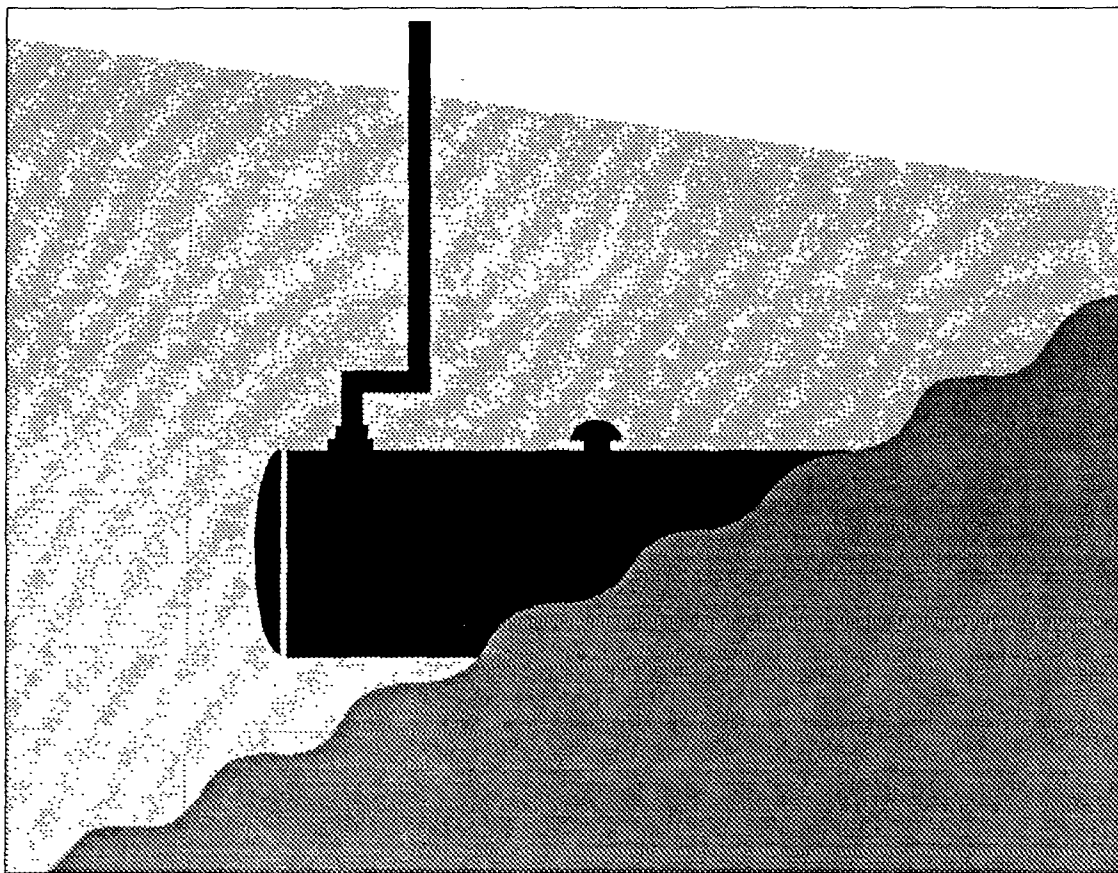




Technologies and Options for UST Corrective Actions:

EPA/542/R-92/010
August 1992

Overview of Current Practice



EPA/542/R-92/010
August 1992

TECHNOLOGIES AND OPTIONS FOR UST CORRECTIVE ACTIONS: OVERVIEW OF CURRENT PRACTICE

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ACRONYMS

B	Benzene
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
C	Celsius
cm/s	Centimeters per Second
DOT	Department of Transportation
E	Ethylbenzene
EPA	Environmental Protection Agency
F	Fahrenheit
F.O.	Fuel Oil
FP	Free product
GAC	Granulated Activated Carbon
IR/F	Infrared and Fluorescence
LTTS	Low Temperature Thermal Strippers
LUST	Leaking Underground Storage Tanks
mg/l	Milligrams per liter (equivalent to ppm for water)
MPCA	Minnesota Pollution Control Agency
N.D.	Not Detected
OUST	Office of Underground Storage Tanks
OVA	Organic Vapor Analyzer
PAH	Polynuclear Aromatic Hydrocarbons
PCS	Petroleum Contaminated Soil
POTW	Publicly Owned Treatment Works
ppb	Parts per billion (equivalent to $\mu\text{g/kg}$ for soils)
ppm	Parts per million (equivalent to mg/kg for soils)
ppmv	Parts per million volume
RCRA	Resource Conservation Recovery Act
S/S	Stabilization/Solidification
SVE	Soil Vapor Extraction
T	Toluene
TC	Toxicity Characteristic
TCLP	Toxicity Characteristic Leaching Procedure
TPH	Total Petroleum Hydrocarbons
TRPH	Total Recoverable Petroleum Hydrocarbons
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency
UST	Underground Storage Tank
VOC	Volatile Organic Compound
X	Total Xylenes (meta-, para-, ortho-)

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

A number of ex-situ and in-situ technologies are currently being used across the U.S. to treat petroleum contaminated media and debris generated at leaking underground storage tank (UST) corrective action sites. The objectives of this study are:

- To examine the current level of use of corrective action treatment technologies at leaking underground storage tank sites;
- To summarize experience with these technologies as documented in the literature in terms of treatment efficiency, relationship of performance to key operating parameters, and costs; and
- To summarize current state requirements that may affect the selection of technologies.

1.2 INFORMATION SOURCES

This study was based on information collected by the Environmental Protection Agency's (EPA) Office of Underground Storage Tanks (OUST) from the following sources:

- State regulatory agencies;
- EPA dockets for various rulemaking packages;
- Published literature;
- EPA data bases; and
- Discussions with technical experts.

This information was collected during the period of August 1990 through June 1991.

State Regulatory Agencies. Underground storage tank officials in 26 states were contacted to request data on UST corrective actions and state standards governing the management of petroleum contaminated media and debris. Initial contacts in each state were identified by EPA UST Regional Program Managers. Subsequent contacts were identified through state agency referrals. Each contact was asked to characterize the types and accessibility of data that the state maintains for UST sites and to explain how their particular state manages petroleum contaminated media and debris, from initiation of UST corrective actions to the final disposal or treatment and closure. Officials were also asked to provide copies of any regulations and/or guidance documents that would outline their requirements and policies.

State officials were contacted by telephone from October, 1990 through February, 1991. The majority of the written comments were received in February, 1991 with the last received in May 1991.

EPA Dockets. Information from the dockets for a number of EPA rulemaking packages was reviewed in early 1991. The most important docket sources for purposes of this study included the Technical Standards for Corrective Action Requirements for Owners and Operators of Underground Storage Tanks (UST) (April 17, 1987), the final Toxicity Characteristic rule (March 29, 1990) and the "Third Third" Land Disposal Restrictions rule (June 1, 1990).

Scientific Publications: A computer-assisted literature search (Dialog) was performed to identify relevant information in published literature. Search criteria included references to USTs, various petroleum classifications, petroleum storage facilities, remedial technologies, analytical procedures, and contamination studies. The search included literature published through June 1991.

EPA Computerized Data Bases. Two EPA-managed data bases were accessed as part of this study effort. The Revelation Data Base, managed by OUST, contains descriptive and numerical information on USTs submitted to EPA by the states on a state, regional and national basis. Of particular interest was information on the ages, sizes and contents of all registered USTs. Information related to this data base was also obtained from OUST on the status of corrective actions and closures in each state, region and nationally as of March 1991. Additionally, the EPA's Technical Information Exchange - Computerized On-Line Information System (TIX-COLIS) was accessed to obtain information on well-documented UST corrective action sites.

Discussions With Technology Vendors. Throughout early 1991 EPA contacted selected corrective action technology vendors to obtain information on technology performance.

1.3 INFORMATION ANALYSIS

Almost all states that were contacted provided some form of written documentation (e.g., guidance, regulations etc.) that allowed for a reliable presentation of their UST program requirements (See Appendix A). However, officials in only 4 of the 26 states contacted were able to readily provide precise statistics on the numbers of sites where each corrective action technology alternative was used. While the other states had the information requested in their files, they generally did not maintain readily accessible centralized records that would facilitate a rapid analysis of trends in technology use and performance. Therefore, in these states, best estimates of the percentage utilization of each technology per state were provided by agency officials. These estimates were applied to information provided quarterly by states to the Office of Underground Storage Tanks indicating the number and status of their corrective actions. This analysis was used to generate information on trends in technology utilization, as discussed in Chapter 2.

The information obtained from the sources listed in Section 1.2 was also reviewed to characterize the performance of each technology alternative in terms of treatment efficiency, operating parameters that affect treatment performance, and conditions that affect treatment costs. The results of this review are summarized in Chapter 3.

CHAPTER 2

CURRENT PRACTICES FOR MANAGING CONTAMINATED MEDIA AND DEBRIS FROM UST CORRECTIVE ACTION SITES

2.1 INTRODUCTION

One objective of this study was to examine the current level of use of each technology alternative under the RCRA Subtitle I program for managing contaminated media and debris generated at UST corrective action sites. The review was performed by contacting 26 state UST agencies (See Table 2-1) to request information on their regulations, policies, and guidance relevant to management of media and debris, and to obtain data on management technologies currently in use. Because of resource limitations EPA was not able to contact every state. Therefore, a subset of states was selected to provide a broad geographic and demographic distribution from each of the EPA Regions.

Table 2-1
States Included in this Review

EPA Region	State(s)
I	Connecticut, Maine, Massachusetts
II	New Jersey, New York
III	Delaware, Maryland, Virginia
IV	Florida, Kentucky, Tennessee
V	Indiana, Minnesota
VI	Louisiana, New Mexico, Texas
VII	Iowa, Missouri
VIII	Colorado, Montana, Utah, Wyoming
IX	Arizona, California
X	Oregon, Washington

Initial contacts in each state were identified by EPA UST Regional Program Managers. Subsequent contacts were identified through state agency referrals. State officials were contacted by telephone from October, 1990 through February, 1991. Information obtained by initial telephone contacts and available guidance was compiled and sent to each state for review and comment. While the 26 states provided substantial information on their requirements, information on current management practices sufficient for this review was not provided by all states, and the level of detail provided for each technology alternative varied considerably. The majority of the written comments were received in February, 1991 with the last received in May, 1991.

This chapter summarizes the information provided by the states on corrective action technologies used at UST corrective action sites. Section 2.2 summarizes the current management practices for petroleum contaminated soil (PCS) and debris. Section 2.3 summarizes the current practices for treating petroleum contaminated groundwater at UST corrective action sites. Section 2.4 provides a summary of the significant findings and conclusions of the state review as they relate to current treatment/disposal practices. See Appendix A for a summary of state requirements for management of petroleum contaminated soils and debris.

2.2 SUMMARY OF CURRENT MANAGEMENT PRACTICES FOR PETROLEUM CONTAMINATED SOIL AND DEBRIS FROM UST CORRECTIVE ACTION SITES

The states contacted during this study were requested to provide information regarding the practices they currently employ for managing soils and debris at UST sites. The responses indicate that a broad range of approaches are used, varying both in the type of remediation method employed and in the extent of their application.

Studies in the published literature on treatment/disposal methods for petroleum contaminated soil have used different interpretations and nomenclature to describe these methods. For example, the term "landfarming" includes aeration and bioremediation in some studies, but not in others. To reduce the potential for confusion, EPA classified the technologies addressed in this study into the five categories outlined below. For consistency, these definitions are maintained throughout this report.

- **In-situ Treatment** (PCS excavation is not a prerequisite for treatment):
 - vapor extraction, volatilization, air/vacuum extraction, and in-situ soil venting.
 - in-situ bioremediation, including bioreclamation.
 - isolation/containment, passive remediation, and groundwater pump and treat.
- **Landfilling:**
 - includes all landfill disposal options.

- **Land Treatment:**
 - landfarming, including ex-situ bioremediation.
 - land application, including land spreading and passive aeration.
 - aeration, including ex-situ soil venting, and air stripping.
- **Thermal Treatment:**
 - treatment in asphalt plants.
 - incineration.
 - low temperature thermal stripping (LTTS).
- **Other:**
 - All other categories reported by the states, including soil fixation and soil washing, and categories reported as "undefined."

State agency officials were asked to supply information regarding the relative use of these technologies at UST sites. Many of the states contacted during this study did not track information of this type and, consequently, the information provided was often based on best estimates provided by state personnel. Because much of the information provided only the percentages of sites employing each type of technology, EPA developed statistics for all of the states contacted by apportioning the percentages reported by states to the number of corrective action sites in these states using the following formula:

$$\text{Frequency (\%)} = \frac{\text{Technology utilization per state (\%)} \times \text{number of corrective actions per state}}{\text{Total number of corrective actions in all states}} \times 100$$

The number of corrective actions per state is based on information reported by the states to the Office of Underground Storage Tanks¹. Reports submitted to OUST as of the first quarter 1991 were used in this study. A total of 25 states supplied information on the major categories of treatment/disposal practices currently in use (Figures 2-1 and 2-2). Of these, 22 states provided sufficient information to quantify the use of specific technologies within each category (Figures 2-3 and 2-4). As of the second quarter of 1991, nearly 34,000 corrective actions had been initiated in these 22 states.

The results of the analysis of petroleum contaminated soil and debris treatment/disposal practices data are presented in a Figures 2-1 through 2-4.

Figure 2-1: Figure 2-1 illustrates the number of states reporting use of treatment/disposal methods for each of the four major categories. The figure includes states that did not provide detailed information on the degree of utilization, but simply indicated the usage of the technology for management of contaminated soils and debris at UST sites.

Figure 2-1
Distribution of PCS Treatment/Disposal Methods
 (From a field of 25 states)

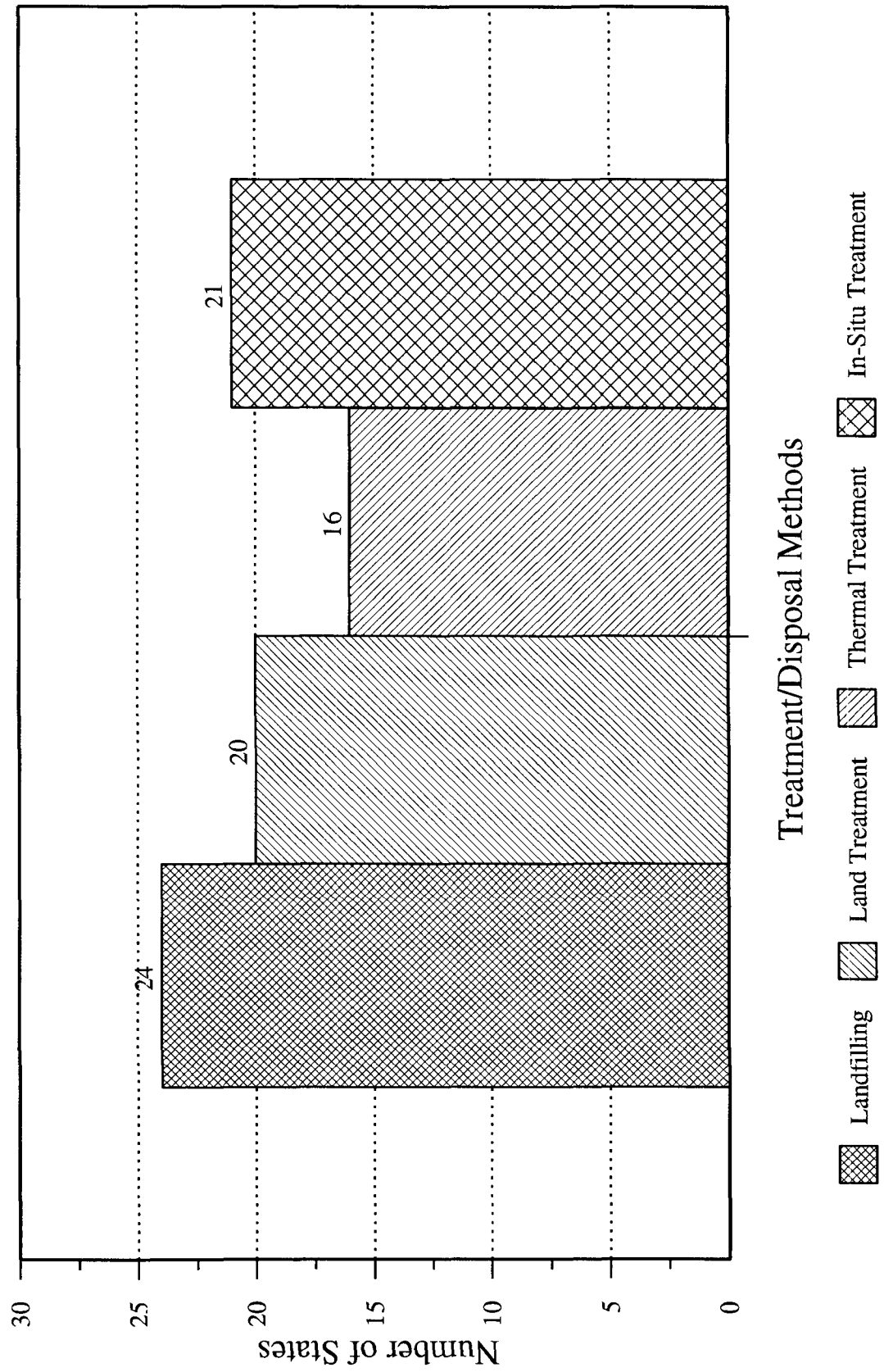


Figure 2-2: Figure 2-2 is a geographical representation indicating the most commonly practiced treatment/disposal method reported by these states. The indicated methods are not necessarily used in a majority of the corrective actions initiated; rather, they are the methods which are the most widely practiced (e.g., in Oregon, only 49 percent of the cleanups initiated involve landfilling, yet it is the most predominant practice).

Figure 2-3: Figure 2-3 summarizes the frequency with which the technologies in each of the four major treatment/disposal categories are currently used in 22 states (In-situ Treatment, Landfilling, Land Treatment, and Thermal Treatment). The "Other" category in Figure 2-3 consists of information from six states where reported corrective action technology utilization was too small to be apportioned, or where states simply reported "Other Technologies."

Figure 2-4: Figure 2-4 presents a more detailed breakdown of the In-situ Treatment, Land Treatment, and Thermal Treatment categories shown in Figure 2-1 (landfilling is completely represented in Figure 2-1). Each of the pie charts provides the percentage of utilization of specific technology options within each of these categories. In regard to in-situ technologies, 14 states reported using vapor extraction and six reported using bioremediation. However, only a few states provided the degree of utilization of these technologies. Therefore, the majority of technologies are identified as "Undefined/Other" in the figure. The "Undefined/Other" pie slice includes corrective action using "pump and treat" methods, as well as the other technologies discussed above.

2.3 SUMMARY OF CURRENT TREATMENT PRACTICES FOR PETROLEUM CONTAMINATED GROUNDWATER AT UST CORRECTIVE ACTION SITES

To supplement the information on current treatment and disposal practices, EPA also collected information on the percentages of sites requiring cleanup of groundwater and the types of groundwater remediation technologies employed. Data of sufficient detail for analysis were provided by 14 states. Approximately 37 percent of the UST corrective action sites in these states maintain active groundwater remediation systems (i.e., the employment of remedial technologies exclusive of monitoring and assessment, and other passive remediation).

