or cement, and occasionally a cement/bentonite mixture, to bind the contaminants and soil in a matrix so that the contaminants do not leach into the environment. Because this technology simply contains the movement of contaminants, it is not considered a treatment technology.
	Capping	In-situ or Ex-situ	The area containing the contaminated soil is simply capped (e.g., under a road surface) or otherwise sealed to prevent the leaching of contaminants.
	Microcontainment by cold-mix asphalt	Ex-situ	In the cold mix treatment of petroleum-contaminated soils, the soils are screened and used without thermal pre-treatment as an aggregate in the asphalt mix.
	Land disposal (landfilling)	Ex-situ	The contaminated soils are excavated and transported off-site to a landfill that is permitted and willing to accept the soils for either disposal or use as landfill cover.

presently exist and that are described further in this synthesis. Soil remediation technologies fall into two general categories: technologies that destroy or treat the petroleum contaminants in the soil, and those designed only to contain the movement or leaching of the contaminants. Remedial options available for the treatment of petroleum-contaminated soils can also be segregated into the following two categories: in-situ treatment technologies that do not require the removal of soil from the ground, and ex-situ treatment technologies requiring excavation of the soils. Once excavated, contaminated soils can be treated on-site or brought off-site for treatment. Finally, treatment technologies also differ by the type of process that is employed e.g., biological, physi-

cal, chemical, thermal, or stabilization to accomplish cleanup objectives. Biological treatment processes use microorganisms and the enzymes they produce to degrade contaminants in the soil. Physical treatment processes change the physical form of the contaminants in order to remove them from the soil or encapsulate them to prevent them from leaching. Chemical treatment processes involve chemical reactions designed to alter or destroy contaminants in the soil. Thermal treatment processes use energy to destroy or detoxify contaminants, and solidification/stabilization processes immobilize contaminants by binding them in an immobile, insoluble matrix.

Table 2 provides an introductory definition of each tech-

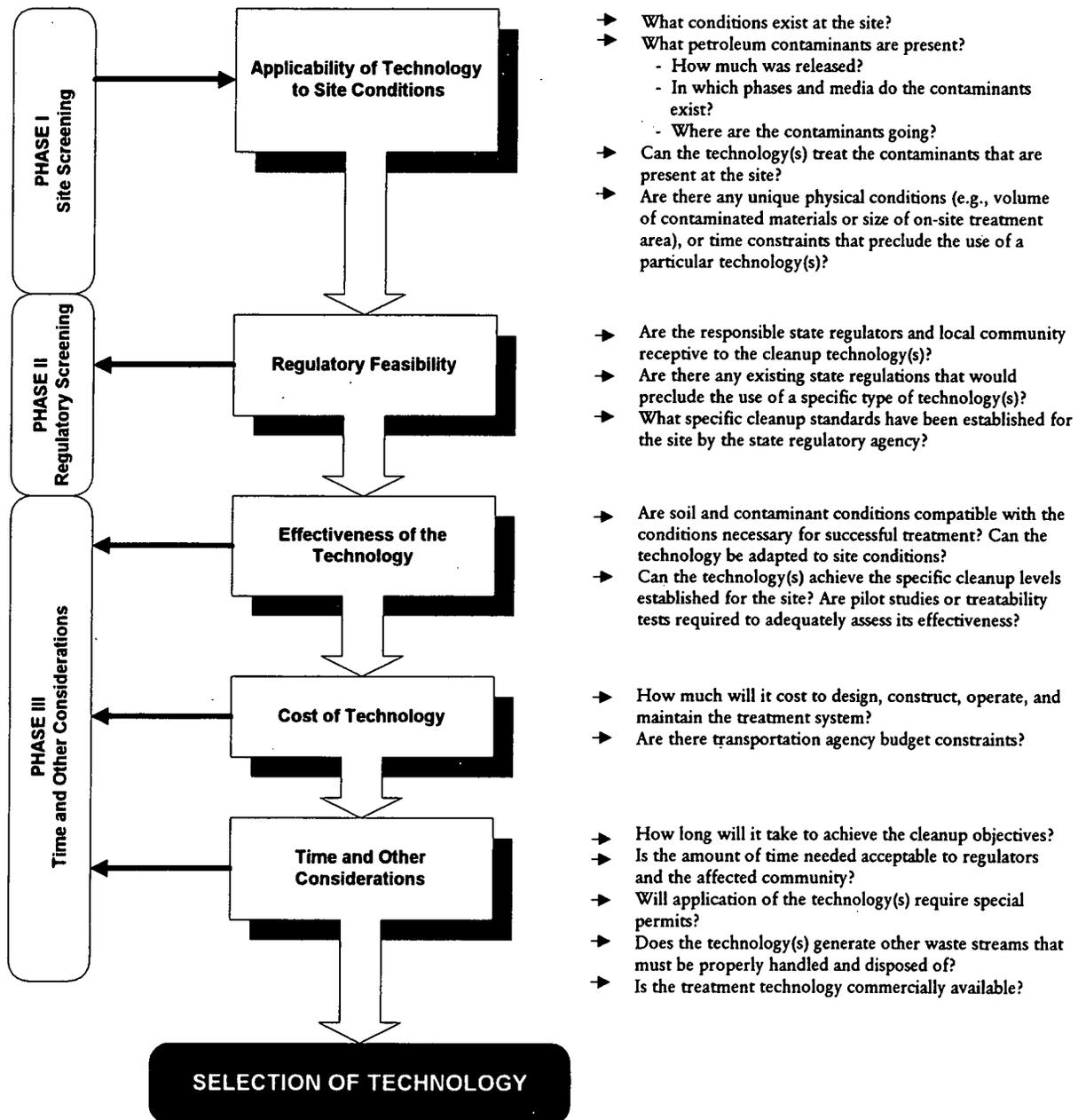


FIGURE 1 Technology selection process.

nology listed in Table 1, with the exception of chemical oxidation/reduction. This technology refers to the process in which oxidization/reduction agents are added to the contaminated soils to promote chemical reactions that involve the targeted contaminants and result in byproducts that are less toxic or mobile. The introduction of hydrogen peroxide into petroleum-contaminated soil whether done in-situ or ex-situ is considered by some to be a chemical technology. For the purpose of this synthesis, the use of hydrogen peroxide to oxygenate contaminated soil is not discussed as a unique chemical treatment technology, but rather as a common method for supplying oxygen to oxygen-deprived microbes during in-situ bioventing or ex-situ soil washing.

FACTORS AFFECTING THE SELECTION OF A SOIL REMEDIATION TECHNOLOGY

To determine which remediation technology(s) to employ at a particular petroleum-contaminated site, a transportation agency or its consultant must evaluate, in a phased approach, a number of conditions associated with the contaminated site and prospective technology(s). The technology selection process and the key information needed at each phase of the process are summarized in Figure 1.

Phase I: Site Screening

In the first phase of decision making, specific conditions at the contaminated site are carefully inventoried and evaluated. The types of contaminants found at the site may immediately eliminate certain remediation technologies from consideration. For example, if the petroleum contaminants requiring treatment are not biodegradable, then the biological treatment technologies (in-situ or ex-situ) will not be effective. Similarly, a lack of space resulting from the presence of numerous buildings or other obstructions on the site may automatically preclude excavation of the contaminated soil and focus attention immediately on in-situ options. Time requirements may also be important during the site screening phase. For example, if the area of contamination is within the right-of-way of a highway project and the project cannot proceed until remediation is completed, a treatment technology such as bioremediation, which can take months to years to complete, may not be a viable option. Also, if the petroleum contamination being treated is on property the transportation agency is preparing for sale or lease, slow processes like bioremediation may again be impractical due to the time constraints imposed by the real estate transaction. While selected technologies can be adapted to address some of these general site conditions, others cannot and can be eliminated from further consideration during this site screening phase.

Phase II: Regulatory Screening

Once a technology has survived the site screening process, it is evaluated for its regulatory feasibility. An environmental regulatory agency's receptivity to a particular

type of remediation technology, the agency's existing corrective action requirements, and its approach to the establishment of cleanup standards at petroleum-contaminated sites can often unduly influence the cleanup options available to a transportation agency.

Resistance to Innovative Technologies. Environmental agencies prefer that "traditional" cleanup technologies be used when remediating petroleum-contaminated sites simply because they are familiar with them (31). A lack of understanding of a particular technology, combined with inadequate field information on its effectiveness, have made many state regulatory agencies reluctant to approve the use of innovative cleanup technologies, such as bioremediation. There is also the fear of liability should the technology not achieve the desired cleanup objectives. In "catch-22" fashion, consultants are less likely to recommend the use of an innovative technology if performance data for the technology are not readily available for regulator review, and/or approval of its use will require expensive and time-consuming permit processes.

Limiting regulations. The content of state agency regulations regarding the cleanup of petroleum-contaminated sites can also have a significant impact on the technology options available to a transportation agency. Until recently amended, Massachusetts regulations required responsible parties to use "Class A recycling" facilities, i.e., asphalt plants, to remediate petroleum-contaminated soils at the unintended exclusion of alternate technologies. Other exclusionary provisions exist in other states' regulations or policies. For example, most bioremediation techniques require the use of enhancements to make soil conditions more suitable for biodegradation. Some state regulations and policies may prohibit the introduction of certain biostimulants into the soil at selected locations for fear of contributing to groundwater contamination. In other states, natural attenuation is not allowed as an option at sites where there is free product in the subsurface. In areas with poor air quality, a technology such as landfarming may be discouraged or prohibited due to its potential for the uncontrolled release of volatile contaminants into the air.

State's Approach to Establishing Cleanup Levels. The most important regulatory influence on the selection of a remediation technology is determined by how a state regulatory agency approaches the establishment of a cleanup level at a site. In general, the lower the cleanup standard established for a site, i.e., the lower the concentration of contaminants that can be left in the soil, the fewer remedial technologies there will be available for selection.

At the present time approaches to establishing cleanup levels at petroleum-contaminated sites still vary widely from state to state (32,33,34). Many states have adopted the approach of using site-specific health-based risk analyses to establish cleanup levels at a site. Such a risk-based corrective action approach allows for the negotiation of treatment levels based on the exposure pathways and contaminant concentrations, or even better the leachable fractions of specific constituents (35), present at a site. In states that have adopted such a risk-based approach based on leachability testing, the achievability of negotiated cleanup levels by a specific tech-

nology can be assessed by simply comparing the levels with available literature and vendor data on the selected process' effectiveness.

In contrast with this preferred site-specific, risk-based approach, other states have established risk-based numeric standards (e.g., New Jersey) that are presumed to be reasonable for all sites. Still others allow for the negotiation of a cleanup standard based on the removal of a certain percentage of the contaminant, or use "perceived standards that purport to be protective of human health and the environment" (36) and have no obvious basis in health risk. In states with these approaches, the unnecessarily low cleanup standards that may be required or negotiated for a site may preclude the employment of selected remediation technologies.

The evaluation of a technology's effectiveness and appropriateness is also made more difficult where the state regulatory agency has specified total petroleum hydrocarbons (TPH) as the basis for determining treatment requirements. Using TPH as the indicator parameter for cleanup levels presents several problems to responsible parties interested in applying a particular technology at a site (37,38). First, there are no national standards for measuring TPH. Different analytic methods employed by different laboratories can yield vastly different results. This analytical inconsistency can make it difficult to justify the effectiveness of bioremediation (indeed the effectiveness of many cleanup technologies). Second, because TPH is a broad indicator of contamination it does not measure the true risk that material at a site may pose to human health and to the environment. High toxicity compounds like benzene are treated the same as low toxicity compounds like hexane. Consequently, a biological treatment approach, for example, that targets the most toxic constituents of petroleum may not be acceptable with TPH as the designated indicator. Third, TPH does not indicate the availability of a contaminant to humans and the environment. Just because a hydrocarbon compound is present in a soil does not mean that it will leach out to adversely affect human health or the environment. Once again, selected technologies may be unfairly disadvantaged by using TPH to determine treatment requirements. Bioremediation technologies, for example, generally yield far greater reductions in the leachable components than other technologies (33).

Other states determine treatment on the basis of the concentration of a total of selected compounds e.g., total benzene, toluene, ethyl benzene, and xylene (BTEX). Still others have adopted specific cleanup levels for individual compounds (e.g., benzene). While these approaches to establish-

ing cleanup levels are definite improvements over the TPH-based approach, they too may not allow for cleanup levels to be based on the leachable fraction. Consequently, while data suggest that bioremediation can treat many leachable biodegradable organics to or very close to current levels of analytical detection, the degradation effects of bioremediation may not be sufficient for regulatory agencies (33,36,37) working under these regulatory schemes.

A historical review of state-by-state standards for petroleum-contaminated soil cleanup indicates a clear trend toward the increased use of site-specific, risk-based approaches that do not use TPH as the indicator parameter for cleanup levels (34,39). As more state regulatory agencies embrace chemical-specific, risk-based cleanup guidelines, and eliminate any exclusionary provisions that may presently exist in their corrective action requirements, transportation agencies will have a greater range of soil remediation technologies from which to choose.

Phase III: Technology Screening

During the third phase of the technology selection process, specific information and data concerning the design of a technology and its anticipated cost and effectiveness are assembled and evaluated. It is during this phase that a particular technology is more carefully matched with the site conditions and site cleanup levels established in earlier phases.

To ensure the compatibility and cleanup effectiveness of a specific technology with site conditions, a transportation agency and its consultant must have a basic understanding of:

- the principles behind the design of each technology;
- the key parameters that affect the performance of the technology;
- the relative costs of designing, installing, and operating the different technologies; and
- the nature of any other requirements associated with employment of the technology at a site (e.g., the need to obtain special permits or employ health and safety measures).

Chapters 3 through 6 provide information on the applicability, effectiveness, costs, and other considerations associated with each alternative soil remediation technology listed in Table 2. References are provided on where to obtain additional general as well as site-specific information on an individual remediation technique.

BIOLOGICAL TREATMENT TECHNOLOGIES

OVERVIEW OF BIOREMEDIATION PROCESSES

Bioremediation is typically the most cost-effective way to treat soils and sludges contaminated with biodegradable organic compounds. Biological treatment of contaminated soils is becoming increasingly popular because it metabolizes contaminants into harmless substances and thereby reduces potential liability to a transportation agency. Bioremediation is also preferred because it is effective in eliminating contaminants as they travel through the vadose zone to the groundwater. By eliminating the source, biological treatment can reduce or eliminate groundwater contamination and thereby reduce the need for extensive groundwater monitoring and treatment requirements (40). Bioremediation is the only proven in-situ remedial technology that can clean up both dissolved (in water) and adsorbed (onto soil) organic contaminants. Hundreds of thousands of cubic meters of soil have been successfully remediated with biotreatment at hundreds of sites across the United States (33, 34).

Bioremediation only works on contaminants that are biodegradable. While most petroleum constituents are biodegradable, there can be significant differences in the rates of biodegradation. There are often substantial differences between the petroleum products manufactured from different sources of crude oil and at different refineries. One refiner's diesel may biodegrade in a significantly different manner than another's. Petroleum products are also composed of many different compounds that do not all degrade at the same rate. In general, the relative biodegradability of petroleum contaminants will depend on their molecular weight and degree of branching.

- Carbon chain length (molecular weight): low molecular weight hydrocarbons are more easily biodegraded than higher chain hydrocarbons. Consequently, heavier and more weathered oils will typically exhibit lower degradation rates than gasoline or diesel fuels. The higher molecular weight hydrocarbons can also degrade into toxic chemicals and become inhibitory.

- Degrees of branching: the higher-branched molecules can be resistant to biodegradation.

Normal branched and cyclic alkanes are the most abundant components of petroleum products. In general, normal alkanes are readily biodegradable. Branched and cyclic alkanes are also degradable, but their rate of degradation decreases with increasing molecular size and complexity. The other major component of petroleum products aromatic compounds are also biodegradable. The monoaromatic compounds such as benzene, toluene, ethylbenzene, and the

xylenes are more rapidly degraded than the two-ring compounds such as naphthalene, which in turn are more easily degraded than the three-, four-, and five-ring compounds (41). In addition, the biodegradation half-lives of naphthalenes, polynuclear aromatics, and polarized molecules increase with an increasing number of rings. Compounds with more than four rings may not degrade quickly enough in a biotreatment environment.

Biological treatment also becomes a potentially feasible alternative only when a site has a viable community of microorganisms to degrade the organic constituents present in the soil. Microorganisms used to degrade organics can fall into three categories: (a) indigenous or naturally occurring microbes; (b) designer or specially cultured microbes; or (c) genetically altered microbes. There are no documented cases in the United States to date where genetically altered microorganisms have been used to treat petroleum-contaminated soils. The biodegradation of organic constituents is usually accomplished by enzymes produced by indigenous or naturally occurring microorganisms in the soil. Where suitable indigenous microbes do not exist, the bacteria can be specially selected or cultured to produce strains that are most amenable to the contaminant of concern and introduced into the soil matrix. While the production of enzymes is genetically controlled, there are identified ranges of critical environmental conditions that affect microbial activity. These conditions are often controllable and can be changed to stimulate the biodegradation process (40).

The principles supporting the use of bioremediation to remediate a petroleum-contaminated site are the same for all remedial operations. However, the specific techniques used will vary depending on soil and site conditions (see Table 3). Contaminated soil and site conditions will determine whether biological treatment can be accomplished in-situ or ex-situ. In an in-situ system, naturally occurring or indigenous microorganisms are allowed to treat the contaminants while they remain in place in the soil. In-situ biotreatment can be enhanced by taking measures to ensure that optimal environmental conditions e.g., soil moisture, oxygen levels, pH levels, salinity, nutrients and temperature for microbial activity exist. Where allowed and necessary, man-made or non-indigenous microbes may also be introduced into the soil to enhance degradation.

Depending on space availability and other site constraints, ex-situ biological treatment can be accomplished at the site of excavation or at a prepared off-site location. In an ex-situ system, the contaminated soil may (a) be moved from its original site to a newly prepared treatment area off-site that has been designed to enhance bioremediation and/or prevent the transport of contaminants from the site; or (b) be removed from the site to a storage area while a treatment bed

TABLE 3
DIFFERENCES BETWEEN ALTERNATIVE BIOTREATMENT TECHNIQUES

Location of Application	Biological Enhancement	Biological Treatment Technique	Description
In-situ	None	Passive biodegradation	Naturally occurring microorganisms are allowed to treat the contaminants
	Oxygen Nutrients	Bioventing	Oxygen is delivered in a gaseous (or liquid) phase to the subsurface to stimulate biodegradation, but not volatilization; nutrients and other enhancements may also be circulated in water-based solutions through the contaminated zone to stimulate biological degradation
		In-situ biodegradation	Microbes in the soil are stimulated by circulating water-based solutions through the contaminated soils to enhance biological degradation
Ex-situ	Oxygen Moisture pH Nutrients Temperature and/or Microbes	Biopiles, biomounds or compost piles	Nutrients and/or other biological enhancements are added to soil mounds or piles; aeration pipes installed in the mound or pile to deliver oxygen
		Land treatment or landfarming	Nutrients and/or other biological enhancements are added to contaminated soil and spread over a land treatment area. Area is periodically tilled to facilitate biodegradation as well as partial release of volatile contaminants
		Slurry biodegradation	Contaminated soil is excavated and treated in an aqueous media (slurry) that may contain specially cultured microbes

is prepared and then returned to the site for treatment. Preparation of the bed may consist of the placement of clay or plastic liners to prevent off-site runoff of the contaminants, or the addition of uncontaminated soil to provide additional treatment medium. Biological enhancements take one of two forms. In some cases, the contaminated soil is biostimulated, meaning that nutrients (usually phosphates and nitrogen) and/or oxygen is added to stimulate the indigenous bacteria that consume the contaminants. In other cases, the soil is bioaugmented, which means that specially cultured bacteria are used along with the nutrients (7). Treatment may also be enhanced with various physical/chemical methods.

The potential of bioremediation as a soil remediation technology has spurred the interest of regulators and consultants in up-to-date information on its effectiveness and cost of application in the field. Transportation agency staff may find the following publications useful in understanding the advantages and limitations of selected bioremediation technologies:

- *Bioremediation in the Field*, (EPA/540/2-91/018, August 1991) is an information update published periodically by the

U.S. Environmental Protection Agency (EPA), Office of Solid Waste and Emergency Response and Office of Research and Development. This publication provides evaluations of the field application of bioremediation technologies to site cleanup. To be placed on the mailing list for "Bioremediation in the Field", contact: Coordinator, Bioremediation Field Initiative, U.S. EPA, Office of Research and Development, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268. Back issues of "Bioremediation in the Field" can be ordered from EPA or from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161. A database on all of the documented field applications of bioremediation is also available from the above Bioremediation Field Initiative contact.

- *Bioremediation Resource Guide*, (EPA/541-B-93-004, September 1993) is a 30-page guide that contains information on readily available bioremediation resource documents, data bases, hotlines, and dockets. It contains abstracts for more than 80 bioremediation documents and provides information on how to obtain copies of them. It also contains a "Bioremediation Resource Matrix" to assist in identifying the publications that describe different technology types and

their use for different media and types of contamination. A copy of this guide can be obtained from the National Center for Environmental Publications and Information (NECPI), 11029 Kenwood Road, Cincinnati, Ohio 42242; or by calling NTIS and requesting NTIS PB94-112307.

IN-SITU PASSIVE BIODEGRADATION

In-situ passive biodegradation, or natural attenuation, relies on microorganisms that already exist in the soil matrix to remove biodegradable petroleum contaminants from the soil. In contrast with other bioremediation techniques, passive biodegradation does not rely on the addition of oxygen or nutrients to facilitate the biodegradation process. Natural biodegradation is often used as the second phase of a more comprehensive remediation plan (42).

Because the natural breakdown of petroleum hydrocarbons is extremely slow, in-situ passive biodegradation will usually be appropriate only when:

- the contaminants released at the site are readily biodegradable;
- site conditions are favorable;
- there are no nearby sensitive human receptors and threatened or endangered species or habitats;
- there is no danger to water supplies or nearby aquifers;
- the time needed for natural degradation to occur is reasonable; and/or
- less than complete removal of all hydrocarbons is acceptable to the regulatory agencies.

In Wisconsin, natural biodegradation is allowed for consideration only at sites where petroleum hydrocarbons exist; where gasoline range organics exist in concentrations of less than 500 parts per million (ppm); or where diesel range organics exist in concentrations of less than 1,000 ppm (42). In San Diego, California, remediators were able to analytically model subsurface conditions together with rates of expected biodegradation to convince regulators that natural degradation would be sufficient to clean up 380 m³ (500 yd³) of soil contaminated with up to 11,000 mg/kg of diesel fuel before it would pose a threat to groundwater (42).

While the process can be described as one of "natural attenuation", it is not a "do-nothing" alternative. The potential for passive biodegradation must first be determined through comprehensive soil studies that (a) identify the types, concentrations, and distribution of contaminants at a site; (b) determine the geological, hydrogeological, and chemical characteristics of the subsurface; and (c) evaluate subsurface microbial characteristics and biodegradation potential. A definitive risk assessment must then be performed and a comprehensive site monitoring plan implemented to ensure that degradation is actually occurring.

Once a site has been characterized as amenable to natural biodegradation, the only design issue involves that of the site monitoring plan. The monitoring plan should identify the number and location of monitoring wells and soil borings, as

well as a sampling plan indicating the analyses to be performed, the number and frequency of samples to be taken, and the analytical methods to be used. In general, the site monitoring plan must be designed to provide regulators with the following information:

- indication that the contaminant concentration is decreasing over time;
- evidence that the decrease is the result of degradation and not contaminant migration; and,
- information on the nature and rate of degradation that is occurring at the site.

The technical and financial feasibility of applying passive biodegradation as the remediation technology at a site will be a function of a number of site, soil and contaminant parameters (18,44). Table 4 identifies the petroleum constituents that passive biodegradation is most effective in removing, the key parameters that affect its effectiveness, and the anticipated range of costs associated with its employment at a site.

IN-SITU BIOVENTING

Most hydrocarbons are biologically degraded by aerobic or oxygen-consuming microbes. Consequently, the amount of oxygen in the pore spaces of the soil can influence greatly the rate of biodegradation. In-situ bioventing is a remediation technique designed principally to supply oxygen in-situ to oxygen-deprived soil microbes by forcing air through contaminated soil at low airflow rates. If necessary, the activity of the indigenous microbes is also enhanced by adding nutrients.

The oxygen is introduced into the contaminated soil in the form of air or pure oxygen, usually via a group of in-situ injection only or combination injection and extraction wells. At many sites, the introduction of hydrogen peroxide is the preferred method used to oxygenate the contaminated zone because it can be added on-line with other nutrients and make aeration wells unnecessary. Concentrations of oxygen as high as 500 mg/l have been achieved using hydrogen peroxide whereas using pure oxygen produces dissolved oxygen concentrations of only 40 mg/l (46).

Bioventing is a modification of the soil venting or vacuum extraction technology (see Chapter 4). In contrast with soil venting or soil vacuum extraction technologies, bioventing uses low airflow rates to stimulate biodegradative activity while minimizing the volatilization of contaminants in the soil (47). Good operational controls are needed, once well spacings have been determined, to ensure the slow airflow necessary for maintaining good bioremediation and minimal surface volatilization (48).

Bioventing may be performed alone or in combination with other measures. At an extremely cold-climate site at Eilson Air Force Base in Fairbanks, Alaska, the U.S. EPA is studying the effectiveness of bioventing in combination with passive and active soil warming techniques (49):

Passive warming: plastic covering or mulch is used to

TABLE 4
FEASIBILITY OF IN-SITU PASSIVE BIODEGRADATION

Effectiveness of Technology	
Targeted Petroleum Contaminants	Appropriate for use in remediating sites contaminated with fresh or weathered gasoline, diesel, jet fuel, or kerosene. Passive biodegradation is effective in eventually degrading volatile organic compounds such as BTEX, as well as residual semivolatile organic compounds such as PAHs.
Treatment Effectiveness	Passive biodegradation cannot typically achieve cleanup standards based on soil TPH concentrations, but can significantly reduce the health and environmental impacts of petroleum contamination. Depending upon the solubility, vapor pressure, volatility, adsorption potential and molecular weight of the hydrocarbons present at the site, removal efficiencies may approach 75-90% over an extended period of time.

Key Parameters Affecting Technology Effectiveness

- Hydrocarbon and Heavy Metal Concentrations.* Depending on its concentration, a contaminant can be a food source or a poison (41). Substances that microbes degrade can be inhibitory or non-inhibitory. In a non-inhibitory substance, microbes grow more rapidly as the concentration of the substance increases. However, hydrocarbons are inhibitory compounds. When hydrocarbon concentrations are low, they are easily degraded. As the concentration of hydrocarbons increases, microbial activity attains a peak and then starts decreasing (62). In general, natural degradation will not be effective at sites with soil TPH concentrations greater than 25,000 ppm TPH, or where free product exists in the subsurface.

The concentrations of heavy metals such as lead (Pb) in the petroleum product being remediated can also have an effect on degradation rates. Natural soils typically contain about 15 ppm Pb, and rarely exceed 100 ppm Pb, yet gasoline can contain up to 7,500 ppm Pb. Some research has shown that high levels of Pb inhibit biodegradation (62).

- Soil permeability and organic content.* Biodegradation works best in permeable unsaturated soils (gravel, sands, coarse silt) with soil permeabilities greater than 10^{-5} cm/sec. Soil permeability measures how readily air or fluids move through soil. The more permeable a soil, the easier it will be to feed and oxygenate the bacteria and create a homogeneous biomass. In contrast, the potential for contaminant adsorption onto the surface of soil particles, and the potential for the diffusion of contaminants into the micropores of particles, is significantly greater with clay soils than with sandy soils. While the existence of high clay content soils does not necessarily render biotreatment impossible, contaminants in clay soils will biodegrade much more slowly than those in more permeable soils.

Biodegradation is also affected by the sorption of contaminants to organic matter. Soils with high carbon content, present at many industrial sites, will adsorb contaminants more easily and slow biodegradation.

- Microbial population and sensitivity.* The soil must contain enough bacteria to degrade petroleum hydrocarbons. The total population of microorganisms in the soil, as well as the number of specific degraders, can be determined by standardized laboratory procedures. Microbial counts exceeding 10^5 cells per gram of soil are required for bioremediation. If microbial counts are not sufficient, it is possible to increase the number of microorganisms by (a) employing a fermenter or other suitable equipment on-site to grow a suitable population from the naturally occurring microorganisms, or (b) introducing specially cultured microbes. Microbes which have been developed at different locations, however, will need time to become acclimated to site conditions (typically 30-60 days), and this may reduce their cost-effectiveness (49).
- Soil Salinity.* The salinity of the soil is a frequent barrier to successful bioremediation at a site. While biodegradation can occur in saline soils, the upper limits for effective degradation are generally in the range of 6 to 10 mmhos/cm (33). Salts can be removed from a soil by leaching the soil in a prepared bed. The resulting leachate is collected and the organic contaminants are removed and typically discharged to a publicly owned treatment works or water body in conformance with a National Pollutant Discharge Elimination System (NPDES) permit.

TABLE 4 (continued)

Key Parameters Affecting Technology Effectiveness (continued)

- *Soil temperature.* As temperature increases, so does biological activity until the high temperature causes enzyme denaturation. Even photooxidation can make higher molecular weight hydrocarbons susceptible to biodegradation. Biodegradation has been shown to effectively stop at a temperature of 0°C (40). To support bacterial activity, soil temperature should be between 15° and 45°C (55° and 110°F). The rate of microbial activity approximately doubles for every 10°C rise in temperature.
- *Nutrient levels.* Microbial metabolism and growth is dependent upon an adequate supply of essential nutrients. The nutrients—typically phosphorus, potassium, and/or nitrogen—must be present and available to the microorganisms in (a) a usable form, (b) appropriate concentrations; and (c) proper ratios (40). Natural biodegradation works best in soils where total organic nitrogen levels are greater than 1.5 percent; the carbon/nitrogen/phosphorus ratio is about 100:10:1; and the carbon:potassium ratio is less than 1:20 (42). General nutrient requirements for bioremediation are well established in the literature.