Figure 2-2

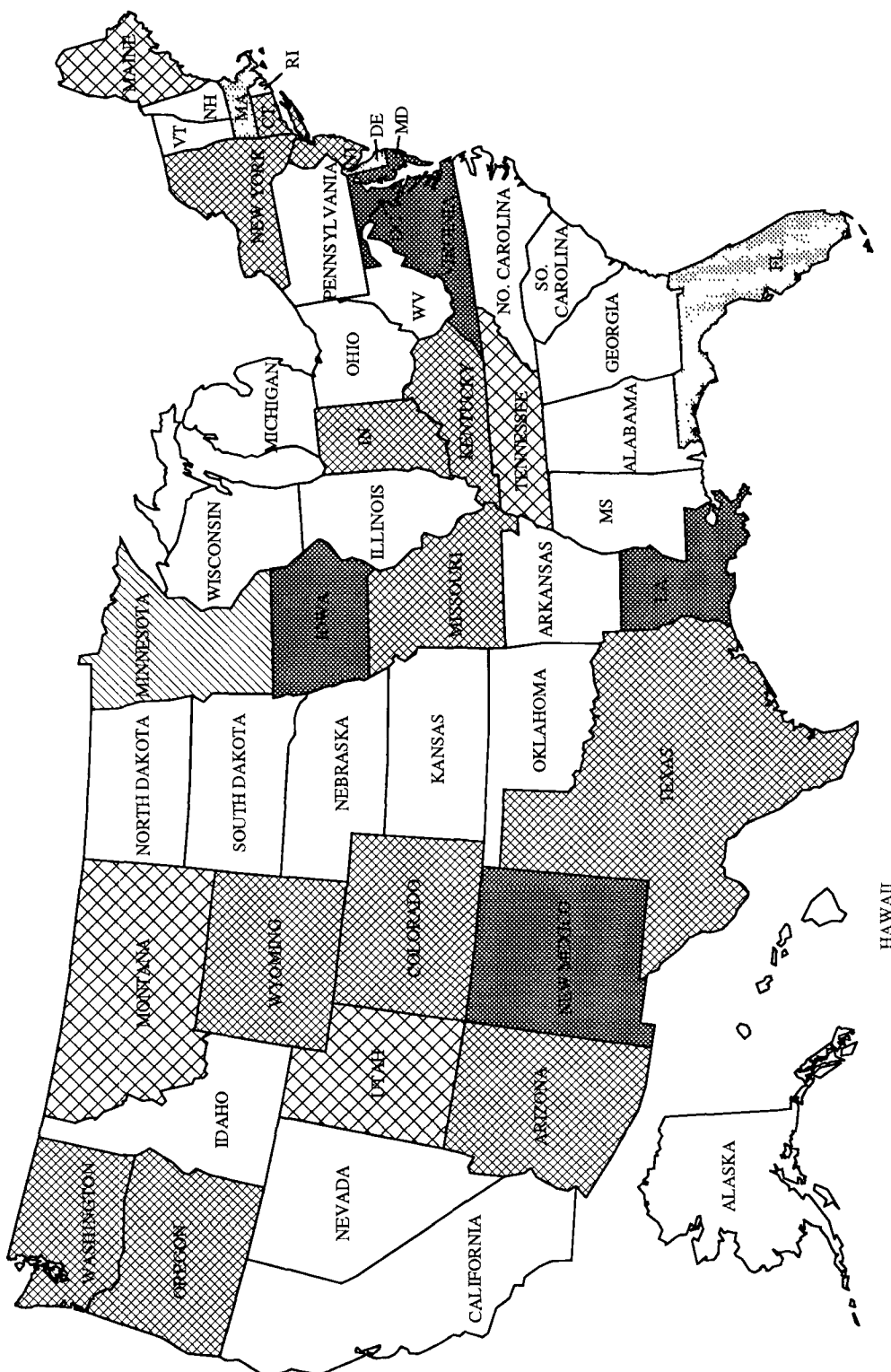


Figure 2-3
Distribution of PCS Treatment/Disposal Methods
By Major Category (Percentage of UST Sites)
(Includes 22 States)

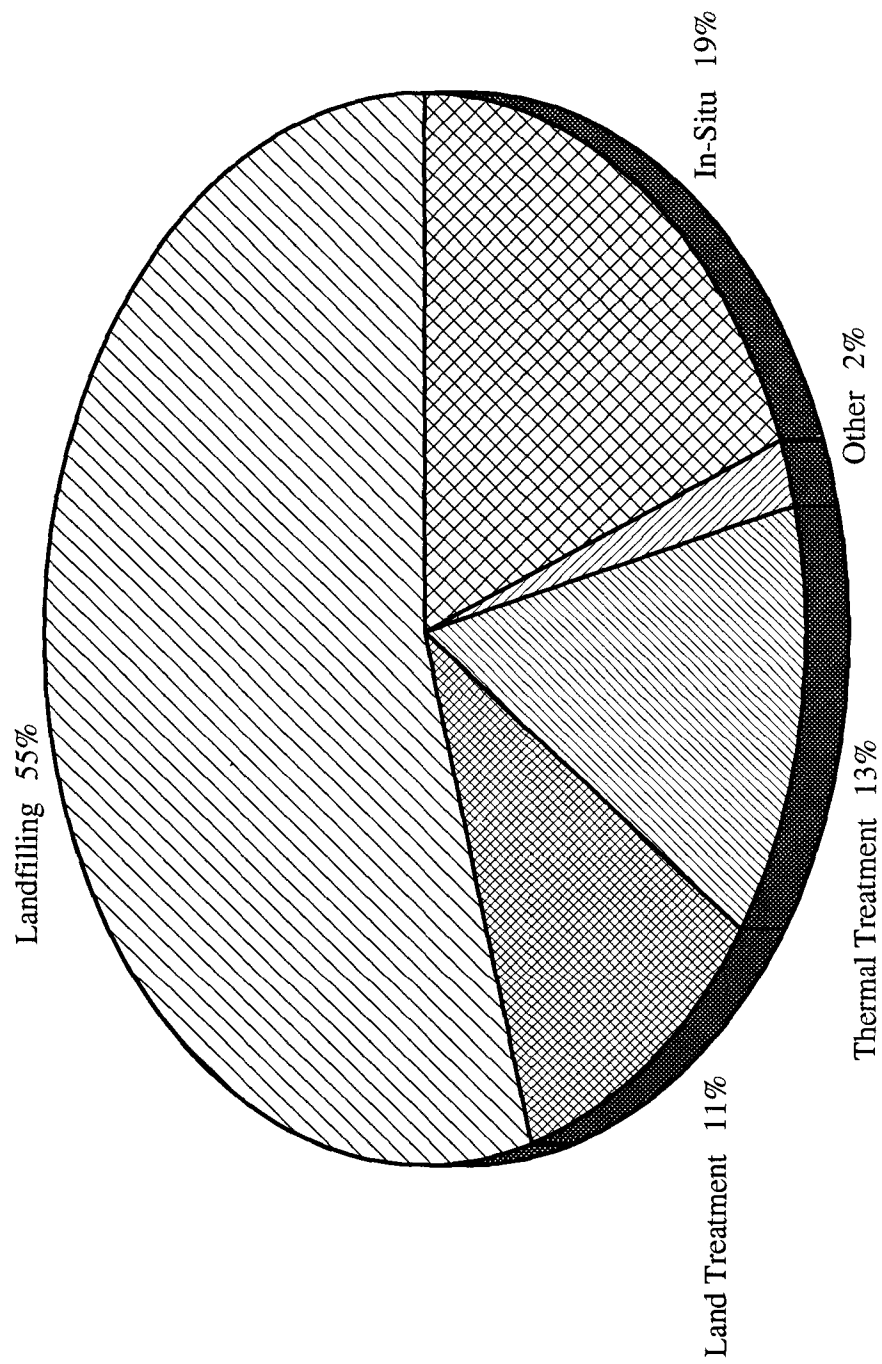
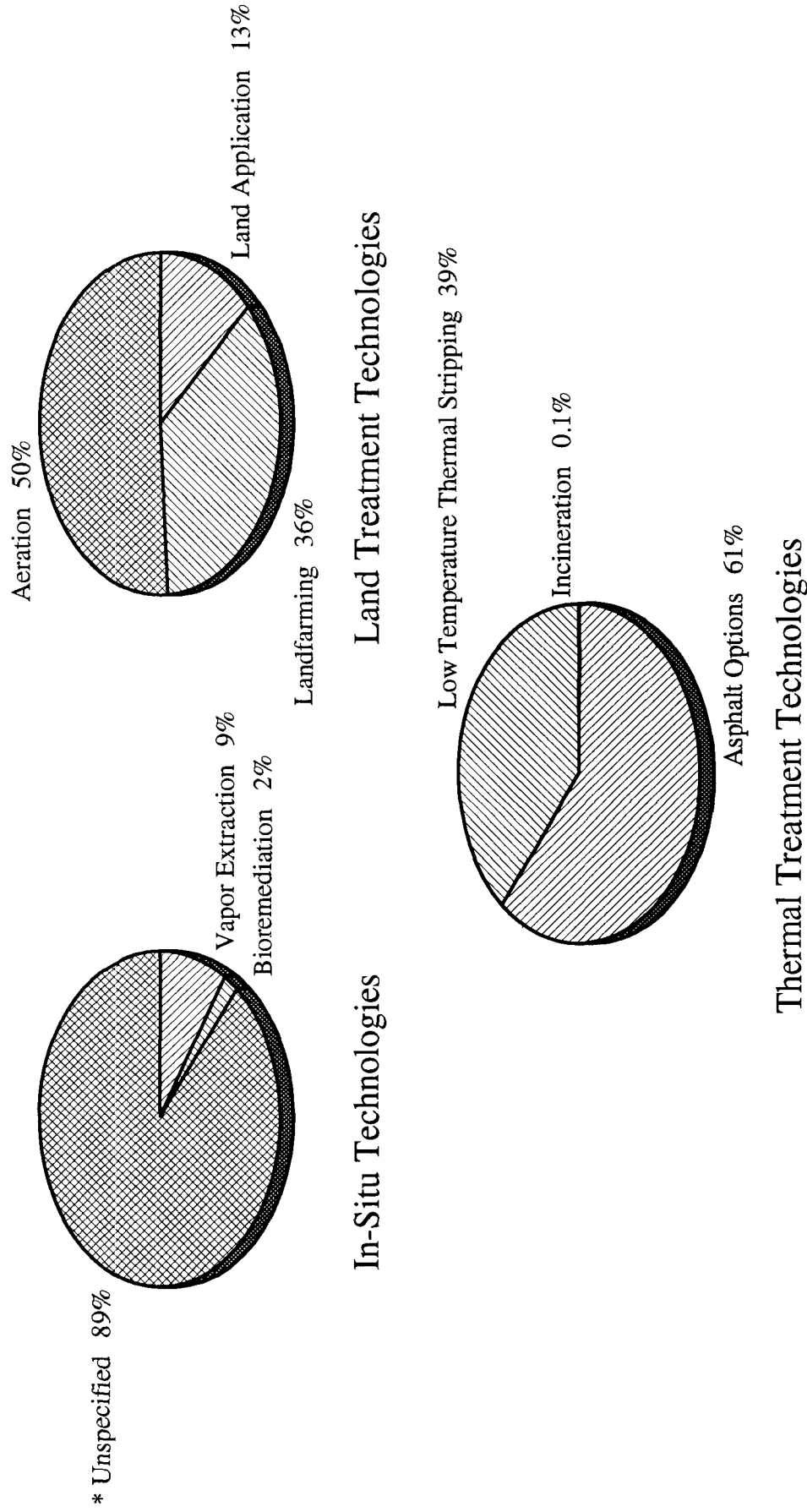


Figure 2-4
Distribution of PCS Treatment/Disposal Methods by Specific Technology
(Percentage of UST Sites in 22 States)



* Information on type of in-situ technology not reported by states (includes Vapor Extraction, Bioremediation, Pump and Treat, Soil Washing, etc.)
 Note: Percentages may not total 100 due to rounding.

Figure 2-5: This figure illustrates the types of groundwater remediation technologies reported for these sites. Approximately 96 percent of the total groundwater remediation activities reported are based on "pump-and-treat" methods, involving the pumping of contaminated groundwater by wells to the surface for treatment. Groundwater treatment methods under this category typically include oil/water separation followed by air stripping and/or carbon adsorption. As shown in Figure 2-5, air stripping and carbon adsorption account for at least 59 percent of the total groundwater remediation reported in these states (for an additional 37% of sites, "pump-and-treat" methods were reported as being used, but no information regarding groundwater treatment technologies was provided).

2.4 SUMMARY AND CONCLUSIONS

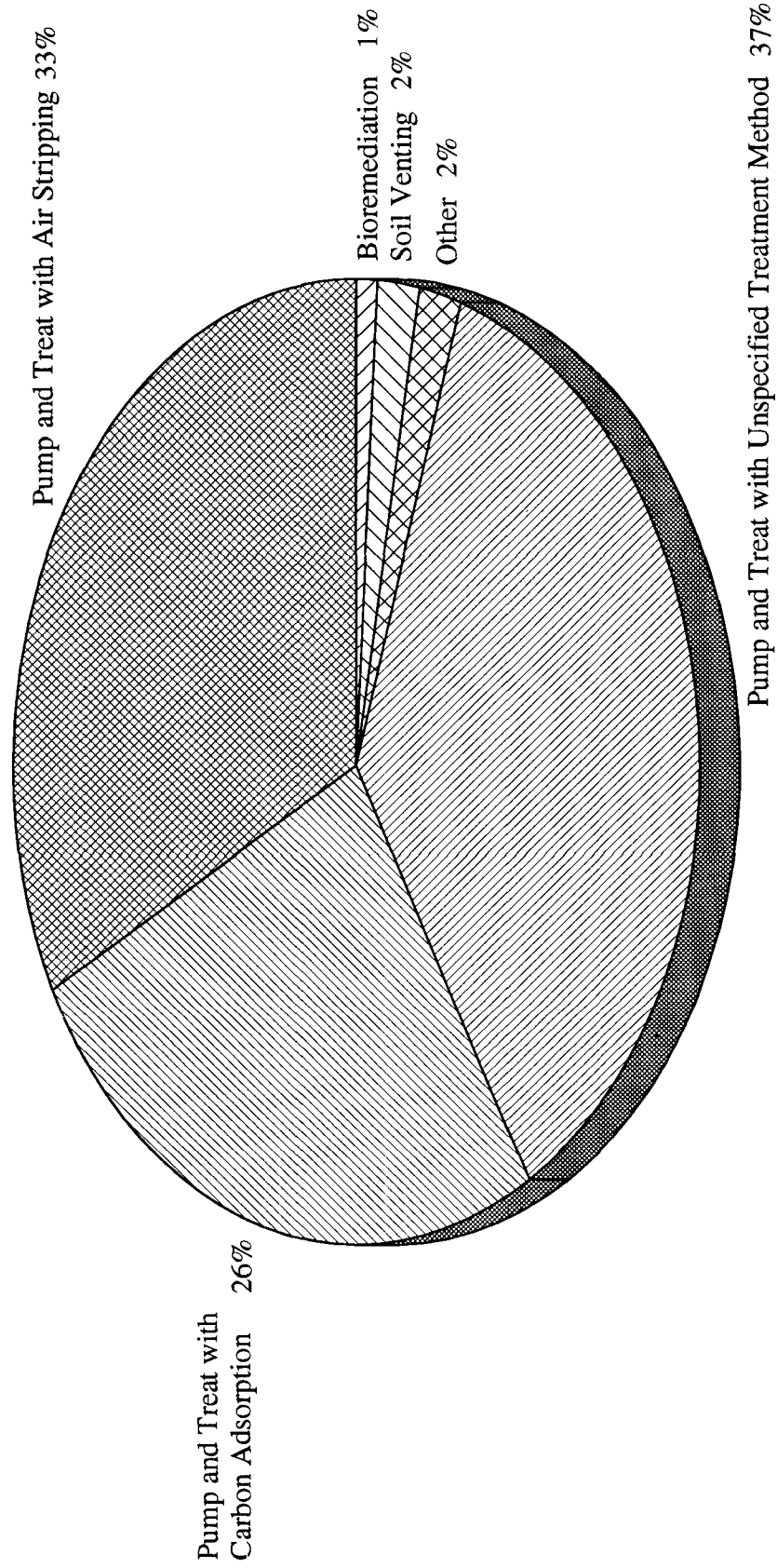
Following are the significant findings regarding current management practices in the states that provided sufficient information for this analysis:

1. The current level of use of the major treatment/disposal options for media and debris generated at UST sites in 22 states are: Landfilling - 55% of corrective action sites; In-situ treatment - 19%; Thermal Treatment - 13%; Land Treatment - 11%; and Other - 2%.
2. Of the thermal options for treating petroleum contaminated soils in the 22 states, treatment in asphalt plants is the most common (61% of sites), followed by low-temperature thermal stripping (39%), and incineration (less than 1%).
3. Of the land treatment in these states, aeration predominates (50% of sites), followed by landfarming (36%) and land application (13%).
4. Within 14 states that provided information sufficient for analysis of groundwater remediation practices, approximately 37% of the UST corrective action sites have groundwater contamination requiring remediation. Pump and treat methods predominate, accounting for about 96% of the sites in these states. Surface treatment of contaminated groundwater is performed by air stripping at about 33% of these sites and by carbon adsorption at about 26%, with the treatment method for the remaining sites using pump and treat methods not specified.

2.5 REFERENCES

1. Information provided by Mr. Greg Waldrip, U.S. Environmental Protection Agency, Office of Underground Storage Tanks.

Figure 2-5
Groundwater Remediation Practices
 (Includes 14 States)



Note: Percentages do not total 100 due to rounding.

CHAPTER 3

OVERVIEW OF TECHNOLOGIES CURRENTLY EMPLOYED FOR MANAGING PETROLEUM CONTAMINATED MEDIA AND DEBRIS FROM UST CORRECTIVE ACTION SITES

3.1 INTRODUCTION

EPA's review of state programs, summarized in Chapter 2, illustrates the types of technologies currently employed in the Subtitle I corrective action program for management of media and debris and the level of utilization of each of these technologies. To better evaluate the Subtitle I program, EPA reviewed information available as of June 1991 documenting the performance of these technologies at UST sites.

This evaluation was limited to a review of information from readily available sources. The primary sources were published literature, as supplemented by information obtained from state UST agencies and selected technology vendors. Priority was placed on collecting the following data for each type of technology:

- Contaminant removal efficiency;
- Operating parameters of equipment or techniques that affect the contaminant removal efficiency; and
- Costs.

This chapter is divided into the following sections. Section 3.2 provides information in each of the categories discussed above for ex-situ technologies for the treatment of petroleum contaminated soils (PCS). Section 3.3 addresses in-situ treatment of these soils. Section 3.4 addresses groundwater remediation technologies. A table is provided at the beginning of each section to summarize information for each technology alternative that has been documented regarding the mode of treatment, costs, residuals generated by the process, emissions equipment, treatment effectiveness, and significant limitations on applicability of the technology at UST sites. This information is then discussed in the text. Finally, Section 3.5 summarizes significant findings and conclusions.

3.2 TECHNOLOGIES FOR THE EX-SITU MANAGEMENT OF PETROLEUM CONTAMINATED SOILS

EPA's review of selected state UST programs (see Chapter 2) indicated that the technologies currently used most extensively for ex-situ management of PCS under the current Subtitle I program (i.e., soil that is excavated prior to treatment) include the following:

- Low Temperature Thermal Strippers (LTTS);
- Asphalt Plants;

- Landfilling; and
- Land Treatment.

Since these technologies are predominant in the current Subtitle I program, priority in this review was placed on collecting performance information on them. This information is summarized in Table 3-1 and discussed in Sections 3.2.1 through 3.2.4. In addition to the above technologies, other alternatives are available and are currently used to a limited extent for the treatment of petroleum contaminated soils. Brief overviews of these technologies are provided in Section 3.2.5. Note that high temperature incineration is not discussed since the performance of incineration for treating contaminated soils has been extensively documented in other studies.

3.2.1 Low Temperature Thermal Strippers

3.2.1.1 Process Description

The treatment of PCS by low temperature thermal strippers (LTTS) consists of the PCS excavation, PCS processing, PCS feed into the LTTS system, thermal treatment of PCS, treatment of volatilized petroleum gases, and discharge of treated solids. The mode of treatment is thermal desorption of contaminants and subsequent treatment of desorbed volatiles. The treatment steps are as follows:

PCS processing. PCS processing prior to thermal treatment may be necessary if the aggregate size of the PCS is large or the PCS contains excessive debris (e.g., asphalt chunks). Processing can include screening, crushing, or grinding¹.

PCS feed into the LTTS system. The feed of PCS is managed by the feed hopper and PCS conveyor. Feed rates are controlled by the system operator to maintain optimum temperatures and PCS residence times in the combustion chamber. PCS process rates of 5 yd³ to 25 yd³ per hour are common. The largest commercial units are reportedly capable of processing 40 to 50 tons per hour^{2,3,4,5}.

Thermal treatment of PCS. LTTS are available in a variety of configurations: hot oil, steam, or electrically heated thermal screws, directly or indirectly fired rotary kilns or infrared/flame radiation heaters (IR/F radiation heaters)² are the most common. Although design considerations may vary among units, the basic treatment process is the same. In the combustion chamber, soils are gravimetrically (rotary kiln) or mechanically (thermal screw or IR/F radiation heater) agitated and moved through the combustion chamber as they are heated to a temperature sufficient to volatilize, not combust, the petroleum hydrocarbons. Soil temperatures during treatment average 250° to 450° celsius (482°F to 842°F)⁵⁰.

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Table 3-1
Corrective Action Technologies for the Ex-situ Treatment of PCS
Generated at Petroleum UST Sites

Corrective Action Technology	Mode of Treatment	Cost ^a	Residual/Process Wastes
Low Temperature Thermal Strippers	Thermal desorption and low temperature destruction (250° to 450° celsius, 482°F to 842°F) with process gas; incineration, dilution or carbon adsorption with/without reclamation of the desorbed volatiles ⁶ .	Treatment costs range from \$74 to \$184 per ton of PCS ^{1,2,13,14} .	Volatile hydrocarbons (if emissions control devices are not used). Process waters. Combustion products. Particulate matter. Processed soils ^{2,8,13} .
Hot Mix Asphalt Plant	Thermal desorption and low temperature destruction (260° to 427° celsius, 500°F to 800°F) with encapsulation , or thermal desorption and low temperature destruction without encapsulation ^{8,17} .	Treatment costs range from \$50 to \$100 per ton of PCS ^{1,8,14,17,22} . (The sources of cost information were not specific in associating their costs with a specific type of asphalt plant).	Volatile hydrocarbons. Combustion products. Scrubber process water (if used). Unencapsulated soils.
Hot Mix Asphalt Plant Converted to LTTS	Thermal desorption and low temperature destruction with process gas; incineration, carbon adsorption, dilution or reclamation of desorbed volatiles.		Combustion products. Scrubber process water. Unencapsulated soils.
Land Treatment	Microbial degradation, photolysis, leaching, adsorption/immobilization, volatilization and aeration ^{8,22} .	Treatment costs range from \$5 to \$70 per ton ^{1,2,8} .	Potential residuals include surface run-off, vapor emissions, leachates and contaminated soils ¹⁷ .
Landfilling	Disposal process; no active treatment process. In some instances state regulations or landfill operating procedures may dictate the use of PCS solely as cover material, where a limited amount of volatilization, photolysis, and biodegradation may occur ³⁴ .	For all solid wastes, median of national annual operating expenditures is \$11 per ton, with expenditures ranging from >\$20 per ton for small landfills (1 TPD) to <\$5 per ton for large landfills (1,000 TPD) ⁵⁴ . Tipping fees in 1988 ranged from \$4.07 per ton to \$132 per ton, with a national average of \$26.93 per ton ⁵⁴ .	PCS contaminant levels may persist, and leachate and vapors may be generated.

Citations quoting costs of disposal/remediation using a particular treatment technology were not specific in identifying what percentage of the costs was attributable to the actual treatment and what percentage, if any, was due to PCS transport and storage, treated soil disposal, or emissions control costs. See text for additional information on factors affecting costs.

Table 3-1 (continued)
Corrective Action Technologies for the Ex-situ Treatment of PCS
Generated at Petroleum UST Sites

Corrective Action Technology	Emissions Control Equipment	Treatment Effectiveness	Limitations
Low Temperature Thermal Stripper	Baghouses. Venturi scrubbers. Cyclones. Carbon adsorption units. Afterburners (secondary combustion units). Condensers/demisters.	Numerous case studies demonstrate LTTS achieving >95% removal efficiencies with removal efficiencies >99% reported in some cases ^{8,10,13} ; however removal efficiencies as low as 27% have been reported ^{9,10} .	Excessive soil moisture limits treatment effectiveness and may require preprocessing. Large concentrations of fines (silts and clays) can limit treatment effectiveness. Debris (e.g., asphalt chunks) reduce effectiveness and may result in unacceptable emissions. Initial PCS concentrations >10,000 ppm TPH may need to be processed more than once to achieve acceptable concentrations. Less effective on heavy end petroleum products (e.g., No. 6 fuel oil). Process waste streams (gas, water, and treated soil) may require proper storage, treatment and disposal ^{1,3} .
Hot Mix Asphalt Plant	Cyclones. Wet scrubbers. Demisters.	93.2-99% for X ²¹ 50-70% for PCS as diesel fuel ²¹ 84-95% for PCS as gasoline ²¹ 94.5-99% removal for B ²⁰ 97-99% removal for TPH ²⁰ >99% removal for T ²⁰ >99.99% for hazardous organic constituents in a drum mix plant ⁶ . 99.25% removal of X&T from contaminated soil ¹⁸ .	Material <200 mesh screen limited to 10% of total weight. High organic content or high fractured rock content in soil is not conducive to treatment. Seasonal operations. Some states limit acceptable PCS to virgin product contaminated ¹⁴ . Off-site transport of the PCS may be necessary ¹³ .
Hot Mix Asphalt Plant Converted to LTTS	After burners (secondary combustion chamber). Baghouses. Venturi scrubbers. Quencher/demisters. Catenary grid scrubbers.		Retrofit may be expensive. Additional manpower may be needed to monitor process ¹³ .
Land Treatment	Proper management is needed to reduce the generation of vapors.	Cited sources and monitoring data collected from state files indicate that land treatment can reduce the concentration of petroleum products in soil by 70% to >99% ^{2,23,36} .	Seasonal operations. Requires a great deal of land (usually agricultural land) relative to other treatment options. May be unreclaimable following PCS treatment. Treatment is slow (requiring years in some instances to achieve remediation goals) ^{2,8,24} .
Landfilling	No technologies exist for the treatment of vapor emissions from uncapped landfills.	No treatment performed	Future liability remains.

Treatment of the volatilized petroleum gases. Volatilized petroleum hydrocarbons, water vapor, and particulates become part of the process gas stream, then exit the primary combustion chamber, and enter the emissions control system. The first step in gas treatment is typically a baghouse or cyclone where entrained particulate matter is removed and collected. Depending upon system design, the volatilized hydrocarbons can be recycled for reuse, immobilized, or destroyed.

Petroleum vapor collection for reuse. If the volatilized hydrocarbons are to be recycled, the process gas is sent to a condenser or demister. Through cooling, the water and volatiles are removed from the gas stream, creating a new waste stream of water and liquid hydrocarbons. The remaining gases are vented to an afterburner or carbon adsorption system where they are treated and finally vented to the atmosphere. The hydrocarbon water mixture is pumped to a oil/water separator where the hydrocarbons are recovered and subsequently transferred to a storage tank for eventual reprocessing. The waste water is treated as necessary.

Petroleum vapor destruction or immobilization. If contaminant levels in the soil and/or soil volumes are too low to warrant recycling, the hydrocarbons can be destroyed through thermal oxidation or immobilized through carbon adsorption. The system design in these instances is much simpler than the design required for petroleum collection for reuse¹⁷.

Discharge of the treated solids. Treated soils are discharged, via a conveyor system, directly from the primary combustion chamber. Unlike incineration units, the discharged soils do not need to be cooled prior to discharge and handling.

3.2.1.2 Treatment Efficiency

Low temperature thermal strippers are cited in the literature as having the capacity to reduce the levels of volatile organic compounds, including petroleum hydrocarbons, in soil by more than 99 percent. However, sources available to the EPA indicate that a wide variation in performance has been experienced. This is summarized in the following case studies:

Case Study Example 1: A feasibility study was performed for the USATHAMA to evaluate the effectiveness of LTTS technology (hot oil heated thermal screw unit) for the removal of volatile and semi-volatile organics from soil. The system was operated under a variety of test conditions: heating oil temperature (100° to 300° celsius, 212°F to 572°F); soil residence times (30 to 90 minutes); and soil discharge temperatures (50° to 150° celsius, 122°F to 302°F). About 165 yd³ of soil was treated during the test, with VOC levels in the soil initially as high as 20,000 ppm¹. Pre- and post- treatment sampling and analysis of soil samples indicated that more than 99.99 percent of the VOCs had been removed from the soil. The process gas was sent to an afterburning unit operating at 1,000° celsius (1,832°F), where it resided for longer than 2 seconds. No VOCs were found in the stack emission gases, indicating a destruction and

removal efficiency for the overall system of more than 99.99 percent⁸. (For more information refer to Noland, McDevitt, and Koltuniak (1986) for a description of this demonstration project conducted by Roy F. Weston for USATHAMA.)

Case Study Example 2: About 700 yd³ of diesel contaminated soil was treated as part of a demonstration project. Pre-burn contaminant levels as high as 67,000 ppm TPH were reduced on average greater than 98.5 percent. Approximately 4.5 yd³ of soil were treated per hour¹. (This demonstration cleanup was performed in October 1986 for San Diego Gas and Electric by Earth Purification Engineering of Fremont, California.)

Case Study Example 3: A private vendor remediated 1,200 tons of leaded gasoline, unleaded gasoline, kerosene, diesel fuel, and No. 4 fuel oil contaminated soil. Pre-treatment TPH levels in the excavated soil ranged from 1,200 ppm to 5,000 ppm. The rotary drier LTTS unit reduced the TPH concentrations in the clayey soil by greater than 99.5 percent, at a soil treatment rate of approximately 11 to 15 tons per hour⁶.

Case Study Example 4: About 11,500 yd³ of contaminated soil at the McKin Superfund Site, Gray, Maine, was treated using LTTS technology. The LTTS system included a thermal dryer, baghouse, scrubber, and carbon treatment system. The system was operated at 121° to 204° celsius (250°F to 400°F). Periodic testing of pre- and post-treatment soil samples indicated that the system consistently removed greater than 90 percent, but ranged as low as 33 percent, of the aromatic compounds from the contaminated soil (selected results are presented in Table 3-2). The lower removal efficiencies were attributed to the low initial contamination levels. This source postulated that removal efficiencies were directly proportional to the initial concentration levels⁹.

In addition to the literature sources, EPA obtained LTTS treatment efficiency data from the Minnesota UST program which tracks the disposition of PCS at its thermal treatment units. Analytical results from pre- and post-burn sampling of PCS from 20 sites are listed in Table 3-3. These are sites where soils were treated with mobile LTTS units¹⁰. The analytical results were used to calculate removal efficiencies (percent reduction = 100% - ((postburn data/preburn data) x 100)) of benzene, total BTEX, TPH as gasoline, and TPH as fuel oil when applicable.

The results indicate that in the majority of cases removal efficiencies were greater than 99 percent. In several cases however, the data indicate low removal efficiencies. A number of factors may contribute to the low removal efficiencies observed. Low pre-treatment contaminant concentrations may contribute to reduced removal efficiencies. The available data, however, did not provide a description of operating conditions or waste stream characteristics sufficient to determine factors may have contributed to the observed results. A review of the data in Table 3-3 shows that, in those cases where contaminant reduction was low, pre-burn concentrations of contaminants were relatively low with respect to the other cases. The data suggest that as the

PCS pretreatment VOC content decrease, the LTTS systems were unable to appreciably decrease the contaminant concentrations.

Table 3-2
PCS Treatment Efficiency Using LTTS⁷

Contaminant Name	Untreated Concentration (ppm)	Treated Concentration (ppm)	Removal Efficiency (%)
xylenes (total)	840	1	99.88
xylenes (total)	160	1	99.37
ethylbenzene	130	1	99.23
ethylbenzene	72	1	98.60
xylenes (total)	62	1	98.38
xylenes (total)	44	1	97.72
xylenes (total)	4.9	0.2	95.91
ethylbenzene	20	1	95.00
xylenes (total)	3.3	0.2	93.93
ethylbenzene	1.5	.2	86.66
ethylbenzene	1.3	0.2	84.61
toluene	4	1	75.00
benzene	2.7	1	62.96
ethylbenzene	1.8	1	44.44
toluene	0.3	0.2	33.33

3.2.1.3 Operating Parameters that Affect Treatment Performance

There are a number of variable operating parameters that affect the PCS treatment effectiveness of LTTS units. The three operating parameters that with the largest influences on LTTS units ability to remove petroleum hydrocarbons from soils are: 1) temperature; 2) residence time; and 3) agitation/exposure¹⁵. These, and other operational parameters typical of LTTS systems used in the Subtitle I program are:

- **Soil characteristics:** Excessive soil moisture can decrease removal efficiencies. The higher the percentage of fines (clay and silt), the lower the expected treatment efficiency¹. Preprocessing of soils may be necessary if aggregate size is too large or excessive debris exists in the waste stream.

Table 3-3
PCS Treatment Efficiency at Mobile Low Temperature Thermal
Strippers in Minnesota¹⁰

Volume (yd ³)	Preburn Analytical Results (ppm)				Postburn Analytical Results (ppm)				Percent Reduction ^a			
	Benzene	Total BTEX	TPH as Gasoline	TPH as F.O.	Benzene	Total BTEX	TPH as Gasoline	TPH as F.O.	Benzene	Total BTEX	TPH as Gasoline	TPH as F.O.
300	ND	ND	ND	1.5	-	<0.09	-	1.55	-	-	-	-
280	7.2	129.2	680	ND	0.01	<0.09	-	1.55	99	>99	-	-
100	0.03	1.15	-	130	0.01	<0.09	-	1.55	67	-	-	98
5000	ND	ND	-	4400	0.001	<0.008	0.051	2	-	-	-	99
200	0.00	0.03	-	2500	0.06	0.5	-	3.3	-	-	-	99
200	ND	0.11	-	7700	0.06	0.5	-	3.3	-	-	-	99
2000	0.00	0.64	-	3400	0.06	0.5	-	3.3	-	21	-	99
2800	0.06	2.23	0.74	1000	0.001	0.007	0.019	ND	98	99.7	97	-
1605	3.37	146.5	-	5696	0.001	<0.017	0.183	2	99.9	>99.9	-	99
160	0.01	1.81	0.5	117	0.01	0.11	1	1	0	93.9	-	99
1000	-	-	-	240	0.001	<0.007	0.019	ND	-	-	-	-
74	0.3	21.6	820	160	0.001	<0.003	0.026	12.3	99	>99.9	99.9	92.3
240	56	161	2400	-	0.001	<0.003	0.026	12.3	99	>99.9	99.9	-
450	0.06	1.38	35.6	-	ND	<0.001	0.019	ND	-	>99.9	99.9	-
65	ND	38	-	4900	-	-	-	18	-	-	-	99
400	0.59	5.96	257	-	0.001	<0.001	0.007	2.4	99	>99.9	99.9	-
48	ND	6.06	-	38	0.001	<0.001	<0.01	ND	-	>99	-	-
450	ND	16.3	25	-	0.005	ND	ND	ND	-	-	-	-
80	ND	6.6	-	27500	0.001	<0.003	0.01	ND	-	99	-	-
450	3.55	131.05	915	-	ND	ND	0.006	ND	-	-	99.9	-

^a For post-burn concentrations below detection limits, percent reduction was calculated based on one-half the detection limit.

- Soil contamination: Soil with contaminant concentrations above 10,000 ppm TPH may not be able to be treated so that post treatment contaminant levels are below state required clean-up levels². Treatment is most effective when treating light end hydrocarbons (gasoline) and less effective as the mean boiling temperature of the contaminant increases (i.e., No. 6 fuel oil)³.
- Temperatures: Temperatures at LTTS units typically range from 250° to 450° celsius (482°F to 842°F)⁶. (Data sufficient to characterize the relationship between temperature and removal efficiency were not found during this study.)
- Emissions control equipment for the removal of particulate matter and volatilized organic compounds: VOC emission control equipment can be designed to destroy the volatilized hydrocarbons (afterburner), immobilize them, (carbon adsorption), or capture them for recycling (carbon adsorption, condenser and oil/water separator)². Afterburner temperatures of approximately 650° celsius (1,202°F) are typical¹⁴. Temperatures of 500° to 650° celsius (932°F to 1,202°F) are needed to oxidize hydrocarbons, and temperatures of 650° to 800° (1,202°F to 1,472°F) are needed to oxidize carbon monoxide⁶.

3.2.1.4 Conditions that Affect Treatment Costs

A wide range of treatment costs using LTTS have been reported in the literature (\$74 to \$184 per ton)^{1,2,13,14}. The sources used in this review are not specific in identifying what amount of the costs was attributable to the actual capital and operating costs, and what percentage, if any, was due to PCS transport and storage, treated soil disposal, emissions control costs, or other factors. Further, since the cost estimates were presented simply as ranges, with no information regarding the numbers of units involved or the distribution of costs within the cited ranges, it is not possible to prepare a statistical analysis of the data. Table 3-4 lists the cost estimates as cited in the literature and the conditions under which these costs were experienced.

Figure 3-1 shows the results of an economic evaluation performed for USATHAMA to examine the costs of LTTS for treating soils contaminated with volatile organics in the following categories: 1,000 tons, 10,000 tons, and 100,000 tons. Based upon this evaluation, it was concluded that System B was the most cost-effective approach for sites with 15,000 to 80,000 tons of soil to be treated (far in excess of volumes found at typical UST sites). The unit costs for this system ranged from \$160 to \$174 per ton without flue gas scrubbing and from \$87 to \$184 per ton with scrubbing. Operating costs for stripping 1,000 tons of soil ranged from \$89 to \$142 per ton for the four systems. Capital costs were a significant portion of the total costs for processing⁴.

Table 3-4
Costs Reported for Treatment of PCS by Low Temperature Thermal Strippers

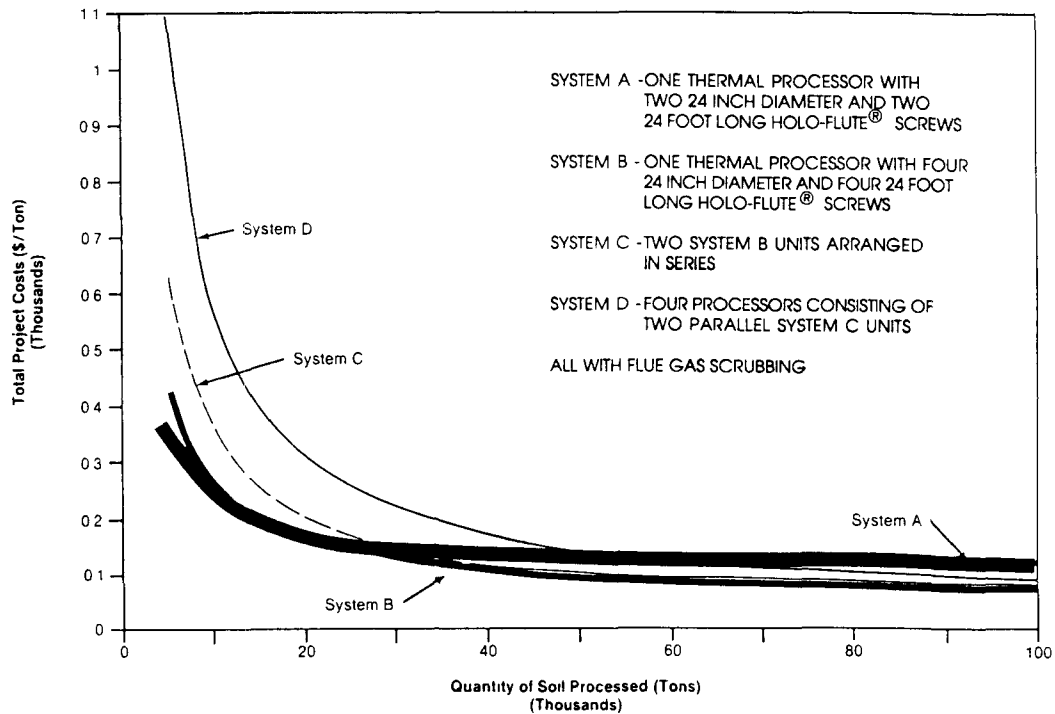
Treatment Costs	Applicable Conditions
\$100 per ton ²	Based on operation of commercial LTTS units in Holland.
\$100 to \$165 per ton ¹	Costs are based on a production rate of 2 to 6 yd ³ per hour and may vary depending on VOC concentration, soil moisture content and grain size of the PCS. Costs are expected to decrease as capacity increases.
\$80 to \$150 per ton ¹³	Based on a capacity of 30 to 50 tons per hour and is dependent on soil characterization and treatment criteria.
\$100 to \$120 per ton ¹³	Based on a 20% moisture content, and a contaminant concentration of 10,000 ppm.
\$74 to \$160 per ton ¹⁴	System does not include a flue gas treatment system. PCS volume to be treated is 15,000 to 80,000 yd ³ . Capital costs are a significant portion of the total costs for processing, and increase as the volume of PCS to be treated decreases. Operating costs for processing less than 10,000 tons would be expected to be in excess of \$200 per ton.
\$87 to \$184 per ton ¹⁴	System includes flue gas treatment system. PCS volume to be treated is 15,000 to 80,000 yd ³ .