The optimal mix of nutrients is typically determined during treatability testing. If the required nutrients are not available naturally, they can be provided through the proper application of commercially available fertilizers.

- *Soil pH.* Low (acidic) or high (alkaline) soil pH is not conducive to optimal biodegradation. Bacteria are not very tolerant of acidic soil conditions (pH < 5). Alkaline conditions (pH > 9) do not support necessary microbial activity. For example, the solubility of phosphorus, an important nutrient in a biological system, is maximized at a pH of 6.5. Optimal biodegradation generally occurs when soil pH values are in the range of 5.5 to 8.5 (40), although biological activity has occurred outside of this range (33). pH levels in soil can be controlled by adding lime, caustic soda, or acids.
- *Soil moisture.* The microbial degradation of contaminants relies upon the solubilization of the contaminant into the water phase where microorganisms can metabolize the contaminants. Consequently, bacterial growth is reduced if the soil is too dry. On the other hand, soil that is flooded inhibits oxygen transfer to the bacteria and provides for a high soil water matric potential. The soil matric potential regulates microbial activity; it is the energy required to extract water from the soil pores to overcome capillary and adsorptive forces (40). Soil water also serves as the transport medium through which many nutrients and organic constituents reach the microorganisms, and through which metabolic wastes are removed. Optimum soil moisture for biodegradation activity is between 50 and 80 percent of the maximum amount of water that can be held in the soil after drainage (called moisture content at field capacity). Soil moisture levels may be unacceptable in areas with high precipitation rates (>60 inches of rain per year).
- *Oxygen availability.* Natural biodegradation will occur only when there is air or oxygen present in the soil pores. In fact, the level of oxygen in the soil may be more essential to biodegradation than the number of microorganisms present. Yet, it is difficult to maintain oxygen concentration in a soil. Microbial respiration, plant root respiration, and the respiration of other organisms remove oxygen from the soil and typically replace it with carbon dioxide. In addition, if there is excessive moisture in the soil pores, oxygen is displaced. It has been suggested that a minimum air-filled pore space of 10 percent by volume must exist to support natural degradation (40).

Soil usually contains oxygen to a depth of 1 meter, and these oxygenated conditions promote digestion of hydrocarbons by the selective bacteria. If, however, contamination is deeper than 1 meter, a more sophisticated strategy may be required to ensure the bacteria have adequate oxygen and nutrients. The oxygen levels in soil can be controlled by (a) controlling the moisture content in the soil, (b) blending the contaminated soil with sandy or loamy soil materials; (c) tilling the soil; or (d) adding additional carbonaceous materials (40).

Cost of Technology

There are no capital or operating and maintenance costs associated with passive biodegradation. However, passive biodegradation will be approved for use by a regulatory agency only after completion of extensive site characterization studies (subsurface sampling and sample analysis) and a risk assessment demonstrating that there will be no adverse human or environmental effects from leaving the contaminated soil in place. Contaminated soil from soil borings used to characterize the site may need to be stored on-site and then sent off-site for treatment. While the cost of soil sampling and analysis may be relatively small (depending on the size of the site), a comprehensive risk assessment will typically cost between \$10,000 and \$50,000 per site. The expected effectiveness of the technology must also be monitored periodically. Monitoring and reporting costs may be between \$10,000 and \$60,000 per site, depending upon the monitoring frequency required.

TABLE 4 (continued)

Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Economical and effective at sites with varying volumes of contaminated soil. • Can be employed anywhere proper soil and other conditions exist without disrupting existing operations; will be effective below buildings and in other areas where excavation is not possible. • Natural attenuation involves no excavation and soil handling. Therefore, neither site workers nor the adjacent community are exposed to contaminated soils or vapors.
Limitations	<ul style="list-style-type: none"> • The effectiveness of natural attenuation must be carefully evaluated by highly skilled risk modelers. • Natural attenuation should be used only where there are no potential receptors nearby. • In some soil types, there may be the risk of contaminant migration to areas where groundwater is used before degradation is complete. • The site may have to be secured (e.g., fenced) until contaminant levels have been reduced. • May need to be used in combination with other technologies at sites containing <u>non</u>biodegradable constituents. • Not effective in soils where hydrocarbon concentrations are high (>25,000 ppm TPH) or where the soils do not have sufficient nutrients, optimum soil moisture and oxygen conditions, an active indigenous microbial population, and/or optimum soil pH.
Time to Cleanup	<ul style="list-style-type: none"> • Natural attenuation is a very slow process because it involves no active remedial measures. Depending on soil conditions, natural attenuation can take anywhere from 50 to 200 years to complete.
Commercial Availability	<ul style="list-style-type: none"> • There are many consultants qualified to perform the risk modeling, sampling and sample analyses necessary to support passive biodegradation.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • Produces no waste stream that must be subsequently handled or treated.
Emission Control Equipment	<ul style="list-style-type: none"> • There is no emission control equipment involved.
Regulatory Issues	<ul style="list-style-type: none"> • Natural attenuation is not always acceptable to regulators because no <i>active</i> treatment is occurring. Regulators will be most receptive to passive biodegradation when (a) all other alternatives are technologically or economically infeasible, and (b) a strong argument can be made for its effectiveness.
Community Acceptability	<ul style="list-style-type: none"> • The public generally prefers <i>active</i> treatment methods over those that rely on natural degradation processes.

enhance solar warming in late spring, summer, and early fall. During the remainder of the year, heat is retained by applying insulation to the surface.

Active warming: groundwater is circulated to an electric heater and heated to 35°C. It is then reinjected below the ground surface to the contaminated soil. The heated water is applied at a very low rate (1 gpm) by five soaker hoses, placed 0.6 meters (2 feet) below the surface.

The design of a bioventing system will typically involve the following activities:

- orientation (vertical or horizontal), placement and construction of extraction (or injection) well(s);
- design of the piping system; design of a pretreatment system for the extracted vapor (if necessary);
- design of the vapor treatment system selection (if necessary);
- selection of blower type and size;
- selection of monitoring instrumentation and control equipment; and

- identification of monitoring locations.

A vapor treating system will be incorporated in the bioventing system design only if pilot study data suggest that extracted vapors will contain concentrations of volatile organic compounds in excess of accepted air quality limits. If nutrients are being added, the design will also address the placement and construction of the nutrient addition well(s) or other delivery systems. Surface seals may need to be designed and installed to prevent water infiltration and maintain desirable airflow rates. Groundwater pumping may also be necessary at sites where there is a shallow groundwater table.

The technical feasibility of bioventing at a site will depend on a number of site and other conditions (50,51). Table 5 identifies the petroleum hydrocarbons that bioventing is most effective in removing, the parameters that influence its effectiveness, and the costs associated with its implementation.

TABLE 5
FEASIBILITY OF IN-SITU BIOVENTING

Effectiveness of Technology	
Targeted Petroleum Contaminants	Appropriate for cleanup of sites contaminated with fresh or weathered gasoline, diesel, jet fuel, kerosene, motor oil, heavy fuel oil, lubricating oils and crude oils. Bioventing is most often used at sites containing diesel and jet fuels (mid-weight petroleum products) because lighter and more volatile products like gasoline can be removed more quickly using soil vapor extraction.
Treatment Effectiveness	Removal efficiencies are site specific; and it is not always possible to achieve low cleanup standards. However, it is typically not possible to attain total petroleum hydrocarbon (TPH) reductions in excess of 95%. In addition, constituent concentrations below 0.1 ppm are generally not achievable by bioventing alone due to the presence of nondegradable petroleum species included in the TPH analysis.

Key Parameters Affecting Technology Effectiveness

- *Soil permeability and structure.* Approximately 3.3 kg of oxygen are needed to degrade 1 kg of petroleum product. The more permeable a soil, the easier it is to transmit air through it. As a result, bioventing is most effective in permeable unsaturated soils such as sand and gravel. Fine-grained soils composed of clays or silts offer resistance to air flow. Other technologies should probably be considered if clay soils are targeted for remediation. However, if the soils are highly fractured, they may still have sufficient permeability to allow bioventing.
- *Contaminant types and concentrations.* In general, the light petroleum distillates such as gasoline and diesel fuel will be more readily degradable than the heavy petroleum distillates such as coal tars and polycyclic aromatic hydrocarbons (PAHs). In addition, high concentrations of selected constituents may be toxic to microorganisms. In general, petroleum hydrocarbons in excess of 25,000 ppm TPH, or heavy metals in excess of 2,500 ppm, will be inhibitory and toxic to aerobic bacteria.
- *Presence of "non-target" organics.* A regulatory agency will usually target specific constituents such as BTEX for cleanup at a site. However, the targeted constituents may represent but a small percentage of the total organics present at the site. These "non-target" organics will compete for the oxygen that is being introduced to facilitate degradation of the target compounds.
- *Microbial population.* The soils must contain sufficient subsurface bacterial population to degrade the targeted hydrocarbons. Bioventing will be most effective when total heterotrophic bacteria counts exceed 1000 colony-forming units (CFU) per gram dry soil.
- *Soil pH.* Low (acidic) or high (alkaline) soil pH is not conducive to optimal bioventing. The optimum soil pH for bioremediation is from 6 to 8. If outside this range, amendments will need to be added to the soil to correct the pH levels.
- *Nutrient concentrations.* Nutrients, such as ammonium and phosphate must either be available in sufficient quantities in the site soils, or added to the soil, to maintain the bacterial population. The carbon:nitrogen:phosphorus ratios necessary to enhance biodegradation are in the range of 100:10:1 to 100:1:0.5, depending upon the constituents involved in the degradation process.
- *Soil moisture content.* The ideal range for soil moisture when bioventing is between 40 and 85 percent of the water-holding capacity of the soil. Bacterial growth is reduced if the soil is too dry, while soil that is flooded prohibits air flow and the delivery of oxygen to bacteria.

Cost of Technology

Capital costs for bioventing system may include cost of vertical or horizontal extraction wells; trenches; vacuum blowers or pumps; injection or passive inlet wells; nutrient injection systems; and/or vapor treatment equipment. The costs for operating a bioventing system average \$20/cubic meter (\$15/cubic yard). In general, this technology does not require expensive equipment and needs to be operated and periodically maintained by only a minimal number of staff.

At sites with relatively homogeneous, permeable soils, the overall cost of purchasing, installing operating and maintaining a bioventing system may cost between \$40,000 and \$120,000 per site. At sites with less permeable soils, or at sites requiring vapor treatment, the total costs may approach \$150,000. It is most economical and effective in treating large volumes of soil (>765 cubic meters or 1,000 cubic yards).

TABLE 5 (continued)

Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Bioventing can permanently destroy selected organic compounds. In addition, bioventing has the potential to biodegrade or remove the semivolatile organic compounds and non-volatile organics that other vapor extraction technologies which rely on volatilization cannot. • Because bioventing equipment is relatively noninvasive, this technology is often used to treat contaminated soils where existing structures and utilities cannot be disturbed—i.e., military bases and gas stations, or under roadways—and at locations where the contamination has migrated under a fixed structure. • Bioventing is effective in treating sites with large volumes (>765 cubic meters or 1,000 cubic yards) of contaminated soils.
Limitations	<ul style="list-style-type: none"> • Bioventing is not appropriate for sites with impermeable soils or where the groundwater table is located less than 1 meter below the land surface. Special considerations may be necessary due to groundwater upwelling at sites where the groundwater table is located less than 3 meters below the surface. Areas with a high water table are best treated by combining bioventing with a dewatering process. • Bioventing is effective on biodegradable constituents only; it will need to be used in combination with other technologies at sites containing nonbiodegradable compounds. • Like passive biodegradation, bioventing is a very slow process that may not be acceptable to a regulatory agency in locations where contaminant migration is possible. • Bioventing may not be very effective where low soil moisture content exists because bioventing tends to dry out the soil. It will also be relatively ineffective where there are high concentrations of heavy metals. • If water-based solutions are circulated through the soil, contaminants may become more mobile. • The injection of microorganisms into the subsurface is not recommended. It is preferable to adapt naturally occurring microorganisms to the contaminants present.
Time to Cleanup	<ul style="list-style-type: none"> • Under optimal conditions, site cleanup can be accomplished in 6 months to 2 years. A typical site may take 1 to 4 years to remove 90% of the targeted hydrocarbons. The Air Force considers 3 years as the typical time for cleaning up sites by bioventing. The time needed for cleanup will be longer for sites contaminated with heavier fuel oils.
Commercial Availability	<ul style="list-style-type: none"> • The components of a bioventing system are readily available.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • No residual products are generated by this process.
Emission Control Equipment	<ul style="list-style-type: none"> • Vapor treatment options—such as a vapor phase biofilter, granular activated carbon, or thermal units—may be needed for high contaminant concentrations.
Regulatory Issues	<ul style="list-style-type: none"> • Bioventing is becoming an increasingly attractive soil remediation technology for use at sites where there are non-volatile organics which other vapor extraction technologies cannot effectively remove. • Regulators do not often accept the in-situ addition of nutrients and other amendments to contaminated soils due to the risk of increasing contaminant mobility and the leaching of contaminants to groundwater. If nutrient injection wells are used, a permit will generally be required from the state regulatory agency. Some states even require permits for air injection wells.
Community Acceptability	<ul style="list-style-type: none"> • The general public may find this in-situ technology to be highly acceptable if convinced that it will eliminate the targeted hydrocarbon contaminants over a reasonable time period.

IN-SITU BIODEGRADATION

In-situ biodegradation stimulates naturally occurring microbial activity and biodegradation by circulating water-based solutions through the contaminated soils. The process typically involves the installation of downgradient groundwater extraction wells or trenches positioned in such a manner to inhibit contaminant migration (19). Water is collected by the extraction wells and cycled through an aboveground mixing vat where nutrients and sometimes oxygen are added. While generally not recommended, microbes acclimated to

the metabolism of the petroleum hydrocarbons may also be added during mixing. The resulting mixture is then reintroduced to the subsurface above or upgradient of the contaminated soil/groundwater area via injection wells, trenches, or infiltration galleries. The injection, recovery, and mixing process is performed until cleanup standards have been achieved.

In-situ biodegradation should be used only where the groundwater is near the surface and the groundwater underlying the contaminated soils has also become contaminated (17). Careful soil studies are also necessary to ensure that the

flow of the injected fluids passes uniformly through the contaminated soils to the groundwater for extraction. Care must also be taken to develop the appropriate infiltrating solution. Circulation of the water-based mixture through the contaminated soils may increase contaminant mobility and require the use of aboveground treatment before reinjection or disposal. Table 6 summarizes the conditions under which in-situ biodegradation will be cost-effective.

EX-SITU BIOPILES

Biopiles use biodegradation to reduce the concentrations of petroleum constituents in soil that has been excavated. Biopiles are also referred to as biocells, bioheaps, biomounds, and compost piles. To produce a biopile, contaminated soil is excavated, placed in a pile (or cell) either on or off of the site, and then aerated and/or enhanced with miner-

TABLE 6
FEASIBILITY OF IN-SITU BIODEGRADATION

Effectiveness of Technology	
Targeted Petroleum Contaminants	Appropriate for cleanup of sites contaminated with fresh or weathered gasoline, diesel, jet fuel, kerosene, motor oil, heavy fuel oil, lubricating oils and crude oils. In general, the lighter petroleum products like gasoline and diesel fuel will be removed more efficiently by this process than heavier weight petroleum products like diesel fuel and heating oils.
Treatment Effectiveness	Removal efficiencies are site specific; and is it not always possible to achieve low cleanup standards. Concentration reductions > 95% and constituent concentrations <0.1 ppm are very difficult to achieve. Long remediation times may be necessary for some petroleum constituents.

Key Parameters Affecting Technology Effectiveness

- *Soil permeability and structure.* It is difficult to ensure a uniform distribution of nutrients and other amendments through fine-grained soils like clays or through soils that clump together. In-situ biodegradation may not work where clayey or heterogeneous soils exist.
- *Contaminant types and concentrations.* In general, the light petroleum distillates such as gasoline and diesel fuel will be more readily degradable than the heavy petroleum products like heating and lubricating oils. In-situ biodegradation is not likely to be effective when petroleum hydrocarbons exist in concentrations greater than 50,000 ppm total petroleum hydrocarbons (TPH), or heavy metals exist in concentrations exceeding 2,500 ppm. Also, the biodegradation process will not be successful in soils containing high levels of heavy metals, highly chlorinated organics, or inorganic salts (19).
- *Soil temperature.* The process will be most effective when the soil temperature is between 10°C and 45°C. If seasonal temperatures exist below or above this range, microbial activity diminishes significantly.
- *Microbial population.* The soils must contain sufficient subsurface bacterial population to degrade the targeted hydrocarbons. For in-situ biodegradation to be effective the minimum heterotrophic bacteria plate count should be 1000 colony-forming units (CFU) per gram dry soil. Plate counts lower than this could indicate the presence of toxic concentrations of organic or inorganic compounds.
- *Soil pH.* Low (acidic) or high (alkaline) soil pH is not conducive to optimal biodegradation. Soils with pH values in the range of 6 to 8 are necessary for successful biodegradation. If outside this range, amendments will need to be added to the water-based solution to adjust the pH levels.
- *Nutrient concentrations.* Nutrients, such as ammonium and phosphate must either be available in sufficient quantities in the site soils, or added to the soil, to maintain the bacterial population. A ratio of 120:10:1 of carbon:nitrogen: phosphorus has been suggested by some, although the most desirable ratio will depend on contaminant concentration levels (19).
- *Soil moisture content.* Soil moisture should be maintained between 25 and 85 percent of the water-holding capacity of the soil for optimal microbial growth conditions.

Cost of Technology

The cost of this technology will be site-specific and depends heavily on soil conditions, nutrients required, and the time period required for remediation. Limited data suggest that average cost for full-scale operation is at least \$165 per cubic meter (\$125 per cubic yard) of contaminated soil (19).

TABLE 6 (continued)

Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Can be used at some sites to effectively remove contaminants from both soils and groundwater. • Can be employed without excavating the soil and disrupting the site. Can be used where contaminants have migrated under buildings and other structures.
Limitations	<ul style="list-style-type: none"> • Extensive treatability tests are required to characterize the site and suitability of this technology. • The circulation of water-based solutions through the subsurface can increase contaminant mobility and require that the extracted water be treated before mixing and reinjection. The effect of the circulated nutrients and other amendments on the soil must be carefully monitored. • Preferential flow paths in the subsurface may interfere with the uniform flow of the injected fluids over the entire area of contamination. • The system should only be used where groundwater has already become contaminated. • The process will not be effective in soils that contain high levels of clay or are heterogeneous. • In-situ biodegradation may not be effective in soils containing high levels of metals, chlorinated organics or inorganic salts. • Requires space on-site for storage of nutrients, the mixing tanks(s), and injection/extraction wells.
Time to Cleanup	<ul style="list-style-type: none"> • The contaminant removal efficiencies of this technique will be site-specific, with remediation usually requiring from 6 months to years to complete. Remediation times of 4-6 years are not uncommon.
Commercial Availability	<ul style="list-style-type: none"> • The components of this technology are all readily available.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • No residual products are typically generated by this process.
Emission Control Equipment	<ul style="list-style-type: none"> • Generally there will be no emission controls required with the operation of an in-situ biodegradation process.
Regulatory Issues	<ul style="list-style-type: none"> • Regulators are generally not receptive to (a) the uncertainties associated with introducing amendments into the subsurface and groundwater, (b) the risk that the process will increase contaminant mobility, and (c) the risk that extraction wells will be less than 100% effective in capturing the contaminated groundwater.
Community Acceptability	<ul style="list-style-type: none"> • Unknown.

als, nutrients, and moisture to stimulate aerobic microbial activity. A biopile is similar to a landfarm in its use of oxygen to promote microbial activity. However, biopiles are aerated by forcing air by injection or extraction through perforated piping placed throughout the pile, while landfarms are aerated by tilling or plowing. The piping that is installed can be used for moisture and nutrient distribution as well as oxygen venting. Standard 4-inch polyvinyl chloride (PVC) aeration pipe is usually used with a blower to distribute the oxygen and prevent dead zones (52). Biopile treatment occurs on a diked pad so that the soil enhancement activities can be efficient and potential discharge from the pile controlled. The biopile technique requires about one-third to one-fourth of the area of landfarming, but requires more maintenance (53).

The biopile process begins with extensive soil and contaminant sampling and characterization. Depending on the size of the site, treatability studies are then performed to assess the viability of the technology for the soils being treated. Once the applicability of the technique has been established, several biopile treatment designs exist. Elements that must be considered in the design of a biopile include (18,53):

Land Requirements: In general, a biopile will be between 1 and 3 meters in height with unrestricted length and width. Space must be allowed along the sides of the pile for access and for containment berms.

Layout: The biopile system can consist of one or more biopiles, depending on the size and amount of land that has been made available.

Biopile Construction: Construction of a biopile will typically involve design and construction of the following items:

- a support pad made either of (a) asphalt or concrete, or (b) soil or clay overlain with an impervious liner, to stockpile soils and perform any necessary soil pre-treatment (e.g., application of amendments, blending before piling);
- the treatment cell containing (a) the air injection, extraction or collection piping system connected to a vacuum blower; and (b) a nutrient application system consisting of collection sump, nutrient tank, and irrigation system;
- a leachate collection and treatment system; and
- a vapor treatment system (if necessary).

TABLE 7
FEASIBILITY OF EX-SITU BIOPILES

Effectiveness of Technology	
Targeted Petroleum Contaminants	Appropriate for cleanup of sites contaminated with fresh or weathered gasoline, diesel, jet fuel, kerosene, motor oil, heavy fuel oil, lubricating oils and crude oils. In general, the lighter, more volatile petroleum products like gasoline are removed from the biopile by the aeration process that is implemented. Biodegradation is the dominant process that breaks down the middle and heavier weight petroleum products like diesel fuel and heating oils.
Treatment Effectiveness	Removal efficiencies are site specific; and is it not always possible to achieve low cleanup standards. Concentration reductions >95% and constituent concentrations <0.1 ppm are very difficult to achieve.

Key Parameters Affecting Technology Effectiveness

- *Soil permeability and structure.* It is difficult to aerate or uniformly distribute nutrients through fine-grained soils like clays or through soils that clump together. Where clayey soils are being placed in a biopile, soil amendments (e.g., gypsum) and bulking materials (e.g., sawdust) may need to be blended into the contaminated soil during construction of the biopile to ensure proper soil texture for biotreatment.
- *Contaminant types and concentrations.* In general, the light petroleum distillates such as gasoline and diesel fuel will be more readily degradable than the heavy petroleum products like heating and lubricating oils. In addition, high concentrations of selected constituents are often toxic to microorganisms. In general, biopiles will not be effective when petroleum hydrocarbons exist in concentrations greater than 50,000 ppm total petroleum hydrocarbons (TPH), or heavy metals exist in concentrations exceeding 2,500 ppm. When contaminant concentrations exceed 10,000 ppm TPH, it is recommended that the contaminated soil be blended with clean soil to reduce the concentration of the contaminants and facilitate biodegradation.
- *Soil temperature.* Microbial activity is maximized when the temperature is between 10°C and 45°C. When seasonal temperatures fall below or above this range, microbial activity diminishes significantly. Temperature-controlled enclosures, heated (or cooled) air injection, or the use of special bacteria should be considered under extreme temperature conditions.
- *Microbial population.* The soils must contain sufficient subsurface bacterial population to degrade the targeted hydrocarbons. For biopiles to be effective the minimum heterotrophic bacteria plate count should be 1000 colony-forming units (CFU) per gram dry soil. Plate counts lower than this could indicate the presence of toxic concentrations of organic or inorganic compounds.
- *Soil pH.* Low (acidic) or high (alkaline) soil pH is not conducive to optimal biodegradation. Soils with pH values in the range of 6 to 8 are necessary for successful biopile operation. If outside this range, amendments will need to be added to the soil to adjust the pH levels.
- *Nutrient concentrations.* Nutrients, such as ammonium and phosphate must either be available in sufficient quantities in the site soils, or added to the soil, to maintain the bacterial population. The carbon:nitrogen:phosphorus ratios necessary to enhance biodegradation are in the range of 100:10:1 to 100:1:0.5, depending upon the constituents involved in the degradation process.
- *Soil moisture content.* The ideal range for soil moisture in a biopile is between 40 and 85 percent of the water-holding capacity of the soil. Because the soil in the biopile becomes dry from the aeration process, it is usually necessary to add moisture periodically to the pile. In areas with high precipitation levels, requirements for special drainage or biopile covers may be necessary to minimize excessive infiltration.

Cost of Technology

Capital costs for bioventing system may include the costs of a plastic liner, an irrigation system, biopile covers (if necessary); the aeration piping system; blowers or pumps; nutrients and nutrient/moisture injection systems; soil vapor sampling probes; and vapor treatment equipment (if necessary). In general, this technology does not require expensive equipment and needs to be operated and periodically maintained by only a minimal number of staff.

The cost of a biopile system is usually between \$60 and \$165 per cubic meter (\$45 - \$125 per cubic yard) of contaminated soil (18,53,54).

TABLE 7 (continued)

Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • In contrast with in-situ bioremediation techniques, the use of biopiles and biomounds provides increased control over the parameters such as aeration, moisture, nutrients and soil texture that are important to the success of biodegradation processes. The biopile system can be designed to meet the needs of the site. • Biopiles are effective in degrading or removing the semivolatile organic compounds and non-volatile organics that other technologies cannot. • Biopiles are relatively easy to design, construct and maintain. • The treated soil from biopiles may be approved and available to a highway agency for reuse as backfill. • Biopiles require less land area than landfarms. • Because a biopile system can be designed as a "closed loop", vapor emissions can be controlled and the potential for human exposure during treatment eliminated.
Limitations	<ul style="list-style-type: none"> • Biopiles will be effective in removing biodegradable constituents only; it will need to be used in combination with other technologies at sites containing nonbiodegradable compounds. • Extreme weather conditions will limit the effectiveness of biopiles, or require the use of environment-controlled enclosures. • Biopiles may require the placement of a bottom liner under the cell if there is a concern about leaching from the pile. • With large quantities of contaminated soils, large areas of land will be needed (although still less than would be required for landfarming). • The volatile constituents in the soil will tend to evaporate during excavation and soil pretreatment. Some regulatory agencies may not find this practice acceptable. • Depending also upon state regulatory requirements, the generation of vapors during aeration may require treatment prior to discharge. • Biopiles may release unpleasant odors and require the use of soil conditioners to mitigate.
Time to Cleanup	<ul style="list-style-type: none"> • The treatment times for biopiles are relatively short. Under optimal conditions, approximately 90% of the biodegradable constituents in the soil can be removed by biomounding over a 6 to 18 month period. An average site may require 2 years to remediate. The time needed for cleanup will be longer for sites contaminated with heavier fuel oils.
Commercial Availability	<ul style="list-style-type: none"> • The components needed for construction of a biopile are readily available.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • No residual products are typically generated by this process.
Emission Control Equipment	<ul style="list-style-type: none"> • The use of granular activated carbon, catalytic oxidation or thermal units to treat the extracted vapors may be needed for high contaminant concentrations.
Regulatory Issues	<ul style="list-style-type: none"> • Regulators are generally more receptive of ex-situ biopiles than in-situ bioremediation techniques because of the increased control that can be exercised over the addition of required enhancements. Nevertheless, permits may be required from the regulatory agency for many of the design features of the biopile system. Special efforts may be required to eliminate the uncontrolled release of organic vapors in air quality non-attainment areas.
Community Acceptability	<ul style="list-style-type: none"> • The public is generally very receptive to the controlled nature of this bioremediation technology, as long as the biopiles are located as far as possible from populated or otherwise sensitive areas.

Depending on specific state air quality regulations, covers or structural enclosures may be required over the biopiles if highly volatile constituents are present in the soil. Vapors in the extracted air may also require vapor treatment if they exceed acceptable regulatory limits. A fence or other barrier may also be needed to secure the site and keep trespassers from disturbing the biopiles.

Like all other biotreatment technologies, the success of biopiles is dependent upon the existence of proper site and soil conditions (53,54). Table 7 summarizes the conditions under which biopiles are most effective and other considerations important when evaluating their appropriateness as a

soil remediation technique at a site.

EX-SITU LAND TREATMENT OR LANDFARMING

Landfarming or land treatment is another process that removes biodegradable contaminants from soil that has been excavated. As was the case with biomounds, the excavated soil is spread over a lined treatment area (or biocell) and nutrients are added to promote biodegradation. In contrast to biopiles, landfarms spread the excavated contaminated soils in a much thinner layer over the ground surface and typically involve tilling the soil to enhance the natural release of

TABLE 8
FEASIBILITY OF EX-SITU LANDFARMING

Effectiveness of Technology	
Targeted Petroleum Contaminants	Appropriate for cleanup of sites contaminated with fresh or weathered gasoline, diesel, jet fuel, kerosene, motor oil, heavy fuel oil, lubricating oils and crude oils. The lighter, more volatile petroleum products like gasoline tend to be removed by evaporation during landfarm aeration processes (tilling or plowing). Biodegradation is the dominant process that breaks down the mid-range hydrocarbon products (diesel fuel, kerosene) and heavier weight petroleum products like heating oils. The heavier petroleum products require a much longer period of time to degrade than do the constituents in gasoline.
Treatment Effectiveness	Removal efficiencies are site specific; and it is not always possible to achieve low cleanup standards. In general, however, relatively rapid rates of degradation can be expected in the first 60-90 days, with increasingly diminishing rates thereafter. Concentration reductions > 95% and constituent concentrations <0.1 ppm are very difficult to achieve, although there have been reported reductions of more than 99% in the TPH, total BTEX and benzene concentrations at landfarms in operation for only 5 months (19).