3.2.2 Hot Mix Asphalt Plants

3.2.2.1 Process Description

Two basic types of asphalt plants are currently in use, batch mix and drum mix, with approximately an equal number of each of these types of plants in operation. Batch mix plants, which separate the heating, screening, blending, and production steps, mix one batch of product at a time. In this process, the drier is stopped and started numerous times during a day. Drum mix plants first size the aggregate and then heat and blend it in one combined production step. Drum mix plants usually run continuously for long periods of time¹³. Most new plants are of the drum mix type¹⁵.

Figure 3-1
Costs of Low Temperature Thermal Stripping Pilot Plant Units⁴



Source: Economic Evaluation of Low Temperature Thermal Stripping of Volatile Organic Compounds from Soil. U.S. Army Toxic and Hazardous Materials Agency Report No. AMXTHOTE-CR 8C085 (Roy F. Weston, 1986)

The manufacture of asphalt, which uses PCS as an aggregate supplement, can either be a cold or hot process. The cold mix process blends untreated PCS directly with the liquid asphalt¹⁶. This process is discussed in Section 3.2.5.1 of this report. The hot mix process is the most common process under the Subtitle I program and is discussed in this section.

Hot mix asphalt plants are typically used as fixed regional treatment centers for PCS¹². The treatment entails either desorption, oxidation and encapsulation, or desorption and oxidation without encapsulation. It is not known, however, to what degree each treatment mechanism contributes to the overall removal/destruction of the petroleum compounds in the soil. The hydrocarbons not volatilized in rotary driers at asphalt plants are expected to be incorporated

into the asphalt mix. None of the literature reviewed in this study, however, addressed with any certainty the fate of these compounds following encapsulation, (e.g., leaching potential).

Asphalt plants process from 20 to 180 tons of gravel, sand, and mineral filler per hour. When PCS is being treated, the standard industry practice is to mix less than 5 percent by weight PCS with clean aggregate to achieve an average treatment capacity of 1 to 9 tons PCS per hour^{6,17}. The asphalt plant rotary driers, in which PCS thermal treatment occurs, are usually maintained at temperatures of approximately 260° to 427° celsius (500°F to 800°F)^{8,17}. The PCS processing capacities of these facilities are limited by air quality concerns and the need to ensure and maintain the quality of the asphalt mix. An improper PCS/aggregate feed may result in a low quality mix, which would not meet Department of Transportation (DOT) road use specifications. Typical aggregate feed into the asphalt mix is 60 percent coarse material and 40 percent fines. To this, 5.5 percent liquid asphalt by weight is added. As the amount of fines less than 200 mesh (very fine sand and silt) becomes greater than 10 percent, the mix quality deteriorates¹⁸. In addition, too high an organic content or fractured rock content in the aggregate feed also will deteriorate the asphalt mix.

A number of asphalt plants have been converted into operational units designed specifically for soil treatment. Modifications are usually made in response to air quality concerns and entail the addition of more efficient and modern emissions control devices, including secondary burners, baghouses, venturi scrubbers, quenchers, and catenary grid scrubbers¹². Minnesota now requires that all asphalt plants that are going to treat PCS within the state be equipped with high efficiency wet scrubbers and afterburner units¹⁹. Other modifications made when PCS are to be handled at a modified asphalt plant may include more and larger aggregate feed bins, cold storage facilities, and the addition of larger staging areas designed specifically for soils management.

Converted asphalt plants can process a much more diversified waste stream in terms of aggregate feed size. Since the PCS treated at these facilities is not incorporated in the asphalt mix, product quality is not an issue¹⁷.

3.2.2.2 Treatment Efficiency

Three sources of information on PCS treatment efficiency were reviewed during this study: 1) pre- and post-burn analytical data from PCS treatment at an asphalt plant in Anchorage, Alaska, 2) the results of a test burn of simulated petroleum contaminated soil at an asphalt plant in Massachusetts, and 3) a study performed for the Minnesota Pollution Control Agency (MPCA) on petroleum contaminated soil treatment test burn results.

Table 3-5 summarizes treatment data for one asphalt plant in Alaska. The pre-burn concentrations of organic constituents are based on analysis of samples from stockpiled soils at

six UST corrective action sites. The post-burn concentrations are based on analysis of samples taken after the soils were transported from the sites and treated at an asphalt plant. Removal efficiencies ranging from 94.5 percent to more than 99 percent were found²⁰.

Table 3-5
PCS Treatment Efficiency at an Asphalt Plant²⁰

Volume (tons)	Preburn Analytical Results (ppm)				Postburn Analytical Results (ppm)				Percent Reduction			
	Benzene	Toluene	Total BTEX	TPH	Benzene	Toluene	Total BTEX	TPH	Benzene	Toluene	Total BTEX	TPH
1374	6.9	15	74	7200	ND	ND	0.007	14	99	99	99	99
2016	0.126	4.13	46	1100	0.00571	0.00908	0.0229	20	95.5	99.7	99	98
141	-	-	-	319	ND	ND	ND	ND	-	-	-	99
257	-	-	-	479	ND	ND	0.019	14.4	-	-	-	97
1398	0.973	-	25.5	-	ND	ND	0.0087	ND	99	-	99	-
1844	0.179	-	83.2	-	0.01	ND	0.04	ND	94.5	-	99	-

The results of a test burn at a Massachusetts asphalt plant indicate that volatilization of organic compounds during pretreatment can be substantial¹⁸. During the test burn, a significant amount of the petroleum compounds' initial mass was lost through volatilization as a result of the material handling and processing (i.e., excavation, crushing, screening, and debris removal) performed prior to treatment. At the initiation of the study, 9 tons of sand were spiked with a 50:50 xylene/toluene mix to 30,000 ppmv. A sample collected from the PCS storage hopper prior to treatment in the asphalt plant showed that the level of the xylene/toluene mix in the sand was 4,000 ppmv. On the aggregate conveyor, the level was 1,500 ppmv; a 95 percent decrease in the concentration of the two compounds prior to the treatment process. This reduction was presumed to be due to volatilization to the atmosphere during processing.

Minnesota performed a test burn evaluating the treatment of PCS at a traditional asphalt plant during routine operations. The asphalt plant chosen for the test represented what the consulting contractor thought were worst-case scenarios for several variables: 1) maximum soil feed rate during test, 2) the asphalt plant operated co-currently, 3) the treated soils had high silt contents, and 4) the wet scrubber used in emissions control was simple and inefficient in comparison to more modern devices. The asphalt plant test burn results indicate that a 99.9 percent soil treatment efficiency for benzene was achieved. Similar results were obtained for xylene, with lower efficiencies reported for total hydrocarbons²¹.

3.2.2.3 Operating Parameters that Affect Treatment Performance

No data were identified during this study to conclusively indicate the relationship between treatment effectiveness of asphalt plants and plant operating parameters. Operation of the dryer, including dryer temperature, residence time, and agitation/exposure, are likely to be among the most important parameters, but other factors (including soil moisture and soil and contamination characteristics) may be equally important. Relevant to these factors, asphalt plants that treat PCS typically operate under the following conditions:

- Dryer temperature: Dryer temperature is normally between 260° and 427° celsius (500°F to 800°F)^{5,9};
- Mesh size: Aggregate content below 200 mesh size normally does not exceed 10 per cent of the total; and
- Feed rate: On average, the feed rate of PCS in plants that mix PCS with product is one to nine tons per hour.

Table 3-6 lists the PCS treatment efficiencies and applicable conditions, if available, that were identified in this study.

3.2.2.4 Conditions that Affect Treatment Costs

As shown in Table 3-1, a wide range of treatment costs using asphalt plants have been reported in the literature, from \$50 to \$100 per ton. The sources used in this review are not specific in identifying what percentage of the costs was attributable to the actual treatment and capital costs, and what percentage, if any, was due to PCS transport and storage, treated soil disposal, emissions control costs, or other factors. Further, since the cost estimates are presented simply as ranges, with no information regarding the numbers of units involved or the distribution of costs within the cited ranges, it is not possible to prepare a statistical analysis of the data. Table 3-7 lists the treatment costs cited and the conditions that apply to the cost estimates. One source cited the cost to retrofit an asphalt plant in the range of \$10,000 to \$100,000⁸.

Table 3-6
PCS Treatment Efficiencies and Associated Conditions in Asphalt Plants

PCS Treatment Efficiency	Treatment Conditions
50.5% when calculated as Fuel Oil No. 2 ²¹	Diesel fuel contaminated soil. The soil was classified as a mixture of sand fill with native silty sand and silty clay. Plant operating conditions were: soil throughput of 280 tons per hour, mix temperature 295° F, and soil moisture content of 11.5%. Pretreatment contaminant concentrations averaged 308 ppm (identified as No. 2 fuel oil).
70.2% when calculated as Fuel Oil No. 1 ²¹	
84.% when calculated as Gasoline ²¹	Gasoline contaminated soil. Soil was classified as a fine to medium sand with silt and a little gravel. Plant operating conditions were: soil throughput of 255 tons per hour, mix temperature of 300° F, and soil moisture content of 5.9%. Sample results indicate that the PCS contaminant was identified as gasoline prior to screening, and that post screening, pre-treatment it was identified as No. 2 fuel oil. It is likely that this is a result of the lighter VOC having volatilized during the screening process. Pretreatment contaminant concentrations averaged 862 ppm (identified as No. 2 fuel oil).
94.1% when calculated as Fuel Oil No. 1 ²¹	
99.25% ¹⁸	Contaminated aggregate was: 3% organics, 50/50 blend of xylene and toluene in a natural sand, with a moisture content of 3.3%. Total run time was one hour. Pre-screening contaminant concentration was 30,000 ppm with a post-treatment concentration of <0.200 ppm.

Table 3-7
Costs Associated with Treatment of PCS in Asphalt Plants

Treatment Costs	Applicable Conditions
\$80 per ton ¹	Excavation, transportation and storage of the PCS would add to the costs. Capital costs vary in proportion to size of the plant.
\$50 to \$75 per ton ⁸	Does not include excavation costs.
\$50 to \$100 per yd ³⁽¹⁷⁾	Assumes off-site operation of the unit with transportation costs additional. 3,700 yd ³ (4,000 tons) of PCS were treated.

3.2.3 Land Treatment

3.2.3.1 Process Description

Land treatment of PCS can be done passively through land application or through active management, which incorporates the PCS in landfarming units.

Land Application: Land application, also referred to as land spreading, is the least labor intensive approach to the land treatment of PCS. In this process, soils are spread uniformly over the land to a relatively shallow depth typically not exceeding four inches. The applied PCS is not incorporated into the soil and is not actively managed. Naturally occurring processes (e.g., microbial degradation, photolysis, leaching, adsorption/ immobilization, volatilization and aeration) decrease the concentration of the petroleum compounds in the soil²³.

Landfarming: Landfarming involves controlled application, incorporation (into the top 4 to 8 inches), and active management (e.g., addition of nutrients, irrigation, tilling) of PCS at prepared sites²³. There are generally two categories of landfarming facilities for the treatment of PCS: single and multiple application²⁴. A single application site is returned to its original function following the application and treatment of PCS generated from one UST release site. Reclamation is typically performed 1 to 3 years following closure of the site as an active treatment facility². A multiple application site is designed to accept and treat PCS generated at more than one UST release site.

The landfarming process consists of six distinct steps: 1) site selection, 2) site preparation, 3) PCS application/incorporation, 4) management, 5) monitoring, and 6) site closure. The initial, most difficult, and potentially most costly step in this process is the selection, permitting, and preparation of a landfarming facility. Numerous factors that need to be considered in site selection have been discussed in the literature, including^{6,8,13,24,25}:

- Location of facility with respect to aquifer recharge zones;
- Topography. The surface should be relatively flat to minimize run-off and erosion problems. In general, recommended slopes are between 2 and 5 percent;
- Climate (precipitation, temperature, and wind speed);
- Distance to surface water;
- Depth to ground water;

- Soil physics and chemistry, including soil depth, texture, drainage (unsaturated and saturated hydraulic conductivities), Ph, organic matter, soluble salts, cation exchange capacity, moisture holding capacity, and microbial counts; and
- Soil types. In general, facilities should not be established on deep sandy soils or on soils with the tendency to form crusts. Desirable soils include loam, sandy clay loam, silty clay loam, clayey loam, and silty clay.

Specific requirements dictating siting (e.g., depth to ground water, distance from surface water, emissions controls, etc.) and management (e.g., application rates and times, nutrient application rates, sampling and reporting requirements, etc.) of these facilities depends largely on the regulatory requirements of the governing state agencies. These requirements vary from state to state, depending upon variations in geology, hydrogeology, soil chemistry, climate, and land use that characterize the different regions of the United States.

In general, PCS is applied (spread) and incorporated (mixed) into the top eight inches of the top soil¹³. PCS landfarming management should maintain soil moisture, nutrient, and Ph levels at optimum conditions for microbial growth. Proper management also should guide the frequency of tilling to ensure optimum aeration/oxygenation. Tilling/aeration of the soil is typically performed more frequently at early stages of the treatment process, with a diminishing need as treatment progresses. Monitoring is needed to ensure that conditions optimal for microbial growth are maintained, that treatment is effective, that contaminants are maintained within the treatment zone, and to indicate when conditions are appropriate for reapplication of PCS.

3.2.3.2 Treatment Efficiency

Few studies were identified during this review that presented quantitative data to demonstrate the effectiveness of treating PCS using land treatment technologies. The available data is insufficient to characterize the reductions in soil contaminant processes that can be attributed to physical, chemical, and biological processes taking place in the soil or that which can be attributed to volatilization to the atmosphere.

One report indicates that removal efficiencies of 70 percent to 90 percent can be achieved with loadings of 1 to 5 percent by weight². Unfortunately, the time required to achieve these reductions was not specified. Another source indicates that relatively rapid rates of degradation can be expected in the first 60 to 90 days following application, with increasingly diminishing rates. This report states that up to two years may be needed for completion of treatment, depending on the initial concentration levels¹. It, however, did not specify what levels were treated or the treatment effectiveness.

Table 3-8 presents analytical data from the pre- and post- application of PCS at several landfarming facilities in Minnesota. As shown, reductions of more than 99 percent in the TPH, total BTEX or benzene concentrations were achieved for sites where PCS were treated for at least five months²³.

Table 3-9 presents analytical results from pre- and post-application of PCS sampling at a Vermont landfarming facility. In this example, approximately 200 cubic yards of soil contaminated with kerosene and No. 2 fuel oil were treated. The monitoring results indicate that the concentration of total petroleum hydrocarbons decreased from 75 to 89 percent over one year, with a higher rate of reduction found in samples taken at 6 inches than those taken at 12 inches²⁶.

Table 3-10 provides data from a site in Vermont where oil contaminated soil was spread on a concrete pad in October 1986. Cow manure was incorporated into the PCS as a source of nutrients, and the treatment site was tilled regularly through the growing season. Within one year, the concentration of oil and grease in the soil was reduced by 87 percent. In October 1987, a second application of PCS was applied. Within 6 months the PCS contamination levels were reduced by 99 percent. However, the data do not indicate the extent to which the observed reductions could be attributed to volatilization²⁶.

3.2.3.3 Operating Parameters that Affect Treatment Performance

A wide range of highly site-specific factors affect performance of land treatment facilities. The following variables have been cited in the literature as important considerations in the management of land treatment facilities:

- PCS loading: PCS loading should not degrade the infiltration, percolation and aeration potential of the land treatment soil²⁵. Loading is generally limited to 5 percent waste by weight of the soil into which it will be incorporated¹³.
- The presence of toxic or leachable constituents: Heavy metals, inorganic salts, heavy halogenated organics, some pesticides, some herbicides, and nitrates diminish the effectiveness of PCS treatment (concentration reduction). Toxics can eliminate the microbial populations, and leachables can potentially impact groundwater¹.

Table 3-8
PCS Treatment Efficiencies at Landfarming Facilities in Minnesota²³

Volume (yd ³)	Preapplication Analytical Results (ppm)				Postapplication Analytical Results (ppm)						Percent Reduction ^a			
	Benzene	Total BTEX	TPH as Gasoline	TPH as F.O.	Months since Application	Benzene	Total BTEX	TPH as Gasoline	TPH as F.O.	Benzene	Total BTEX	TPH as Gasoline	TPH as F.O.	
180	ND	ND	-	7.9	5	<0.005	<0.02	<0.5	<0.2	-	-	-	99	
250	<0.005	<0.02	-	50	3	<0.005	<0.02	ND	<0.5	-	-	-	>99	
350	ND	ND	-	50	3	0.075	<0.022	0.75	<2	-	-	-	98	
35	0.11	13.7	-	2000	2.5	<0.005	<0.15	2.1	12.2	98	99	-	-	
700	45.3	214.1	1193	-	3	0.56	1.42	3.5	2	99	99	>99	-	
220	7	142	180	-	8.3	ND	ND	ND	ND	>99	>99	>99	-	
1630	9	232	-	251	3.5	<0.005	<0.02	ND	<0.5	>99	>99	-	>99	
690	14.3	273.6	2455	63	5	<0.005	<0.02	<0.5	<0.5	>99	>99	>99	>99	
850	4.5	45.7	170	-	5.8	<0.005	<0.02	ND	1.04	>99	>99	>99	-	

^a For postapplication results less than method detection limit, percent reduction was calculated based on one-half the detection limit.

Table 3-9
PCS Treatment Efficiency at a Landfarming Facility in Vermont²⁶

Monitoring Date	6" Sampling Depth		12" Sampling Depth	
	TPH Concentration (mg/kg)	Percent Reduction From First Data Point	TPH Concentration (mg/kg)	Percent Reduction From First Data Point
8/87	3,271	0	233	0
9/87	1,379	58	1,622	--
10/87	946	71	1,250	23 ^a
5/88	1010	69	1,220	25 ^a
6/88	450	86	700	57 ^a
7/88	370	89	410	75 ^a

^a As compared to 9/87 sample.

Table 3-10
Oil Contaminated Soil Treatment Efficiency at a Landfarming Facility in Vermont²⁶

Oil and Grease Concentration (mg/kg)		
Monitoring Date	Average Concentration from Composite Samples	Percent Reduction from First Data Point
10/7/86	7,280	
6/26/87	1,128	84
10/2/87	944	87
10/22/87 ^a	4,000	--
4/26/88	3,727	7
7/12/88	800	80
10/7/88	23.3	99

^a More contaminated soil added.

- Nutrient additives: Addition of nutrients is often required to maintain and promote biological activity. Recommendations cited in the literature include:
 - Nitrogen: Levels should be maintained in excess of 5 ppm¹. Added nitrogen is in the form of NH_4^+ or NO_3^- (ammonium chloride is a common additive)². Application rates quoted in the literature range from 50 lbs to 500 lbs per acre^{2,24};
 - Phosphorous: Levels should be maintained in excess of 1 ppm². Added phosphorous is in the form of PO_4^{3-} (sodium phosphate is a common additive)². Application rates quoted in the literature range from 5 lbs to 120 lbs per acre^{2,24};
 - Potassium^{2,6};
 - Iron Fe^{2+} ; and
 - Sulfur.
- Soil Ph: A neutral (Ph = 7) or slightly alkaline Ph (Ph > 7) is optimum for microbial activity and for minimizing the mobility of heavy metals^{1,6,27}. An acceptable range is between Ph of 6 and a Ph of 8^{2,6}. Lime can be added to the field to adjust the Ph;
- Soil moisture: Soil moisture should be maintained between 30 percent and 80 percent. Optimum conditions for microbial activity are soil moisture contents of between 40 percent and 55 percent^{1,27}. Excessive moisture limits the available oxygen and its capacity for exchange⁶;
- Soil temperature: Temperature directly affects microbial activity rates. Microbial activity has been shown to slow at 10° Celsius (50°F) and effectively cease at 5° celsius (41°F)⁶. On average, degradation rates of petroleum products can be expected to be 15 percent less in cold climates as opposed to those more southerly^{6,27};
- Aeration: Aeration (tilling, disking, etc.) promotes oxygen exchange and the maintenance of aerobic conditions. The literature suggests that aeration should be performed every 2 to 4 weeks²; and
- Reapplication: Reapplication of PCS or petroleum products must not occur too soon so as not to overwhelm the load-bearing capacity of the soil, or too late so as not to maintain elevated levels of microbial activity¹³.

3.2.3.4 Conditions that Affect Treatment Costs

A wide range of treatment costs using land treatment have been reported in the literature (\$5 to \$70 per ton)⁸. The sources used in this review are generally not specific in identifying what percentage of the costs was attributable to the actual treatment and capital costs, and what percentage, if any, was due to PCS transport and storage or other factors. Further, since the cost estimates were presented simply as ranges, with no information regarding the numbers of units involved or the distribution of costs within the cited ranges, it is not possible to prepare a statistical analysis of the data. Table 3-11 lists the specific references and the conditions that apply to the cost estimates.

Table 3-11
Costs Associated with Treatment of PCS at Land Treatment Facilities

Treatment Costs	Applicable Conditions
\$5 to \$50 per yd ³⁽²⁾	Costs are a function of the extent of contamination, waste type and biodegradation rates. Depending on location, the need for surface runoff/run-on controls will increase costs.
\$10 to \$40 per yd ³⁽¹⁾	Includes sampling and analysis costs.
Approximately \$17 per metric ton (1986 dollars) ⁸	Total costs break down as follows: cultivation and site operation \$1.65 to \$2.20 per metric ton; materials transportation and handling \$9.35 per metric ton; and soil analysis \$5.50 per metric ton.

3.2.4 Landfilling

3.2.4.1 Process Description

Under current practices, PCS from UST corrective action sites is excavated, stored, and transported to a commercial or industrial landfill, where it is placed in disposal cells or spread as daily cover. If PCS is used as daily cover, it is typically spread and compacted to a depth of 6 to 18 inches. Deeper covers may be required by state regulatory officials in response to odor or vector complaints. Whether PCS is disposed of in cells or as daily cover is dependent largely on state or local regulations³⁴.

If the PCS is used as daily cover, partial reduction of contaminant concentrations occurs because volatile compounds are emitted during the spreading and compacting process. If, however, PCS is placed in a cell and covered, microbial degradation of the organic compounds is the major treatment mechanism. Petroleum range hydrocarbons biodegrade under aerobic conditions (oxygen is consumed and CO₂, H₂O, organic acids, and intermediate degradation

compounds are generated) and are fairly resistant to degradation under anaerobic or methanogenic conditions (sulfates, nitrates, carbon dioxide and other fixed oxygen compounds are consumed to produce methane and other products of incomplete metabolism)^{14,30}. Section 3.3.2 of this report gives a more complete discussion of the biological degradation of petroleum range hydrocarbons.

3.2.4.2 Treatment Efficiency

Although landfilling is not a treatment process, natural degradation of contaminants in landfilled PCS can occur over time. However, the EPA could find no data regarding the fate of soils that have been disposed of and covered in landfills. In regard to PCS used as landfill covers, one study sponsored by the Iowa Department of Natural Resources Solid Waste Section examined the concentration of organic contaminants remaining in PCS spread and aerated prior to disposal at three solid waste landfills. A total of 18 PCS samples (six from each landfill) were collected and analyzed for dissolved hydrocarbons (gasoline, benzene, toluene, and xylene), extractable hydrocarbons (diesel, motor oil), EP Toxicity for lead, and TCLP for organics (Toxicity Characteristic Leaching Procedure for 35 organic substances). The results of the analysis are summarized in Table 3-12³⁵.

No data regarding containment levels in the PCS prior to treatment were provided in the report. However, since Iowa's clean-up level for soil is 100 ppm TPH, the initial concentrations in at least some of the soils may have been above this level. If so, this would indicate that spreading and aerating the soil prior to actual disposal was effective in reducing the level of contamination.

3.2.5 Other Ex-situ Corrective Action Technologies

The technologies discussed above account for the vast majority of UST sites using ex-situ management of petroleum contaminated soils. Other technologies are emerging or under consideration by state agencies. These are discussed in this section.

Table 3-12
PCS Treatment Efficiency at Three Iowa Landfills

Analytical Procedure	Landfill One	Landfill Two	Landfill Three
Extractable Hydrocarbons (detection limit of 3 ppm)	6 to 47 ppm	5 to 11 ppm	2 to 81 ppm
Dissolved Hydrocarbons (detection limit of 100 ppb)	< 100 to 150 ppb	all < 100 ppb	all < 100 ppb
Benzene (detection limit of 1 ppb to 5 ppb)	< 1 to < 5 ppb	all < 1 ppb	< 1 to 10 ppb
Toluene (detection limit of 2 ppb to 10 ppm)	< 2 to 10 ppb	< 2 to 3 ppb	all < 2 ppb
Xylene (detection limit of 2 ppb to 10 ppb)	< 2 to 8 ppb	2 to 6 ppb	all 5 ppb or less
EP Toxicity-lead (detection limit of 0.50 mg/l)	all < 0.50 mg/l	all < 0.50 mg/l	all < 0.50 mg/l
TCLP organics	all < detection limits	all < detection limits	all < detection limits

3.2.5.1 Cold Mix Asphalt Plants

In cold mix treatment of PCS, the soils are screened and used, without thermal pretreatment, as an aggregate in the asphalt mix. The number of asphalt plants practicing this approach or that have the capacity to treat PCS in such a fashion is not known. The PCS treatment mode is encapsulation/inclusion in the asphalt. Soils contaminated with Nos. 2, 4, and 6 fuel oil are the most frequently cold mixed petroleum contaminated soils. Gasoline contaminated soils can be used at low contaminant levels and small volumes, but are less commonly treated in cold mix plants, because the light fraction hydrocarbons in gasoline soften the asphalt mix, resulting in a low quality asphalt product. A regulatory official contacted during this study said that the petroleum content of the soil allows the asphalt plant operators to reduce the volume of asphalt emulsion added to the mix. The reduction in the volume of emulsion required is small. The final product usually does not meet DOT standards; however, as non-specification product, it can be used in road foundations for fill material or for paving parking lots or farm roads¹⁶.

3.2.5.2 Stabilization and Solidification

The objectives of stabilization and solidification (S/S) treatment may involve: 1) improving the physical handling characteristics of the waste, 2) decreasing the surface area of the waste and thus its susceptibility to leaching, or 3) limiting the solubility through chemical binding or detoxification of the hazardous constituents in the waste^{8,17,36}.

Stabilization also may include solidification. The process goal is to limit the solubility or mobility and to maintain the hazardous constituent in a chemically stable form, irrespective of changes in the physical characteristic of the hazardous waste^{6,37}. The addition of a chemical agent to transform the hazardous constituents into a new less toxic form also can be considered stabilization. The process goal of solidification is to produce a solidified block exhibiting high structural integrity. The hazardous contaminants, which may or may not be chemically bonded to the additive, are physically sealed within the solid block or monolith^{6,36,37,38}.

Contaminated soils can be stabilized and solidified through the addition and mixing of a variety of standard and proprietary chemical agents. These agents can be grouped into several general categories: 1) cements, 2) limes plus pozzalans (fly ash, cement kiln dust, hydrated silic acid, etc.), 3) thermoplastics (asphalt, bitumen, polyethylene, etc.), 4) thermosetting organic polymers (ureas, phenolics, epoxides, etc.), and 5) miscellaneous others. In addition, organic contaminants may require pretreatment to improve the binding properties of the additives. Waste organic chemicals and compounds (such as oil and grease, sugars, formaldehyde, xylene, benzene, methanol, and others) with concentrations above 10 percent by weight have been demonstrated to interfere with S/S processes. Some additives that improve the binding properties of the additives are: selected clays, emulsifiers, surfactants, and proprietary adsorbents including activated carbon, zeolite minerals, and cellulose materials^{6,36,38}.

In-situ S/S treatment uses modified auguring drill rigs or earth-moving equipment; on-site ex-situ treatment uses transportable trailer mounted tanks, earth moving equipment and mixing drums^{1,6,36,38}. In-situ S/S is not as common as bulk mixing in surface impoundments or excavation and treatment in tanks^{36,38}.

3.2.5.3 Cement Kilns

Cement kilns are another potential option for treating petroleum contaminated soils. The two basic cement production processes are: 1) the wet-process, where the feed materials (sand, clay and limestone) are hydrated from 30 to 35 percent and then interground, forming a uniform mix, and 2) the dry-process, where the feed stock is dried to less than 1 percent moisture, then ground, and mixed⁶. A 1986 EPA report stated that there were 147 commercial cement kilns in the United States at that time, of which 65 units used the more energy-intensive wet process.

According to the report, most new units under construction or planned at that time would use the dry process, and many of the older facilities were converting to the dry process ²⁸.

The treatment of solid wastes in cement kilns has been limited to the extent that it can be suspended or dispersed into the flame zone of the kilns. Recent developments, such as a new method for introducing solid waste-derived fuel into the middle of the kiln, are likely to increase the capacity of cement kilns for treating solid materials²⁹. In spite of these new developments, the potential capacity for cement kiln treatment of PCS over the next several years appears to be very low. Concerns for product quality, combined with the low heating value of these soils, are major impediments to the use of cement kilns for soil treatment. The cement manufacturing industry is currently placing emphasis on treating hazardous pumpable sludges. It is therefore unlikely that cement kiln treatment will be a significant option for PCS treatment under the Subtitle I program for at least the next two to three years.

3.2.5.4 Biological Processes

There are a number of ex-situ technologies that take advantage of biological processes to decompose contaminants in soils. Although they are not currently used to any significant degree for treating PCS from UST sites, they may be viable options for certain sites. These include:

- Composting;
- Prepared bed bioremediation; and
- Bioreactors.

Composting is a system of waste treatment involving the engineered biological decomposition of solid or solidified biodegradable residues under controlled conditions independent of the soil medium⁶. In 1985, 115 facilities composted sludge in the United States⁸. However, no data were found in the literature to indicate the current usage of this technology for the treatment of PCS.

Results from controlled experiments show that the more recalcitrant compounds can be treated using this technology. The applicability of the treatment technology is, however, inherently limited by the biodegradability of the compounds. In addition, composting in itself is not typically the final stage of the PCS treatment process. During EPA's review, no data were found to indicate the treatment effectiveness of this technology, although one published source indicated that additional treatment of the residual soils is usually needed to reduce contaminant concentrations to acceptable levels⁸.

Three general processes can be defined as composting: windrowing (turned), static piles (forced aeration: mechanical pulling, negative pressure or pushing, positive pressure), and in-

vessel. In the windrowing process, PCS is mixed with a bulking agent (wood chips, cow manure, straw, etc.). The bulking agent is a source of carbon and microbes, and a means of increasing the porosity and permeability of the soil piles. The PCS bulking agent mixture is aligned in rows on ideally an impermeable surface (e.g., a plastic liner or asphalt), because potentially noxious run-off and leachate can be generated when PCS is treated in windrows. The shape and dimensions of the windrow is partially dependent on the meteorological conditions of the site, the physical characteristics of the PCS and bulking agent, and the mechanical limitations of the equipment used for turning. The piles are periodically turned, approximately two times a week, with more frequent turning occurring early in the treatment. Turning the pile aerates the soil and promotes the exchange of gases. If necessary, nutrients and Ph control additives are added periodically. After a given period, approximately three to four weeks, the piles are flattened and left alone to cool, dry, and off gas. If recovery of the bulking agent is desired, the piles can be screened and then the residual PCS may be landfarmed if additional treatment is required.

With the static pile process, a system of perforated pipes and bulking agent is constructed on an impermeable layer. PCS is added to this system in roughly one to two foot lifts until the desired height is achieved. Nutrients and Ph adjusters are added as deemed necessary at this point in the soil pile construction¹. The soil pile is covered, and a berm is constructed to control run-off²². Air or oxygen is then pulled or pushed through the soil pile, promoting and enhancing the volatilization and microbial metabolism of the PCS. The flux of air through the pile is adjusted to optimize the moisture content and temperature of the pile and to satiate the biological oxygen demand⁶. This process is typically conducted for two to three months²².

In-vessel composting is performed in closed vessels where conditions can be closely monitored and controlled²². The numerous variations to the basic technology are based in part on the capacity, orientation, configuration, and means of agitation of the system. In general, all in-vessel composting technologies use a means of agitation or aeration of the composted mass or a combination of the two⁶. Because the use of this technology is presently limited, there is little related information available. Moreover, this technology is more expensive compared to windrow or static pile composting technologies.

Prepared bed bioremediation is comparable to land treatment and composting technologies, but requires a much more involved design and management of the treatment facility. The treatment site is first prepared by the addition of an impermeable layer (e.g., asphalt, clay, or synthetic liners) to limit the leaching and migration potential of the contamination^{1,34}. Perforated piping may be laid across the impermeable layer prior to the loading of the excavated PCS on the impermeable layer or may be placed across one to three foot lifts of PCS. The piping is connected to a blower or vacuum pump³¹. Some designs incorporate a separate series of perforated pipes along the top of the soil pile for the introduction, as needed, of nutrients, moisture, Ph control, and so forth. Others use only the pre-existing perforated pipe network^{1,31}.

Once the soil pile has been completed, typically to a height not exceeding 10 feet, an impermeable synthetic cover is installed, as well as a containment dike for run-off and run-on control¹. To maintain optimum levels to support aerobic microbial activity, oxygen is drawn or pushed through the soil pile via the perforated pipes. Nutrients, moisture and other essential requirements are added as needed to the soil pile until remediation is complete ^{30,31}.

Bioreactors also use biodegradation processes. With bioreactor units, soils are batch, sequencing batch, or continuously fed into a mixing vat². Soil introduced into the vat is hydrated sufficiently to create a slurry. The slurry is continuously mechanically agitated to ensure adequate exposure of the PCS to the microbial organisms. The physical and chemical properties of the soil slurry are monitored and adjusted to ensure optimum microbial growth conditions. Nutrients, trace elements, and all additional requirements are added on an as-needed basis. Oxygen is typically introduced into the reactor vessel via air sparging technologies. Microbes acclimated to the metabolism of petroleum range hydrocarbons may be added as desired.

Once acceptable reductions in the contaminant concentration levels or the technological limits of the system have been achieved, the slurry is dewatered. The dewatered soils can be returned to the excavation or disposed of as required. The process/residual water may require additional treatment prior to discharge. Information in the literature indicates that removal efficiencies exceeding 90 percent are achievable, with slightly higher efficiencies expected when ambient temperatures are greater than 24° celsius^{1,2,32,33}.

3.3 TECHNOLOGIES FOR THE IN-SITU MANAGEMENT OF PETROLEUM CONTAMINATED SOILS

This section presents descriptions of soil vapor extraction and bioremediation technologies used for the in-situ treatment of PCS. Unlike the ex-situ technologies discussed in Section 3.2, PCS does not need to be excavated with these technologies. Table 3-13 summarizes information regarding treatment effectiveness, costs, and residuals generated by these technologies.

3.3.1 Soil Vapor Extraction

Soil vapor extraction (SVE) (also referred to as in-situ soil venting, in-situ volatilization, enhanced volatilization, and vacuum extraction) is an in-situ corrective action technology for the treatment of PCS. Given proper site and environmental conditions, this technology can effectively remove gasoline and some diesel range petroleum compounds from soil. It is an attractive alternative to other remedial technologies when contamination is extensive (i.e., when more than 500 cubic yards of soil is contaminated), deep, or unreachable by other alternatives (e.g., under a building)^{1,2,7}.

Table 3-13
Corrective Action Technologies for the In-situ Remediation
of PCS at Petroleum UST Sites

Corrective Action Technology	Mode of Treatment	Cost	Residual/Process Wastes
Soil Vapor Extraction, also known as: In-situ Soil Venting, In-situ Volatilization, Enhanced Volatilization, or Vacuum Extraction	Volatilization/evaporation of the volatile organics with enhanced biodegradation of the heavier petroleum compounds ⁵⁵ .	Considered cost effective when the volume of soil to be treated is > 500 yd ³ (^{13,14}). The major capital costs involve vent well installation, pump purchase and emissions controls ¹ . Emissions controls can be as much as 50% of total costs ⁷ . Quoted estimates are \$20 to 25 per yd ³ (\$22 to \$28 per ton) ^{13,14} and \$10 to 50 per yd ³ (\$11 to \$75 per ton) ¹ .	SVE removes petroleum laden air from the soil which is vented or treated ² . If an air/liquid separator is used, petroleum contaminated water may be generated ⁷ . If carbon adsorption units are used, the spent carbon may be more cost effectively disposed of rather than recycled ⁸ .
Bioremediation	Microbial populations metabolize/consume the petroleum range hydrocarbons as an energy source. Oxygen is consumed and CO ₂ , H ₂ O, organic acids and intermediate degradation products are produced ^{14,30,44} .	In-situ: Cited costs from case studies and literature sources range from \$6 to \$125 per yd ³ (\$7 to \$138 per ton) ^{1,44} .	No waste streams are expected in normal operations ⁸ .

Table 3-13 (continued)
Corrective Action Technologies for the In-situ Remediation
of PCS at Petroleum UST Sites

Corrective Action Technology	Emissions Control Equipment	Effectiveness	Limitations
<p>Soil Vapor Extraction, also known as: In-situ Soil Venting, In-situ Volatilization, or Enhanced Volatilization</p>	<p>Liquid vapor separators may be used to preserve the VOC extraction and control equipment⁷. Carbon adsorption units are useful for product recovery or for dilute air streams. Diffuser stacks are useful for dilute air streams. Vapor incineration. Catalytic oxidation. Condensers.</p>	<p>Experimental results indicate that >99% of the gasoline present as residual saturation in sand can be removed¹⁴. Recovery rates diminish with time typically 6 to 12 months^{8,13}. SVE has removed free product and reduced groundwater concentrations to 0.5 to 1.0 mg/l¹⁴. Emissions control devices can reduce petroleum vapor emissions by > 99%¹.</p>	<p>Limited by the physical properties of the petroleum compound and soil matrix (4). Effectiveness is reduced when: $P^v > 0.001 \text{ atm}^2$, Henry's low coefficient $> 0.01^{1,7,13}$, contaminant is low volatility (e.g., crude oil or jet fuel)², contaminant is highly soluble¹, soil permeability $< 1 \text{ darcy}^2$, or soil has high adsorptive capacity (e.g., clay or organic rich)³⁹,</p>
<p>Bioremediation</p>	<p>Generally there are no emission control units associated with the operation of in-situ bioremediation processes.</p>	<p>Removal efficiencies are site specific, with remediation typically requiring 6 months to years to complete. Degradation rates diminish with time^{1,8}. Achievable reductions are typically > 80% in the low ppm range^{8,44}.</p>	<p>For aerobic biodegradation to be effective some critical environmental factors must exist or be achieved in order to maintain optimum growth conditions for the microbial populations. Soil water content: 25% to 85% of holding capacity, Oxygen: $> 0.2 \text{ mg/l}$ dissolved O_2, minimum air filled porosity of 10%^{2,30}, Ph: slightly acidic to slightly basic, 5.5 to 8.5^{8,30}, Nutrients: sufficient nitrogen, phosphorous, trace metal and other available to support microbial growth^{2,30}, Temperature: 15° to 45° celsius³⁰, Redox potential: > 50 millivolts for aerobic microbial degradation^{8,30}, In addition, high contaminant concentrations can be lethal to the microbial populations². The permeability of the soil must be sufficient to allow the introduction of nutrients and oxygen and the circulation of water.</p>

3.3.1.1 Process Description

SVE achieves its remedial goals by artificially increasing the natural processes of volatilization and biodegradation. Vapor laden air is drawn from the soil and replaced with clean air drawn or forced into the soil via passive or active injection wells. This mechanically induced circulation of air also serves to remove oxygen depleted air from and reintroduce oxygen rich air into the zone of contamination. The continual presence of oxygen is essential to the promotion and maintenance of aerobic microbial activity⁸.