Key Parameters Affecting Technology Effectiveness

- *Soil permeability and structure.* It is difficult to aerate or uniformly distribute nutrients through fine-grained soils like clays or through soils that clump together. Where clayey soils are being placed in a landfarm, soil amendments (e.g., gypsum) and bulking materials (e.g., sawdust) may need to be blended into the contaminated soil during construction of the landfarm to ensure proper soil texture for biotreatment.
- *Contaminant types and concentrations.* In general, the light petroleum distillates such as gasoline and diesel fuel will be more readily degradable than the heavy petroleum products like heating and lubricating oils. In addition, high concentrations of selected constituents are often toxic to microorganisms. In general, landfarming will not be effective when petroleum hydrocarbons exist in concentrations greater than 50,000 ppm TPH, or heavy metals exist in concentrations exceeding 2,500 ppm. Furthermore, when contaminant concentrations exceed 10,000 ppm TPH, it is recommended that the contaminated soil be blended with clean soil to dilute the concentration of the contaminants and facilitate biodegradation.
- *Soil temperature.* Microbial activity is maximized when the temperature is between 10° C and 45° C. The period of the year when temperatures fall within this range is called the "landfarming season." When seasonal temperatures fall below or above this range, microbial activity diminishes significantly. Temperature-controlled enclosures, heated (or cooled) air injection, or the use of special bacteria should be considered under extreme temperature conditions.
- *Microbial population.* The soils must contain sufficient subsurface bacterial population to degrade the targeted hydrocarbons. For landfarming to be effective the minimum heterotrophic bacteria plate count should be 1000 colony-forming units (CFU) per gram dry soil. Plate counts lower than this could indicate the presence of toxic concentrations of organic or inorganic compounds. Where plate counts are low, landfarming may still be effective by conditioning or amending the soil to reduce the toxic concentrations and increase microbial activity.
- *Soil pH.* Low (acidic) or high (alkaline) soil pH is not conducive to optimal biodegradation. Soils with pH values in the range of 6 to 8 are necessary for successful landfarming. If outside this range, amendments will need to be added to the soil to adjust the pH levels.
- *Nutrient concentrations.* Nutrients, such as ammonium and phosphate must either be available in sufficient quantities in the site soils, or added to the soil, to maintain the bacterial population. The carbon:nitrogen:phosphorus ratios necessary to enhance biodegradation are in the range of 100:10:1 to 100:1:0.5, depending upon the constituents involved in the degradation process.
- *Soil moisture content.* The ideal range for soil moisture in a landfarm is between 40 and 85 percent of the water-holding capacity of the soil. Because the soil in a landfarm becomes dry from the aeration process, it is usually necessary to add moisture periodically by a spray applicator or other technique. It is recommended that dechlorinated water be used; chlorinated water can inhibit microorganisms. In areas with high precipitation levels, requirements for special drainage or covers may be necessary to minimize excessive infiltration and potential erosion of the landfarm.

TABLE 8 (continued)

Cost of Technology	
<p>Landfarming costs depend on the type and physical setup of the system (e.g., size and number of treatment cells); the amount of equipment required; the nutrients required; type and amount of contamination present; and level of remediation required. In most landfarming operations, however, aeration is the only process applied and this can be performed by relatively unskilled personnel. Although a wide range of treatment costs associated with landfarming has been reported in the literature, from \$10 to \$140/cubic meter, a range of \$60-\$120/cubic meter is considered reasonable for screening purposes.</p>	
Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • In contrast with in-situ bioremediation techniques, landfarming allows increased control over the parameters such as aeration, moisture, nutrients and soil texture that are important to the success of biodegradation processes. The landfarm design can be effectively used to remove a variety of contaminants from many soil types. • Although longer treatment times are needed, landfarms are effective in degrading or removing the semivolatile organic compounds and non-volatile organics that other technologies cannot. • Landfarms are relatively easy to design, construct and maintain. • The treated soil from landfarms may be approved and available to a highway agency for reuse as backfill or construction material.
Limitations	<ul style="list-style-type: none"> • Landfarming will be effective in removing biodegradable constituents only; it will need to be used in combination with other technologies at sites containing nonbiodegradable compounds. • Extreme weather conditions will limit the practicality and effectiveness of landfarming in certain areas of the U.S. (e.g., Northeast), or require the use of environment-controlled enclosures. • Landfarms require a relatively large dedicated area for an extended period of time; may be difficult to find and permit a suitable location. • Landfarms may require the placement of a bottom liner under the cell if there is a concern about leaching from the pile. • Dust and vapor generation during the aeration process may produce emissions unacceptable to some regulatory agencies; volatile constituents tend to evaporate rather than degrade during aeration. • Landfarms may release unpleasant odors and require the use of soil conditioners to mitigate. • Extensive monitoring is required to ensure the effectiveness of the landfarm design.
Time to Cleanup	<ul style="list-style-type: none"> • The treatment times for landfarms are relatively short. Under optimal conditions, approximately 90% of the biodegradable constituents in the soil can be removed within 6 months of landfarm operation. The time needed for cleanup will be longer for sites contaminated with heavier fuel oils.
Commercial Availability	<ul style="list-style-type: none"> • The components needed for construction of a landfarm are readily available. There are numerous examples of successful landfarming operations.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • No residual products are typically generated by this process.
Emission Control Equipment	<ul style="list-style-type: none"> • No emission control equipment is typically required at landfarms.
Regulatory Issues	<ul style="list-style-type: none"> • Regulators are generally more receptive of ex-situ landfarming than in-situ bioremediation techniques because of the increased control that can be exercised over the addition of required enhancements. Nevertheless, acceptability will vary from state to state. Many states make it difficult to permit landfarming operations in response to air quality concerns at sites located in ozone non-attainment areas.
Community Acceptability	<ul style="list-style-type: none"> • Even though landfarming requires soil excavation, the public is generally very receptive to the controlled nature and low cost of this bioremediation technology, as long as the landfarms are located away from populated or otherwise sensitive areas.

TABLE 9
FEASIBILITY OF EX-SITU SLURRY BIODEGRADATION

Effectiveness of Technology	
Targeted Petroleum Contaminants	Slurry phase biological treatment is appropriate for use at sites contaminated with the full range of petroleum products.
Treatment Effectiveness	Slurry biodegradation is effective in treating soils and sludges with contaminant concentrations as high as 250,000 ppm (59). While volatile petroleum contaminants can be efficiently removed by the mixing process, heavier weight petroleum products will be more difficult to remediate and require much longer residence times in the bioreactor vessel. A variety of contaminants in the soil may also make it difficult to design an efficient biodegradation process.

Key Parameters Affecting Technology Effectiveness

- *Soil structure.* The residence time in the bioreactor depends on the size of the soil particles. Particle size reduction or separation may be necessary prior to treatment in order to maximize the effectiveness of the biodegradation process and lower required residence time in the reactor vessel.
- *Contaminant types and concentrations.* In general, the light petroleum distillates such as gasoline and diesel fuel will be more readily degradable than the heavy petroleum products like heating and lubricating oils and require less residence time in the bioreactor vessel. In addition, high concentrations of heavy metals, selected constituents are often toxic to microorganisms.
- *Soil temperature.* Microbial activity is maximized when the temperature is between 10° C and 45° C. When temperatures fall below 10°C, a soil bioreactor will lose most of its ability to degrade volatile organic compounds (60). Temperature-controlled enclosures or other measures may be necessary if temperatures within the reactor vessels fall outside this range.
- *Microbial population.* The soils must contain sufficient subsurface bacterial population to degrade the targeted hydrocarbons. Where plate counts are low, it will be necessary to add conditioners or amendments to the soil to increase microbial activity.
- *Soil pH.* Low (acidic) or high (alkaline) soil pH is not conducive to optimal biodegradation. Soils with pH values in the range of 6 to 8 are necessary for successful bioremediation. If outside this range, amendments will need to be added to the soil to adjust the pH levels.
- *Nutrient concentrations.* Nutrients, such as ammonium and phosphate must either be available in sufficient quantities in the site soils, or added to the soil, to maintain the bacterial population. The carbon:nitrogen:phosphorus ratios necessary to enhance biodegradation are in the range of 100:10:1 to 100:1:0.5, depending upon the constituents involved in the degradation process.

Cost of Technology

The cost of slurry bioremediation is highly dependent on the volume and concentration of the contaminants. It is estimated that full-scale operation costs between \$105 and \$200/cubic meter (\$80 - \$150/cubic yard) of soil. Higher costs can be expected if there is the need for substantial pre- and post-treatment, and the need for emission control equipment.

volatile organic compounds and the biodegradation of less volatile contaminants. Although landfarming usually involves the excavation of contaminated soils, surface-contaminated soils (located at depths less than one meter) can sometimes be treated in place without excavation. And although contaminant removal may be relatively slow, landfarming is inexpensive to design, operate, and maintain. Table 8 summarizes the site and soil conditions under which land treatment is effective. It also identifies the general advantages and limitations of landfarming vis-a-vis other soil remediation technologies.

A landfarm can contain single or multiple plots, determined by the configuration of land available and by dividing the amount of soil to be treated by the desired depth of the landfarm soils. The depth of soil typically varies between

300 and 450 mm (12 to 18 in.), depending on the tilling equipment being used. Additional land is also needed for access and the construction of containment berms.

The construction design of a typical landfarm will address the issues of site preparation (clearing and grading); berm construction; liner placement and need; leachate collection and treatment; soil pretreatment (methods and equipment for blending, etc.); and the nature of any vapor treatment system (if needed)(18,55). If nutrients and soil pH adjustments are necessary, consideration will also be given to the methods for applying the needed fertilizers and/or lime. Nutrients and other enhancements can be added to the contaminated soils while disking to blend soils, or can be applied periodically by using a sprayer. Access by the public to the landfarming area will also need to be controlled by

TABLE 9 (continued)

Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Slurry bioremediation allows for the control of all of the parameters important to the success of biodegradation. As a result, slurry biodegradation can be used to effectively remove a variety of contaminants from many soil types.
Limitations	<ul style="list-style-type: none"> • A slurry phase treatment process is more complex than a solid phase biological process such as landfarming. • The presence of heavy metals and chlorides may inhibit microbial activity and require pretreatment. • Large quantities of wastewater from dewatering the slurried soil may need to be stored and properly disposed of. • Treatability tests are essential to determine the biodegradability of the contaminants and the extent of solid/liquid separation needed at the end of the process. • The loading of contaminated soils into the mixing reactors can be slow, depending on the contaminants targeted for removal. As a result, the overall time for the cleanup of sites containing large volumes of contaminated soil could become quite long. • Pre-treatment requirements can be costly. For example, the sizing of material prior to slurry formation and mixing is very important but can be difficult and expensive. • It is often difficult and expensive to remove soil fines during the dewatering treatment process.
Time to Cleanup	<ul style="list-style-type: none"> • Treating petroleum-contaminated soils in a slurry bioreactor can be accomplished in a relatively short time period due to the control exercised over processing conditions. Under optimal conditions, approximately 90% of the biodegradable constituents in the soil can be removed within 6 months of operation. The time needed for cleanup will be longer for sites contaminated with heavier fuel oils. <p>The total time needed to cleanup a site will be highly dependent upon the capacity of the bioreactor vessel(s) and the quantity of soil being remediated. Slurry biodegradation may not be very practical or cost-effective for large quantities of contaminated soils.</p>
Commercial Availability	<ul style="list-style-type: none"> • There are a number of vendors capable of providing mobile or fixed full-scale slurry biodegradation systems (59).
Residuals/Wastes Produced	<ul style="list-style-type: none"> • Slurry bioremediation produces treated solids (sludge or soil), process wastewater, and possible air emissions. If the sludge remains contaminated with heavy metals it will have to be stabilized before disposal. The process wastewater may also have to be treated before discharge, although it is typically recycled in the system to create slurry. Air emission control equipment may be necessary to capture vapors released by the biodegradation activity.
Emission Control Equipment	<ul style="list-style-type: none"> • Air pollution control equipment, such as activated carbon, may be necessary.
Regulatory Issues	<ul style="list-style-type: none"> • Regulators will generally be more receptive of ex-situ biological processes than in-situ bioremediation techniques because of the increased control that can be exercised over the addition of required enhancements. While acceptability may vary from state to state, most state regulators will probably find slurry biodegradation acceptable as long as the vapor emissions from pre-treatment and mixing operations are satisfactorily controlled.
Community Acceptability	<ul style="list-style-type: none"> • The public is generally very receptive to the controlled nature of this bioremediation technology as long as potential air emissions are controlled.

fencing or other security measures. Although regulators may require that vapors above the landfarm be monitored during the initial phases of landfarm operation, vapor treatment technologies are usually not part of landfarm systems. When tilling is involved, it is recommended by some that the soil be tilled at least once a week for "optimum effect and economy" (52). Others suggest aeration or tilling more frequently, even on a daily basis (56). If contamination exceeds 10,000 ppm, Golden and Hopkins (57) recommend the use of a polyethylene liner when landfarming. Use of the liner helps eliminate problems of leaching, aeration, tilling, and excessive water retention.

In New York, construction of a generic biocell calls for

the following activities (58):

- clear an area such that it is sloped toward a sump to collect leachate,
- place a double-layered 8-mil polyethylene liner on top of 50 to 76 mm (2 to 3 in.) of sand and cover the liner with 150 to 300 mm (6 to 12 in.) of sand or gravel,
- build 150 to 300 mm (6 to 12 in.) berm around the cell,
- spread the contaminated soil in a layer 450 to 700 mm (18 to 24 in.) deep on top,
- add lime and fertilizer to the contaminated soil while

spreading in the cell, and spray with dechlorinated water,

- cover the cell with a roof or cover to prevent puddling and protect against rainfall,
- construct a safety fence around the area.

Landfarming is a relatively inexpensive but effective technology for removing gasoline and other light petroleum distillates from soils in areas where there are no air quality concerns.

EX-SITU SLURRY BIODEGRADATION

Table 9 summarizes the conditions under which bioreactor systems may be most appropriate along with factors that may limit their applicability and effectiveness.

In a bioreactor unit, soils are batched or continuously fed into a self-contained reactor vessel where they are mixed with water and other additives to form an aqueous slurry (17,59,60). Mixing can also occur in a lined lagoon, but the use of a lagoon usually complicates the operation by requiring the installation of a synthetic liner and the use of a more

expensive vapor capture and control system. The slurry is mechanically agitated to enhance the exposure of contaminated soil to microorganisms. As needed, nutrients and other enhancements are added to the soil slurry to ensure that the proper physical and chemical conditions for biodegradation exist. Oxygen is typically introduced into the reactor vessel via air sparging. Microbes that are acclimated to the range of petroleum hydrocarbons in the soil may also be added. Depending on soil and site conditions, the slurry biodegradation process can require that the excavated soil undergo size separation. Operation of the system may also require air emissions equipment, such as activated carbon.

Once the maximum degradation potential of the system has been achieved, the treated slurry is processed through a separator/dewatering system. The processed water may require additional treatment prior to discharge, while the treated soils may be acceptable for reuse. Removal efficiencies of 90 percent are achievable (23).

Slurry-phase biological treatment can be an attractive soil remediation technology when low molecular weight hydrocarbons are present, clayey soils are contaminated, the amount of contaminants in the soil is small, and there is a need to remediate the site quickly.

PHYSICAL TREATMENT TECHNOLOGIES

Although not widely used, physical and chemical treatment technologies can be very effective in removing petroleum contaminants from soils. Transportation agency staff may find the following publications useful in understanding the advantages and limitations of selected physical and chemical technologies:

- *Physical/Chemical Treatment Technology Resource Guide*, EPA/541-B-94-008, September 1994.
- *Soil Vapor Extraction (SVE) Treatment Technology Resource Guide*, EPA/542/B-94/007, September 1994.

Physical/Chemical Treatment Technology Resource Guide is a 40-page guide that contains information on readily available resource documents, data bases, hotlines and dockets. It contains abstracts for over 110 physical/chemical treatment technology documents and provides information on how to obtain copies of them. It also contains a "Physical/Chemical Treatment Technology Resource Matrix" to assist in identifying the publications that describe different technology types and their use for different media and types of contamination. A copy of this guide can be obtained from the National Center for Environmental Publications and Information (NECPI), 11029 Kenwood Road, Cincinnati, Ohio 42242.

IN-SITU SOIL VENTING

In-situ soil venting refers to the technique of removing residual hydrocarbons from the vadose or unsaturated zone by passing air through the contaminated area and volatilizing the hydrocarbons (63,64,65). Soil venting is also known as:

- soil vapor extraction (SVE)
- enhanced volatilization
- in-situ vaporization
- in-situ soil ventilation
- in-situ vapor extraction
- vacuum extraction
- in-situ air stripping.

The principle of soil venting is quite simple. Airflow is induced in the subsurface by a pressure gradient applied through vertical or horizontal wells or trenches. The flowing air carries out the volatile organic compounds (VOCs) by vaporizing volatile components from soil pores, and the contaminated soil air is collected by extraction wells. The air from the extraction wells is then treated by an off-air treatment system. The technique is applicable at sites where contamination is located above the water table in soil whose pore spaces are predominantly filled with air. It is best suited for contaminants that are relatively volatile (e.g., gasoline and solvents like tetrachloroethylene) and exert a vapor pressure

PVC >.001 atm at the ambient temperature. In-situ venting with steam extraction has been shown to be effective in removing VOCs including chlorinated organic solvents, gasoline, and diesel (66). Typically, venting does not effectively remediate soils contaminated with heavy fuels such as crude oil or jet fuels.

Conventional System Design. There are *passive* and *active* soil venting systems (63). A *passive* soil venting system simply consists of vents, typically wells with perforated sections or gravel-packed holes, that extend from the contaminated soils to the ground surface. The hydrocarbons in the soil spaces volatilize in the presence of air in the soil and are carried by the extraction vents or wells to the surface where they are captured and treated. Passive systems do not utilize energy for the extraction of vapors, although a wind-driven turbine on a stack vent is considered a passive system (67). A passive soil vapor isothermal process like this can take a long time, especially when the VOCs are trapped either (a) by capillary forces, (b) in stagnant, dead-end pore passageways, or (c) in low permeability zones (68).

In contrast, an *active* soil venting or soil vapor extraction system uses pressure or vacuum pumps to force or induce air into or through the unsaturated soil zone to enhance the natural rate of volatilization. The air in which the volatile compounds have partitioned is then extracted with vapor recovery or extraction wells. With a vacuum pump system (pump and blower), a vacuum created on the extraction well removes the contaminated vapors. In a pressure system, a blower fan system (motor and blower) is used to force atmospheric air into the soil and accelerate the vapor flow rate and vapor removal. Pressure and vacuum systems are often used in combination to increase the rate at which hydrocarbons are removed from the soil.

Contaminated vapors and entrained water are drawn by the induced air (or steam) flow through an extraction well(s) to the surface. The technology is flexible and is usually implemented in-situ by using vertical well(s). Horizontal wells can be used to remove vapors that are located or have migrated beneath fixed structures.

In general, vapor extraction trenches may be used instead of wells if the contamination is less than 4 meters (13 feet) below the ground surface (69,70). It is also possible to apply soil venting in an aboveground treatment cell (71). Venting wells are usually 50 to 100 mm (2-4 in.) diameter PVC pipe screened through the contaminated zone and sealed at the soil surface. Johnson et al. (70) provide a formula and standard values for certain parameters that can be used to estimate the likely vapor flow rate per unit well screen thickness. Computer models are available to approximate soil air and VOC movement during the venting process (72).

Proper venting system design can address certain site conditions and produce sufficient airflow through the contaminated zone. The effectiveness of a soil venting system has been maximized by (67,73,74):

- increasing the number of air extraction wells installed, the size and type of blower used, and/or the amount of vacuum applied;
- locating the extraction wells as close to hot spots (concentrated areas of contaminants) as possible to accelerate cleanup times;
- using short slotted sections at the bottom of the import vent to provide more efficient vapor removal than continuous slot vents; the filter pack should be as coarse as possible;
- sealing the soil surface of the venting area to prevent vapor flow short-circuiting and ensure that the exhaust air is drawn laterally, not downward from the soil surface;
- initiating venting at high flow rates (16 L/min or greater) to reduce the majority of vapors so that the flow rate can be subsequently reduced to conserve energy;
- initiating soil venting before removing free product to minimize the amount of groundwater that needs to be extracted and treated.

Once at the surface, the entrained water and contaminated vapors are separated and contained for treatment. The contaminated vapors will typically be treated by:

- *Combustion units* that incinerate vapors with removal efficiencies of 95 percent. This process will be economical with vapor concentrations >10,000 ppm and treatment time long enough to justify the capital and operating costs of such units;
- *Catalytic oxidation* units that heat the vapor stream and pass it over a catalyst bed with removal efficiencies of >95 percent. Catalytic oxidation will be effective with vapor concentrations <8,000 ppm.
- *Carbon beds* which can treat any vapor stream, but which are economical only for initial phase treatment or where low emission rates are expected (69).

Other methods, such as direct venting to the atmosphere, biological degradation, and ultraviolet light (75) have also been applied as treatment methods to a limited extent.

Hot Air or Steam Stripping Design. Because chemicals become more volatile at higher temperatures, raising subsurface temperatures can also increase the effectiveness of the venting process (66,76). Consequently, hot air or steam is often injected in place of ambient air in a vacuum and/or pressure system to accelerate the stripping of volatile contaminants from the soil. The moisture and warmth associated with subsurface steam injection also has the beneficial effect of stimulating hydrocarbon-consuming, indigenous microbes. Steam extraction will be effective in removing less volatile compounds than ambient vacuum extraction systems because most semivolatiles will volatilize only if the temperature is increased (66).

There are a limited number of commercial-scale in-situ

steam extraction systems in operation. An available mobile system volatilizes contaminants in small areas by injecting steam and hot air through rotating blades that move through the subsurface. While mobile steam extraction systems can treat large areas at depths of up to 9.2 meters (30 feet), substantial subsurface obstacles (e.g., underground piping, drums, trash) will preclude their use at some locations.

The major problem with air heating is that air cannot retain much heat; steam heating becomes a problem when the steam condenses to form saturated soil or mud and thereby reduces the air flow and system effectiveness. There may be residual contamination after in-situ steam extraction. The steam extraction process also produces condensed liquid contaminants that must be recycled or treated prior to disposal (66).

The heating of subsurface air by radio frequency has also been used, but with little success (71). Similarly, hot water and patented flushing fluids have also been used with the vacuum extraction process to increase the amount of residual contamination recovered from the soil (68,77).

Although soil venting systems are used at many sites, a significant number of installations have failed to perform efficiently (70,71,78). The general performance of a vapor extraction system will depend on:

- the amount of airflow that can be induced through the soil;
- the distance it will flow relative to the contamination; and
- the chemical composition and physical characteristics of the contaminant to be removed.

The specific parameters that influence the performance of this technology are summarized in Table 10. The relative advantages, limitations, and costs of soil venting are also presented in the table.

IN-SITU SOIL FLUSHING

In-situ soil flushing refers to the process in which contaminants are flushed from the soil by water, water plus an additive, or special chemical surfactants. Flushing with water is practical only for highly water soluble contaminants; for petroleum hydrocarbons that have low water solubility, surfactant solutions or solvents are usually required (79). The treatment or flushing solutions are either (a) forced to the contaminated zone by various pumping techniques, or (b) delivered by gravity. Gravity methods include surface flooding, ponding, spraying, ditching, or subsurface infiltration beds (80).

There are four basic surfactant types classified according to the hydrophilic portion of their molecules. One of the most common surfactants, sodium dodecyl sulfate, carries a negative charge (anionic), while other types will carry a positive charge (cationic), both negative and positive charges (zwitterionic), or no charge (nonionic). The selection of a particular surfactant (there are over 13,000 different types of surfactants) at a petroleum-contaminated site will be based

TABLE 10
FEASIBILITY OF IN-SITU SOIL VENTING

Effectiveness of Technology	
Targeted Petroleum Contaminants	Appropriate for use in remediating sites contaminated with gasoline and diesel fuel located in the vadose zone. Not very effective on petroleum contaminants with low volatilities (e.g., jet fuel or crude oil). Soil venting can be used to reduce high concentrations of contaminants to levels which are more conducive to bioremediation.
Treatment Effectiveness	Soil venting can usually remove up to 90% of all volatile and semivolatile compounds in the soil. In general, compounds with high water solubilities will be more difficult to remediate because their tendency to dissolve in the soil moisture will retard volatilization. Contaminants that adsorb to subsurface soils or rock will also be less amenable to soil extraction. Similarly, soils with high surface areas (such as clays) or with high organic carbon contents will be more difficult to remediate because the contaminants tend to adsorb more easily onto such fine-grained soils than they do onto coarse-grained soils.

Key Parameters Affecting Technology Effectiveness

- *Volatility of contaminant.* In general, the higher the volatility or vapor pressure of the contaminant, the greater the success of a soil venting system. Less volatile chemicals cannot be extracted easily or quickly. Compounds with a high Henry's constant will also be more amenable to soil venting. Henry's law constants are expressed as ratio of a contaminant's vapor pressure and its solubility and reflect the tendency of a contaminant to release from the natural soil moisture into the soil air. Compounds with higher vapor pressure and lower solubility have a correspondingly higher Henry's constant. In general, effective soil venting requires that the Henry's constant be greater than 10^{-5} atm-m³/mole and that vapor pressures be greater than 1 mm Hg (88).
- *Soil permeability.* Soils with limited pore space due to compacted conditions or fine-grained texture restrict the rate at which air moves through the soil and also the ability of the air to pass effectively over all contaminated soil particles. Consequently, the soil venting process works best with permeable unsaturated soils such as gravel, sands, and coarse silt where soil permeabilities are in the range of 1×10^{-4} to 1×10^{-5} cm/sec. Finer-grained soils require higher air entry pressures and are more likely to form significant gas pockets and fingers. While petroleum hydrocarbons will volatilize in finer, dense soils (e.g., clays), removal rates will be much slower (89) even if there is smaller well spacing (which increases project costs). Researchers have cautioned that it may not always be appropriate to use Darcy's Law to estimate volatile contaminant gas flow and soil permeability (90).
- *Soil heterogeneity.* Heterogeneous soils or geologic structures, such as fractures, will hinder air flow because vapors follow the path of least resistance. Subsurface heterogeneity also makes it more difficult to position extraction and inlet wells. In heterogeneous soils, the extraction rate will depend upon the contaminant diffusion rate from fine-grained to coarse-grained material.
- *Soil moisture.* The performance of soil venting is better in soils that are not too moist. Soil moisture occupies void spaces in the soil, creating barriers to advective air flow. Soil moisture, however, is needed by the microbes that degrade contaminants. Optimal biodegradation occurs when soil moisture field capacities are in the range of 40 to 75 percent.
- *Depth to groundwater.* Shallow groundwater can prevent effective system operation, and groundwater upwelling can cause contamination to spread to groundwater or groundwater to block the air flow in contaminated soils (71). There should be at least 3 meters from the ground surface to the water table to ensure protection from groundwater contamination. A vacuum extraction well may cause the water table to rise and saturate the soil in the area of the contamination. If contamination has already penetrated the water table, a pumping system will be required to draw the water table down and allow for effective vapor venting. When the contamination has reached an aquifer, groundwater pumping and air stripping will be necessary in combination with soil vapor extraction to remediate the site.
- *Site conditions.* The air flow rate possible at a site will also depend upon the presence of various site conditions. Soil venting will be most successful at sites where it is feasible to achieve an effective surface seal and there are no artificial conduits or air flow obstructions. An effective surface seal is necessary to ensure that the air flow is horizontal through the contaminated zone and not vertical from the ground surface. The area of contamination should also be free of artificial conduits and other obstructions to air flow (91). Artificial conduits such as backfilled trenches or utility trenches can short-circuit the air flow paths that are desired. Building foundations and underground storage tanks can also obstruct the desired air flow at a site.

TABLE 10 (continued)

Cost of Technology

The costs of a soil venting system will be highly variable due to the variety of designs possible to respond to differing site conditions, soil and contaminant characteristics. The capital costs for conventional soil venting systems will reflect the costs of (a) extraction and injection well installation; (b) the acquisition of vacuum or blower pumps; (c) the cost of vapor treatment system (if any); (d) the cost of vapor and liquid treatment systems piping, valves and fittings; and, (e) the cost of instrumentation. Operations and maintenance costs will include labor, power, maintenance and monitoring activities. In general, off-gas and collected water treatment are the largest cost items, with the cost of cleanup doubled if treated with activated carbon.

The type and range of costs associated with the feasibility evaluation, design, installation and operation of a "conventional" soil venting system are summarized below. Average soil vapor treatment costs \$98/cubic meter (\$75/cubic yard) for treatment of soil, excluding the cost of treating off-gases and collected groundwater. Costs have ranged from a low of \$20 per cubic meter (\$15/cubic yard) for a passive system to \$295 per cubic meter (\$225/cubic yard) for an active system.

Feasibility Study	Site characterization	\$5,000 - \$200,000
	Venting feasibility study	\$5,000 - \$20,000
System Design	Air permeability test	\$10,000 - \$20,000
	Groundwater pump test	\$5,000 - \$50,000
	System Design	\$10,000 - \$40,000
System Installation	(Assumes vapor treatment)	\$100,000 - \$200,000
System Operation		\$3,000 - \$10,000/month
System Shutdown		\$15,000 - \$100,000

Source: (71) Representative cost estimates for a 2-5 acre site where groundwater has not been affected.

The operating costs for a steam injection system are usually higher than that of a conventional vapor extraction system because of the extensive energy required for the injected steam. The rate of wastewater production and subsequent treatment are also considerably higher with a steam injection system. Nevertheless, the overall cost of a steam injected system may still be less than a conventional system due to reduced operating time (76). For a mobile steam extraction system, the most significant factor affecting cost is time of treatment or treatment rate and the equipment's on-line efficiency. At one site, costs of mobile steam extraction ranged from \$145 - \$415/cubic meter (\$111 - \$317/cubic yard) (65).