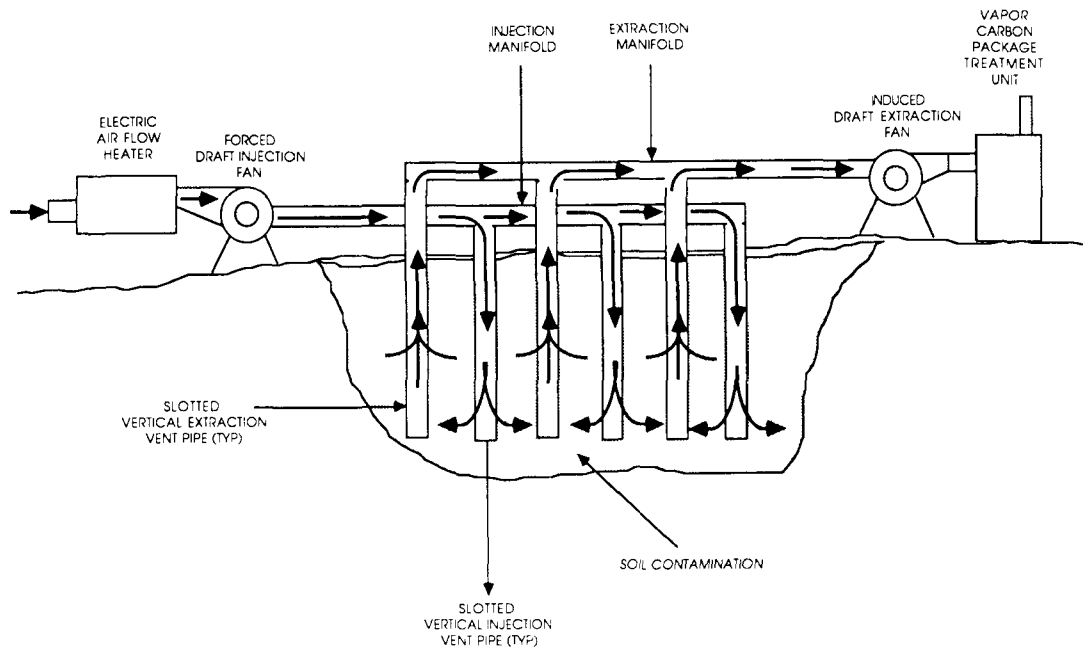
The SVE system and operation are fairly simple. To be effective and efficient, however, the system must be designed and constructed properly. Primary design considerations are flow rate and flow pattern. The more vents (e.g., wells or trenches), the higher the rate at which volatile contaminants can be removed and the higher the capital and operating costs^{7,39}.

Extraction vents are typically placed in the area of highest contamination, whereas injection or passive vents are typically placed along the edges of the contamination. Some primitive systems do not incorporate passive or injection wells into their design; rather, they rely on air drawn from the surrounding medium. Actual vertical and aerial placement of the vents is partially a function of the distribution of contamination and site geology (including stratification, soil porosity, and soil permeability).

Field results indicate that a SVE system is most effective when the extraction wells are screened only near or through the zone of contamination. Vents typically do not circulate air effectively below their installation depth, limiting their ability to draw in petroleum vapors^{1,8,7,39}.

Figure 3-2 is a generalized schematic drawing of the SVE system. Piping (most commonly PVC), originating at the extraction vents, is attached to a pump. The pump creates a negative pressure in the extraction well, drawing vapors from the soil pores. If the soils are highly saturated, the air flow from the vents may be routed through a liquid vapor separator to preserve the extraction and control equipment. In addition, the extraction system design must incorporate safe equipment and be operated so that explosive vapor concentrations are not generated or exposed to potential ignition sources^{8,14}. The petroleum contaminated vapors are then treated, if needed, to reduce the levels of contamination to applicable emissions standards. Four basic technologies can be used to treat petroleum contaminated vapors: 1) carbon absorbers, 2) thermal incineration, 3) catalytic incineration, and 4) condensers⁴⁰. In addition, diffuser stacks may be useful to dilute air streams². Monitoring is required to ensure that the treatment objectives are achieved.

Figure 3-2
Generalized Schematic of Soil Vapor Extraction System⁴



3.3.1.2 Treatment Efficiency

SVE has successfully removed gasoline, benzene, toluene, ethylbenzene, and xylene from soil¹. Estimates in the literature state that treatment can take from one month to one year or more to complete³⁹. However, the determination of whether a site is clean or when a SVE system is not effective in reducing the additional contaminant levels and should be turned off are dependent upon individual state guidelines.

Concentration data for one extraction well in each of two case studies are presented below. The data were collected as part of the data collection efforts for another study being conducted by the EPA:

Case Study Example 1: Approximately 1,600 gallons of gasoline were released from an UST, contaminating a municipal groundwater source. The aerial extent of contamination was

approximately 7,432 square meters. The subsurface media was a clean sandy soil. Corrective action was initiated in May 1986, and is currently ongoing. Table 3-14 presents corrective action monitoring data and calculated values for the removal efficiency (percent reduction in contaminant concentrations)⁴¹.

Case Study Example 2 More than 3,500 gallons of gasoline were released from an UST system contaminating a municipal water supply. The subsurface media was an integrated mixture of sand, silt, and clay. Corrective action was initiated in April 1990, and is ongoing⁴¹.

Table 3-14
SVE Technology Pre-Treatment Effluent Vapor Concentrations⁴¹

Site Location (Number)	Sampling Date (Cumulative count)	Concentration (ppmv Benzene)	Percent Reduction
California 1	11/2/88 (0)	1720	-
	8/7/89 (278)	240	86
	1/10/90 (434)	54	97
	12/20/90 (778)	2.5	> 99
California 2	5/15/90 (0)	24	-
	8/14/90 (91)	1.6	93
	9/19/90 (127)	1.9	92
	10/10/90 (148)	0.38	98
	11/16/90 (185)	0.46	98

For these two case studies, the data indicate that the contaminant concentrations in the soil vapor extracted from the soil was diminished by well over 99 percent and 98 percent, respectively, during the remediation efforts. Other studies show that as remediation time increases, the composition of the SVE system vapor effluent changes, becoming richer in the less volatile compounds¹³. However, soil sample analysis results giving the reduction in soil contaminant levels with time or confirmatory sampling data that could be used to calculate approximate values for overall removal efficiency were not available to EPA at the time of preparation of this report. Since the SVE systems in the two case studies presented were still in operation, it was not possible at the time of preparation of this report to draw conclusions as to the actual effectiveness of this technology in remediating the contaminated soil.

In some instances, SVE remediation can be enhanced by depressing the groundwater table. This practice exposes more of the residual contamination to the induced vapor flow. Contaminant removal then becomes independent of the rate limiting diffusion of the product through and from the groundwater to the soil vapor. In one example in the literature, free product was removed and groundwater concentrations were reduced to 0.5 to 1.0 ppm with the assistance of SVE. In addition, theoretical studies indicate that in sandy soils SVE would be able to remove 99 percent of the gasoline present as residual saturation. However, no data from field sites were included¹⁴.

SVE technology produces an effluent stream of contaminated vapor. This waste stream can be treated using any of the technologies summarized in Table 3-15. Table 3-15 also lists the effectiveness of these technologies in removing or destroying the contaminants in the effluent stream.

Table 3-15
Treatment Effectiveness of VOC Emissions Control Technologies⁷

Vapor Treatment System	Removal/Destruction Efficiency	Conditions
Carbon Adsorption	Can be designed to achieve 99%, although actual efficiencies may be as low as 60%.	Efficiency is dependent upon: inlet concentration, stream temperature, moisture content, and maintenance. Well suited for variable inlet flow rates.
Thermal Incineration	Achieves >99% destruction when inlet concentrations above 200 ppmv; >95% destruction when concentrations are as low as 50 ppmv.	Not well suited to variable inlet flow rates. Supplemental fuel usually required.
Catalytic Incineration	Although 99% efficiencies have been reported, 95% destruction efficiency is typical.	Sensitive to pollutant characteristics, process conditions, and inlet stream flowrates.
Condensation	Removal efficiencies range from 50% to 80% using chilled water; can be increased to 90% when using subzero refrigerants (e.g., ethylene glycol, freon).	Primarily used as raw material and/or preliminary air pollution control devices for removing VOCs prior to other control devices.

3.3.1.3 Operating Parameters that Affect Treatment Performance

SVE removes volatile organics from the soil by increasing and directing the flow of air through the porous medium. To be effective, the physical properties of the porous medium

(e.g., porosity, moisture content, permeability, organic content) and chemical properties of the contaminant (e.g., vapor pressure, solubility) must be conducive to the application of SVE technology. SVE system designs are site specific, dependent upon the site and contaminant properties for determination of the most effective and efficient design. Design variables include: number of pumps, size of pumps, induced flow rate, induced vacuum pressure, location, depth and screen placement of extraction wells/trenches, location, depth and screen placement of induction wells/trenches, and choice of emissions control equipment. Table 3-16 summarizes some of the major site-specific factors that limit the effectiveness of SVE systems. Table 3-17 provides a summary of the characteristics of vapor streams that affect the performance of systems for treating the extracted vapors.

Table 3-16
Conditions Which Generally Limit the Effectiveness of SVE

Conditions	Method of Changing Conditions
Vapor pressure of the petroleum compound < 0.001 atmospheres ² .	None
Henry's law coefficient of the petroleum compound < 0.01 (dimensionless) ^{1,13,7} .	None
Soils have high adsorptive capacities (high organic or clay contents) ³⁹ .	None
Petroleum contaminant is crude oil or jet fuels ² .	None
Soil has high clay or silt contents, permeability < 1 Darcy ² .	One company claims that it has remediated soils with high clay contents and permeabilities < 1 Darcy ⁴² .
Soils have high moisture contents, low air-filled porosity ^{14,39} .	One company claims that it has dewatered a soil prior to remediation using the SVE system ⁴² .
Depth to groundwater is < approximately 5 feet.	Pumping wells can be installed to lower the water table, exposing more of the contamination to the influence of the system.

3.3.1.4 Conditions that Affect Treatment Costs

A wide range of treatment costs using soil vapor extraction systems have been reported in the literature (\$11 to \$75 per ton)^{2,3,4,46}. Table 3-18 lists the factors cited in these sources that affect costs. Since the cost estimates were presented simply as ranges, with no information regarding the numbers of units involved or the distribution of costs within the cited ranges, it is not possible to prepare a statistical analysis of the data.

Table 3-17
Key Emissions Stream Characteristics Important to
Performance of VOC Treatment Systems⁷

Vapor Treatment System	Emissions Stream Characteristics			VOC Characteristics
	Concentration ^a	Flowrate Moisture	Temperature Variation	
Carbon Adsorption	> 700 ppmv	< 50%	Insensitive < 65° celsius	Molecular weight of VOC should range from 50 - 150 grams per mole for best performance.
Thermal Incineration	> 100 ppmv	--	Sensitive --	Can control most VOCs without operational difficulty.
Catalytic Incineration	> 100 ppmv	--	Sensitive --	Phosphorous, bismuth, lead, mercury, arsenic, iron oxide, tin, zinc and halogenated compounds may foul catalyst.
Condensation	> 5,000 ppmv	--	Sensitive < 93° celsius	Removal efficiency limited by vapor pressure, temperature, and characteristics of VOCs present.

^a For optimum efficiency. These techniques will control emissions at lower concentrations than those given, although usually at reduced efficiencies.

3.3.2 Bioremediation

3.3.2.1 Process Description

Bioremediation is the controlled use of microbial biodegradation for the reduction of petroleum hydrocarbon concentrations in soil or water. Microorganisms essentially metabolize (consume) the hydrocarbons as a source of energy (to support growth) using a terminal electron acceptor (e.g., oxygen), and in the process generate water, carbon dioxide, organic acids and a range of intermediary degradation compounds⁴³. In some instances, the enzymes produced for a specific purpose by one organism may unintentionally degrade (co-metabolize) a nontarget compound, providing no benefit to the original organism⁴⁴. It has been postulated that this form of biodegradation is the mechanism by which low contaminant concentrations are achieved.

Table 3-18
Costs Associated with Treatment of PCS with an In-situ Soil Vapor Extraction System

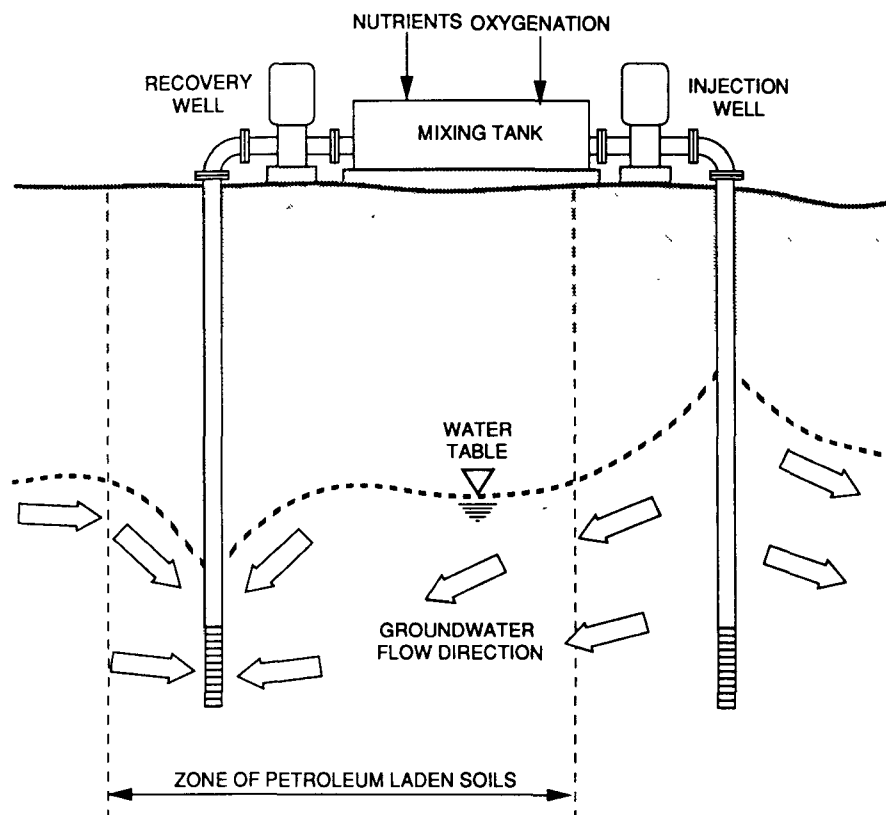
Treatment Costs	Applicable Conditions
\$11 to \$75 per ton ¹ \$300 per ton if steam used to enhance volatilization.	No information provided on conditions affecting operating costs. Systems not including wells can be purchased for \$30,000 to \$60,000 or leased for about \$5,000 to \$10,000 per month.
\$11 per ton ¹	Approximately 50,000 yd ³ of gasoline contaminated soil remediated. Catalytic oxidizer used for vapor treatment. Total remediation time estimated to be four months.
\$20 to \$25 per yd ³⁽¹³⁾	Cost effective when more than 500 yd ³ of PCS is to be treated.
\$15 to \$20 per yd ³⁽¹⁴⁾	Costs excludes treatment of vapor emissions. Operating costs vary depending on utility costs and time of operation. Some of the capital costs include: \$40 per foot for a 20 foot, 2-inch diameter slotted Schedule 40 PVC pipe; \$500 to \$2,000 for vacuum pump capable of moving 40 to 60ft ³ per minute at 1.5 in H ₂ O; or \$4,000 for a vacuum pump capable of moving 1000 standard ft ³ per minute at 25 inches Hg (costs are in 1986 dollars).
Total annualized costs of \$108,360 per year ⁷	Costs are for a 4,000 lbs of activated carbon capacity system, 3.05 foot diameter, 27.3 foot in length regenerative carbon adsorption system for vapor treatment. Includes operating costs associated with maintenance, utilities, and operation.
Total annualized costs of \$203,380 per year ⁷	Costs are for a 5,000 scfm system with no heat exchanger unit. Costs include the price of operation, maintenance and utilities. Replacement catalyst costs are not included.
Total annualized costs of \$18,820 per year ⁷	Costs are for a 2,000 lbs canister system, replaced 14 times and disposed of at a cost of \$72 per canister. Costs include the price of operation, maintenance and utilities.

The microbial populations capable of metabolizing hydrocarbons can be roughly categorized by the terminal electron acceptor used in the metabolic oxidation of the hydrocarbon compound. Microbial degradation can be aerobic (O₂ is the terminal electron acceptor), anaerobic (fixed oxygen compounds, nitrate (NO₃⁻), sulfate (SO₄²⁻) or iron (Fe³⁺), manganese (Mn²⁺), as well as other ions acting as the terminal electron acceptor), or methanogenic. Of these, the alkane and aromatic compounds in gasoline degrade much more readily under aerobic conditions^{8,14}. For aerobic bioremediation technologies to be successful, the oxygen and nutrients required to support microbial activity must be in contact with the carbon source (petroleum contamination) and the indigenous or cultured (artificially introduced) microbial populations⁴³. In addition, environmental conditions (e.g., Ph, moisture, temperature, redox

potential, etc.) conducive to microbial life must be attained and maintained throughout the duration of the corrective action.

The addition of nutrients and oxygen into the ground to control environmental conditions typically involves the installation of downgradient groundwater extraction wells or trenches in such a configuration and pumped at rates sufficient to create a barrier to contaminant migration (see Figure 3-3). The collected water is cycled through a mixing vat where nutrients and in some instances oxygen are added⁸. The mixture is reintroduced above or upgradient of the contaminated soil zone via injection wells, trenches or infiltration galleries. If oxygen is not added to the water in the mixing vat, it may be introduced into the soil in the form of hydrogen peroxide via injection wells or infiltration galleries, or it may be introduced using air sparging technology^{8,45}. Microbes acclimated to the metabolism of petroleum hydrocarbons also may be added to the mixing vat and introduced to the soil system if desired^{2,32,46}. Most soil systems, however, already support microbe species capable of metabolizing petroleum range hydrocarbons. This operation is continued until satisfactory contaminant levels or the technological limitations of the system have been achieved.

Figure 3-3
Basic Components of an In-situ Bioremediation System⁵²



3.3.2.2 Treatment Efficiency

Removal efficiencies of in-situ bioremediation technologies are site specific, with remediations typically requiring six months to years to complete. The hydrocarbon degradation rates observed using this technology decline with time^{1,8}. This decline is partially due to the competitive advantage of using more common organic molecules as a carbon source while the concentration of available hydrocarbons decreases¹⁴. Some examples of achievable reduction levels and remediation times using in-situ bioremediation are presented in Table 3-19^{1,8,14,44}.

Table 3-19
Residual Concentrations and Remediation Times
for Some In-situ Bioremediation Projects⁴⁴

Contaminant	Residual Concentrations	Remediation Time (months)
BTX	< 5 mg/kg (ppm)	12
diesel oil	150 mg/kg (ppm)	18
diesel oil	4,600 mg/kg (ppm)	12
fuel oil	< 100 mg/kg (ppm)	9
diesel/aromatics	30 mg/kg (ppm)	3
gasoline	< 10 mg/kg (ppm)	48

3.3.2.3 Operating Parameters that Affect Treatment Performance

The effectiveness of all aerobic bioremediation systems is dependent upon the maintenance of optimal microbial growth conditions including:

- Soil moisture: Soil moisture should generally be maintained at 25 percent to 85 percent of soil moisture capacity^{2,8,30};
- Oxygen: Oxygen levels optimum for maintenance of aerobic microbial activity are > 2 mg/l dissolved^{30,47};
- Redox potential: Redox potential for aerobic microbial activity should be > 50 millivolts³⁰;
- Soil Ph: The Ph should be in the range of 5.5 to 8.5^{2,53};

- Nutrients: Major nutrients important to the bioremediation process are nitrogen, phosphorous, and hydrogen. Suggested carbon: nitrogen: phosphorous ratio is 120:10:1 (A ratio of 250:10:3 has also been proposed as ideal). Actual quantities will be dependent on the contaminant concentration levels^{30,44,47};

Minor nutrients (1 to 100 mg/l) include sodium, potassium, ammonium, calcium, magnesium, iron, chloride, and sulfur⁴⁷;

Trace nutrients (less than 1 mg/l) include manganese, cobalt, nickel, vanadium, boron, copper, zinc, various organics (vitamins), and molybdenum (Concentration requirements for many of these have not been established⁴⁷; and

- Temperature: The temperature range is recommended at between 15° and 45° celsius^{1,2,8,30,47}.

3.4 TECHNOLOGIES FOR THE TREATMENT OF PETROLEUM CONTAMINATED GROUNDWATER

This section presents corrective action technologies for the remediation of petroleum contaminated groundwater and for the removal of free product. The technologies presented, free product recovery and pump and treat, are those identified during this study as most commonly employed in ongoing corrective action projects. Table 3-20 lists these technologies and presents a summary of the information contained in the following sections.

3.4.1 Free Product Recovery

3.4.1.1 Process Description

Two approaches for the recovery of free product from an UST release are: trenches (passive trenches/drains and active trench systems/sumps) and extraction wells. The choice of approach is dependent upon a variety of site specific conditions outlined in Table 3-21¹⁴. For both approaches, the recovery process is similar. A trench or well(s) is installed downgradient of the migrating contamination plume. Under the influence of gravity (e.g., mechanically induced hydraulic head differences), the groundwater and free product flow into the well or trench. Once there, the free product is either separated from groundwater and removed, or the groundwater and free product are pumped to the surface where the mixture is treated and the free product collected for disposal or recycling^{14,48}. The waste water, which can still contain unacceptable levels of dissolved petroleum compounds, can be reinjected in an attempt to wash residual contaminants from the unsaturated zone, treated (e.g., carbon adsorption, air stripping

Table 3-20
Corrective Action Technologies for the Treatment
of Petroleum Contaminated Groundwater

Corrective Action Technology	Mode of Treatment	Cost	Residual/Process Wastes
Free Product Recovery	FP is isolated directly through product sensitive sensors and floating filters, submerged pumps or surface pumps. Alternatively, the FP and water mixture is pumped to the surface where oil/water separators remove the product for storage, treatment (e.g., blending, reprocessing) or disposal ^{14,48} .	Recovery costs that include the recovery trench/well installation, product recovery, separation, labor, monitoring etc. for four case studies range from \$2.07 to \$93.00 per gallon of product recovered ¹⁴ .	Recovered product may not be suitable for direct consumption as fuel and may require reprocessing. The water generated during the recovery of FP is contaminated with dissolved petroleum compounds ¹⁴ .
Pump and Treat	One of the most common groundwater remediation options is the pumping of contaminated groundwater to the surface for treatment ⁵¹ . The three most common technologies for the ex-situ treatment of contaminated groundwater are: airstripping, carbon adsorption, and bioremediation.	Air stripping: One literature source cited an average cost of remediation to be \$0.05/1,000 gallons to \$0.25/1,000 gallons of influent ¹⁴ .	Potential residuals include the treated waste water if the remedial technology did not achieve acceptable contaminant concentration levels. Biosludges may be generated during the bioremediation of petroleum contaminated groundwater.
	Airstripping: Volatile hydrocarbons exposed to air in packed towers, diffuser trays or spray basins partition from the contaminated groundwater ^{8,14} .	Carbon adsorption: One literature source cited costs for the treatment of influent concentrations > 1 mg/l to range from \$0.45/1,000 gallons to \$2.52/1,000 gallons of influent; and for influent concentrations < 1 mg/l range from \$0.22/1,000 gallons to \$0.54/1,000 gallons of influent ¹⁴ .	
	Carbon adsorption: Hydrocarbons in contact with activated carbon partition from the contaminated groundwater ⁸ .	No cost data for the bioremedial treatment of petroleum contaminated groundwater was identified in the literature.	
	Bioremediation: Hydrocarbons are metabolized by microbial organisms ⁴³ .	Costs for each system can be expected to increase as the residual concentration acceptable in the groundwater approaches the low ppb range ¹⁴ .	

Table 3-20 (continued)
Corrective Action Technologies for the Treatment
of Petroleum Contaminated Groundwater

Corrective Action Technology	Emissions Control Equipment	Effectiveness	Limitations
Free Product Recovery	No emissions control technologies were identified.	No FP recovery system can recover 100% of the release once it is in the soil system. In 4 case studies examined, an average recovery of 25% of the initial spill volume was observed. For the separation techniques, filters and product pumps are capable of reducing product thickness to a sheen, and above ground oil/water separators are capable of reducing petroleum concentrations to approximately 15 ppm ¹⁴ .	Different recovery systems are applicable to a variety of hydrogeologic and geologic conditions. Systems can not recover entire volume of released product. Due to the high concentration of petroleum compounds processed, all equipment must be explosion proof and resistant to dissolution. Large volumes of waste water may be generated by the process, requiring secondary treatment ^{12,14,48} .
Pump and Treat	Emissions control equipment may be associated with the air stripping treatment process. If contaminant emission levels exceed regulatory guidelines the exhaust from these systems can be channeled through a vapor emissions control device (e.g., carbon adsorption canisters, incinerator, catalytic oxidizer). If carbon adsorption technology is used, the vapor laden air must be dehumidified in order to preserve and extend the life of the adsorption units ¹⁴ .	Both carbon adsorption and air stripping systems are capable of achieving > 90% VOC removal efficiencies. Carbon adsorption technology can reduce gasoline range hydrocarbon concentrations to the low ppm levels. In addition, bioremediation systems are cited as being able to reduce contaminant levels to the 100 to 1,000 ppb range ^{8,14} . The effectiveness of pump and treat technology in removing contamination from the ground is not certain. A recent publication indicated that no contaminated aquifers have been remediated to date to acceptable EPA or State standards using pump and treat technology ⁴⁹ .	Air stripping: Limited by the volatility of the contaminant (BTEX compounds are sufficiently volatile to be removed), iron and manganese content of the water, and the suspended solids content of the effluent water ¹⁴ . Carbon adsorption: Limited by the absorbability of the target compounds, the iron and manganese content of the effluent, as well as the cost and availability of carbon adsorption unit recycling or disposal ¹⁴ .

Table 3-21
Site Specific Conditions Which Favor Either a
Trench or Extraction Well for the Removal of Free Product ¹⁴

Trench	Extraction Well
<p>Simple strategy is sufficient.</p> <p>Rapid installation is necessary due to product migration concern.</p> <p>Intercept of entire plume is possible.</p> <p>Groundwater is shallow (<4.6 meters).</p> <p>Soil above groundwater table is firm and well aggregated so that the trench is self supporting.</p> <p>Permeable formations exist.</p> <p>Minimal product thickness exists.</p>	<p>Time is available for hydrogeologic investigations necessary to optimize the placement of extraction wells.</p> <p>Water table is too deep for trenches to be effective.</p> <p>Entire plume can not be intercepted by trenching (multiple wells may needed).</p>

towers), or discharged into the municipal sewer system for treatment at the local publicly owned treatment works (POTW). For UST sites, reinjection of groundwater is not a common practice.

There are a variety of in-situ and ex-situ techniques used to separate free product from groundwater. The selection of a particular technique is dependent on site specific conditions, applicable state and/or local regulations, and costs. Table 3-22 presents these techniques, their operating principles, applications, advantages, and disadvantages¹⁴. It is important to understand that the devices listed in Table 3-22 are only able to remove free product from groundwater that has been drawn from the formation to a collection area such as a recovery well, trench or separation tank.

Free product removal technologies are traditionally limited by the physical impossibility of drawing 100 percent of the petroleum released from an UST system from the saturated and unsaturated soil zones. Petroleum released into the soil system will form a residual saturation between and in the micro- and macropores of the soil which is extremely difficult to remove due to the complex physics of the soil system. Corrective action techniques commonly used to reduce the level of residual contamination in the soil matrix include: excavating the contaminated soil above and below the groundwater table, applying in-situ soil washing technology, relying on natural processes (e.g., biodegradation, oxidation, volatilization), or enhancing the flow of product toward the recovery well(s) and conducting product recovery operations (e.g., vacuum-enhanced-free product recovery).

Table 3-22
Free Product Groundwater Separation Techniques¹⁴

Separation Technique	Operating Principles	Application	Advantages	Disadvantages
Skimmers	Skimmers float and respond when electronic sensors detect the presence of gasoline(pumping gasoline to the surface for storage or treatment).	Used in trenches. Water table depression is not critical for recovery. Low formation hydraulic conductivities. Water table fluctuations are large.	Easily deployed, and may be set permanently or temporarily, or operated manually. Skimmers are relatively insensitive to small suspended particulates (e.g., <0.64 cm).	Since the pump is located at the ground surface, skimmers are physically restricted to operate at depths less than approximately 7.6 meters. Recovery is limited to reducing the product thickness to a sheen.
Filter Separators	An oleophilic-hydrophobic filter floats at the water surface, allowing petroleum products to pass through into a collection compartment, but preventing water. A surface pump acting upon an electronic signal pumps the accumulated gasoline once a set volume has been collected.	Used in trenches. May be used in conjunction with a dual pump system in shallow recovery wells. Formation hydraulic conductivities are low to moderate (e.g., 10^{-4} to 10^{-2} cm/s).	Easily deployed. Separation energy requirements are limited.	Since the pump is located at the ground surface, skimmers are physically restricted to operate at depths less than approximately 7.6 meters. Recovery is limited to reducing the product thickness to a sheen.
Single Pump System	A submersible or surface pump is used to pump both gasoline and water to storage tanks or an oil/water separator	Useful for small spills, when recovery rates are relatively low (e.g., <500 gal/hr)	No information provided	Large volumes of water must be treated or stored, and during pumping gasoline is mixed.
Dual Pump System	A groundwater extraction pump is lowered into the well. Water is removed until a sensor, located above the probe indicates that a cone of depression has been established. The product pump is located just above the water sensor and is triggered by an electronic sensor to pump when product is detected above a set minimum thickness.	Applicable when large amounts of gasoline must be recovered. Sites that require minimal on-site treatment and separation of gasoline/water mixture.	Two pumps reduce the volume of water that needs to be stored or treated. Electronic sensors allow the system to function automatically.	No information provided
Aboveground Oil/water Separators	Groundwater and gasoline mixture is pumped into a series of tanks where its velocity and turbulence are reduced, allowing gravity to separate the petroleum emulsion from the water. A variety of internal baffles can be used to enhance the separation.	Most useful when single pump system is used, and water flow through the system is slow.	Under optimum operating conditions the contaminant levels can be reduced to approximately 15 ppm.	Proper design dictates that the capacity of the separator is 10 times the volume of mixture to be treated per minute. Optimum residence time for separation is 10 to 12 minutes.

The latter option involves the application of SVE technology in conjunction with extraction wells. The groundwater extraction pumps lower the groundwater elevation and expose areas of residual contamination. The well system is sealed, and a vacuum is applied to the extraction well that pulls air through these exposed areas into the extraction well, expediting the volatilization of the petroleum compounds⁴¹. Refer to Section 3.3.1 for a more detailed description of SVE technology.

3.4.1.2 Treatment Efficiency

No free product recovery system can recover 100 percent of the released product. The best these systems can achieve is the removal of a majority of the mobile product, because there is a limit to the effectiveness of the collection systems to separate free product from water. A number of case studies support this statement.

Case Study Example 1: Approximately 83,000 gallons of JP-4 jet fuel were released. The groundwater elevation was 5.2 meters below the surface, and the soil type was sand. A series of extraction well points were installed downgradient of the plume and attached to a surface-mounted centrifugal pump. Five weeks after the initiation of recovery operations, the system was shut down when no additional product was being recovered. A total of 20,800 gallons of fuel were finally collected, with only 25 percent of the original spill volume. The remedial engineers concluded that the unrecovered 62,200 gallons of fuel remained as residual saturation in the pore spaces of the soil¹⁴.

Case Study Example 2: Approximately 100,000 gallons of gasoline were released from service station UST. Product recovery was initiated using the monitoring wells as extraction points. An automated system of three 0.66 meter recovery wells, submersible groundwater extraction pumps, and surface mounted product recovery pumps was eventually installed down gradient of the advancing plume. After 7 months of operation, 28,500 gallons of gasoline were recovered. The recovered product was recycled for re-use¹⁴.

3.4.1.3 Conditions that Affect Treatment Costs

The Office of Underground Storage Tanks has identified treatment costs for free product recovery at four UST sites. Table 3-23 summarizes this information and the conditions that apply to the cost estimates. As shown, costs range from \$2.07 to \$93 per gallon of product recovered.

Table 3-23
Costs Associated with Free Product Recovery¹⁴

Treatment for Costs for Individual Sites	Applicable Conditions
\$2.07 per gallon recovered	Oil/water separator used to treat well point effluent. 25% of the 83,000 gallons spilled recovered prior to termination of recovery project. Installation and equipment rental for five weeks totalled \$21,500.
\$70.31 per gallon recovered	Costs include the price of free product recovery, well drilling costs, oil/water separator, pumps, and construction and engineering services. 700 of the 3,000 gallons released have been recovered.
\$93 per gallon recovered	Costs include the purchase and installation price of a 6 inch recovery well, 75 gallon per minute submersible recovery pump, and a 3 foot diameter packed air stripping tower. 1,200 of the 2,000 to 4,000 gallons spilled were recovered.
\$7.89 per gallon recovered	Costs include the price of three 26 inch recovery wells, three 15 horsepower submersible pumps, three surface mounted recovery pumps, and air stripping towers. 28,500 of the 100,000 gallons released were recovered.

3.4.2 Pump and Treat

3.4.2.1 Process Description

"Pump and treat" systems involve the extraction and ex-situ treatment of contaminated groundwater. To be effective, the groundwater extraction system (i.e., wells/trenches and associated pumps and piping) must be installed and operated so that the contaminant plume is contained and removed. A thorough site characterization must be performed prior to extraction well/trench installation in order to determine their optimum location. Once the system is installed and operational, contaminated groundwater is pumped to the surface where it is treated or stored for future on-site or off-site treatment. Storage and off-site treatment may be more economically advantageous when the volume of water to be treated is small or permitting requirements inhibit the rapid installation of an on-site treatment system.

For small sites (typically service station locations) well placement can be determined after the collection and analysis of the characterization data, but larger and more complex sites may need to be modelled (e.g., analytical, numerical) to determine the appropriate well-installation approach. Groundwater extraction wells or trenches/ditches need to be installed so that the contaminant plume is contained when contaminant groundwater extraction/pumping is initiated.

A variety of options exist for the ex-situ treatment of petroleum contaminated water: air stripping, activated carbon adsorption, bioremediation, resin adsorption, reverse osmosis, ozonation, oxidation with hydrogen peroxide, ultraviolet irradiation, and land treatment. Of these, air stripping and activated carbon adsorption are the most commonly employed technologies¹⁴. Airstripping and carbon adsorption are frequently used in series to enhance the removal efficiencies and to prolong the life of the carbon adsorption units.

Air stripping technologies employ four alternative types of aeration methods: diffused aeration, tray aeration, spray aeration, and packed towers. Of these, packed towers are the most commonly used to treat petroleum contaminated water. All of the systems, however, treat contaminated groundwater by enhancing the ability of the dissolved volatile hydrocarbons to partition from the groundwater to the air. This is accomplished by greatly increasing the surface area of the contaminated water exposed to the air⁵¹.

Diffused aeration systems sparge air from a diffuser grid upward through the contaminated water. The volatile hydrocarbons partition from the water into the rising bubbles until they exit the system saturated with organic vapors. Spray aeration systems pump contaminated water through nozzles generating a fine mist. The volatile organics partition from the mist into the air. The treated water is collected in prepared ponds or basins. Treatment can be enhanced by recirculating the collected water through the nozzles. Tray aeration systems are designed so that contaminated groundwater fed through the systems top, cascades (under the influence of gravity) through a series of slat trays. The water is aerated as it descends, allowing the volatile hydrocarbons to partition into the air. Packed towers are similar to tray aeration systems. Contaminated groundwater is fed through the top of a tower, packed with inert packing material, where it cascades through the packing material. Concurrently, air is forced up the column¹⁴.

Carbon adsorption units used for the treatment of petroleum contaminated water are very similar to those used for the treatment of petroleum laden vapors. Groundwater is pumped through a series of canisters (typically 2 to 4) filled with activated carbon. The dissolved organic compounds adhere to the carbon. Eventually the carbon in the first canister in the series will become saturated and will no longer be able to remove dissolved hydrocarbons. The system is temporarily shut down as a new canister is added to the end of the series and the first canister is removed and either regenerated on site (steam cleaned), or transported off-site for regeneration or disposal, dependent on site-specific costs.

3.4.2.2 Treatment Efficiency

A recent publication indicates that no contaminated aquifers have been remediated to date to acceptable EPA or State standards using pump and treat technology⁴⁹. Table 3-24, which presents groundwater monitoring data collected during a pump and treat corrective action

Table 3-24
Groundwater Pump Effluent Monitoring Data

Site Location Number	Sampling Date (Cumulative Count)	Benzene Concentration (ppm)	Removal Efficiency (%)
California (2) Well 1	8/5/87 (0)	20	-
	12/6/88 (489)	2.1	90
	3/2/89 (575)	17.7	12
	7/12/89 (707)	11	45
	9/29/89 (786)	5	75
	2/22/90 (932)	10	50
California (2) Well 2	8/5/87 (0)	15	-
	12/6/88 (489)	9.7	35
	3/2/89 (575)	22.3	-49 ^a
	7/12/89 (707)	22	-47 ^a
	9/29/89 (789)	10	33
	2/22/90 (932)	19	-27 ^a

Negative numbers indicate that the measured concentration after the initiation of pumping was greater than the initial concentration measured.

activity, illustrates the limitations to this treatment approach. These data were collected by the Office of Underground Storage Tanks as part of another EPA study. In the first case, after 900 days the concentration of benzene in the groundwater was reduced only 50 percent, to 10 ppm. In the second case, after 932 days the concentration of benzene in the groundwater increased 27 percent, to 19 ppm. Corrective action activities had not reduced dissolved benzene concentrations to levels acceptable to state environmental agencies in either case.

The effectiveness of the pumping well effluent treatment, however, is considerably better. Once the contaminated groundwater has been removed, ex-situ treatment technologies are capable of substantially reducing contaminant levels although reported removal efficiencies vary widely. Removal efficiencies for halogenated organics reported in the literature for air stripping technologies ranged from 70 to 90 percent for diffused aeration, 10 to 90 percent for tray aeration, and 90 to more than 99 percent for packed towers. Granulated activated carbon (GAC) units can remove aromatic compounds by more than 99 percent. Air stripping and GAC in series can remove more organics and produce a treated water of higher quality than either system alone¹⁴.

3.4.2.3 Operating Parameters that Affect Treatment Performance

The design of a pump and treat groundwater remediation system is dependent upon the characteristics of the site to be remediated, including factors such as depth to groundwater, permeability of the porous medium (e.g., soil or rock), stratigraphy of the subsurface, type of contamination and geographic, political, economical and territorial restrictions to the placement of extraction wells and equipment. There are, therefore, a variety of potential design and associated operating parameters. Two basic design philosophies are:

1. Installation of few large diameter deep extraction wells with large volume pumps that are capable of affecting the flow of a large area: Under this design, the water table is significantly depressed and extracted groundwater is circulated through large volume treatment or disposal systems. This design may be more advantageous when space restrictions limit the placement of extraction and treatment equipment.
2. Installation of numerous, small diameter wells, that are screened through the contaminated zone: In this design, small volume pumps are used to collect the groundwater and circulate through treatment or disposal systems.

The treatment performance of pump and treat systems under either approach is highly dependent on site-specific conditions.

3.5 SUMMARY AND CONCLUSIONS

This chapter has provided an overview of information documenting the performance of remediation technologies most commonly used at UST sites under the current Subtitle I program, in terms of contaminant removal efficiency, operating parameters that affect contaminant removal efficiency, residuals generated, and costs. The information was compiled from a variety of sources, including published literature, state agencies, and equipment vendors. No new data was generated in developing this overview.