Time and Other Considerations

Advantages	<ul style="list-style-type: none"> • As oxygen is introduced into the subsurface, the biological degradation of contaminants will typically increase as the result of increased microbial activity. This degradation process is essential to degrading the less volatile components of gasoline. • Is effective in treating areas where the spill has penetrated to depths of more than 6-9 meters, the contamination has spread through an area of 30-60 meters, and there are large volumes (>375 cubic meters or 500 cubic yards) of contaminated soil. • Can be employed to remove contaminants situated close to or under a fixed structure (e.g., building extensive utility trench network, a roadway or rail line); if necessary, system can also be set up to cross boundary lines. • Can be used when there is a need to avoid disrupting an existing business, or to protect nearby sensitive receptors from volatile organic compound emissions that might be associated with other technologies. • In contrast with other in-situ technologies, soil venting has few secondary impacts because only blower-induced air is being introduced into the contaminated soils; it does not involve the addition of reagents that must be delivered to and subsequently recovered from the contaminated area. • Soil venting systems can be left unattended for long periods of time. They can also be successfully operated during severe weather conditions.
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TABLE 10 (continued)

Limitations	<ul style="list-style-type: none"> • Soils that are not homogeneous or exhibit low air permeability will be difficult to treat with soil venting, require a higher number of properly placed wells, or require longer treatment times. • Soils with high organic carbon content will be difficult to remediate with soil venting due to their high sorption capacity. • Low soil temperatures make volatilization more difficult. • Difficult to employ successfully at sites that contain a high degree of soil heterogeneity due to variable flow and desorption characteristics. • May need to be used in combination with other technologies at sites where there is contamination of varying volatility and media (e.g., air sparging, pump and treat). • If steam is injected into the soil, the increase in soil temperatures may destroy some microbial populations or adversely affect other soil properties. • Contaminated soil tailings from drilling may have to be collected and stored on-site and then sent to an off-site, permitted facility for treatment by another technology such as incineration.
Time to Cleanup	<ul style="list-style-type: none"> • A soil venting system can be designed and installed as soon as possible to prevent further dispersion and migration of contaminants. As new information becomes available, the system can then be upgraded (e.g., new wells installed or blower power changed). During the initial stages of operation, removal rates will be high but decrease substantially with time during venting. Nevertheless, sites with relatively homogeneous, permeable soils can achieve up to 90% reduction in volatile and semivolatile organic compound levels in 6 months to 1 year. Sites with moderately heterogeneous and permeable soils may take 6 months to 3 years to achieve 90% reduction. Longer times are required for heterogenous soils and less volatile constituents.
Commercial Availability	<ul style="list-style-type: none"> • Most of the components of a soil venting system are readily available off the shelf.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • If an air/liquid separator is used, petroleum contaminated water may be collected and have to be disposed of properly. If carbon adsorption is used, the spent carbon will need to be disposed of or recycled.
Emission Control Equipment	<ul style="list-style-type: none"> • May require use of liquid vapor separators, carbon adsorption units, vapor incineration unit, catalytic oxidation unit, or condensers.
Regulatory Issues	<ul style="list-style-type: none"> • Treatment of contaminated vapors may require air quality permit from regulatory agency; specific air quality limits or the general sensitivity of those residing in an area may restrict venting of selected constituents to the atmosphere (e.g., benzene). • Contaminated water that is collected may be treated and discharged on-site or need to be transported and treated off-site; National Pollutant Discharge Elimination System (NPDES) permit may be required if water quality regulations prohibit the release of selected constituents (e.g., benzene).
Community Acceptability	<ul style="list-style-type: none"> • No adverse reaction from the public is typically associated with this technology.

on the following considerations:

- **Toxicity** - cationic surfactants are known to be germicides and toxic to a wide variety of aquatic organisms. Nontoxic surfactants should be selected whenever possible.

- **Solubility** - micelle formation, essential to the process of solubilization, occurs above a critical concentration of surfactant. This concentration is referred to as the critical micelle concentration (CMC) and is different for every surfactant. Surfactants with low CMCs should be used to keep the cost of the soil flushing operation as low as possible.

- **Biodegradability** - biosurfactants that are readily biodegradable are usually preferred over synthetic chemical surfactants. Regulators like to avoid the risk that some of the surfactant will remain in the soil after its use.

- **Compatibility with Soil and Groundwater Quality** - surfactants should be carefully chosen for their compatibility with the soil and other site conditions. For example, the surfactant selected should have approximately the same chain

length as the petroleum contaminant targeted for removal (81). In addition, if biological processes are to be used during or after soil flushing, the compatibility of the soil flushing solution with subsurface bacteria must be considered (80). The selection of an inappropriate surfactant can also foul the infiltration and treatment units being used.

There are two basic ways that surfactants can act to remove petroleum products from the saturated zone. Surfactant solutions can increase the mobile-phase solubility of a contaminant through micelle formation (82, 83). Alternatively, surfactants can be used to enhance the mobility of the contaminants by reducing the capillary forces or surface tension that keeps the contaminants trapped in the soil pore spaces. Surfactant-enhanced remediation based on mobilization is generally more effective than that designed to increase contaminant solubility, but can be riskier because of the potential for movement of the contaminants from the site.

When the treatment solution interacts with the contaminants, the contaminants are solubilized, emulsified, or chemi-

cally modified and transported downward to a saturated zone. The flushing solution and associated contamination is then captured by a groundwater extraction system and pumped to the surface. In some cases, the flushing solution may be treated to remove the contaminants and reused; in others, it may need to be disposed. Because the contaminants are mobilized by the solution, barriers may be required to prevent the transport of contaminants away from the site.

Soil flushing can be used to recover metals and a wide range of organic and inorganic compounds from coarse-grained soils (17), but should be used only when the site hydrology will allow the flushed contaminants and soil flushing fluid to be contained and recaptured. Prior to the use of soil flushing at a site, a comprehensive groundwater hydrologic study must be performed. Treatability and pilot-scale demonstration tests will also be required. Because expensive laboratory and field treatability studies must always be performed to determine its potential suitability at a site, soil flushing has not been used often for the remediation of petroleum contamination in soils. While soil flushing can recover hydrocarbons trapped in the soil above and below the water table more quickly than is possible with conventional pump-and-treat systems, there is little practical experience with its employment at small petroleum-contaminated sites. Soil flushing has been used most widely by the oil production industry for oil recovery, and is only now being considered at several large Superfund sites. (83,84). When suitable soil and site conditions exist, soil flushing is usually used in conjunction with other treatment technologies.

Soil flushing is only applicable at sites where there is favorable hydrology and field testing can demonstrate the success of a particular surfactant or flushing fluid. Table 11 summarizes the soil and site conditions under which soil flushing will be successful. It also identifies other considerations to be weighed when deciding whether soil flushing will be a cost-effective soil remediation technology at a site. The need to optimize conditions in a very delicate and precise subsurface environment makes soil flushing a relatively risky and costly soil remediation technology in comparison with other available options.

EX-SITU SOIL WASHING

Soil washing is similar to soil flushing in that contaminated soils are cleaned with a washing solution, but in the case of soil washing the soil is treated ex-situ. Soil washing is designed on the principle that contaminant residence is directly related to particle size. Soil particles can be broken into five basic size fractions (81):

- *Gross oversize*: materials more than 203 mm (8 in.) in diameter (e.g., concrete rubble, trees and branches, scrap metal and tires).
- *Oversize*: material between 51 and 203 mm (2 and 8 in.) in diameter (e.g., gravel and shredded wood).
- *Large, coarse-grained soils*: soil particles between 6.3 and 51 mm (1/4 in. and 2 in.) in size, (e.g., sands and gravel).

- *Coarse-grained soils or sand*: materials less than 6.3 mm (1/4 in.) in size and sand between 40 and 60 microns in size.

- *Fine-grained clays and silts*: materials with average particle sizes less than 40 microns.

Once the contaminated soil has been separated into the different particle sizes, the best treatment for each size fraction is determined and implemented. One of these fractions will typically not be contaminated. Aboveground soil washing tends to yield better results than in-situ flushing because the liquid/soil contact and interaction can be better controlled. And in contrast with the relatively slow process of soil flushing, ex-situ soil washing has particular merit when it is desirable to remediate the contaminants before they reach the water table.

The equipment used by companies to perform soil washing is fairly standard, although the procedures used differ from company to company (85). In general, the following activities are involved when conducting soil washing operations (86):

- *Treatability studies*: soil samples are taken to characterize the soil conditions and contaminants present at the site. If the soil appears suitable for soil washing, bench-scale studies are performed to help identify the proper screening, hydrocycloning, air flotation, and air filtering techniques to use. These studies will also identify the need for surfactants and the best processing flow rates (87).

- *Excavation and Screening*: the contaminated soil is excavated and a working pile is created at the site. Different screening techniques (e.g., wet screening and high-pressure nozzles) are then employed to break the soil into less than 50 mm (2 in.) material.

- *Separation*: the coarse-grained and fine-grained soils are then separated by using a hydrocyclone or gravity separator.

- *Washing of coarse-grained sands*: the coarse-grained materials are then treated by froth flotation (other techniques, such as landfarms have also been used). Surfactants and other detergents (if needed) are placed in an air flotation tank with the contaminated materials causing the contaminants to release from the sand and eventually float to the top and form a froth. The froth is directed to a filter press where it is dewatered into a 50-60 percent solid cake that must then be either incinerated or disposed of in a RCRA permitted facility. The sand is usually reused and the water recycled.

- *Washing of Fines*: the fine-grained materials are also treated usually by dewatering or by slurry biotreatment. This also produces a sludge cake that must be properly disposed of.

Soil washing has been used extensively in Europe and is becoming more common in the United States. By exercising increased control over the washing process, the removal of contaminants by ex-situ soil washing can be achieved more efficiently and much more quickly than in-situ soil flushing (several months versus years). Soil washing is not

TABLE 11
FEASIBILITY OF IN-SITU SOIL FLUSHING

Effectiveness of Technology	
Targeted Petroleum Contaminants	Soil flushing is appropriate for use in remediating sites where soil or groundwater has been contaminated with the full range of petroleum products. Semivolatile or nonvolatile petroleum hydrocarbons are especially suitable for soil flushing. Targeted contaminants can be adsorbed to the soil, trapped in the interstitial pores of the soil, slightly dissolved, or in non-aqueous phase liquid (NAPL) pools.
Treatment Effectiveness	The level of treatment that can be achieved by soil flushing will be dependent on the selection of an appropriate flushing solution, the surfactant concentration used, the extent and time of contact between the solution and petroleum constituents, the soil partition coefficients of the petroleum constituents, and the hydraulic conductivity of the soil (80,83,92). Because soil flushing requires the optimization of numerous sensitive soil parameters, it is not always capable of reducing contaminant concentrations to acceptable levels. It may be most effective when used to reduce toxic or extremely high concentrations of contaminants to lower levels suitable for removal by other technologies such as in-situ bioremediation.

Key Parameters Affecting Technology Effectiveness

- *Types and concentrations of contaminants.* The type and concentration of the petroleum contaminants present are key chemical parameters that determine the type and amount of surfactant that will be needed, as well as the need for post-treatment of the recovered flushing fluids.
- *Soil permeability.* For in-situ soil flushing to be successful, the soil must be permeable to liquid flow (i.e., sandy soils). Soils with limited pore space due to compacted conditions or fine-grained texture (e.g. clayey soils) will have low permeability and limit the soil flushing rate. Soil flushing will be most effective in permeable soils ($K > 1.0 \times 10^{-3}$ cm/sec)(84).
- *Soil heterogeneity.* Heterogenous soils or geologic structures, such as fractures, may adversely affect the distribution of the flushing fluids through the subsurface. Sufficient heterogeneities in the soil may result in the incomplete removal of contaminants.
- *Soil moisture.* The amount of moisture in the soil will affect the amount of surfactant or flushing fluids required. Dry soils will require more flushing fluids. The moisture content of the soil will also affect the rate of treatment (84).
- *Total organic carbon and clay content.* The adsorption of contaminants on soil increases with increasing total organic carbon levels and increasing clay content. High total organic and clay content in the soil will make contaminant removal by soil flushing more difficult. Soil flushing will work best in soils where the carbon content is 0.12-1.00% by weight and clay content is <10% by mass (81).
- *Site conditions and soil structure.* The flow of liquids through the subsurface will also depend upon the absence of artificial conduits or other obstructions to the flow of the flushing fluids, such as building foundations and underground storage tanks.
- *Soil temperature.* The formation of micelles can be very sensitive to temperature. Micelles will not form below certain critical temperatures. In addition, the aqueous-phase solubility of many surfactants is also sensitive to temperature fluctuations (83,92). As a result, soil flushing may show erratic results in geographic areas that experience large temperature fluctuation.

Cost of Technology

Reliable data on the costs associated with soil flushing are not available. Soil flushing is generally very expensive, however, with its cost dependent on (a) the extent of treatability and pilot-scale testing required, (b) the surfactant flushing method used (e.g., ditches, injection wells, infiltration galleries, surface spraying), and (c) the wastewater treatment technologies used. The capital cost of this technology can be increased significantly if slurry walls or other containment structures (berms, dikes) are needed along with hydraulic controls to ensure the capture of contaminants and flushing fluids. The separation of surfactants from the recovered flushing fluid for reuse in the process is also a major factor in the cost of soil flushing. Soil flushing will not be cost-effective at sites containing small amounts of petroleum contamination. It may not be cost-effective at larger sites as well unless there are no other remediation technologies capable of achieving the desired removal efficiencies.

TABLE 11 (continued)

Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Soil flushing does not require the excavation of soil from the petroleum source area. Consequently, it can be very cost-effective when large volumes of soil are contaminated and the contamination has migrated under buildings or other fixed structures.
Limitations	<ul style="list-style-type: none"> • The environmental chemistry, hydrology, and transport mechanisms are not well understood for many surfactants. While its effectiveness in removing petroleum contaminants from soils has been demonstrated in the laboratory, field studies have not always demonstrated similar success. • The presence of several compounds or mixtures at a site makes it difficult to find or formulate a single surfactant that will reliably remove all of the contaminants from the soil. • Depending on the flushing solution used, soil flushing may introduce toxins into the soil, which may in turn alter the physical/chemical properties of the soil system. The presence of residual flushing additives in the soil may be an important concern in some areas. • Heterogeneity in soil permeability can result in the incomplete removal of contaminants. • Contaminants in soils containing a high percentage of silt- and clay-sized particles will be difficult to remove. Soil flushing should be used in combination with other technologies where this condition exists. • Soil flushing requires that there be a substantial amount of land available at the site for soil flushing and wastewater treatment equipment. Access is also required for vehicles to transport the flushing materials and wastewater treatment products to and from the site. • The use of certain surfactants can cause fine soil particles to become suspended in the flushing fluid. In some cases, the narrow spaces between soil particles can become blocked and the movement of the surfactant stopped.
Time to Cleanup	<ul style="list-style-type: none"> • Very long times (one to many years) are typically needed to achieve cleanup levels with this technology. Soils with low permeability will have low surfactant flushing rates and require the longest times for complete contaminant removal.
Commercial Availability	<ul style="list-style-type: none"> • All of the equipment necessary to develop a soil flushing system is commercially available.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • Liquid containing the flushed contaminants and the soil flushing fluid must be captured and treated or disposed of properly. Oil/water emulsions can form to adversely affect the waste treatment process (79). In addition, bacterial fouling of infiltration and treatment units can occur if high iron concentrations are present in the groundwater or if biodegradable surfactants are being used (84).
Emission Control Equipment	<ul style="list-style-type: none"> • When surfactants or solvents are used, carbon beds cannot be used to treat the contaminated groundwater. Air strippers or biotreaters will need to be used.
Regulatory Issues	<ul style="list-style-type: none"> • Because the contaminated flushing fluids are usually considered hazardous, their handling requires the development and implementation of a site safety plan during waste treatment operations. • An Underground Injection Control (UIC) Permit may be required if subsurface infiltration galleries or injection wells are used (84). • If groundwater is not recycled, an National Pollutant Discharge Elimination System (NPDES) permit may be required before discharge to the local publicly owned treatment works (POTW). • Air emissions of volatile contaminants from the recovered flushing fluids may need to be collected and treated to meet applicable regulatory standards.
Community Acceptability	<ul style="list-style-type: none"> • That the fate of the flushing fluids in the subsurface cannot always be sufficiently controlled makes many regulators and the public skeptical about both the effectiveness and secondary impacts of technology.

cost-effective, however, for small sites. It often becomes an attractive soil remediation option only when contaminated soil volumes exceed 15,300 m³ (20,000 yd³). Table 12 summarizes the conditions under which soil washing will be technologically feasible and cost-effective.

EX-SITU COAL-OIL AGGLOMERATION

The *coal-oil agglomeration process* was developed by The Alberta Research Council (32). It is an ex-situ process that uses a solid sorbent (fine coal particles) instead of a liquid surfactant or sorbent to remove petroleum contaminants from excavated soil. Oily petroleum constituents in the soil

matrix are removed by being adsorbed onto the surface of fine coal particles mixed into the soil. The coal-oil agglomeration that is formed is then separated from the soil in an aqueous slurry and the recovered agglomeration used as boiler fuel.

A detailed description of the coal-oil agglomeration process and information on its effectiveness and cost were not available. It can be expected, however, that the advantages, limitations, cost, and other considerations associated with this technology will be comparable to those shown in Table 12 for soil washing. As a technology that is not widely available, coal-oil agglomeration is not a very cost-effective soil remediation method for a "typical" petroleum-contaminated site.

TABLE 12
FEASIBILITY OF EX-SITU SOIL WASHING

Effectiveness of Technology	
Targeted Petroleum Contaminants	Soil washing is appropriate for use in remediating sites where soil has been contaminated with the full range of petroleum products (gasoline, diesel fuels, oils and sludges) as well as other organics and heavy metals. It is most effective in removing contaminants from coarse sand and gravel.
Treatment Effectiveness	The removal efficiency of soil washing will depend on the type of contaminant present and the type of soil. Between 90 and 99% of all volatile organic contaminants can be easily removed by soil washing. Only 40-90% of all semi-volatile organics will be removed by soil washing, given the selection of the proper surfactant (85). Soil washing systems that rely solely on water will have relatively low petroleum removal efficiencies (45-55%). Treatment will be less efficient when the contaminated soils contain large amounts of fine particles. Depending on the treatment levels established, the soil fractions obtained during soil washing may require additional treatment to meet total petroleum hydrocarbon (TPH) standards (93).

Key Parameters Affecting Technology Effectiveness

- *Types and concentrations of contaminants.* The type and concentration of the petroleum contaminants present are key chemical parameters that determine the type and amount of surfactant that will be needed, the likely washing efficiency, and the need for post-treatment of the recovered flushing fluids.
- *Particle size distribution.* Soil washing is especially effective in removing petroleum contaminants from coarse soils. In contrast, soils consisting mostly of finer sand, silt, and clay particles, and those with higher humic content, will tend to adsorb the contaminants strongly and be much more difficult to treat.
- *Total organic carbon and clay content.* The adsorption of contaminants on soil increases with increasing total organic carbon levels and increasing clay content. High total organic and clay content in the soil will make contaminant removal by soil flushing more difficult. Soil flushing will work best in soils where the carbon content is between 0.12 and 1.00% by weight and clay content is <10% by mass (81).

Cost of Technology

Soil washing is not particularly cost-effective at small petroleum-contaminated sites due largely to the costs of treatability studies and the mobilization/operation of the soil washing equipment. Although there are a relatively large number of vendors that provide soil washing technology, they are not always located within close driving range. As a result, soil washing is most cost-effective at sites containing more than 15,300 cubic meters (20,000 cubic yards) of contaminated soil. Soil washing on this scale usually costs between \$65 - \$260/cubic meter (\$50 to \$200 per cubic yard) (17,85,86), including the costs of excavation. The upper range of these costs reflects the need for sludge disposal. The cost of soil washing can increase significantly with soils that contain too many fines. It can also be increased by the need to construct berms, dikes or other runoff devices to control surface runoff and water infiltration. In many cases, soil washing will be most cost-effective when used in combination with other technologies.

TABLE 12 (continued)

Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Soil washing is a process designed to focus treatment on the fraction(s) of soil that are contaminated. This process makes for more efficient and less expensive treatment. • Soil washing produces clean sand that can usually be used as backfill at a site or construction-grade materials for concrete production or roadways. • Soil washing is effective in treating a broad range of petroleum hydrocarbons as well as inorganic metals. • Many soil washing systems produce no air emissions or wastewater discharges, making them easy to permit.
Limitations	<ul style="list-style-type: none"> • Soils containing a large amount of clay and silt are not well suited to soil washing, especially if it is applied as a stand-alone technology at a site. The cost of soil washing can also be quite high if the amount of soil is small and the percentage of fine-grained materials is high. • Many soil washing systems produce and require the discharge of contaminated water. • Some systems are not designed to handle soils containing more than 20-30% fines; greater percentages of fines also produce more sludge. • Soil washing equipment may require 1.5 acres or more of space either at the contaminated site or at an off-site location. Some mobile units occupy up to 4 acres of land; the exact amount of space required will depend upon the vendor system selected, the amount of soil storage space needed, and the number of tanks or ponds needed for washwater preparation and wastewater treatment. • The presence of several compounds or mixtures at a site can make it difficult to find or formulate a single surfactant that will effectively remove all of the different types of contamination from the soil particles. Sequential washing steps may be needed to achieve the established cleanup levels. • As an ex-situ technology, the health and safety of workers involved in excavation and soil processing activities must be a concern with soil washing operations.
Time to Cleanup	<ul style="list-style-type: none"> • The time to remediate a "typical" site of 15,300 cubic meters (20,000 cubic yards) by soil washing would be less than 3 months (17).
Commercial Availability	<ul style="list-style-type: none"> • There are a large number of vendors available to provide soil washing services.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • A soil washing operation will produce oversize material, gross oversize material, and clean sand which can usually be disposed of in a municipal landfill or reused at the project site. In addition, however, the soil washing process generates (a) the contaminated solids from the soil washing unit (i.e., sludge cake) (b) wastewater, (c) wastewater treatment sludges and residuals, and (d) air emissions. The sludge cake must be incinerated or otherwise properly disposed of in a permitted RCRA facility. The wastewater treatment sludges and residuals solids, such as spent carbon, must also be appropriately handled and disposed (85).
Emission Control Equipment	<ul style="list-style-type: none"> • Vapor treatment equipment, such as carbon adsorption or incineration, may be required for the emissions released during soil excavation and processing.
Regulatory Issues	<ul style="list-style-type: none"> • Because the contaminated flushing fluids are usually considered hazardous, their handling requires the development and implementation of a site safety plan during soil washing operations. • A National Pollutant Discharge Elimination System (NPDES) permit may be required before discharging any blowdown water that is not recycled. • Vapor treatment may be required during excavation, soil screening/separation and the soil washing operations to eliminate air emissions, especially in nonattainment areas.
Community Acceptability	<ul style="list-style-type: none"> • This technology is usually well received by the general public because it is removing and destroying the contaminants. Proximity to a residential neighborhood, however, may require extra attention to plant noise and air emissions (17,85).

CHEMICAL AND THERMAL TREATMENT TECHNOLOGIES

EX-SITU SOLVENT EXTRACTION

In *solvent extraction*, petroleum contaminants are removed from the soil by mixing them with a leaching solvent into which the contaminants preferentially partition (94,95). The technology differs from soil washing in that it uses an organic chemical as a solvent rather than water or water with additives. A solvent gas, such as propane or carbon dioxide, may also be used. When a solvent gas is used, the process is referred to as supercritical fluid extraction (96). The solvent extraction process begins with the excavation and screening of the contaminated soils into sizes suitable for processing. Air emission control equipment may be required during this step to capture and remove the volatile contaminants released during the separation process. The excavated soils are then mixed with a suitable solvent in a mixing chamber or "extractor." Small changes in system pressure or temperature will cause large changes in solvent density and its ability to solubilize volatile organic and semivolatile organic contaminants. The mixture is then sent to a solid/liquid separator where the pressure or temperature is changed causing the organic contaminants to separate from the solvent. The concentrated contaminants that remain are removed from the separator and treated or otherwise disposed of properly. The solvent is compressed and recycled to the extractor.

The solvent extraction process is designed primarily to separate contaminants from soils, not treat or destroy them. As a result, solvent extraction is not usually used alone but rather in combination with other technologies such as soil washing and solidification/stabilization (17). One commercially available solvent extraction system involves aqueous soil washing followed by solvent extraction. Aqueous washing cleans the coarse soil particles and reduces significantly the material that must be treated by solvent extraction. The fine fraction that remains is then mixed with a solvent in a series of tanks. The solvent/slurry mixture is then separated by a centrifuge, the solvent removed by distillation and recycled back to the process. Hydrocarbon removal efficiencies are reported to be 95 to 99 percent for this combination process (94).

Table 13 summarizes the important considerations associated with the use of this technology. Solvent extraction processes, as well as supercritical fluid extraction, are used primarily in the petroleum refinery industry for the treatment of refinery sludges. These technologies are not widely accessible or employed outside the refinery industry.

IN-SITU RADIO FREQUENCY HEATING

In-situ radio frequency (RF) technology heats the contam-

inated area "with controlled electromagnetic energy much like a microwave oven heats food." (97,98) An RF system consists of a subsurface radio frequency heating applicator or antenna, a transmission line to the downhole antenna(s), and a radio frequency generator to supply energy to the transmission lines. The temperature in the subsurface soils surrounding each antenna rises as the electromagnetic energy radiating from the antennas is absorbed by the soil. The level and radial extent of heating that is achieved in the soil is controlled by the operating frequencies selected, electrical phase relationships, antenna element lengths, and antenna locations. The applicators at a typical RF heating site will be from 25 to 152 mm (1-6 in.) in diameter and be placed to depths anywhere from 1.5 to 15.3 meters (5-50 feet). A typical heating system will operate on an authorized transmitting frequency of 6 to 40 MHz with radiated power levels of up to 25,000 watts per applicator. Metallic ground plates will be placed at the surface around high power applicators to provide better heating efficiency and to ensure that Occupational Safety and Health Administration (OSHA) and Federal Communication Commission (FCC) safety and emission standards are satisfied.

As the temperature in the contaminated area rises, the petroleum contaminants that are present volatilize, flow toward the borehole, and are carried to the surface for treatment by a non-metallic vapor extraction tube that is co-located in the applicator. The area of the heating zone will be expanded considerably if there is water in the soil and it is converted to steam by the RF energy. Multiple heating applicators or antennas can also be employed to heat larger areas or to focus on a particular thermal region in the subsurface. RF heating overcomes many of the problems associated with the alternatives of hot air and steam injection.

In-situ RF heating is currently available from several vendors. Although the technology is mobile and can be transported by truck to a site, the cost of mobilization and the cost of energy to generate the required radio frequencies, can make this technology relatively expensive as a stand-alone remediation technology. Although RF heating is effective when used alone, its most effective use may be to enhance the recovery of petroleum contaminants by other technologies, such as soil venting. Table 14 summarizes the advantages, limitations, and other considerations associated with the use of RF heating at a contaminated site.

IN-SITU AND EX-SITU VITRIFICATION

In-situ vitrification is a thermal technology that uses an electric current to heat and melt contaminated soils in order to destroy the contaminants. To vitrify petroleum-contami-

TABLE 13
FEASIBILITY OF EX-SITU SOLVENT EXTRACTION

Effectiveness of Technology	
Targeted Petroleum Contaminants	Solvent extraction is appropriate for use at sites containing soils or sludges contaminated with the full range of petroleum wastes.
Treatment Effectiveness	Solvent extraction is used primarily for the treatment of hazardous sludges containing PCBs and other industrial wastes. However, it can be used to remove petroleum wastes from the soil. The effectiveness of the process will depend heavily on the type of petroleum contamination present in the soil and the nature of the extraction solvent chosen. Removal efficiencies over 95% have been achieved when used on a mix of volatile and semi-volatile hydrocarbons (94); up to 90% removal has been achieved on soils contaminated with oil and grease (95). Solvent extraction is most commonly used in combination with solidification/stabilization, soil washing, or thermal treatment.
Key Parameters Affecting Technology Effectiveness	
<ul style="list-style-type: none"> • <i>Types and concentrations of contaminants.</i> The type and concentration of the petroleum contaminants present are key chemical parameters that determine the type and amount of solvent that will be needed, the likely removal efficiency, and the need for post-treatment of the separated materials. The selection of appropriate solvents will be difficult with mixtures of different contaminants. Many solvents will not work on soils contaminated with metals. • <i>Particle size distribution.</i> Solvent extraction will be most effective in removing petroleum contaminants from coarse-grained soils which can be mixed easily with the selected solvents. Extra preparation may be needed with heterogeneous soils. Some solvent extraction processes do not work with soils that contain high plasticity clays. 	
Cost of Technology	
<p>The cost of employing this technology will depend on the solvent used, the solvent:waste ratio, the throughput rate, the needed extractor residence time, the number of extraction stages required, and the need for emissions controls. It is estimated that this technology costs between \$98 and \$650 per cubic meter (\$75-\$500 per cubic yard) of contaminated soil to use at a typical site (95). This is an extremely high cost for a technology that is designed primarily to separate contaminants from soil particles, not destroy the contaminants.</p>	
Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Solvent extraction is most cost-effective when used in combination with other technologies such as soil washing or solidification/stabilization to speed the removal of contaminants from the soil.
Limitations	<ul style="list-style-type: none"> • Solvent extraction is not designed to destroy contaminants; it separates them from the soil and thereby reduces the amount of contaminant that needs to be subsequently treated or disposed. • Metals may be extracted with the targeted contaminants and thereby create special problems with the handling and disposal of the residuals. • The detergents and emulsifiers that may be needed during the extraction process will often interfere with the separation process. • Solvent extraction will not be effective on all soil types and moisture content levels. • Personal protective equipment may be required during the excavation and soil preparation process. • Traces of solvent may remain in the soil following separation; the toxicity of the solvent may therefore impact the usefulness of the cleaned soil (17).
Time to Cleanup	<ul style="list-style-type: none"> • Depending upon the capacity of the extraction unit (will vary from 4.5 to 68 megagrams (5 to 75 tons per day), the time for cleanup may take from weeks to several months.
Commercial Availability	<ul style="list-style-type: none"> • There are a limited number of vendors available to provide the solvent extraction technology.

TABLE 13 (continued)

Residuals/Wastes Produced	<ul style="list-style-type: none"> This technology may produce a number of waste streams: (a) emissions from handling the waste during the preparation stage, (b) treated soil or sludge, and (c) separated water and solvent.
Emission Control Equipment	<ul style="list-style-type: none"> Depending on the solvent used and the extent of metal or other inorganic contaminants in the soil, both the solids and water produced from the process may require additional treatment before disposal or reuse. Vapor treatment equipment, such as carbon adsorption or incineration, may also be required to remove the emissions released during soil excavation and preparation.
Regulatory Issues	<ul style="list-style-type: none"> Vapor treatment may be required during excavation, and soil screening/separation to eliminate air emissions, especially in nonattainment areas. A National Pollutant Discharge Elimination System (NPDES) permit may be required before disposal of any process waters. Solvent extraction processes are not well known to the regulatory community involved with underground storage tank cleanups; they are used most often by the petroleum refinery industry to treat refinery sludges and wastes.
Community Acceptability	<ul style="list-style-type: none"> Solvent extraction poses little threat to the community.

nated soils in-situ, electrodes are placed around the perimeter of the contaminated area. A conductive mixture of graphite and glass is then usually placed over the area to act as a starter path. An electric current then heats the soils up to 1980°C (3,600°F) with the area of the melt extending downward and outward a distance of approximately 50 percent of the electrode spacing. The extremely high heat melts the rocks and sediments present and destroys the organics by pyrolysis. If gases are produced, they either become incorporated in the melt or need to be collected by a vacuum hood placed over the contaminated area and then treated by off-gas equipment. Due to electrical power constraints, in-situ vitrification is usually employed at depths not exceeding 7.6 meters (25 feet) (99). When the heating process is completed and the soil cools, a solid, glass-like block of material remains. This material is inert and is reported to permanently immobilize all hazardous organics. Material testing of this substance for heavy metals has shown the leach rate to be very low (5×10^{-5} g/cm²/day or lower).

Higher temperatures may be reached by the use of plasma torches (100). Plasma is a highly ionized gas that exists at temperatures between 4000°C and 12 000°C. The plasma is created by also using electricity and creating an arc between electrodes through which all fluids and gases are volatilized and all solid materials are turned into glass (vitrified). At present, only laboratory-scale tests of the in-situ vitrification process by plasma torch have been conducted.

Ex-situ vitrification operates much like in-situ vitrification except that the contaminated soils are excavated before being melted by electrically induced high temperatures in a furnace. In plasma arc vitrification, for example, heat from a transferred plasma arc torch creates a molten bath at temperatures in excess of 1600° C in a plasma centrifugal furnace (14). While ex-situ vitrification is designed primarily to encapsulate the inorganic contaminants (metals) in soil, the high temperature needed to form the vitrified mass destroys virtually all organic contaminants as well.

The in-situ vitrification technique is presently offered by

only one vendor which severely limits its availability to most state highway agencies. There are five known vendors with proprietary ex-situ vitrification processes (17). Both in-situ and ex-situ vitrification are fairly expensive technologies, especially for petroleum-contaminated sites, due to their energy requirements and the costs of mobilization that result from such a limited number of vendors. Table 15 describes the advantages and disadvantages of vitrification and its cost.

EX-SITU THERMAL DESORPTION SYSTEMS

Thermal desorption is a process that uses heat to remove the volatile petroleum hydrocarbons from soils. As the soil is heated, the contaminants volatilize and are desorbed or separated from the soil matrix (18,101,102). Depending on the design of the system, the vaporized contaminants are then either destroyed in the heating chamber, or collected in a separate unit, condensed and recovered, or incinerated. The thermal desorption process is applied to soils ex-situ, and can be conducted on- or off-site. If applied on-site, mobile or transportable thermal units are used (103-105). Mobile units are generally truck-mounted and require short periods of time to mobilize and make operational. A transportable system is also truck-mounted but requires a substantial foundation and more time to erect in the field. In general, thermal desorption will be a cost-effective technology for remediating petroleum contaminants on-site when there are more than 3825 m³ (5,000 yd³) of the soil containing high concentrations of hydrocarbons (106); mobile systems may sometimes be cost-effective for sites containing more than 765 m³ (1,000 yd³) of contaminated soil (103). Off-site stationary or fixed thermal facilities are almost always used for the treatment of contaminated soils in quantities less than this.

Thermal desorption processes can be categorized by the temperatures they achieve and petroleum contaminants they target. Low temperature desorbers attain temperatures

TABLE 14
FEASIBILITY OF IN-SITU RADIO FREQUENCY HEATING

Effectiveness of Technology	
Targeted Petroleum Contaminants	In-situ radio frequency heating can be used to remediate soils contaminated with gasoline, diesel fuel, and fuel oils, as well as other liquid hazardous wastes.
Treatment Effectiveness	No reliable field data is currently available on the effectiveness of this technology. Nevertheless, it can be expected to achieve relatively high removal efficiencies when used to heat and remove petroleum products with high volatilities. Even heavy oil with its low thermal conductivity can be heated to temperatures that will facilitate its removal through the boreholes, although such a process may consume considerable energy and take many months to complete. Radio frequency heating may be most effective in raising soil temperatures to levels that provide for more efficient use of other technologies—e.g., bioremediation or soil venting.
Key Parameters Affecting Technology Effectiveness	
<ul style="list-style-type: none"> • Soil conductivity: The conductivity of the soil at the site will determine the rate of heating that can be accomplished at different power levels. 	
Cost of Technology	
<p>The availability of a single vendor, coupled with the potentially high energy costs associated with this process, can make this technology expensive to employ. No reliable field data on the cost of this technology to remediate petroleum-contaminated soils is available. Nevertheless, the developers of the technology estimate that the radio frequency processing of contaminated soils "can be competitive with the cost of excavation and ex-situ incineration or thermal treatment." (97)</p>	
Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Radio frequency heating may be a cost-effective technology when the petroleum contaminated soil is located at least 5 meters below the ground surface. Boreholes can extend to depths of 300 meters, if necessary. • Radio frequency can be used in combination with horizontal drilling techniques to remove contamination that is located beneath buildings and other structures. • Radio frequency can be used effectively in combination with other technologies—e.g., vapor extraction—to accelerate the removal of petroleum contaminants. • The radio frequency system established at a site requires minimal setup and can be easily automated and controlled over a phone line; limited field monitoring is required during its operation.
Limitations	<ul style="list-style-type: none"> • The systems energy costs and time requirements can be extensive, depending on the size of the contaminated area and the number of boreholes required. • The field experience with this technology is still quite limited. • There may be difficulty in collecting the heated vapors or liquids from the heated region unless a suitable pressure can be maintained by the thermal gradient. • Suitable protection must be provided to workers from the electromagnetic fields produced by the process. May be difficult to achieve uniform heating over significant distances of the subsurface without a substantial number of closely spaced boreholes.
Time to Cleanup	<ul style="list-style-type: none"> • It is estimated that a single 13.56 Mhz applicator could achieve temperatures in excess of 100°C in between 150 and 450 cubic meters of soil around a single borehole over a period of 3 weeks to 3 months of continuous operation, depending on the soil conditions (97).
Commercial Availability	<ul style="list-style-type: none"> • This technology is available only from KAI Technologies, Inc., Woburn, MA. No other commercial vendors of this technology are known at this time.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • None.
Emission Control Equipment	<ul style="list-style-type: none"> • Vapor collection and treatment systems may be needed on-site for the heated contaminants.
Regulatory Issues	<ul style="list-style-type: none"> • Authorization for the use of specific transmitting frequencies must be obtained from the Federal Communications Commission (FCC). • This is not a technology well known to state environmental agencies.
Community Acceptability	<ul style="list-style-type: none"> • Unknown, although it is suspected that there would be some concern on the part of residents or others adjacent to the site over the electromagnetic field that is produced by the process.

from 177-260°C (350°- 500°F). They are suitable for use in remediating sites that contain volatile organic compounds such as gasoline, but “are not suitable for the remediation of semivolatile organic contaminants because the unit temperature is insufficient to desorb multi-ring polycyclic aromatic hydrocarbons.” (107) A number of vendors offer low temperature thermal desorbers for deployment on a site or at fixed, off-site facilities. Low temperature systems can be either direct or indirect in the method used for soil heating. *Medium* temperature desorbers are designed to achieve temperatures from 260-482°C (500°-900°F). As a result, they are effective in desorbing multi-ring polycyclic aromatic hydrocarbons (PAHs) such as fuel oil and diesel contamination. Although several vendors offer mobile units that can achieve these temperatures, most of the medium temperature desorbers are fixed facilities. *High* temperature thermal desorbers reach temperatures greater than 480°C (900°F) and often in excess of 650°C (1200°F). All high vapor pressure volatile organics and low pressure semivolatiles are effectively desorbed at temperatures this high. Because they are very costly to construct and operate, high temperature desorbers are usually reserved for the treatment of RCRA hazardous waste and are not cost-effective for treating petroleum-contaminated soils.

Different system designs and equipment can be used to obtain the operating temperatures and residence times necessary for the combustion process to occur. The thermal treatment process can be performed using (a) rotary dryers, (b) hot-mix asphalt plant aggregate dryers, (c), thermal screws, or (d) a conveyor furnace (101,106).

Rotary Dryers

Rotary dryers are the most commonly used thermal desorption technique. A rotary dryer is an inclined, cylindrical metal drum that relies on direct heat transfer to volatilize petroleum contaminants as they are passed through it. Before entering the dryer, the contaminated soil is screened to remove large debris that could clog the system. The soil then enters the dryer and is conveyed while rotating over a series of longitudinal lifters toward the burner flame located at the other end. Contaminated soil may remain in the dryer for as long as 7 minutes and be subjected to temperatures from 150-537°C (300 - 1,000°F). During this processing time, lighter-end petroleum products are destroyed, while the remaining contaminants vaporize from the heated soil and are carried toward the top of the dryer (called counter-flow design).

After exiting the dryer, the vaporized contaminants and process gases are passed through a cyclone and baghouse to remove the entrained particulates. The filtered off-gases are then directed to an afterburner where they are subjected to temperatures as high as 870°C (1,600°F) and destroyed. When the soil that exits the dryer is rehydrated and nutrients are added (if necessary) it is usually suitable for recycling.

Hot-Mix Asphalt Plants

The equipment used to dry aggregate before mixing it

with asphalt at asphalt plants has also been adapted to facilitate the thermal desorption of petroleum-contaminated soils. There are two basic types of hot-mix asphalt facilities: the batch plant and the continuous flow drum-mix plant. In a batch mix plant, the screening, blending, and heating steps of the asphalt production process are separate with one batch of product made at a time. Because the drier is stopped and started numerous times during the day, it is possible to modify the process to ensure that the levels of contamination in the soil do not exceed safe concentrations for the equipment and that proper temperatures in the drier are attained. In contrast, drum-mix plants size the aggregate, blend and heat it in one combined production step, and usually run continuously for extended periods of time. As a result, continuous flow drum-mix plants are not used as often as batch plants for petroleum-contaminated soil remediation.

While the processes are quite different, rotary dryers are commonly used and minimal process design changes can be made in them to achieve temperatures suitable for the removal of petroleum contaminants from soils being used as aggregate. Depending on the requirements of the state regulatory agency, improved soils-handling facilities and emission control devices such as wet scrubbers, afterburners, and baghouses may also be required to satisfy air quality concerns. While converted asphalt plants can handle a wide range of different soil feed sizes, and have considerable throughputs (up to 900 kilograms/hour), not all types of contaminated soils will be suitable for use in asphalt. Asphalt recycling requires a specific soil matrix if the end product is to meet U.S. Department of Transportation (DOT) specifications for road use. High concentrations of petroleum hydrocarbons in the soil may also preclude asphalt batching, although blending may be allowed to address this problem.

It is important to note that the treatment of petroleum-contaminated soils in asphalt batch plants may not destroy all of the petroleum contaminants like other processes. The temperatures used in the production of asphalt are typically high enough only to remove volatile organic compounds and three-ring PAH compounds. The heavier PAHs are generally incorporated into the basic asphalt product and may represent a product liability should the leaching of harmful compounds occur (101).

Contaminated soils have also been approved for use as replacement feed stock in cement kilns. As with asphalt production, contaminated soils used in this process must satisfy fairly strict acceptance criteria. However, cement kilns are very tightly regulated as incinerators (temperatures over 1370°C (2,500°F)) and require extensive and expensive permitting under RCRA Part B. While several cement kilns are now permitted to accept petroleum-contaminated soils, the cost of permitting new facilities under new federal and state boiler regulations will effectively eliminate cement kilns as viable mechanisms for thermal desorption in the future.

Thermal Screws

A thermal screw differs substantially from a rotary dryer. A thermal screw system typically includes one to four hollow screws, or augers, in a series or parallel configuration

**TABLE 15
FEASIBILITY OF IN-SITU AND EX-SITU VITRIFICATION**

Effectiveness of Technology	
Targeted Petroleum Contaminants	In-situ and ex-situ vitrification was designed primarily to encapsulate non-volatile inorganic materials. However, due to the extremely high temperatures that can be reached (up to 1,980°C), vitrification will also destroy by pyrolysis the full range of petroleum hydrocarbons that may exist in the soil matrix.
Treatment Effectiveness	The high temperatures achieved by the process will destroy all of the petroleum hydrocarbons that are present in the soil.
Key Parameters Affecting Technology Effectiveness	
<ul style="list-style-type: none"> <i>Depth to Groundwater:</i> In-situ vitrification will be effective only in the vadose zone. As long as water is not "free-flowing", water-saturated soils can be remediated although at significant cost. 	
Cost of Technology	
<p>The availability of a limited number of vendors, coupled with the high energy costs associated with this process, makes this technology extremely expensive to employ. The actual cost of vitrification will be most dependent on amount of water present in the soil and the cost of electricity in the area. In-situ vitrification can be expected to cost \$1,300 - \$1,570 per cubic meter (\$1000 - \$1200 per cubic yard) of contaminated soil; the overall cost of ex-situ vitrification will be \$1,045 - \$1,310 per cubic meter (\$800 - \$1000 per cubic yard)(17).</p>	
Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> Vitrification results in the complete destruction and permanent immobilization of all contaminants. As a result, the long-term liability and health/safety risks associated with excavation (in-situ only), treatment and other disposal options are eliminated. Vitrification can remediate an extremely wide range of different contaminants.
Limitations	<ul style="list-style-type: none"> In-situ vitrification is limited to contamination in the vadose zone and will only be effective to limited depths (7-15 meters). The field experience with in-situ vitrification is still somewhat limited; a recent problem with a sudden gas release at a large-scale test has raised some technical concerns. The high voltage used in the process, and the control of the off-gases, represent considerable health and safety risks for those operating the technology. The technology is complex and requires highly skilled staff to operate safely. Personal protective equipment may be necessary during the excavation process associated with ex-situ vitrification.
Time to Cleanup	<ul style="list-style-type: none"> Vitrification can be applied to approximately 3.6-4.5 megagrams (4-5 tons) of soil per hour and time is needed to move the processing equipment from one location to another. Wet soils will take the longest to remediate because the water must first be vaporized before melting of the soil matrix can occur. It is estimated that 7-8 months would be needed to remediate a site containing 15,300 cubic meters (20,000 cubic yards) of contaminated soil (17).
Commercial Availability	<ul style="list-style-type: none"> This technology is being developed principally by the Department of Energy. To date, only one vendor has been licensed by DOE to perform in-situ vitrification in the U.S. There are five vendors with proprietary ex-situ vitrification processes.
Residuals/Wastes Produced	<ul style="list-style-type: none"> No residual wastes are generated by in-situ vitrification, although the solid crystalline material that remains is effectively unusable. The use or disposal of the vitrified mass that results from ex-situ vitrification will be required.
Emission Control Equipment	<ul style="list-style-type: none"> A vacuum hood may need to be placed over the treatment area to capture off-gases. Contaminants may then need to be filtered from the off-gases.
Regulatory Issues	<ul style="list-style-type: none"> While in-situ vitrification has been used at a number of large sites, technical information about the process has been limited to the Department of Energy. A comparable lack of public information exists on the ex-situ processes.
Community Acceptability	<ul style="list-style-type: none"> Unknown.

within an enclosed vessel. The method of heat transfer is indirect; heated oil (steam or molten salt) is circulated from a process heater through the screw auger's hollow flights and jacketed vessel. As the hollow augers rotate and heat the soil, hydrocarbon contaminants vaporize and rise to the top of the vessel. The off-gases are then treated by a vapor recovery system that may include a condenser system combined with a baghouse and activated carbon adsorbers. Although thermal screws tend to operate at low throughputs, they generate smaller volumes of off-gases and thereby require smaller off-gas treatment systems than rotary dryers.

Conveyor Furnace

One vendor, U.S. Waste Thermal Processing (Irvine, California) uses a proprietary mobile conveyor furnace to heat the contaminated soils. The conveyor furnace is designed with propane burners that fire directly into a primary furnace. A flexible metal belt continually conveys the contaminated soil into the furnace chamber where it is heated by the burners. The off-gases that exit the furnace are passed through a treatment system that consists of an afterburner, a quench chamber, and a venturi-type scrubber.

All types of thermal desorption equipment follow the same basic treatment processing steps:

- Preparation of excavated soils for processing;
- Volatilization of petroleum hydrocarbons in a heating chamber;
- Exiting and recycling of clean soils;

Treatment of vaporized off-gases is an appropriate treatment system. However, the effectiveness of any particular desorption process will depend highly on its specific characteristics and specifications. Table 16 compares the general characteristics of the different thermal desorption equipment types. Figure 2 identifies the capabilities of the different types of thermal desorption systems to achieve soil discharge temperatures necessary to treat different types of petroleum products.

There are many low temperature thermal desorption units, including modified asphalt plants, that have been permitted to process petroleum-contaminated soils. Due to the high removal efficiencies that can be accomplished by thermal desorption, thermal units are most often found in states that have stringent soil cleanup standards. For cost competitive reasons, they are also located primarily in densely populated areas where the cost of landfilling is relatively high. Table 17 summarizes the conditions under which thermal treatment can be successful and cost-effective.

TABLE 16
GENERAL CHARACTERISTICS OF DIFFERENT THERMAL DESORPTION EQUIPMENT TYPES

Characteristic	Rotary Dryer	Asphalt Plant	Thermal Screw	Conveyor Furnace
Estimated No. of Systems	40 - 60	100 - 150	18 - 22	1
Mobility	Fixed & Mobile	Fixed	Mobile	Mobile
Soil throughput (Mg/hour)	9 - 45	23 - 91	3 - 14	5 - 9
Heat transfer method	Direct	Direct	Indirect	Direct
Soil mixing method	Drum rotation	Drum rotation	Auger	Soil agitators
Soil discharge temperature (°C)	150 - 315 ^a 315 - 480 ^d	315 - 650 ^b	150 - 260 ^c 150 - 425	150 - 260 ^c 540 - 870 ^c
Soil residence time (minutes)	3 - 7	3 - 7	30 - 70	3 - 10
Gas/solids flow	Parallel or Counter-current	Parallel or Counter-current	NA	Counter-current
Afterburner temperature (°C)	650 - 980	760 - 980 ^f	Generally not used	760 - 980
Removal efficiency (%):				
TPH	95 - 99.9	NA	64 - 99	>99.9
BTEX	NA	NA	>99	NA

Source: after (101)

^a Construction of carbon steel materials

^b Construction of alloy materials

^c Hot oil heat transfer system.

^d Molten salt heat transfer system.

^e Electrically heated system.

^f Not used on all systems.

NA =not available

TPH = total petroleum hydrocarbons

BTEX = benzene, toluene, ethylbenzene, xylene

TABLE 17
FEASIBILITY OF THERMAL DESORPTION SYSTEMS

Effectiveness of Technology	
Targeted Petroleum Contaminants	Thermal desorption is effective in reducing concentrations of a wide range of petroleum products including gasoline, diesel fuel, jet fuels, kerosene, heating oils and lubricating oils. Thermal desorption will be effective on all petroleum constituents that are volatile at temperatures up to 650°C.
Treatment Effectiveness	Depending upon the temperatures that are obtained by the specific process design, thermal desorbers often achieve removal efficiencies of >99%. The ability to achieve such high removal efficiencies at reasonable costs has made thermal treatment a popular method for achieving the relatively low TPH cleanup standards that exist in many states.

Key Parameters Affecting Technology Effectiveness

- **Contaminant Type and Concentration:** High molecular weight petroleum hydrocarbons (e.g. No. 6 fuel oil) will require higher treatment temperatures than the lower molecular weight hydrocarbons like gasoline. In addition, the concentrations of hydrocarbons in the soil must not exceed the safety limits set for the equipment being used. To minimize the risk of an explosion, steps may need to be taken to ensure that the hydrocarbon concentration in the soil does not result in overheating and damage to the desorber. The maximum allowable hydrocarbon level may also be limited by the capacity of the afterburner (101).
- **Soil moisture content:** The amount of moisture in the soil will influence soil processing rates and operating costs. In general, the higher the moisture content, the more difficult and costly it is to transfer heat and promote desorption. The optimal soil moisture range for thermal treatment is from 10 to 25 percent (18). Pre-treatment air drying or mechanical mixing with drier soils may be necessary to reduce soil moisture levels.
- **Soil type and particle size:** The conveyor systems of most thermal desorbers cannot handle large diameter soils, thereby requiring that the contaminated materials be carefully screened, crushed and/or shredded before processing. In addition, sand and gravel will desorb contaminants more quickly than clays and other fine-grained soils. Silt and clays can become entrained in the process gas and pass through the equipment without sufficient residence time. Treatment capacity is reduced by having to recycle this material back into the unit. A high fraction of fine silt or clay will also generate more dust and place a greater burden on the air pollution control equipment.
- **Metals Concentrations in Soil:** Some sites may be contaminated with petroleum product that contains high levels of lead. High metal concentrations may affect the suitability of the processed soil for reuse or disposal, and require greater emission controls.
- **Dryer Temperature and Residence Time:** The temperature reached in the heating chamber must be sufficient to destroy the targeted contaminants. The temperature that can be achieved by a unit will be affected by the moisture content of the soil, the concentration of contaminants present (heat capacity), particle size, and the heat transfer and mixing characteristics of the system. Soil residence time will also be important. Lower temperatures and longer residence times (which affect processing capacity) can produce the same results as higher temperatures and shorter residence times (101).

Cost of Technology

Mobile and Transportable Systems: There will be a number of fixed and operational costs associated with the use of mobile and transportable thermal desorption units. Fixed costs will include the costs of site preparation, permitting, equipment mobilization and demobilization, and will generally not depend on site size. Operational costs include the costs of labor and fuel oil which will be determined by the systems design capacity. In general, the following total costs might be expected for different sized sites (108):

< 5,000 tons	\$500 - \$1,500 per ton
5,000 - 15,000 tons	\$300 - \$900 per ton
15,000 - 30,000 tons	\$200 - \$600 per ton
> 30,000 tons	\$100 - \$400 per ton

On average, it is estimated that the cost of treatment by mobile systems will be in the range of \$98 - \$245 per cubic meter (\$50 to \$125 per ton) of soil (101).

Fixed Facilities: As with the mobile systems, the cost of processing petroleum-contaminated soils at fixed facilities will be very dependent on the quantity of soil to be processed, its moisture content, the nature of the contamination, and the cleanup standards to be achieved. The cost of treating petroleum-contaminated soils using asphalt plants will generally be the lowest--ranging from \$60-\$98 per cubic meter (\$30 to \$50 per ton). The cost of thermal stripping by new fixed facilities using rotary kiln or thermal screw technology will be higher--in the range of \$60 - \$160 per cubic meter (\$35 - \$80 per ton) (101). Costs will be higher for long transport distances.

TABLE 17 (continued)

Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • By completely destroying the petroleum contaminants, thermal treatment eliminates the long-term liability that is associated with other soil remediation technologies. • Excavation and off-site treatment allows for minimal (no) project delays; even on-site thermal treatment can be accomplished in far less time than bioremediation or soil venting. • Extensive treatability studies are usually not required; thermal treatment has been shown to consistently reduce TPH levels below 10 ppm and BTEX below 100 ppb (or lower). • Most thermal processing units are already permitted for use by the state regulatory agency; valuable time may be saved by utilizing a facility/treatment that has already received regulatory agency approval. • The thermal treatment process usually produces soil that with minimal enhancement and regulatory agency approval can be used for backfill or other construction uses. • Thermal desorption systems are relatively simple to design, construct and operate, either on-site or off-site. • Thermal soil remediation units can process large quantities of contaminated soil in short time periods; most units have processing capacities of at least 25 tons/hour.
Limitations	<ul style="list-style-type: none"> • May not be appropriate or cost-effective for wet soils or soil with high clay content; dewatering may be required to achieve satisfactory soil moisture content levels. • Care must be taken at the contaminated site to limit the excavation to contaminated soils only or risk increased project cost. • Transportation of excavated soils off-site can be expensive if the permitted thermal treatment facility is not located within a reasonable distance of the site. Also, many states require that the transport of the excavated soil be performed by carrier under manifest. • Use of on-site thermal units will require air permit from state regulatory agency. • Personal protective equipment may be required during soil excavation and handling; at fixed facilities, special measures may be required to ensure that Occupational Safety and Health Administration (OSHA) permissible exposure level for benzene is not exceeded. • Considerable space (up to 1 acre) may be needed to store the contaminated soils, prepare them for processing, and then store again following treatment. An on-site laboratory may also be required to characterize the pre- and post-treatment soils. • Some metals may be volatilized by the thermal desorption process and present special treatment problems.
Time to Cleanup	<ul style="list-style-type: none"> • The time needed for remediation will depend upon the amount of contaminated soil and the throughput capacity of the desorption equipment being used.
Commercial Availability	<ul style="list-style-type: none"> • There are numerous commercial thermal desorption units permitted and in operation throughout the U.S.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • Off-gases from heating chambers must be processed through treatment system to oxidize the remaining volatile contaminants and remove particulates.
Emission Control Equipment	<ul style="list-style-type: none"> • Volatiles in the off-gases may be burned in an afterburner, collected on activated carbon, or recovered in condenser equipment. A cyclone, baghouse or wet scrubber may be used to collect and reduce particulate emissions.
Regulatory Issues	<ul style="list-style-type: none"> • Most states require that operators of desorption systems obtain an air emission discharge permit and a solid waste permit. Many states also require pre- and post-treatment laboratory analysis of the soils.
Community Acceptability	<ul style="list-style-type: none"> • Low temperature thermal desorption units are generally well accepted by the public. However, high temperature units that are often perceived as incinerators capable of processing hazardous wastes and, as a result, vigorously opposed.

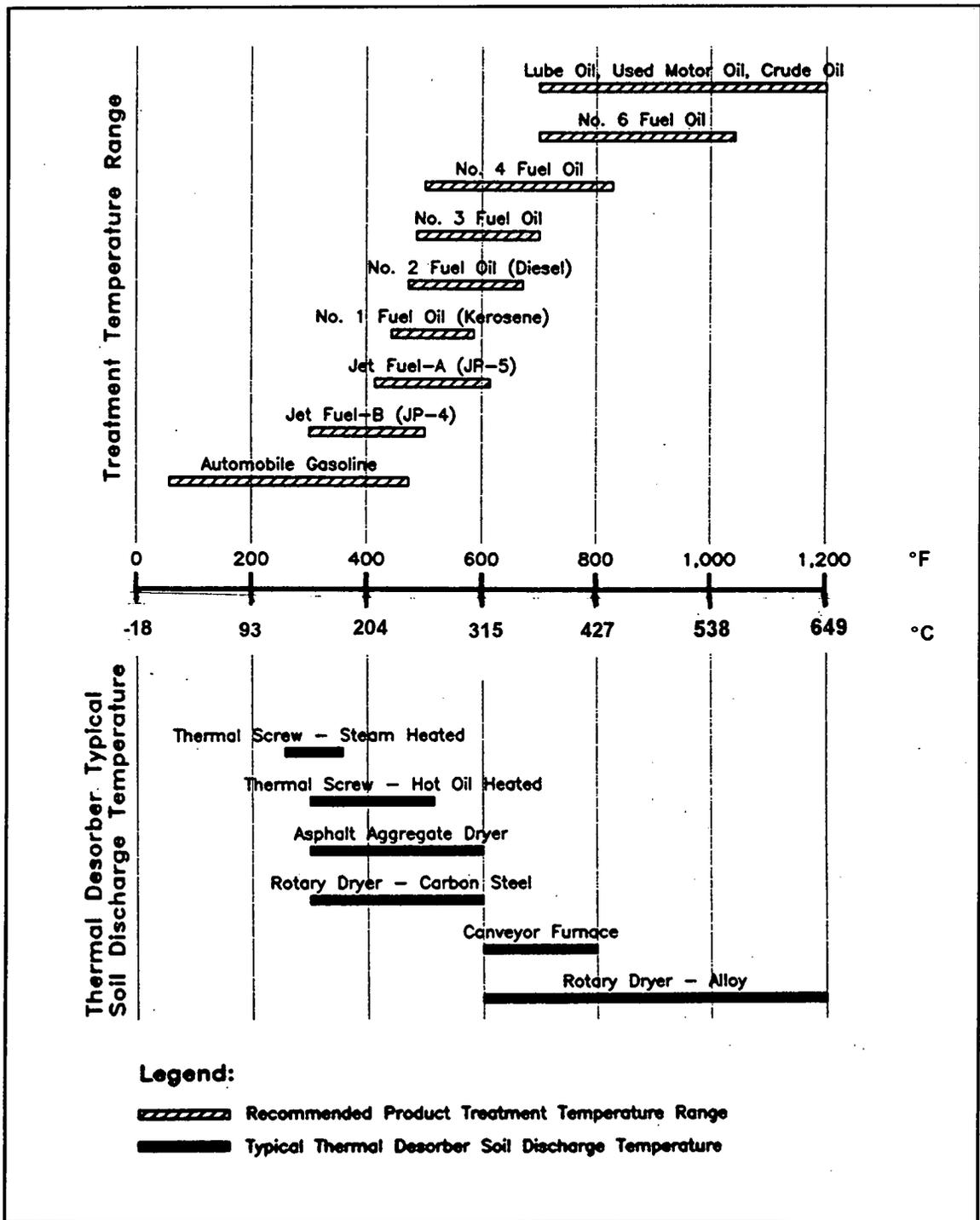


FIGURE 2 Ability of different thermal desorption equipment types to treat petroleum products.

CONTAINMENT TECHNOLOGIES

IN-SITU AND EX-SITU SOLIDIFICATION/STABILIZATION

Solidification/stabilization is one of the most frequently applied remedial technologies for cleaning up soils contaminated with hazardous organics or heavy metals (109), but is rarely used exclusively for petroleum-contaminated soils. Solidification/stabilization processes are designed to (a) physically bind or enclose the contaminants within a stabilized mass (solidification) and/or (b) induce chemical reactions in the soil that affect the susceptibility of the contaminants to leaching by reducing their solubility, mobility, or toxicity (stabilization). Solidification/stabilization processes produce solidified blocks of material with high structural integrity.

Contaminated soils can be stabilized and solidified by adding and mixing, in-situ or ex-situ, a variety of standard and propriety chemical agents. There are several groups of treatment chemicals commonly used (19):

- cements;
- limes plus pozzolans (fly ash, cement kiln dust, silicates, etc);
- thermoplastics (asphalt, bitumen, etc.);
- thermosetting organic polymers (ureas, phenolics, etc.).

The solidification and stabilization of soils containing petroleum hydrocarbons is usually accomplished by mixing the soil with cement or silicates. Silica encapsulation uses silica to micro-encapsulate hydrocarbons in a nonpermeable, nonporous amorphous silica matrix (110). Researchers at the Stevens Institute of Technology in Hoboken, New Jersey have performed several studies of the potential for substituting petroleum-contaminated soils in concrete for cement material (111,112). Their studies support the conclusion that, "the fixation of low hydrocarbon levels within concrete is a technically viable and safe technology for recycling petroleum-contaminated soil." (4) Soils containing petroleum contaminants in concentrations greater than 10 percent by weight have been found to interfere with the water-cement binding process and result in weaker concrete (19). In addition, fine soils that are contaminated with petroleum products are difficult to prepare for concrete incorporation, and tend to yield lower strength concrete than sand soils (111).

In-situ solidification/stabilization treatment processes use modified drill rigs with mixing blades to mix, aerate, and chemically treat the contaminated soils in place (113). When performing solidification/stabilization in place, proper mixing equipment must be used to produce uniform mixing of the contaminants and treatment chemicals (e.g., cement). There are several types of mobile injection treatment units

available (114,115,116) to provide stabilizing or other agents to the soil while traversing a site. Different configurations of the units allow for the delivery of microbial nutrients, the stripping of volatile organic compounds, vacuum extraction, soil flushing, and chemical extraction in addition to solidification/stabilization as the units traverse the site. A basic unit consists of a modified hydraulic excavator mounted to a trenching unit fitted with a series of interchangeable injector systems and full vapor recovery. Units are available to mix soils in place up to depths of 9.1 meters (30 feet). The unit works by pulling soil into the sealed housing while microbial nutrient mixtures, hot air, or cement slurry is added to facilitate biodegradation, vaporization, or cement construction. A dust collection shroud and vapor treatment system capture and treat the organic vapors produced by the mixing process. Ex-situ treatment will typically involve the use of trailer-mounted tanks, mechanical mixers, earth-moving equipment, and mixing drums.

The in-situ solidification/stabilization of petroleum-contaminated soils is not performed commonly. It is typically much more cost-effective to excavate and treat contaminated soils in aboveground tanks (117,118). The applicability, advantages, disadvantages, and costs of performing in-situ or ex-situ solidification/stabilization at petroleum-contaminated sites are summarized in Table 18.

IN-SITU OR EX-SITU CAPPING AND RE-USE

If the level of petroleum contamination in the soil is sufficiently low, some regulatory agencies will allow the soil to remain without treatment at the site, or be "reused" as construction material elsewhere, as long as it is capped by an impermeable surface (e.g., roadway or parking lot) to prevent future leaching. There are a number of reported instances where state regulatory agencies have allowed petroleum-contaminated soils to be contained by capping when (a) the concentration of petroleum product in the soil is *extremely* low (less than 100-200 ppm TPH), (b) and the location of the contamination is sufficiently removed from a groundwater source so as to make the risk of leaching and future contamination minimal or nonexistent. The stability of the soils must also be suitable for their intended use.

Regulatory agencies are generally reluctant to view in-situ or ex-situ capping as an acceptable soil remediation technology because doing so often undermines the real (or perceived) health risk basis of their soil cleanup standards. Most states allow petroleum-contaminated soils to be used as backfill only when the concentration of contamination is below state action levels. Where capping is allowed, regulatory agencies may require (a) that extensive soil analyses be

**TABLE 18
FEASIBILITY OF IN-SITU AND EX-SITU SOLIDIFICATION/STABILIZATION**

Effectiveness of Technology	
Targeted Petroleum Contaminants	Solidification/stabilization is most appropriate for use at sites containing inorganic wastes or heavy metals. Although the process can result in the fixation (in-situ or ex-situ) of low hydrocarbon levels, it is not usually performed at sites contaminated with petroleum products only.
Treatment Effectiveness	The ex-situ solidification/stabilization of soils containing low levels of petroleum contamination can be effective in fixating the petroleum hydrocarbons using either concrete or silicates. The removal efficiencies of in-situ solidification/stabilization processes are extremely variable due to the difficulty in achieving uniform mixing within the subsurface. Most in-situ solidification/stabilization processes are designed to stabilize heavy metals or other inorganics in the soil matrix, while removing the organic vapors by venting and aboveground treatment.
Key Parameters Affecting Technology Effectiveness	
<ul style="list-style-type: none"> • <i>Concentrations of Contaminants:</i> High concentrations of petroleum contaminants in the soil matrix can interfere with the solidification process and render the resulting material unusable. 	
Cost of Technology	
<p>No reliable data was found on the cost of remediating petroleum-contaminated soils by solidification/stabilization. The costs of remediating soils containing heavy metals and other hazardous wastes is usually in the range of \$200 - \$260 per cubic meter (\$150-\$200 per cubic yard). The cost of in-situ treatment is influenced mostly by the types and depth of contamination; ex-situ treatment by the type of solidification process or agents being employed.</p>	
Time and Other Considerations	
Advantages	<ul style="list-style-type: none"> • Both in-situ and ex-situ solidification/stabilization are simple processes performed with readily available equipment. • In-situ solidification/stabilization can be performed to depths of 12 meters or more without excavation.
Limitations	<ul style="list-style-type: none"> • It is often difficult to achieve uniform mixing of the treatment agent and contaminants when stabilization is performed in-situ; ex-situ treatment allows for better control over the mixing process. • Not cost-effective when concentrations of hydrocarbons in the soil matrix exceed 10 percent by weight. • Produces a solid block of material which if not recyclable or of sufficient quality (e.g., cement product) may render the site unsuitable for many types of activities (e.g., road or parking lot). Some processes produce material that is up to double the volume of the original mass. • Ex-situ treatment requires the availability of an area large enough for the mixing and treatment processes (if any). • Ex-situ processes may require the use of personal protective equipment during excavation operations.
Time to Cleanup	<ul style="list-style-type: none"> • Solidification/stabilization processes can be performed relatively quickly on large volumes of soil. For example, 23,000 cubic meters (20,000 tons) of contaminated soil would require less than 1 month to process ex-situ.
Commercial Availability	<ul style="list-style-type: none"> • There are numerous vendors capable of providing solidification/stabilization services.
Residuals/Wastes Produced	<ul style="list-style-type: none"> • Depending on the chemical reaction that takes place, the resulting mass may have to be handled and disposed of as a hazardous waste.
Emission Control Equipment	<ul style="list-style-type: none"> • For most in-situ processes, a vapor collection and treatment system (activated carbon bed) is needed to capture the hydrocarbon vapors produced by the mixing activity.
Regulatory Issues	<ul style="list-style-type: none"> • Although EPA and state regulatory agencies prefer treatment over containment, solidification/stabilization is one of the most frequently used remedial technologies.
Community Acceptability	<ul style="list-style-type: none"> • No community resistance to the use of this technology is expected.

performed, (b) that a soil reuse plan be developed and approved, and/or (c) that periodic monitoring be performed to ensure that contaminant migration is not occurring.

EX-SITU MICRO-CONTAINMENT BY COLD-MIX ASPHALT

Asphalt paving material is typically made by mixing aggregate and/or sand (90-95 percent by weight) with asphalt (5-10 percent by weight). The aggregate/sand provides the load-bearing properties of the mixture, while the asphalt serves as a binder and protective coating. In the cold-mix treatment of petroleum-contaminated soils, the contaminated soils are substituted for clean aggregate in the asphalt mix and the petroleum contaminants are encapsulated in the asphalt (19,119). Soils that are lightly contaminated with gasoline may be incorporated into cold-mix asphalt but will produce low quality asphalt, particularly if the soils contain high clay fractions and moisture content. Soils contaminated with No. 2, 4, or 6 fuel oil are more frequently cold-mixed, but also produce a final product that does not usually meet DOT paving standards. The asphalt product produced by using petroleum-contaminated soils has been found suitable as fill material and for the surfacing of light-duty access roads, storage areas, and parking lots (119,120).

The extent to which petroleum-contaminated soil is being incorporated into cold-mix asphalt paving material is not known. While the use of petroleum-contaminated soil results in the use of smaller quantities of asphalt emulsion, the cost savings to asphalt plant operators are not substantial. Depending on air quality requirements in the area, plant operators wanting to use contaminated soils as aggregate may have to institute emission control measures during their handling of the soil. Despite vendor claims, the ability of the cold-mix asphalt to immobilize contaminants is not well understood. As a result, regulatory agencies are not overly supportive of this technology.

EX-SITU LAND DISPOSAL OR LANDFILLING

Land disposal or landfilling involves disposing of the petroleum-contaminated soils in an approved municipal solid waste landfill where it is either placed in designated disposal cells or spread as daily cover. State regulations determine what type of petroleum contamination (if any) is allowed to be landfilled, the maximum concentration level of contaminants allowed, and the approved method of disposal (19). Importantly, the variability among states regarding the disposal of petroleum-contaminated soils at landfills is substantial. For example:

- In Connecticut, petroleum-contaminated soils can be

disposed of at municipal landfills only if the total BTEX concentration (benzene, toluene, ethylbenzene, and xylene) is <50 ppm and they pass the EP Toxicity Test.

- In Iowa, landfills are allowed to accept soils with total petroleum hydrocarbon (TPH) concentrations <100 ppm and use it as cover material.

- In Texas, landfills can accept soils with BTEX levels <500 ppm or TPH <1000 ppm.

- In Kentucky, only landfills that have incorporated certain technologies (liners, etc.) are permitted to accept petroleum-contaminated soils.

- In Maine, landfills are allowed to accept petroleum-contaminated soils, but are limited to the volume of soil they can accept each year.

- In Wyoming, soils contaminated with gasoline, diesel, fuel oil, or crude oil may be routinely accepted for disposal at permitted landfills. Soils containing waste oil and other petroleum products require special approval and can be disposed of only at approved landfill facilities.

- In Minnesota, landfilling of petroleum-contaminated soils is not allowed at all.

Landfill operators are also becoming creative in their use of petroleum-contaminated soil. It is reported that some landfills are actively seeking approval from state regulators to accept petroleum-contaminated soils and mix them with asphalt to create their landfill caps (121).

Because landfilling is a containment strategy and not a treatment technology, there are no data available on its effectiveness in reducing petroleum contaminant levels in the soils. However, if the petroleum-contaminated soil is spread and used as daily cover, the spreading and aeration activity will likely reduce the level of contamination. If the contaminated soils are placed in a special cell and covered, hydrocarbon concentrations can also be expected to decrease over time as the result of natural biological degradation.

In states where it is allowed, the cost of landfilling petroleum-contaminated soils depends largely on the transport distance from the site to the landfill, the availability of alternate landfills in the area, and the soil acceptance requirements (if any) placed on landfills in the state. In states that allow the use of petroleum-contaminated soils for daily cover, the cost of employing this technology equals the cost of transport from the site plus landfill tipping fees. Based on national statistics, the cost of landfilling petroleum-contaminated soils is estimated to be as low as \$20/m³ (\$10/ton) and as high as \$395/m³ (\$200/ton) (19). The highest costs will be incurred at landfills with lined disposal cells. Average landfill disposal costs will be in the range of \$40 to \$60/m³, plus excavation and transportation costs.

TRANSPORTATION AGENCY USE OF SOIL TREATMENT

A comprehensive questionnaire (see Appendix A) was sent to state transportation agencies in each of the 50 states, the District of Columbia, and Puerto Rico during the fall of 1994. The questionnaire requested information on the types of soil remediation technologies employed by the agency or its consultants in cleaning up petroleum-contaminated sites during the previous 2-year period. States were asked how frequently different soil remediation methods were used, why they were selected, and what alternative technologies were considered during the selection process. For a representative site that had been treated by a specific type of technology, site-specific information was also requested describing the type of petroleum contamination present, the media affected, the quantity of contaminated soils remediated, the reasons for selecting the technology, and the cost and effectiveness of the technology. A total of 37 states provided responses to the survey questionnaire.

The site-specific information that was requested in the survey has been summarized in tabular form in Appendix B by type of remediation technology. A total of 10 summary tables are provided. Each table describes for each of the states that submitted site-specific information:

- the type of contamination present at the representative site;
- the state action levels for the contaminants;

- the maximum concentrations of the contaminants found at the site;
- the quantity of contaminated soil that was treated/disposed;
- the cost of the cleanup;
- the primary reason(s) for selection of the remediation technology; and,
- the alternative technology(s) considered (if any).

Not all respondents provided site-specific information for every type of technology they indicated had been employed by their agency during the 2-year period. Nevertheless, the data that were provided are considered representative of transportation agency practices and have been used to profile and compare the remediation activities of state transportation agencies with other parties involved in petroleum-contaminated site cleanups.

PROFILE OF SITES BEING TREATED BY TRANSPORTATION AGENCIES

Types of Petroleum Products at Sites Treated by Transportation Agencies

Most petroleum-contaminated sites remediated by transportation agencies involve gasoline and/or diesel fuel releas-

TABLE 19
TYPE OF PETROLEUM PRODUCTS PREVALENT AT TRANSPORTATION AGENCY SITES

	Type of Petroleum Product Being Treated						TOTAL
	Gasoline	Diesel Fuel	Heating Fuel	Kerosene	Lubricating Oils	Solvents	
No. of Sites	66	48	5	5	4	2	130
Percent of Sites	50	38	4	4	3	1	100
Cumulative Percent	50	88	92	96	99	100	-
Remediation Technology Used: Most frequently Often Occasionally	Landfarming Thermal/Asphalt Plants Landfilling		Biopiles Landfarming Landfilling		Thermal/Asphalt Plants Landfilling Soil Washing		

Source: Appendix B

es. Table 19 summarizes the prevalence of different types of petroleum products found at the sites being cleaned up by transportation agencies that responded to the survey. As shown, almost 90 percent of the petroleum-contaminated sites that have been cleaned up by transportation agencies during the past 2 years have been contaminated with gasoline or diesel fuel. Transportation agencies have also been responsible for removing kerosene and heavier weight petroleum products such as heating oil and lubricating and waste oils, but at far fewer sites.

The prevalence of gasoline and diesel fuel contamination is indicative of the fact that most transportation agency encounters with petroleum contamination are the result of leaking underground fuel storage tanks at (a) agency maintenance facilities, and at (b) gasoline stations targeted (in whole or part) for acquisition due to a highway project. It may also reflect an awareness on the part of transportation officials to avoid sites whenever possible that are contaminated with heavier weight petroleum products, such as heating oils, that are more difficult and costly to treat than the lighter, more volatile gasoline and mid-distillate diesel products. This high incidence of gasoline and diesel fuel contaminated soil has allowed transportation agencies and their consultants to choose from among a much broader range of soil remediation technologies than would have been possible with soil containing heavier weight petroleum products.

Size of Petroleum-Contaminated Sites Being Treated by Transportation Agencies

Transportation agencies are not involved in the remediation of sites containing large amounts of petroleum-contaminated soils. Table 20 profiles the size of sites remediated by transportation agencies that responded to the survey. Approximately 62 percent of all the sites remediated by

transportation agencies during the 2 years prior to the fall, 1994 survey involved less than 383 m³ (500 yd³) of contaminated soil; 75 percent of all the sites involved less than 765 m³ (1,000 yd³) of soil. These statistics suggest that transportation agencies may be avoiding the acquisition of parcels containing large amounts of contaminated soils or are acquiring the minimal amount of right-of-way necessary to proceed with an impacted project.

These figures may also reflect a changing attitude on the part of some state environmental agencies toward the responsibility a transportation agency may have to treat the petroleum contamination found in agency right-of-way. Under Texas environmental regulations, for example, the Texas Department of Transportation is allowed to "do nothing" as long as the petroleum-contaminated area is not disturbed by road construction activities. When this is possible, responsibility for cleaning up the contaminated site falls on the Texas Natural Resource Conservation Commission. In one of the most important rulings of its kind, the Illinois Environmental Protection Agency recently concluded, based on a ruling by the U.S. EPA, that petroleum-contaminated soil excavated in a right-of-way can be redeposited in the same excavated area if the following five conditions are met (122):

- 1) The placement of the underground equipment, such as a storm sewer, cannot be allowed to act as a conduit for further migration of the contamination;
- 2) Impervious geological features, such as a clay till, cannot be punctured so as to open a path for contamination to migrate into an aquifer;
- 3) Cross-contamination of stacked fill material, which expands the area of contamination, cannot be allowed (the soil should not be stirred);
- 4) Migration of contamination from storm runoff due to the stockpiling of consolidated excavated soil cannot be

TABLE 20
AMOUNT OF PETROLEUM-CONTAMINATED SOIL TREATED
AT TRANSPORTATION AGENCY SITES

	Quantity of Treated Soil (cubic meters)					TOTAL
	0-38	39-77	78-383	384-765	> 765	
No. of Sites	11	7	33	11	21	83
Percent of Sites	13	9	40	13	25	100
Cumulative Percent	13	22	62	75	100	-
Remediation Technology Used:						
Most frequently	Landfarming		Landfarming/ Bio-piles		Thermal/Asphalt Plants	
Often	Thermal/Asphalt Plants		Landfilling		Soil Venting	
Occasionally	Bioremediation		Thermal/Asphalt Plants		Landfilling	

Source: Appendix B

1 cubic meter = 1.31 cubic yards

allowed (The agency did not put a time limit on stockpiling the excavated soil, but the material should be redeposited in the trench by the end of the day; otherwise, it should be covered with plastic until it is); and

5) Inversion of layers of contamination in the replaced soil is not allowed. (The contaminated soil needs to be placed back in the trench at the same layer from which it came.)

To meet these conditions, a profile of the contaminated zone at the site of excavation must be carefully delineated and the excavated soil cannot be graded. Where allowed, there may be many transportation agency sites where the nature of the construction activity and long-term use of the property might warrant the redeposition of contaminated soil into the site of excavation in place of costly treatment.

SOIL REMEDIATION METHODS IN PRACTICE

Types of Treatment Technologies Used by Transportation Agencies

Given the types of petroleum-contaminated sites for which they are responsible, state transportation agencies and their consultants have been able to select from and employ a broad range of alternative soil-remediation technologies. Table 21 indicates the number of sites in each responding state at which different soil remediation technologies were reported being used during the 2 years prior to the survey. The frequency of technology used to remediate transportation agency sites is also summarized in Figure 3.

Costs Incurred by Highway Agencies to Treat Petroleum-Contaminated Sites

Because every contaminated site is different, it is not possible to arrive at definitive cost estimates for the deployment of a specific soil remediation technology. The cost to remediate a site is heavily influenced by the amount of contaminated soil, the type and concentration of petroleum contamination present, the cleanup standard established for the site, the design requirements of the actual system that is employed, and the need for site treatability or pilot studies. As a result, the approximate cost to clean up a site by a particular technology is best represented by a range of costs expressed in terms of cubic yards or tons of contaminated soil.

Table 22 summarizes the reported range of costs that were incurred by transportation agencies to clean up sites using different types of soil remediation technologies. The range of reported costs in some cases is substantial. For example, landfarming was reported to cost anywhere from \$15/m³ to \$690/m³ to achieve cleanup. While these reported costs must be used cautiously, they appear to be comparable and consistent with the costs incurred by others involved in petroleum-contaminated site cleanups.

SUMMARY OF FINDINGS

Comparison of Transportation Agency Practices with State UST Programs

Transportation agencies are very comparable to other responsible parties in their selection and use of soil remedia-

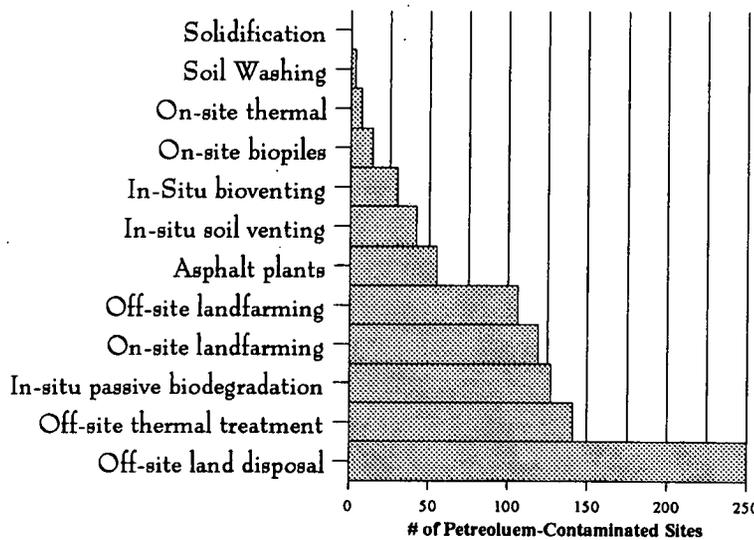


FIGURE 3 Number of sites treated by different soil remediation technologies.

TABLE 21 State Transportation Agency Use of Alternative Soil Remediation Technologies

Area	State	In-Situ/On-site Technologies					Ex-situ Technologies						Other	
		Soil Venting	Bioventing	Passive Biodegradation ^a	Thermal	Soil Washing	On-site Biotreatment		Excavation with Off-site Treatment					
							Biopiles	Landfarming	Landfarming ^b	Thermal	Asphalt Plants	Solidification		Land Disposal
NE	Massachusetts	2	1							2				
	Maine						1	1	2		1		3	1
	New Hampshire									4			1	
	Vermont	1					1							2
	New Jersey										19		23	6
	New York						1				6		44	2
	<i>Total for Area</i>	5	2	-	1	-	3	1	2	21	48	-	105	*
	Mid Atlantic	Delaware							1	22				
Maryland		1											1	
Pennsylvania										1			20	
West Virginia			1										11	
<i>Total for Area</i>		1	1	-	-	-	-	-	1	23	-	-	32	-
SE	Alabama	1						1	>25				>25	
	Georgia								1		4			
	Mississippi							2					3	
	North Carolina				3		2	25	7	29				
	South Carolina			28				13		16				
	<i>Total for Area</i>	1	-	28	3	-	2	41	>33	45	4	-	>28	-
North Central	Illinois	1											25	
	Indiana	1	1					1					17	
	Michigan	3		23		1							7	
	Minnesota						6		12	8	1			
	Wisconsin	1	1		1		1			6	1			
	<i>Total for Area</i>	6	2	23	1	1	7	1	12	14	2	-	49	-

^a The numbers in this category of technology must be interpreted cautiously. In the majority of states that reported the use of passive biodegradation (natural attenuation), its existence is **not** the result of risk assessment and regulatory approval, but rather a reflection of agency inaction or a lack of cleanup funds.

^b Composting is included in this category.

= No. of sites during past 2 years at which the soil remediation technology was used

TABLE 21 State Transportation Agency Use of Alternative Soil Remediation Technologies (Continued)

Area	State	In-Situ/On-site Technologies					Ex-situ Technologies							Other
		Soil Venting	Bioventing	Passive Biodegradation ^a	Thermal	Soil Washing	On-site Biotreatment		Excavation with Off-site Treatment					
							Biopiles	Landfarming	Landfarming ^b	Thermal	Asphalt Plants	Solidification	Land Disposal	
South	Arkansas						1		25					
	Louisiana							17					48	
	New Mexico	10					1	34	6		1		2	
	Oklahoma	1		11										
	Texas	2	5	50				3					- ^c	1
	<i>Total for Area</i>	13	5	61	-	-	2	54	31	-	1	-	50	*
Mid West	Kansas			12		1			3					
	Missouri							2	2				305	
	North Dakota												1	
	South Dakota	3											68	
	Utah	6	12	2				5					7	
	Wyoming												1	
	<i>Total for Area</i>	9	12	14	-	1	-	7	5	-	-	-	382	-
West	Arizona	4	3		2					1			5	
	Nevada	3	2							15			3	
	Oregon		1					8	12	17			11	
	Washington	1	2	1		1		9	8	5			2	
	<i>Total for Area</i>	8	8	1	2	1	-	17	20	38	-	-	21	-

No. of States	16	11	7	4	3	8	14	12	11	10	0	25	5
No. of Sites	43	30	127	7	3	14	121	>104	141	55	0	667	*
Percent of Total Sites	3	2	10	<1	<1	1	9	8	11	4	0	51	*

^a The numbers in this category of technology must be interpreted cautiously. In the majority of states that reported the use of passive biodegradation (natural attenuation), its existence is **not** the result of a risk assessment and regulatory approval, but rather a reflection of agency inaction or a lack of cleanup funds.

^b Composting is included in this category.

^c Although no estimate of the number of sites is given here, the Texas Department of Transportation relies heavily on excavation and off-site disposal to remediate petroleum-contaminated sites.

= No. of sites during past 2 years at which the soil remediation technology was used

**TABLE 22
COSTS INCURRED BY TRANSPORTATION AGENCIES
TO TREAT PETROLEUM-CONTAMINATED SITES**

Technology	# Sites	Transportation Agency Reported Cost of Cleanup (\$/cubic meter) ^a		Expected Range (\$/cubic meter) ^b
		Minimum	Maximum	
In-situ soil venting	7	\$ 7	\$ 249 ^c	\$100 - \$165 ^d
In-situ bioventing	3	\$ 12	\$ 17	\$13 - \$20
Passive biodegradation	1	\$ 8		\$7 - \$13 ^e
In-situ soil washing	1	\$ 175		\$65 - \$265
On-site thermal	2	\$ 55	\$ 160	\$100-\$245
On-site biopiles	6	\$ 20	\$ 225	\$60-\$165
Ex-situ landfarming	11	\$ 15	\$ 260 ^f	\$60 - \$120
Off-site thermal	8	\$ 55	\$ 260	\$69 - \$160
Asphalt plants	6	\$ 55	\$ 260	\$40 - \$65
Landfilling	12	\$ 5	\$ 220	\$40 - \$60

1 cubic meter - 1.31 cubic yards

^a Source: Appendix B.

^b Source: Chapters 3-6, Tables 4-15, 17, 18.

^c Involved heavily contaminated groundwater.

^d Excludes the cost of treating any offgases and collected groundwater.

^e There are no capital, operating or maintenance costs associated with natural attenuation. Costs are for initial site characterization, modeling, and periodic sampling to confirm degradation.

^f Involved excavation and off-site landfarming.

tion technologies. In 1992, the U.S. Environmental Protection Agency, Office of Underground Storage Tanks, conducted a limited survey of state agency officials to identify the range of alternative remediation technologies that were being employed nationally to clean up contaminated soils at underground storage tank (UST) sites (19). State officials responsible for the oversight of corrective action treatment technologies at leaking UST sites provided their best estimates of the number and status of corrective actions in their states. In its analysis of this survey data, EPA estimated the number (or percentage) of sites that had been remediated by technologies that fell into one of the following five major treatment/disposal categories:

- *Landfilling*: Includes all landfill disposal options.
- *Land Treatment*: Includes all forms of landfarming and other land applications, such as biopiles.
- *Thermal Treatment*: Includes all forms of thermal treatment, including treatment in asphalt plants.
- *In-Situ Treatment*: Includes all treatments that do not involve excavation, such as soil venting, bioventing, and passive biodegradation.
- *Other*: Includes soil washing and solidification/stabilization.

Figure 4 compares the findings of this EPA survey with the current practices of state transportation agencies. The percentage of transportation agency use of the above treatment categories is based on the data summarized in Table 21. In determining the percentages shown for transportation

agencies, it was assumed that roughly one-third or approximately 40 of the 127 sites where passive biodegradation was being used were actually state-approved corrective actions.

The comparison shown in Figure 4 indicates that the cleanup practices of state transportation agencies at petroleum-contaminated sites mirror closely those of overall state efforts to remediate UST sites, with the exception that state transportation agencies use land treatment technologies (e.g., landfarming) more frequently and in-situ treatment technologies (e.g., soil venting and bioventing) less frequently than may be the national norm. The higher rate of land treatment, especially landfarming, on the part of transportation agencies may be attributed to (a) the volatile nature of the petroleum products agencies typically deal with (see Table 19); and (b) the availability of space, typically at DOT maintenance facilities, to perform the land treatment process on relatively small quantities of contaminated soils (see Table 20). The lower rate of in-situ treatment may be the result of highway agency efforts to avoid the acquisition of sources of petroleum contamination and, whenever possible, become involved only in small strip cleanups.

Transportation Agency Selection of the Most Cost-Effective Technologies

The data summarized in tables 21 and 22 also indicate that transportation agencies and their consultants routinely select the most cost-effective soil remediation technology when remediating petroleum-contaminated sites. Moreover, what constitutes a cost-effective technology differs not only

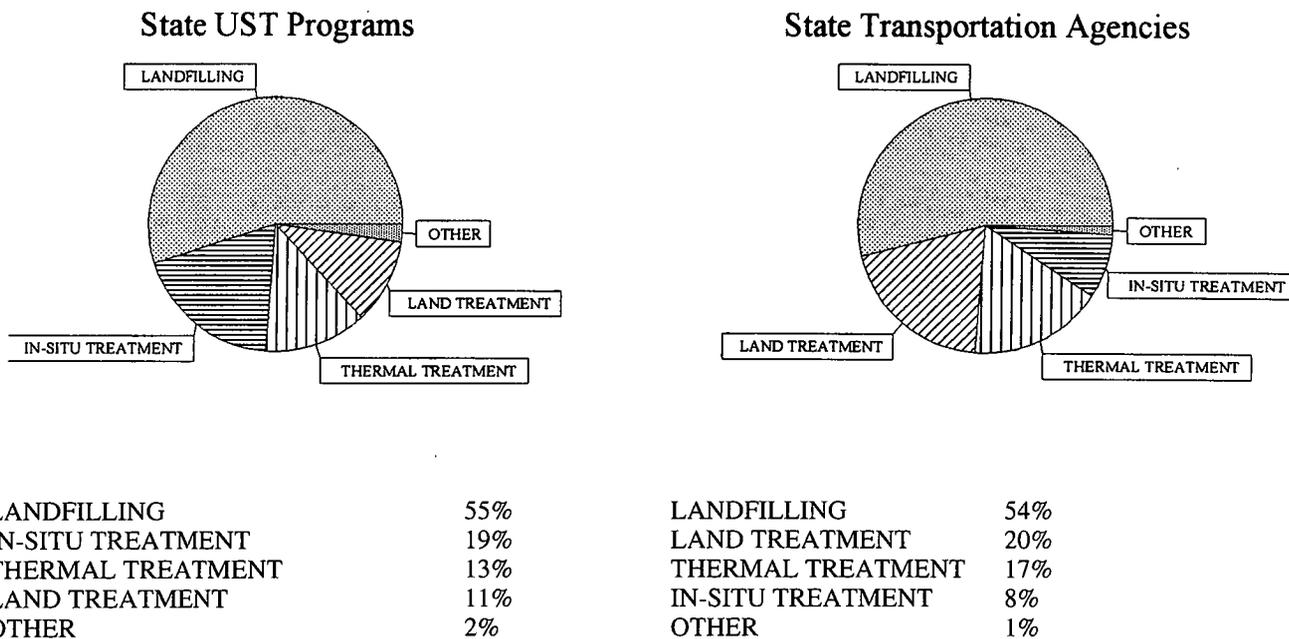


FIGURE 4 Reported use of soil remediation technologies by state transportation agencies and UST programs.

TABLE 23
RANKING OF TREATMENT/DISPOSAL TECHNOLOGIES BY GEOGRAPHICAL AREA

Ranking of Treatment/Disposal Categories by Geographical Area								
Rank	Northeast	Mid Atlantic	Southeast	North Central	South	Midwest	West	National Rank
1	Landfilling	Landfilling	Land Treatment	Landfilling	Land Treatment	Landfilling	Land Treatment	1 Landfilling
2	Thermal Treatment	Thermal Treatment	Thermal Treatment	Thermal Treatment	Landfilling	In-Situ Treatment	Thermal Treatment	2 Land Treatment
3	Land Treatment	Land Treatment	Landfilling	In-Situ Treatment	In-Situ Treatment	Land Treatment	Landfilling	3 Thermal Treatment
4	Other	In-Situ Treatment	In-Situ Treatment	Land Treatment	Other	Other	In-Situ Treatment	4 In-Situ Treatment
5	In-Situ Treatment	Other	Other	Other	Thermal Treatment	Thermal Treatment	Other	5 Other

Note: In ranking in-situ treatment, it was assumed that approximately one third of the reported number of sites where passive biodegradation was occurring were state-approved corrective actions.

from site to site but also from one geographic region of the country to another. The most cost-effective technology is the technology that can achieve the cleanup standards established for a specific site at the lowest overall cost.

Table 23 uses the data summarized in Table 21 to rank the five major treatment/disposal categories described earlier by geographical area of the United States. For each geographical area, the treatment/disposal options are assigned a rank on the basis of the number of sites at which the technology was reported used by a transportation agency during the past 2 years. A treatment category with a 1 ranking is the most frequently used in the region; a category with a 5 ranking is the least used technology in the region. The information in this table, together with Appendix B data, supports a number of conclusions.

Landfilling. Landfilling is the most cost-effective option available to many transportation agencies for disposing of petroleum-contaminated soils, particularly in states where petroleum-contaminated soil has not been banned or become too costly to dispose of in landfills. The high frequency of landfilling occurs despite the long-term liability that may accompany this activity.

That landfilling is currently the most preferred soil remediation option for most transportation agencies can be explained by the fact that the cost of landfilling petroleum-contaminated soils is still relatively inexpensive in many states (see Table 22), especially when small quantities of soil are involved. For example, under Texas' environmental regulations the Texas Department of Transportation can dispose

of mildly contaminated soil (TPH < 1500 ppm, BTEX < 10 ppm) in Type 1 municipal landfills for approximately \$13/m³. Soils containing higher levels of petroleum contamination are sent to commercial biopads where they are treated to below 1500 ppm TPH and then sent to a municipal landfill for use as daily cover. Even this intermediate processing is relatively inexpensive at approximately \$40/m³. In Wyoming, the Department of Transportation has adopted the policy of employing excavation and off-site disposal whenever small quantities (less than 380/m³ or 500/yd³) of contaminated soil are involved.

In addition, many state transportation agencies resort to the landfill option only when disposing of soils that contain very low concentrations of petroleum hydrocarbons (typically volatile gasoline). The contaminated soil that is landfilled in some states would not even be subject to cleanup in others. Consequently, the use of landfills as the preferred disposal option may not pose as great a risk as would their use for disposing of soils contaminated with heavier petroleum products or hazardous waste. In Illinois, the Department of Transportation limits the extent of its potential liability by requiring that all petroleum-contaminated soils be disposed of only in Illinois landfills (no out-of-state disposal) and only at landfills where the DOT already has liability as the result of its historical disposal of operational (maintenance) wastes.

Land Treatment. Where landfilling is either not possible, too costly, or discouraged for legal reasons, landfarming, including the use of biopiles, often becomes the most cost-effective soil remediation technology of choice to a highway

agency. As shown in Table 23, land treatment is the most frequently employed soil remediation option by transportation agencies located in those areas of the United States, the South and West, that (a) experience temperatures throughout most of the year in the range that is suitable for biodegradation, and (b) have sufficient land area available for use for extended periods of time. As was the case with landfilling, land treatment can be very cost-effective when there are relatively small quantities of lightly contaminated soils. In South Carolina, for example, the DOT routinely uses landfarming on any site with soils containing less than 100 ppm TPH and consisting of volatile constituents.

Thermal Treatment. The thermal treatment of contaminated soil typically off-site is also a preferred alternative for many state transportation agencies that cannot avail themselves of land treatment options. Thermal treatment technologies are used most frequently by transportation agencies in northern states (Northeast, Mid-Atlantic, Mid-East) with climates that are not conducive to landfarming. Although the cost of thermal treatment is typically greater than the cost of landfarming, environmental conditions in many states render landfarming either impractical or cost prohibitive due to the need to construct and maintain temperature-controlled enclosures. Therefore, where commercial thermal units exist within reasonable transport distances of a contaminated site, whether in the form of modified asphalt plants or low temperature thermal strippers, they are attractive options because (a) they are capable of effectively removing and destroying a broad range of petroleum hydrocarbons; (b) they do not generate harmful waste streams; (c) their use can eliminate the liability that would exist with landfilling; and (d) their existence indicates an acceptance of the technology on the part of regulatory agencies.

In-situ Treatment. With the emphasis placed by responsible parties (including transportation agencies) on the use of cost-effective soil remediation technologies, it would be expected that in-situ technologies that remediate the contaminated soil in-place and eliminate the need for and cost of soil excavation and on-site storage or treatment would rank very high. Of the in-situ treatment technologies now used by transportation agencies, soil venting is the most frequently used. That soil venting is not used more often is probably a reflection of the fact that (a) soil vapor extraction is best suited for larger sites and most sites being cleaned up by transportation agencies are relatively small in the volume of contaminated soil that must be treated; and (b) there is often insufficient time or space available on the right-of-way for the employment of the soil venting process. In addition, petroleum products do not generally require treatability tests or site pilot testing when venting is proposed. However, site pilot testing is often desired (or required by the regulatory agency) to determine the most effective system design. This additional cost can often make the overall cost of soil venting more expensive than alternative ex-situ processes. While soil washing is being performed in several states, it is not commonly used only to remove petroleum hydrocarbons. Soil washing (as well as soil flushing) is most appropriate at sites where the treatment of organics is also required.

What is perhaps most interesting about the use of soil remediation technologies by transportation agencies is the relatively low utilization of in-situ biological treatment technologies, particularly when the type of petroleum contamination targeted for cleanup consists primarily of gasoline and diesel fuel. Despite its well-publicized advantages, bioremediation is not presently being used on a widespread basis either in-situ or on-site (biopiles) by state transportation agencies. The somewhat limited use of bioremediation by state transportation agencies, indeed any responsible party, can be explained by the following conditions:

First, seasonal weather conditions in many states make both in-situ biotreatment as well as ex-situ land treatment impractical. While unsuitable soil conditions can be easily addressed by the addition of various amendments, maintaining suitable temperatures for degradation can become costly if environmentally controlled enclosures become necessary. Given the long periods of time needed for degradation to occur, biotreatment in the weather extremes of the Northeast, for example, may not be effective for at least 5 months of the year without temperature controls. The cost of such controls often makes the overall cost of this technology higher than other alternatives.

Second, the unavailability or high cost of land also makes biotreatment a relatively unattractive option in many states and areas. When petroleum-contaminated soils are discovered during highway project development in an urbanized area, it often becomes necessary to transport the excavated soils substantial distances to a suitable landfarming location. This additional cost of off-site transport may also render biotreatment uneconomical in comparison with other alternatives.

Third, although bioremediation is a viable remediation option for most petroleum-contaminated soils, its use requires extensive site characterization studies and usually treatability tests. Regulatory oversight is also generally greater with in-situ technologies. As a result, the projected costs of biological treatment technologies are often higher than alternative technologies in states that have yet to evaluate the feasibility of biotreatment carefully. A large investment in a treatability study to determine the applicability of a biotreatment technology at a site may not be viewed as a prudent use of limited transportation agency monies, nor be viewed as consistent with Federal Highway Administration (FHWA) policy toward the cleanup of contaminated sites (123).

Fourth, as described in chapter 2, many states still use total petroleum hydrocarbons (TPH) as the basis for determining treatment requirements and this approach to establishing cleanup levels makes it difficult to justify the effectiveness of bioremediation. There may also be provisions in the regulations of some states that effectively exclude or prohibit certain types of biological treatments. Until all state environmental regulatory agencies adopt chemical-specific, risk-based cleanup guidelines, the potential for biological technologies may be compromised.

Other Technologies. The majority of the technologies being used by transportation agencies fell into one of the above treatment/disposal categories. The states of Maine and

New Jersey, however, indicated that they had been allowed by their environmental agencies to "reuse" or dispose of their contaminated soils on their project sites as long as certain conditions were satisfied. In Maine, the DOT was allowed to dispose of petroleum-contaminated soils in the embankments of a bridge approach because (a) the concentration of volatile organic compounds in the soil was low (<200 ppm) and (b) it was located in a Maine Department of Environmental Protection "non-attainment area" where strict cleanups are not required. In New Jersey, soil that was contaminated was allowed to be reused as a subbase on a roadway project as long as (a) it had suitable characteristics for a subbase material; (b) a satisfactory cap was provided over the contaminated soil; and (c) the roadway was located far enough away from any groundwater source.

Chemical technologies are not being used by transporta-

tion agencies. Although chemical technologies are commercially available, they are not widely accepted by state environmental regulators.

In general, transportation agencies look to ex-situ soil remediation techniques far more often than they do in-situ techniques. The high rate of ex-situ treatment may also be a reflection of the fact that highway agencies continue to discover petroleum-contaminated sites late in the project development process. Faced with project deadlines and the unavailability of suitable space for treatment within the right-of-way, there remains no alternative but to excavate the contaminated soils and perform off-site treatment. Most importantly, ex-situ technologies, even with the cost of excavation and transport, are often the lowest cost option available to an agency when dealing with relatively small volumes of contaminated soils.

CONCLUSIONS

Despite concerted efforts to minimize their exposure to cleanup responsibility, transportation agencies often become responsible for cleaning up the petroleum-contaminated soils encountered when acquiring the land for or constructing new highway facilities. Agencies also shoulder the responsibility for cleaning up petroleum products that may have leaked into the soil from storage tanks located at transportation agency vehicle maintenance, storage, or other facilities. The selection of a soil remediation technology to employ at a petroleum-contaminated site is a difficult decision for a transportation agency. It requires the evaluation, in a phased approach, of numerous conditions associated with the contaminated site and alternative soil remediation technology(s). Because of the technical nature and data needs of the remedy selection process, many transportation agencies rely on environmental consultants or DOT specialists to provide the expertise needed to complete the process and to identify the most cost-effective alternative for the agency.

Based on the 1994 survey responses received for this synthesis, transportation agencies and their consultants are very much like other responsible parties involved in petroleum cleanups in the preferences they show toward the use of available soil remediation technologies. For example, transportation agencies are not in the business of environmental cleanup and, therefore, not disposed to devote considerable monies or staff resources to the cleanup of petroleum-contaminated soils. As a result, the majority of transportation agencies show a strong preference for soil cleanup technologies that are commercially available and thus relatively low cost. By using proven, state-permitted technologies, transportation agencies can avoid the economic risk often associated with the selection of an "innovative" cleanup technology.

Transportation agencies prefer ex-situ over in-situ technologies because they remove the petroleum contaminants either from the soil or from the site as quickly as possible. The need to commence or continue highway related work or agency vehicle maintenance activities as soon as possible within the area of contamination makes it impractical for most highway agencies to consider unproven in-situ technologies that often take a considerably long period of time to work. Off-site treatment/disposal is often the only viable alternative for highway agencies faced with imminent project construction and scheduling demands. Moreover, in-situ technologies are not particularly cost-effective when remediating the relatively small-sized sites that most transportation agencies are responsible for cleaning up.

Transportation agencies show a preference for technologies that are acceptable to the state environmental regulatory agency. A specific technology is "acceptable" if (a) the technology is considered by the regulatory agency to be an effective

method for remediating the petroleum contaminants in the soil that have been targeted for cleanup; (b) there are no specific state or local regulations inhibiting or discouraging field application of the technology; (c) no general state policies (e.g., restrictions on emission sources in air quality nonattainment areas) inconsistent with its use; (d) use of the technology does not require air quality or water discharge permits from the agency(s); and (e) the technology is one that does not generate adverse community reaction. By avoiding controversial "innovative" technologies, transportation agencies avoid the high cost and risk often associated with them.

Transportation agencies and their consultants also strive to select the most cost-effective soil cleanup technology whenever remediation at a petroleum-contaminated site is required. The most cost-effective technology at a site is the one that will achieve the soil cleanup standards established by the state regulatory agency at the lowest cost while also being responsive to anticipated time constraints and/or space limitations. Importantly, what constitutes a cost-effective technology is determined on a site-by-site basis. Soil remediation technologies that work well at one site may not be effective at another because of differences in the targeted petroleum compounds, unique soil or site conditions, and/or changes in the subsurface environment. What constitutes a cost-effective technology in a state is also affected by the range of effective technologies that are available. Important environmental (primarily temperature) differences between different geographic areas of the country, the commercial (un)availability of a particular soil remediation technology in an area, and/or the presence of state regulations or policies that inhibit or discourage the use of specific soil treatment technologies, can have a significant effect on the range of alternative options from which a transportation agency can choose to remediate petroleum-contaminated soil.

It appears that most transportation agencies have now adopted and are actively implementing policies and procedures which, by identifying petroleum-contaminated sites as early in project development as possible, provide the opportunity to avoid their acquisition and subsequent cleanup. This emphasis on early identification and avoidance of contaminated sites is clearly the best option. When avoidance is not possible, the early identification of a contaminated site may be very important in creating the time necessary to accomplish the cleanup by in-situ technologies that would otherwise not be practical.

At this time, transportation agencies and their consultants also appear to be selecting the most cost-effective soil remediation technologies appropriate for the petroleum-contaminated sites they encounter. However, the cost and regulatory

feasibility of soil remediation technologies cannot be considered static. In terms of cost, for example, it is unclear how much longer petroleum-contaminated soils will be welcome at landfills. While relatively inexpensive now in many geographic areas, the cost of landfilling petroleum-contaminated soils will inevitably rise as landfill space becomes more scarce and landfill operators become more selective in what they accept. As the cost of landfilling escalates, many transportation agencies may find that land disposal no longer emerges as the most cost-effective technology at even small petroleum-contaminated sites.

The regulatory environment surrounding petroleum-contaminated sites is also changing. Biological treatment technologies are becoming more widely accepted by environmental regulatory agencies and the risks of petroleum contamination better understood. State environmental regulations and policies that have hindered or prohibited the use of certain soil remediation techniques are being re-evaluated. In addition, many states are now adopting approaches to the establishment of site cleanup levels that are site-specific, risk-based, and do not use TPH as the indicator parameter. In states that do not have such risk-based standards, transportation agencies will benefit by becoming active participants in processes to change the existing standard cleanup procedures. As more state regulatory agencies embrace such chemical-specific, risk-based cleanup guidelines, the use of biological treatment methods (including natural attenuation) by transportation agencies at many of their sites may be viewed more favorably. This change in regulatory attitude may also provide transportation agencies with greater opportunity to argue for the controlled "reuse" of lightly contaminated soils within the limits of their projects as suitable sub-base or other construction material.

Much of the regulatory and technology related information needed during the technology selection process is constantly subject to change. The relative cost-effectiveness of alternative soil remediation technologies will differ not only from site to site, but also over time as the cost of existing treatment/disposal options change and/or new options (e.g., permitting of local asphalt plants to accept petroleum-contaminated soils) become commercially available in a particular geographic area. Transportation agencies and their consultants are encouraged to accumulate and use the most up-to-date cost and other information available as they undertake the technology evaluation and selection process at each petroleum-contaminated site they encounter.

The general guidance documents and computer databases that are now available to provide up-to-date information on the different soil remediation technologies, commercial vendors available, and field application results should help transportation agencies and their consultants make the best decisions possible when evaluating remediation options for a site. However, there are a few areas deserving additional information and research.

Development of Cost Information Database

Available information on the cost of employing alterna-

tive soil remediation technologies is typically available only on a total site-by-site basis. Due to different site conditions, and the differences in technology designs necessary to address those conditions, representative cost information for a particular type of technology must be expressed in terms of a fairly wide range of either total costs or cost per kilogram (ton) or cubic meter (cubic yard) of contaminated soil. In addition, the data provided are not always standardized. When cost estimates are given it is often not known which specific cost items they include (e.g., site characterization, treatability or bench-scale/pilot studies, capital and operating costs of the equipment, post-treatment monitoring costs, etc.). Improved cost data on alternative soil remediation technologies need to be collected and disseminated to transportation agencies so that the cost of competing technologies can be fairly compared.

Comparison of Estimated and Actual Costs of Soil Remediation

The selection of a specific remediation technology for use in treating the petroleum-contaminated soil at a site is based in part on the *estimated* costs of designing, installing, and operating the technology. These estimated costs are typically developed by a transportation agency or its consultants on the basis of site characterization studies and the technical and cost information provided by vendors who supply the elected components of the technology.

Several transportation agencies reported that the actual cost of employing a selected soil remediation technology at a site exceeded substantially the estimated cost on which its selection was based. A detailed evaluation of why such cost discrepancies developed would be useful to transportation agencies looking to avoid cost overruns whenever possible.

Evaluation of the Fate of Petroleum Contaminants in Landfills

As described in chapter 7, transportation agencies display a strong preference for the landfilling of petroleum-contaminated soils. The landfilling or *containment* of petroleum-contaminated soils occurs despite the availability of alternative *treatment* technologies and the potential for future liability that is assumed to accompany this practice. While the landfill choice is most often made on the basis of its immediate low dollar cost, the risk on the part of a transportation agency of having to participate in the future cleanup of a failed landfill may represent a far greater cost not represented in the selection decision.

Importantly, the risk that petroleum-contaminated soil will become a source of future liability when placed at a landfill depends not so much on its regulatory status as it does on its fate in the environment after disposal. Because landfilling is perceived as a containment strategy and not a treatment strategy, virtually no data are available on its effectiveness in reducing contaminants in the disposed soils. Yet, if the petroleum-contaminated soil is spread as daily cover,

the spreading and aeration activity is likely to reduce the level of contamination. Similarly, if the contaminated soils are placed in a special cell and covered, hydrocarbon concentrations can be expected to decrease over time from biological degradation. Further research on the fate of petroleum contaminants following their placement in landfills is necessary to better understand the risk associated with this soil

remediation option and its importance (if any) in the technology selection process. In the meantime, transportation agencies can minimize their potential liability (a) by limiting the total number of landfills they use, and (b) by sending their petroleum-contaminated soils only to those landfills in which they already have liability from their historical disposal of other hazardous wastes.

GLOSSARY

Adsorption: The adhesion of molecules of gas, liquid, or dissolved solids onto the surface of another substance.

Air Sparging: The injection of air below the water table to strip dissolved volatile organic compounds and/or oxygenate the ground water to facilitate the aerobic biodegradation of organic compounds.

Anaerobic: A process that occurs in, or is not destroyed by, the absence of oxygen.

Aquifer: An underground geologic formation, or group of formations, containing usable amounts of ground water that can supply wells or springs.

Aromatic: Compounds that resemble benzene in their chemical behavior.

Attainment Area: An area considered to have air quality as good as or better than the national ambient air quality standards as defined in the Clean Air Act. An area may be an attainment area for one pollutant and a non-attainment area for others.

Berm: A sloped wall or embankment used to prevent inflow or outflow of material into/from an area. Usually constructed of earth, hay bales, or timber framing.

Biodegradable: The ability to break down or decompose rapidly under natural conditions and processes.

Biodegradation: A process by which microbial organisms transform or alter the structure of chemicals introduced into the environment.

Biological Treatment: A treatment technology that uses microorganisms and the enzymes they produce to break down organic materials.

BTEX: Benzene, toluene, ethylbenzene, xylenes.

Characteristic: Any one of the four categories used in defining hazardous waste: ignitability, corrosivity, reactivity, and toxicity.

Chemical Treatment: Any one of a variety of technologies that use chemicals or a variety of chemical processes to alter or destroy contaminants in the soil.

Cleanup: Action taken to deal with a release or threat of release of a hazardous substance that could affect humans or the environment. The term "cleanup" is used interchangeably with the terms remediation, removal action, response action, or corrective action.

Constituent: An essential part or component of a group (e.g., an ingredient of a chemical mixture). For example, benzene is one constituent of gasoline.

Cost-Effective Alternative: An alternative treatment method identified after analysis as being the best available in terms of reliability, permanence, and economic considerations. Although costs are one important consideration, regulatory and other considerations may be more important in

some instances.

DOT: U.S. Department of Transportation.

Effluent: Wastewater treated or untreated that flows out of a treatment facility, sewer, or industrial outfall. Generally refers to wastes discharged into surface waters.

EPA: U.S. Environmental Protection Agency.

Ex-Situ: Moved from its original place; excavated; removed or recovered from the subsurface.

FCC: Federal Communications Commission.

Free Product: A petroleum hydrocarbon in the liquid phase.

Ground Water: The supply of fresh water found beneath the Earth's surface, usually in aquifers, which is often used for supplying wells and springs. Because ground water is a major source of drinking water, there is growing concern over areas where substances from leaking underground storage tanks or other waste areas are contaminating ground water.

Hazardous Waste: A solid waste that can pose a substantial or potential hazard to human health or the environment when improperly managed. Hazardous wastes possess one of four characteristics (ignitability, corrosivity, reactivity, or toxicity), or appear on special EPA lists.

Henry's Constant: The ratio of the concentration of a compound in air (or vapor) to the concentration of the compound in water under equilibrium conditions.

Hydrocarbon: Chemical compounds composed only of carbon and hydrogen.

Hydrology: The science of dealing with the properties, distribution, and circulation of water.

In-Situ: In its original place; unmoved; unexcavated; remaining in the subsurface.

Indigenous: Living or occurring naturally in a specific area or environment.

Injection Well: A well used to inject under pressure a liquid or gas into the subsurface.

Landfills: Sanitary landfills are land disposal sites for non-hazardous solid wastes at which the waste is spread in layers, compacted to the smallest practical volume, and cover material applied at the end of each day. Secure chemical landfills are disposal sites for hazardous wastes. They are designed to ensure that no wastes enter the environment.

Leachate: Any liquid, including any suspended materials in the liquid, that has percolated through or drained from a hazardous waste or other type of contamination.

Leaching: The process by which soluble constituents are dissolved and carried down through the soil by a percolating fluid.

Listed Waste: Wastes listed as hazardous under the Resource, Conservation and Recovery Act (RCRA) but

which have not been subjected to the Toxicity Characteristic Leaching Procedure because the dangers they present are considered self-evident.

Microorganisms: Microscopic organisms including bacteria, protozoans, yeast, fungi, mold, viruses, and algae.

National Pollutant Discharge Elimination System (NPDES): A provision of the Clean Water Act that prohibits discharge of pollutants into waters of the United States unless a special permit is issued by the U.S. Environmental Protection Agency, a state, or other designated agency.

Nutrients: Major elements (e.g., nitrogen and phosphorus) and trace elements (e.g., sulfur, potassium, calcium, and magnesium) that are essential for the growth of organisms.

Organic: Used to describe that which either is, contains, or relates to carbon compounds, especially compounds in which hydrogen is attached.

OSHA: Occupational Safety and Health Administration.

Permeability: A qualitative description of the relative ease with which rock, soil, or sediment will transmit a fluid (liquid or gas). For the purposes of this synthesis, permeability refers to Darcy's coefficient of permeability, expressed in units of cm/sec. This term can also be referred to as hydraulic conductivity, although in some fields the units of permeability and hydraulic conductivity differ.

pH: A measure of the acidity of a solution. A pH of 7 is neutral. Values less than 7 are acidic, and values greater than 7 are basic.

Physical Treatment: Processes designed to change the physical form of contaminants so they can be removed from the soil or encapsulate them to prevent them from leaching.

Polyaromatic Hydrocarbon (PAH): Aromatic hydrocarbons containing more than one fused benzene ring. Polyaromatic hydrocarbon is synonymous with polynuclear aromatic hydrocarbon (PNA).

ppm: parts per million.

Publicly Owned Treatment Works (POTW): A waste treatment works owned by a state, unit of local government, or Indian tribe, usually designed to treat domestic wastewaters.

Resource Conservation and Recovery Act (RCRA): a federal statute enacted as regulation 40 CFR 261 and designed to regulate the generation, treatment, storage, and disposal of hazardous waste.

Risk Assessment: The qualitative and quantitative evaluation performed in an effort to define the risk posed to human health and the environment by the presence or potential presence of specific contaminants or pollutants.

Saturated Zone: A subsurface area in which all pores and

spaces are filled with water under pressure equal to or greater than that of the atmosphere.

Site: The land area where any facility or activity is physically located or conducted, including any adjacent land used in connection with the facility or activity.

Solubility: The amount of mass of a compound that will dissolve in a unit volume of solution.

Thermal Treatment: Processes that use energy to destroy or detoxify contaminants.

Total Organic Carbon (TOC): A measure of the carbon present in a sample as part of organic compounds.

Total Petroleum Hydrocarbons (TPH): A measure of the concentration or mass of petroleum hydrocarbon constituents present in a given amount of soil, air, or water. The term total is misleading because the procedures for quantifying hydrocarbons are not capable of measuring all fractions of petroleum hydrocarbons present in a sample. Volatile hydrocarbons are often lost in the process and not quantified. Additionally, some non-petroleum hydrocarbons may be included in the analysis.

Toxic: Able to produce injury or disease in a living organism upon exposure, ingestion, inhalation, or assimilation.

Treatability Studies: Studies performed to better define the physical and chemical parameters of the technology and processes being evaluated.

Treatment: Any method, technique, or process designed to change the physical, chemical, or biological character or composition of a waste stream so as to eliminate it or render it nonhazardous.

Underground Storage Tank: A tank located all or partially under ground that is designed to hold gasoline or other petroleum products or chemical solutions.

Unsaturated Zone: The zone between the land surface and the capillary fringe within which the moisture content is less than saturation and pressure is less than atmospheric. Soil pore spaces also typically contain air or other gases.

Vadose Zone: The vadose zone refers to that region of soil that extends from the soil surface to the upper surface of the principal water-bearing formation at the location.

Volatile Organic Compound (VOC): Any organic compound that participates in atmospheric photochemical reactions.

Water Table: The water surface in an unconfined aquifer at which the fluid pressure in the pore spaces is at atmospheric pressure.

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APPENDIX A

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Project 20-5, Topic 26-01

ON-SITE REMEDIATION OF PETROLEUM-CONTAMINATED SOIL

QUESTIONNAIRE

Name of Respondent: _____

Agency: _____

Title: _____

Telephone No.: _____

INSTRUCTIONS

We would like to collect information from your agency on the type(s) of remediation technologies being employed to clean up sites that have soil contaminated with different types of petroleum (e.g., gasoline, diesel fuel, heating oil). These sites may be located on existing agency property (e.g., maintenance facilities) or on rights-of-way being acquired for new projects. While the removal of free petroleum product and petroleum hydrocarbons dissolved in groundwater is extremely important, this survey is interested only in collecting information on the technologies being used to remove **petroleum contamination from soil**.

This questionnaire should be filled out by staff who have responsibility for cleaning up petroleum contamination at agency facilities as well as on sites acquired during project development. These staff persons may have responsibilities for either (a) directly managing the cleanup of these petroleum-contaminated sites by in-house staff, or (b) managing contractors hired by the agency to perform such cleanups. If petroleum-contaminated site cleanup in your state is performed by a contractor(s), it may be necessary to forward this questionnaire to the appropriate contractor representative(s) for response.

Please answer as many of the following questions as possible. Please also provide copies of any supporting data or reports whenever it is available. Please send your completed questionnaire and supporting documentation to:

David J. Friend
19 Notre Dame Road
Bedford, MA 01730
Tel/Fax 617-275-4845

If you have any questions, please feel free to contact Mr. Friend at 617-275-4845, or Mr. Stephen Maher, TRB Program Officer, at 202-334-3242.

We would appreciate your response by October 15, 1994.

APPENDIX A (Continued)

1. During the past 2 years, how many petroleum-contaminated sites have been cleaned up by your agency? [Note: a site is a location that required the cleanup of petroleum contaminated soils using a specific treatment technology, regardless of the number or type of tanks from which the petroleum leaked.

_____ (#)

2. During this 2-year period, which of the following technologies were selected to remediate the petroleum-contaminated soil at these sites? Please indicate with a ✓ the technology(s) that was selected and the number of sites at which it was employed.

<i>Alternative Remediation Method</i>	<i>Check ✓ If Used</i>	<i># of Sites</i>
In-situ Soil Vapor Extraction (also known as vacuum extraction or soil venting; includes steam enhanced extraction)		
In-situ Bioremediation (includes bioventing)		
In-situ Passive Biodegradation		
On-site Low Temperature Thermal Desorption		
On-site Soil Washing (includes water flushing and vacuum enhanced recovery)		
Ex-situ Bioremediation: Biomounding		
Land Farming		
Composting		
Excavation/Off-site Treatment by: Landfarming		
Thermal treatment		
Asphalt incorporation		
Solidification		
Excavation with Off-site Land Disposal		
Other (please specify):		

APPENDIX A (Continued)

3. For *each* of the unique soil remediation methods checked above, select a *single* representative site from among those at which the technology was used and provide the following information for that site.

We would like following information for each unique type of remediation technology that has been employed by your agency. If there is any technical difference in the remediation method used at different contaminated sites, please answer the following questions for each of the technologies/sites. For example, assume your agency was involved in the cleanup of petroleum-contaminated soil at 12 sites during the past 2 years. The petroleum hydrocarbons in the soil at eight (8) of the sites were removed using the same type of soil vapor extraction method; the remaining four (4) sites were cleaned up using ex-situ bioremediation (specifically composting). Select one of the sites remediated by vapor extraction and provide the following information. Also select one of the sites where composting was selected and provide the following information for that technology/site as well.

Please make additional copies of this and the following pages if you are providing information on more than two soil remediation technologies.

<i>Description</i>	<i>Units</i>	<i>Technology: _____</i>	<i>Technology: _____</i>
Location of site:	Examples: Maintenance Facility Old Gasoline station		
Type of petroleum contamination:	Examples: gasoline diesel fuel fuel oil kerosene		
Media affected by the contamination:	Examples: soil only soil and groundwater		
Quantity of Petroleum-Contaminated Soil	Specify in cubic yards or tons		
State Action Level* for petroleum in soil (Please indicate action level for each parameter/constituent of interest)	Examples: 100 ppm TPH BTEX > 10 ppm		
Maximum concentration of petroleum parameter/constituent found at the site	Examples: 300 ppm TPH 50 ppm BTEX		

* The state action level refers to the concentration of a specific parameter/constituent above which action must be taken to remediate the contaminated soil.

APPENDIX A (Continued)

4. For the same technology/sites described above in #3, please indicate with a ✓ who actually performed the cleanup of the site once the petroleum-contaminated soil was discovered and found to exceed acceptable state action levels:

<i>Responsibility for Cleanup</i>	<i>Technology:</i> _____	<i>Technology:</i> _____
Cleanup activities completed in-house by Agency staff		
Cleanup activities performed by specialty contractor(s)		
Other (please describe): _____ _____		

5. For the same technology/sites described above, please also provide brief answers to each of the following questions about the specific soil remediation method that was used. If additional space is needed for your answers, feel free to attach separate sheets of explanatory information.

	<i>Technology:</i> _____	<i>Technology:</i> _____
Was the selected technology commercially available or developed specifically for this site?		
What were the most important factors that influenced your decision to use this soil remediation technology at this site?		
What alternative soil treatment methods were considered at this site? Why were they rejected?		

APPENDIX A (Continued)

	<i>Technology:</i> _____	<i>Technology:</i> _____
How effective was the selected technology in achieving the designated state cleanup standard for petroleum in soil? What percentage of the petroleum hydrocarbons in the soil were removed by the process?		
How much time was needed to remediate this petroleum-contaminated site using the selected technology? This should reflect the time needed to achieve a "clean" site.* Was the amount of time needed greater than expected?		
How much did it cost to employ the selected soil remediation technology? Costs should include equipment, operation and maintenance. Provide a breakdown of cost, if available. Were these costs greater than anticipated?		
Based on your experience at this site, what are the constraints or limitations of this soil remediation technology?		
What regulatory requirements and other considerations required compliance in order to use the selected remediation technology at this site?		

* For technologies applied on-site, this will include the time spent obtaining necessary regulatory approvals/permits, mobilizing equipment on-site, and operation of the process until the desired cleanup standard was achieved. For technologies involving excavation and off-site treatment/disposal, this will include the time spent getting the contaminated soil off-site to the treatment/disposal facility.

APPENDIX A (Continued)

	<i>Technology:</i> _____	<i>Technology:</i> _____
<p>Did your use of contractors to provide the soil remediation technology at this site require the use of special contract provisions? If yes, please indicate the contract requirements that were important to the successful implementation of this technology. Samples of contract provisions would be appreciated.</p>		
<p>Will you use this technology to clean up future sites containing petroleum-contaminated soils? If yes, why? If no, why not?</p>		

6. Please provide a brief description of the process used in your agency for selecting a soil treatment method. Please also provide copies of any reports that describe the soil remediation technology that was employed at the above sites. If the remediation was performed by a contractor, please provide below the name, address, and telephone number of the contractors' representative to contact for clarification and additional information, if needed.

7. Based on your experiences in cleaning up sites with petroleum-contaminated soil, what additional guidance or information would help you in the future when selecting a remediation technology for different sites? _____

Thank you for participating in this important survey.

APPENDIX B**Biological Treatment**

TABLE B-1	Reported Use of In-situ Passive Biodegradation by State Transportation Agencies
TABLE B-2	Reported Use of In-situ Bioventing by State Transportation Agencies
TABLE B-3	Reported Use of Ex-situ Biopiles by State Transportation Agencies
TABLE B-4	Reported Use of Ex-situ Landfarming/Composting by State Transportation Agencies

Physical Treatment

TABLE B-5	Reported Use of In-situ Soil Venting by State Transportation Agencies
TABLE B-6	Reported Use of In-situ Soil Washing or Flushing by State Transportation Agencies

Thermal Treatment

TABLE B-7	Reported Use of On-site Thermal Treatment by State Transportation Agencies
TABLE B-8	Reported Use of Off-site Thermal Treatment by State Transportation Agencies
TABLE B-9	Reported Use of Asphalt Plants by State Transportation Agencies

Containment

TABLE B-10	Reported Use of Land Disposal (Landfilling) by State Transportation Agencies
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APPENDIX B (Continued)

TABLE B-1 Reported Use of Passive Biodegradation (Natural Attenuation) by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
S. Carolina	South Carolina indicated that 28 sites are "passively biodegrading." Importantly, the employment of this technology at these sites is not the result of risk assessments and regulatory approvals but rather the unavailability of funding for cleanup from the State Underground Petroleum Environmental Response Fund (SUPERB). Alternative, in-situ methods will be actively evaluated once cleanup funds become available.						
Michigan	Michigan indicated that in-situ passive biodegradation was being employed at "at least 23 sites." It is expected, however, that the use of this technology at the majority of these sites is not the result of an explicit regulatory decision allowing its use, but rather the reflection of regulatory inaction.						
Oklahoma	In Oklahoma., eleven sites at ODOT maintenance facilities are currently being remediated by passive biodegradation. Although it appears that the Oklahoma Corporation Commission (OCC) might prefer alternative remediation technologies at some or all of these sites, it has yet to issue its final recommendations . In the meantime, ODOT is actively monitoring contaminant levels at the sites and reporting to the OCC.						
Texas	Texas DOT indicated that passive biodegradation was occurring at over 50 petroleum-contaminated sites. Once again, these appear to be sites which have yet to be acted upon by the Texas Natural Resource Conservation Commission. Texas environmental regulations allow TxDOT, as a petroleum tank owner, to "do nothing" if the contamination will not be directly disturbed by road construction.						
Kansas	Gasoline and diesel fuel in soil and groundwater	100 ppm TPH in soils 5 ppb Benzene in water	7700 ppb Benzene in water	NA	NA	Groundwater contamination was isolated and not migrating off-site Low cost Regulatory agency approval	None
Utah	Diesel fuel in soil	500 ppm TPH	480 ppm TPH	50 cy	\$320.00 lab fees	Concentrations at site were below the recommended cleanup levels to begin with	Excavation and landfarming
Washington	Gasoline in soil	100 ppm Gas	3000 ppm Gas	160 cy	NA	NA	NA

NA = information not available

cy = cubic yards

APPENDIX B (Continued)

TABLE B-2 Reported Use of In-Situ Bioventing by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Connecticut	Diesel fuel and fuel oil in soil	100 ppm TPH	5000 ppm TPH	NA	NA	Minimize liability Expected lowest cost	Ex-situ thermal Excavation/off-site disposal
W. Virginia	Gasoline in soil and groundwater	100 ppm TPH	<100 ppm to 4,000 ppm TPH	800 cy	+ \$500,000	Allowed for construction of bridge without having to excavate and dispose of all contaminated soil at site	Soil vapor extraction Excavation/off-site disposal
Wisconsin	Gasoline in soil and groundwater	NA	NA	11,000 cy	+ \$100,000 (\$9/cy)	Appropriate for site Minimize long-term liability Low cost	Landfilling rejected due to liability
Utah	Gasoline and diesel fuel in soil and groundwater	NA	NA	5,000 cy	> \$63,500 (\$13/cy)	Location of site and soil conditions compatible with bioventing	None
Nevada	Diesel fuel in soil	100 ppm TPH	10,000 ppm TPH	NA	NA	Excavation alternatives unacceptable to nearby residential area	Excavation/off-site disposal
Washington	Gasoline in soil	100 ppm TPH	400 ppm TPH	50 cy	NA	Low cost Appropriate to site	NA

NA = information not available

cy = cubic yards

* Most of the contaminated soil in the W. Virginia project was excavated and disposed of off-site. However, the bioventing being performed to remediate the contaminated groundwater is also degrading the hydrocarbons remaining the soil.

The states of Massachusetts, Indiana, Texas, Arizona and Oregon have also indicated using bioventing to remediate sites, but did not provide sufficient information to complete this table. In several instances, bioventing projects were just getting underway.

APPENDIX B (Continued)

TABLE B-3 Reported Use of Ex-Situ Biopiles by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Maine	Gasoline in soil	50 ppm Gas	300 ppm	1000 cy	\$105,600 ^a (\$106/cy)	Required by regulatory mandate Low cost Availability of site	Thermal treatment
Minnesota	Gasoline in soil and groundwater	50 ppm TPH	1600 ppm TPH	310 cy	\$13/cy	Effective Low cost	Thermal treatment
New York	Gasoline in soil and groundwater	10 ppm	7800 ppm BTEX	370 cy	\$1.4 million ^b	DOT told that system would remove contaminants quickly	Soil venting
North Carolina	Gasoline, diesel fuel, and kerosene in soil and groundwater	10 ppm TPH gas 40 ppm TPH diesel/kerosene	11,6299 ppm gas 2,966 ppm diesel 761 ppm kerosene	150 cy	\$4,100. (\$27/cy)	Low cost	In-situ soil venting
Wisconsin	Gasoline and diesel in soil	250 ppm DRO	290 ppm DRO	325 cy	\$56,000 (\$172/cy)	Minimize liability Low cost	NA
Arkansas	Diesel and kerosene in soil	100 ppm TPH > 5 ppm BTEX	21,000 ppm TPH	110 cy	\$40/cy	Availability of space and time to deal w/high concentrations	In-situ bioremediation

NA = information not available

cy = cubic yards

^a This cost reflects the use of Maine DOT staff to operate the biopile system.

^b This original estimate for establishing the bioremediation system was \$555,000; contractor inexperience has contributed to excessive costs for this remediation effort.

The states of Vermont and New Mexico also indicated using biopiles to remediate petroleum-contaminated soils, but did not provide the above requested information.

APPENDIX B (Continued)

TABLE B-4 Reported Use of Ex-Situ Landfarming/Composting ^a by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Maine	Diesel and fuel oil in soil and groundwater	10 ppm TPH	300 ppm TPH	100 cy	\$52,500 ^b	Availability of land and treatment equipment Low cost	Ex-situ thermal treatment
Delaware	Gasoline in soil and groundwater	100 ppm TPH 10 ppm BTEX	678 ppm TPH 294 ppm BTEX	28 tons	\$1,600 (\$86/cy)	Immediate soil removal needed to expedite bridge project	Ex-situ thermal treatment
Alabama	Gasoline and diesel fuel in soil	100 ppm TPH 10 ppm BTEX	2000 ppm TPH 5 ppb benzene	500 cy	\$100,000 (\$200/cy)	Lowest cost Project required off-site treatment	Excavation/off-site landfill
Georgia	Diesel fuel in soil and groundwater	500 ppm TPH 100 ppb BTEX	3,362 ppm TPH 450 ppb BTEX	700 cy	NA	Lowest cost	None
Mississippi (on-site)	Gasoline in soil	100 ppm BTEX	243 ppm BTEX	450 cy	\$15,000 (\$33/cy)	Low cost Convenience	None
North Carolina	Gasoline and diesel fuel in soil and groundwater	10 ppm Gas 40 ppm Diesel	568 ppm Gas 56 ppm Diesel	NA	\$10, 000	Donation of land/equipment Low Cost	Thermal treatment Ex-situ composting
North Carolina (on-site)	Gasoline and diesel fuel in soil and groundwater	40 ppm Gas 250 ppm Diesel	1,650 ppm Gas 850 ppm Diesel	480 cy	\$5,350 (\$11/cy)	Availability of treatment area Low cost	Composting
Minnesota	Diesel fuel in soil and groundwater	50 ppm TPH	1,100 ppm TPH	300 cy	\$3,600. (\$12/cy)	Effectiveness Low cost	None
Arkansas	Gasoline and diesel fuel in soil	100 ppm TPH	200 ppm TPH	50 cy	\$1,750 (\$35/cy)	Low cost Ease of removal Availability of treatment site	None
New Mexico	Gasoline and diesel fuel in soil	100 ppm TPH	550 ppm TPH	150 cy	\$5,000 (\$33/cy)	Low cost Rural site = available land	None

APPENDIX B (Continued)

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Kansas	Gasoline and diesel fuel in soil and groundwater	100 ppm TPH	> 100 ppm TPH	150 cy	\$5,000 (\$33/cy)	Availability of nearby landfarming facility Low cost Agency approval	In-situ treatment
Missouri	Gasoline in soil	200 ppm TPH 1 ppm Benzene 5 ppm Toluene 10 ppm Ethylben 10 ppm Xylene	2,588 ppm TPH 48 ppm Benzene 366 ppm Toluene 170 ppm Ethylben 944 ppm Xylene	981 cy	NA	Low cost versus landfilling	On-site landfarming Off-site landfilling
Missouri (on-site)	Gasoline and diesel fuel in soil	25 ppm TPH	400 ppm TPH	75 cy	\$7,975 (\$106/cy)	Availability of space on-site	Excavation/off-site land disposal Excavation/off-site landfarming
Missouri (off-site)	Gasoline in soil	200 ppm TPH	2588 ppm TPH	980 cy	NA	Low cost	Excavation /off-site land disposal
Oregon	Diesel fuel in soil	40 ppm Gas 100 ppm Diesel	NA	212 tons	\$3,500 (\$25/cy)	Availability of space Low cost Low contaminant levels	Excavation/off-site thermal Excavation/off-site land disposal
Washington	Gasoline and diesel fuel in soil	100 ppm Gas 200 ppm Diesel	17,000 ppm Gas 12,000 ppm Diesel	500 cy	NA	Low cost Effectiveness	NA
Washington (on-site)	Gasoline and diesel fuel in soil	100 ppm Gas 200 ppm Diesel	2,400 ppm Gas	2,000 cy	NA	Low cost Effectiveness	NA

NA = information or data not available

cy = cubic yards

^a All of the landfarming activities described above were performed off-site, unless otherwise specified.

^b This cost reflects the use of Maine DOT staff to operate the land treatment areas.

APPENDIX B (Continued)

TABLE B-5 Reported Use of In-Situ Soil Venting by State Transportation Agencies

State *	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Connecticut	Gasoline in soil and groundwater	100 ppm TPH Total VOC	3000 ppm BTEX	NA	NA	Minimize liability Lowest cost	Ex-situ thermal Excavation/off-site disposal
Massachusetts	Gasoline in soil and groundwater	1000 ppm TPH 10 ppm BTEX	14,720 ppm BTEX (in groundwater)	2500 cy	\$475,000 (\$190/cy)	Contaminant plume affecting residential dwelling unit and nearby river	None
Maryland	Gasoline and chlorinated solvents in soil and groundwater	100 ppm TPH	NA	> 4000 cy	\$ 1 million	Presence of chlorinated solvents	NA
Illinois	Gasoline and diesel fuel oil in soil and groundwater	NA	1,100 ppm TPH	> 15,000 cy	NA	Proximity of existing facilities	Excavation/off-site disposal
Michigan	Gasoline in soil and groundwater	24 ppb Benzene 16,000 ppb Toluene 1,500 ppb Ethylben 5,600 ppb Xylene	Pure product	> 30,000 cy	\$ 450,000 (\$ 15/cy)	Size of site required in-situ, inexpensive solution	Excavation/off-site disposal
Wisconsin	Gasoline in soil and groundwater	NA	6,600 ppm BTEX	7-10,000 cy	> \$200,000 (\$20/cy)	Most appropriate for site conditions Minimize long-term liability Lowest cost	NA
New Mexico	Gasoline and diesel fuel in soil and groundwater	100 ppm TPH	1,200 ppm TPH	149 cy	> \$220,000	Consultant recommendation	None
Oklahoma	Gasoline, diesel fuel and kerosene in soil and groundwater	0.5 ppm Benzene 40 ppm Toluene 15 ppm Ethylben 50 ppm Xylene	290 ppm Benzene	NA	NA	Pilot program performed by OSU	None
S. Dakota	Gasoline in soil	10 ppm TPH	11,600 ppm TPH	400 cy	> \$45,600 (\$114/cy)	Contamination had migrated under building	Excavation/off-site disposal
Utah	Gasoline and diesel fuel in soil and groundwater	30 ppm TPH	1,900 ppm TPH	>50,000 cy	> \$225,000 (\$5/cy)	Presence of contaminated groundwater	Ex-situ solutions too costly Bioremediation
Arizona	Gasoline and diesel fuel in soil	100 ppm TPH 13 ppm Benzene 200 ppm Toluene 68 ppm Ethylben 44 ppm Xylene	45,800 ppm TPH 10.3 ppm Benzene 9 ppm Toluene 29 ppm Ethylben 72 ppm Xylene	120,000 cy	NA	Size and depth of contaminated area Lowest cost	NA
Washington	Gasoline in soil	100 ppm TPH	1400 ppm TPH	2,000 cy	NA	Lowest cost	NA

NA = information or data not available
cy = cubic yards

The states of Alabama, Indiana, Nevada, Texas, and Vermont also indicated that in-situ soil venting had been used to remediate DOT sites during the past 2 years. However, insufficient information was provided to complete this table.

APPENDIX B (Continued)

TABLE B-6 Reported Use of In-Situ Soil Washing or Soil Flushing by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Kansas	Gasoline and diesel fuel in soil	100 ppm TPH	>100 ppm TPH	150 cy	\$20,000 (\$133/cy)	No groundwater contamination Low cost Regulatory agency approval	Off-site disposal Off-site soil washing Off-site landfarming
Washington	Hydraulic fluid in soil	200 ppm TPH	30,000 ppm TPH	20 cy	NA	Low cost Proven effectiveness Short remediation time	NA

NA = information not available

cy = cubic yards

The state of Michigan also indicated that soil washing had been used to remediate a petroleum-contaminated site, but did not provide sufficient information to complete this table.

TABLE B-7 Reported Use of On-Site Thermal Treatment by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Connecticut	Gasoline, diesel, and fuel oil in soil	100 ppm TPH 10 ppm VOC	1000 ppm TPH 1000 ppm VOC	NA	\$35/ton	Minimize liability Low cost Reuse soil	Excavation/off-site disposal Off-site thermal
North Carolina	Gasoline in soil	40 ppm Gas	1594 ppm Gas	204 cy	\$9,156 (\$45/cy)	Lack of adequate time and space for alternative technologies Willingness to try new technology	Landfarming Off-site thermal
Wisconsin	Gasoline in soil	250 ppm GRO	2100 ppm GRO	300 tons	\$30,000 (\$100/ton)	Minimize liability Low cost	NA

NA = information not available

cy = cubic yards

APPENDIX B (Continued)

TABLE B-8 Reported Use of Off-site Thermal Treatment (non-asphalt plant) by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Connecticut	Gasoline and diesel fuel in soil	100 ppm TPH 10 ppm VOC	1000 ppm TPH 1000 ppm VOC	NA	\$90/ton	Low cost Minimize liability Project logistics	Excavation w/off-site landfilling
Delaware	Gasoline in soil	100 ppm TPH 10 ppm BTEX	2780 ppm TPH 0.015 ppm BTEX	65 tons	\$4,000. (\$92/cy)	Minimize liability Need to immediately remove soil for project construction	None
Pennsylvania	Diesel fuel in soil	200 ppm TPH	18,000 ppm TPH	1812 tons	\$152,000 (\$126/cy)	Easy to implement Low cost	None
North Carolina	Gasoline, diesel fuel, and kerosene in soil	10 ppm gas 40 ppm diesel 40 ppm kerosene	216 ppm gas 1310 diesel/ kerosene	NA	\$47,500 (\$39/cy)	Need to immediately remove soil from site Low cost	Ex-situ composting
South Carolina	Gasoline, diesel fuel and waste oil in soil and groundwater	100 ppm TPH	6900 ppm TPH	250 cy	\$80/cy	Requested use due to high concentrations of contaminants Commercially available and commonly used Need for immediate removal	None at time, although off-site bioremediation would be considered now
Minnesota	Gasoline, diesel fuel and used oil in soil	50 ppm TPH	20,000 ppm TPH	165 cy	\$45/cy	Lack of suitable space for biomounding or landfarming	Biomounding Landfarming
Wisconsin	Gasoline and diesel fuel in soil	250 ppm GRO	1,250 ppm GRO	500 cy	\$51,000 (\$102/cy)	Minimize long-term liability Low cost	NA
Nevada	Diesel fuel in soil	100 ppm TPH	10,000 ppm TPH	50 cy	NA	Most efficient method for such small quantity Low cost	NA
Oregon	Gasoline and diesel fuel in soil	40 ppm gas 100 ppm diesel	8,500 ppm gas 12 ppm diesel	431 tons	\$45,500 (\$158/cy)	Most convenient	None
Washington	Mixed non-chlorinated solvents in soil	200 ppm	400 ppm	150 cy	NA	Low cost Effectiveness	NA

NA = information not available

cy = cubic yards

The state of Arizona also indicated that off-site thermal treatment was being used to remediate petroleum-contaminated soils, but did not provide sufficient information to complete this table.

APPENDIX B (Continued)

TABLE B-9 Reported Use of Hot-Mix Asphalt Plants by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Connecticut	Gasoline in soil	100 ppm TPH	500 ppm TPH 950 ppm VOC	NA	\$40/ton	Low silt content	Excavation w/off-site disposal Off-site thermal
Maine	Gasoline in soil	10 ppm TPH	7800 ppm TPH	2,000 cy	\$160,000 (\$80/cy)	Allowed for prompt cleanup of the site	Bioventing Landfarming
New Hampshire	Gasoline in soil and groundwater	100 ppm TPH 10 ppm gas 1 ppm BTEX	1,700 ppm TPH 400 ppm BTEX	9100 tons	\$478,000 (\$80/cy)	Need for removal to expedite project	In-situ bioremediation
New York	Gasoline in soil and groundwater	Site specific	4,877 ppm TPH 458 ppm BTEX	2,685 cy	\$60 - \$120 cy	Low cost Eliminate future liability	None
Georgia	Diesel fuel in soil	100 ppm TPH 20 ppb BTEX	21,559 ppm TPH 501 ppb BTEX	928 tons	\$26/ton	Lowest cost	None
Minnesota	Hydraulic oil in soil	50 ppm TPH	8,700 ppm TPH	16 cy	NA	Lowest cost for such small quantity of soil	None
Wisconsin	Gasoline and diesel in soil	250 ppm GRO	1,230 ppm GRO	250 tons	\$34,000 (\$200/cy)	Eliminate long-term liability Low cost	NA

NA = information not available

cy = cubic yards

The states of Massachusetts, New Jersey, and New Mexico also indicated that asphalt plants were being used to remediate petroleum-contaminated soils, but did not provide sufficient information to complete this table.

APPENDIX B (Continued)

TABLE B-10 Reported Use of Land Disposal (Landfilling) by State Transportation Agencies

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Connecticut	Organics and inorganics in soil	100 ppm TPH 10x DWS (TCLP) Inorganics	300 ppm TPH 21 ppm Pb	NA	\$80/ton	High concentration of inorganics	None
Maine	Gasoline in soil	50 ppm gas	Unknown	150 cy	\$2,000 (\$13/cy)	Need for immediate removal to continue project construction	None
New Hampshire	Gasoline in soil	100 ppm TPH 10 ppm gas 1 ppm BTEX	130 ppm TPH	900 cy	\$2,000 (\$3/cy)	Low cost	None
New York	Gasoline in soil and groundwater	Site specific	47,402 ppm TPH 0.4 ppm BTEX	600 cy	\$55-\$150/ton	Necessary to avoid project delay Low cost Readily available option	None
Maryland	Gasoline in soil	100 ppm TPH	>100 ppm TPH	>100 cy	\$30/ton	Most expedient	None
Alabama	Gasoline and diesel fuel in soil and groundwater	100 ppm TPH	120,000 ppm TPH	6000 tons	\$800,000 (\$200/cy)	Large volume of soil and high concentrations of contaminants precluded other options Low relative cost Needed to remove for project	Bioremediation
Mississippi	Gasoline in soil	100 ppm BTEX	4,583 ppm BTEX	3,500 tons	\$106,000 (\$45/cy)	Removal required to avoid project delay	None
Indiana	Gasoline in soil	100 ppm TPH	2,080 ppm TPH	200 cy	NA	Need to remove soil quickly and avoid project delay	None

APPENDIX B (Continued)

State	Type of Contamination	State Action Level(s)	Maximum Concentration at site	Quantity of Contaminated Soil	Cost of Cleanup	Primary reason(s) for selecting this technology	Other technologies considered ?
Louisiana	Gasoline, diesel fuel, and used oil in soil and groundwater	1500 ppm gas 300 ppm diesel 100 ppm BTEX	5000 ppm gas 800 ppm diesel 1500 ppm BTEX	3500 cy	\$100/cy	Needed to remove from site quickly for project schedule Low cost Quantity of soil required off-site removal (no on-site storage) High concentrations levels limited on-site options	NA
Missouri	Diesel fuel and kerosene in foil	100 ppm TPH	940 ppm TPH	150 cy	\$25,000 (\$167/cy)	Excavation and off-site disposal minimized disruption to existing operations at facility Low overall cost Lack of area to landfarm	Landfarming (on- or off-site)
South Dakota	Gasoline and fuel oil in soil	100 ppm TPH	3150 ppm TPH	128 cy	\$21,100 (\$165/cy)	Low cost	None
Utah	Gasoline, diesel fuel, and used oils in soil	Site-specific	12,800 ppm TPH	500 tons	\$42.85/ton	Location required removal	Bioremediation
Oregon	Gasoline and diesel fuel in soil	80 ppm gas 500 ppm diesel	264 ppm gas 177 ppm diesel	1,400 cy	\$7,700. (\$6/cy)	Convenient option Low cost Least amount of time required	Thermal treatment
Washington	Diesel and fuel oil in soil	200 ppm diesel	1100 ppm	600 cy	NA	Low cost-effectiveness	NA

NA = information not available

cy = cubic yards

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**Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
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