Major findings for each of the technology alternatives are as follows:

1. For low temperature thermal stripper (LTTS) systems, treatment costs range from \$74 to \$184 per ton, while additional costs can be greater if stringent gas treatment is performed. Treatment efficiencies for volatile organic constituents in soils of more than 99 percent have been reported, although available data indicates a wide range of removal efficiencies has been experienced (as low as 27%). Major factors contributing to this variation include the concentrations of contaminants in soils and soil conditions. However, information that comprehensively characterizes the effects of operating

parameters and soil/contaminant characteristics on treatment effectiveness for petroleum contaminated soils has not been documented.

2. Soils treatment in hot mix asphalt plants currently ranges from about \$50 to \$100 per ton. More than 99 percent removal efficiency of benzene in soils has been reported, although treatment performance is highly variable. The extent to which each of the various treatment mechanisms involved (including desorption, oxidation, and encapsulation of contaminants) contributes to removal and destruction of petroleum compounds has not been documented. Data that provides a definitive characterization of the effects of variations in operating parameters and soil/contaminant characteristics on treatment effectiveness is not available.
3. Land treatment of soils costs from \$5 to \$70 per ton. Treatment efficiencies for organic contaminants ranging from 70 to greater than 99 percent have been reported after five months of treatment. The extent to which these reductions can be attributed to physical/chemical/biological processes in the soil and to volatilization to the atmosphere has not been documented.
4. Disposal of soils generated at UST sites in municipal solid waste landfills is currently the most common practice in states contacted during this study. Disposal costs range from \$4 to \$132 per ton, with a national average of \$27 per ton reported in 1988. No data characterizing the extent to which petroleum contaminated soils contribute to contaminants in leachates generated at municipal landfills were found during this study.
5. In-situ treatment of soil by soil vapor extraction is considered to be cost effective when the volumes of soil are greater than 500 cubic yards. Reported costs range from as low as \$11 per ton to as high as \$75 per ton. While data on treatment effectiveness at UST sites is limited, results indicate that removal of 98 to 99 percent of volatile constituents has been achieved at some sites.
6. In-situ bioremediation is gaining popularity in a number of state UST programs. Treatment costs and effectiveness are dependent on site-specific conditions. Reported costs range from \$7 to \$138 per ton. Reductions of organic constituents by more than 80 percent can be achieved at certain sites.
7. Free product recovery is very commonly used at UST sites at the initial stage of groundwater treatment. Recovery costs range from \$2 to \$93 per gallon of recovered product. In four case studies, recovery of about 25 percent of the initial spill volume was observed. No free product recovery system can remove the entire volume of released product.

8. Pump and treat methods are commonly used for treating contaminated groundwater at UST sites. The most common methods for treating groundwater that is pumped to the surface is oil/water separation followed by air stripping or carbon adsorption. Costs of \$0.05 to \$0.25 per thousand gallons of influent have been reported for air stripping, while costs as low as \$0.22 per thousand gallons to as high as \$2.52 per thousand gallons have been reported for carbon adsorption. Carbon adsorption and air stripping units are capable of removing more than 90 percent of volatile organic compounds from contaminated groundwater.

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APPENDIX A

SUMMARY OF STATE REQUIREMENTS FOR MANAGEMENT OF PETROLEUM CONTAMINATED SOIL GENERATED AT UST CORRECTIVE ACTION SITES

A.1 SUMMARY OF STATE REQUIREMENTS

As part of this study, EPA performed a review of selected state programs under RCRA Subtitle I in order to identify the types of state requirements currently in place for managing petroleum contaminated soils generated at UST corrective action sites, from initial generation and characterization through their final treatment and/or disposal. Table A-1 is a summary of these requirements in each of the 26 states contacted during this study. The information in each column of the table describes state requirements for each major step in the corrective action process, from the characterization of the media and debris through the ultimate disposition of these materials. The table provides a snapshot of the state requirements based on examples provided by states through the first quarter of 1991. It is not intended to be a comprehensive compilation of all current requirements that could affect selection of corrective action technologies.

A.2 CORRECTIVE ACTION TECHNOLOGIES USED IN EACH STATE

A number of ex-situ and in-situ corrective action technologies are currently used to treat petroleum contaminated media and debris generated at UST corrective action sites in accordance with applicable state requirements. As discussed in Chapter 2, states contacted during this review indicated that the following technologies are commonly used to treat petroleum contaminated soils: low temperature thermal strippers, asphalt plants, landfarming, landfilling, soil vapor extraction, and ex-situ and in-situ bioremediation. Table A-2 list the ex-situ and in-situ corrective action technologies reported by selected states to be in current use.

Table A-1^a
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TESTING REQUIREMENTS		CLEANUP STANDARDS	REGULATORY STATUS OF PCS
	SAMPLING	ANALYSIS		
Arizona (IX)	Site-specific	BTEX (EPA Method 8020) TPH (Modified EPA Method 8015 for gasoline; modified 418.1 for diesel/waste oil).	Specific concentration levels (guidance); Site-specific risk-based levels are optional.	Solid waste permit generally required unless PCS treated on-site within 12 months.
California (IX)	Three different sampling methods based on suspected level of soil/groundwater contamination: core/trowel sampling (no evidence of contamination), soil boring (known contamination), and grab sampling (groundwater).	Sample analysis dependent on type of sample and substance to be analyzed: BTEX (EPA 8020), TPH (Dept. of Health Services Method), and HVO (EPA 8010) for gasoline; TPH (DHS Method), TRPH (EPA 418.1) for diesel.	Standards are established on a site-specific basis using several analyses (leaching potential analysis and general/ alternative risk appraisals). CAEPA recommended maximum contaminant levels are: 10- 1,000ppm TPH for gas, 100 to 10,000ppm TPH for diesel, 0.3-1ppm benzene, 0.3-50ppm toluene, 1- 50ppm xylene, 1-50ppm ethylbenzene.	Soils classification is dependent on the determined contaminant concentrations. Soils failing classification standards are considered hazardous.
Colorado (VIII)	Field screening used as guidance for location, type and number of sample selections. Grab sampling to characterize area and borings to locate maximum concentration. Minimum of 3 samples below each tank excavated.	All samples analyzed for BTEX. If the contaminant is unknown, then Hydrocarbon Scan for all tests. Known contaminants: TVH for gasoline, TEH for diesel and weathered gas, oil/grease method for oil and grease.	Three Remedial Action Categories (RAC) based on groundwater usage determine standards. Soils in contact with RAC groundwater should be remediated accordingly: <20 - 100mg/kg BTEX, <100 - 500mg/kg TPH.	If PCS are not characterized as hazardous wastes, they are considered as solid wastes and require disposal in accordance with the Solid Waste Disposal Act or at regulated UST facilities.
Connecticut (I)	Sampling in pit; Grab samples from stockpiles (minimum number based on volume).	BTEX (EPA Method 8010/8020); EP Tox.	Site-specific based on designated water quality in area.	Hazardous waste if total hydrocarbons (BTEX) > 50 ppm or if EP Toxicity exhibited.
Delaware (III)	Sampling in pit at points of maximum contamination; Composite samples from stockpiles (minimum number based on volume).	BTEX (EPA Methods 3810/8020; 5030/8020; 3810/8240);TPH (Modified EPA Method 418.1); APHA Methods 5520E/5520C; APHA Methods 503B/503E).	Action levels for BTEX and TPH based on site category (3 categories, based on risk).	Regulated as "regulated substance waste" under state solid waste program.
Florida (IV)	Number of samples determined on a site- specific basis, dependent on the size of the excavation and degree of potential contamination. Composite and grab sampling are used.	Organic vapor analysis (OVA) to determine level of soil contamination.	Standards vary - excavated soils taken to thermal treatment facility must meet "criteria for clean soil" in accordance with Dept. rule; if remediated in another manner, other criteria apply, but are not mandated by Dept. rule.	500 ppm - excessively contaminated, should be remediated but not required; 10 to 500 ppm - contaminated, cleanup may be necessary; <10 ppm - not contaminated, remediation not necessary.

Table A-1 (continued)^a
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TREATMENT/DISPOSAL RESTRICTIONS		TRANSPORTATION REQUIREMENTS	ON-SITE STORAGE REQUIREMENTS
	ON-SITE	OFF-SITE		
Arizona (IX)	Soil meeting cleanup standards may be returned to excavation.	Solid waste permit required. For treatment, substantial information must be submitted prior to approval.	Solid waste permit required.	Stockpiles must be on impervious liner, covered, and bermed. For long-term storage, air permit may be required.
California (IX)	Permitting required for mobile or fixed treatment of hazardous wastes. Air permits typically are required to control emissions from incineration systems. Waste discharge permits typically required for all post-treatment use of PCS. Non-hazardous waste is regulated by local jurisdictions, not the CAEPA.	Same as onsite.	"Hazardous" soils require a manifest and transport by a registered hauler.	Local authorities may require management activities to minimize off-site migration.
Colorado (VIII)	On site (excavated or in-situ) PCS exceeding appropriate RAC levels must be managed in accordance with an approved corrective action/contaminated materials handling plan.	PCS > appropriate RAC levels managed off-site may be: disposed of at approved facility, with incorporated approval at asphalt batch plant for construction application. Recycled PCS with certification used in road construction are not considered solid waste.	N/A	Stockpiles should be placed on plastic liner or asphalt, bermed and covered to prevent contaminant migration.
Connecticut (I)	N/A	Soils with total BTEX < 50 ppm and which pass EP Tox may be disposed in Solid Waste landfills. Otherwise, must go to permitted hazardous waste facility.	Hazardous waste must be transferred by licensed hazardous waste handlers.	Stockpiles must be on impervious liner and covered.
Delaware (III)	The state recommends on-site treatment of PCS as a succession to the removal/abandonment of an UST. Must complete remediation within a year or more aggressive measures will be required.	Regulated under solid waste program.	N/A	Soils must be secured with plastic lining to prevent erosion, runoff, leaching, air emissions and unauthorized access. On-site storage is limited to one year.
Florida (IV)	Mobile thermal treatment units must be permitted.	Thermal treatment facilities are permitted, regulated and have specific sampling and analysis requirements for all accepted wastes.	N/A	PCS stored on-site must be stockpiled on an impermeable liner and covered.

Table A-1 (continued)^a
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TESTING REQUIREMENTS		CLEANUP STANDARDS	REGULATORY STATUS OF PCS
	SAMPLING	ANALYSIS		
Indiana (V)	Number of samples is dependent on the number of tanks removed and the size of the excavation. Grab sampling is the preferred approach.	TPH analysis using California modified 8015. Landfill operators may require TCLP analysis prior to acceptance of waste.	Site by site basis. Attempt to remediate the soil to "as clean as possible."	PCS classified as special wastes.
Iowa (VII)	Samples are collected from beneath the tank bottom. The number of samples depends on the size of the tanks. Only grab samples are accepted.	Total Organic Hydrocarbons (from Iowa Method OH-1 and OH-2)	Soils are "clean" if Total Organic Hydrocarbons is below 100 ppm.	PCS considered a special waste.
Kentucky (IV)	Sample number and location dependent on excavation size and whether contamination is suspected or not. Sampling is designed to demonstrate that soil remaining on site is clean.	Landfills require EPA paint filter test, PAH and BTEX for diesel contaminated soil, TPH and BTEX for gasoline, EP Tox (lead) for old gas and a metals screen for waste oil contaminated soils.	Background or detection limits.	PCS regulated as a "pollutant" requiring notification and proof of remediation via a receipt (similar to a manifest). Only soils exceeding EP Toxicity standards for lead are considered hazardous.
Louisiana (VI)	Samples are collected below tank pad in an excavation. If these samples are contaminated then a total site assessment is required.	Gasoline contaminated soils: BTEX (EPA Method 8020); Diesel contaminated soils: TPH (modified California procedure); waste oil contaminated soils: EP Tox, oil and grease (Method 503E), total organic halogens (D808) and volatile hydrocarbon scan (EPA Method 8240).	Established on a case by case basis.	Soils removed from a site are considered a solid waste.
Maine (I)	Sample location and numbers determined on a site by site basis.	Testing is dependent on released compound. Use department developed hydrocarbon analyses: total gasoline or total fuel analysis. TPH only in rare circumstances (e.g. heavy oils).	No uniform requirements, but 50 ppm total gasoline hydrocarbon typically required. New risk based policy in development.	Regulated as special solid waste.
Maryland (III)	Determined on site-specific basis.	TPH and BTEX are required.	100 ppm TPH for soils; Non-measurable level for free product; Attainment of asymptotic level for ground water.	No unique regulatory status.
Massachusetts (I)	Sampling in pit; Grab samples from stockpile (minimum number based on volume).	Jar Headspace Field screening procedure for gasoline; TPH for other petroleum products.	Site-specific risk based levels.	Waste petroleum products are listed hazardous wastes.

Table A-1 (continued)*
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TREATMENT/DISPOSAL RESTRICTIONS		TRANSPORTATION REQUIREMENTS	ON-SITE STORAGE REQUIREMENTS
	ON-SITE	OFF-SITE		
Indiana (V)	Permission of the state required prior to initiation of corrective action. Technology employed must be demonstrated effective under the given conditions.	Permitted special waste landfills and hazardous waste disposal facilities.	Permit required.	PCS stockpile must be stored on plastic and covered.
Iowa (VII)	Special approval required before bioremediation may be employed. Passive remediation - monitoring and continued assessment.	Landfill must land treat soils until TPH is < 100 ppm when the soil is used as cover material. Incineration - emission standard with continual approval.	N/A	Site-specific requirements, temporary option.
Kentucky (IV)	On-site remedial treatment must comply with the air emissions standards and other safeguards. Most forms of remediation are acceptable provided feasibility study is performed to demonstrate effectiveness.	Landfills that incorporate certain technologies are permitted to accept PCS. Landfarming operations require a registration for > 500T and a special permit for < 500T, as do all other alternative remedial technologies.	N/A	Soils isolated with thick plastic sheeting. Receipt must indicate duration of storage.
Louisiana (VI)	On-site aeration is permitted as a means of reducing contaminant levels so that soils may be returned to the excavation. Its use is limited to areas where there is no potential risk to human health.	Only disposal options are designated commercial and hazardous waste landfills.	Soils removed from a site are governed by the regulations governing the transport of solid waste.	Excavated PCS must be stored on plastic and encircled by a protective berm to contain run-off.
Maine (I)	No specific permits are required. There are siting and operation and maintenance restrictions.	Landfills are restricted in the volume of soil they can accept each year. Land application is restricted to petroleum products from known sources with extensive siting restriction criteria.	Currently none.	Stockpile must be stored on plastic and covered.
Maryland (III)	If > 100 TPH, can be stored on site for more than 48 hours, and can be returned to pit only if monitoring well is installed: if < 100 TPH, can be returned to pit.	No specific requirements.	No specific requirements.	Stockpile must be on impervious liner and covered. Storage may not be allowed if odor problem exists.
Massachusetts (I)	On-site re-use is restricted based on concentrations of contaminants in soils and on environmental vulnerability of site.	Soils with > 1800 ppm total headspace volatiles or > 3000 mg/kg TPH cannot be disposed of in landfills. Operational restrictions for landfilling PCS are specified.	Bill of lading must be signed by state.	Stockpiles must be on impervious liner and covered, with public access minimized; Storage limited to 4 months.

Table A-1 (continued)^a
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TESTING REQUIREMENTS		CLEANUP STANDARDS	REGULATORY STATUS OF PCS
	SAMPLING	ANALYSIS		
Minnesota (V)	Grab samples from stockpiles; minimum number based on volume of soil.	BTEX (EPA Method 8015) TPH, and lead for soils with regular gasoline and aviation fuel; TPH, metals and PCB, (EPA Method 8080) for soils with waste oils.	Gasoline and aviation fuels: 10 ppm vapor headspace; TPH < 50 ppm. Other contaminants: vapor headspace above background.	Distinct Regulatory Classification.
Missouri (VII)	Composite and grab samples in pit.	BTEX (EPA Method 8020 or 8240); TPH (modified EPA Method 418.1). For soils with waste oils, EP Tox.	Site-specific risk-based levels for BTEX and TPH.	Disposal of soil contaminated with virgin fuel oil or gasoline does not require permission prior to disposal. Soil contaminated with waste oil is restricted as "special waste".
Montana (VIII)	Site-specific for sites with confirmed releases; Sampling requirements in pit specified for clean closures.	BTEX and/or TPH (site-specific) for gasoline; TPH for diesel and heavy oils.	Site-specific, but normally 100 ppm TPH and 10ppm BTEX is maximum.	N/A
New Jersey (II)	Recommended targeting of areas of potential contamination. One sample for every 20 cubic yards; up to 5 samples per analysis. For total VOC analyses, one subsurface sample for every 50 cubic yards. Total VOC is only used to determine if PCS is below regulatory concern (BRC).	Recommended to determine if PCS is BRC: gasoline contaminated soils - TPH and Total VOC analyses; other Virgin fuels - TPH only; if source is unknown - TPH, Priority Pollutant Metals and VOC using a Photo- Ionization Detector/Organic Vapor Analyzer; if VOC level > background, test Total VOC. For classification purposes: TPH, PCBs, cyanide and sulfur reactivity, and TCLP metals for 1/10 of all samples. If only one sample, TCLP required.	Site-specific depending on classification of soils into one of three categories. Classification determined by specific contamination limits: Hazardous waste (HW) > Nonhazardous waste (NHW), NHW > Category 3 limits, Below Regulatory Concern (BRC) < Category 3 limits.	Regulated according to soil classification: HW soils must be managed as HW in accordance with NJAC 7:26-1, NHW soils have various options (disposal, landfill covering, reuse) BRC soils do not need to be classified and may be used without treatment or prior approval (conditions apply).
New Mexico (VI)	Minimum number of 3 samples collected from variety of locations. A discrete sample must be taken from the excavation.	Gasoline contaminated soils: EPA Method 8240, 8020, or modified 8015; Diesel fuel, motor oil and other heavy petroleum products: EPA Method 418.1 or another approved method.	Soil contamination is reduced to levels which will not contaminate ground water or produce harmful vapors. Gasoline contaminated soils: Total BTEX < 50 ppm and B < 10 ppm. Diesel, motor oil, kerosene or jet aviation: TPH < 100 ppm.	"Highly contaminated soils" are saturated with petroleum products to the extent that free product is observable in the soil. Soils which are not saturated but have benzene concentrations > cleanup standards must be remediated under conditions defined by the state.

Table A-1 (continued)*
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TREATMENT/DISPOSAL RESTRICTIONS		TRANSPORTATION REQUIREMENTS	ON-SITE STORAGE REQUIREMENTS
	ON-SITE	OFF-SITE		
Minnesota (V)	PCS below action levels may be used as backfill only at original site. Landfarming on-site with approval.	Landfilling not allowed. Landfarming or thermal treatment require approval, subject to specific restrictions.	N/A	Stockpiles must be on impervious liner, covered, and contoured.
Missouri (VII)	Soils must have < 10 ppm TPH or < 1 ppm total BTEX to be used as clean fill.	Soil contaminated with waste oil requires state approval prior to disposal in solid waste landfills; soil contaminated with virgin fuel oil or gasoline does not require approval.	N/A	N/A
Montana (VIII)	If landfarming 1 to 100 yd ³ on PCS owner's property - require verbal approval from state and possible sampling and monitoring. If landfarming > 100 yd ³ at any site - require written approval from state and soil sampling and monitoring.	If landfarming 1 to 100 yds on another's property - require verbal approval from state, written permission from owner, and possible soil and groundwater monitoring. If applying > 100 yd ₃ from more than 1 site - permit required.	N/A	Must choose location which will not cause groundwater, soil, or air pollution. State can require covering and/or berming. Local authorities should be contacted prior to storage.
New Jersey (II)	Soil reuse plan must be approved by NJDEP. Soils should not be stockpiled on-site longer than 6 months from time of excavation.	Must follow NJ Waste Flow Management Program for PCS disposal. HW soils require a manifest; removal and disposal must be conducted by a registered contractor. Options for NHW soils are subject to Department approval.	N/A	Stockpiles should be completely isolated, preventing any hazardous materials from contact or release into the environment.
New Mexico (VI)	Soil meeting cleanup standards for benzene may be returned to the excavation or used as road mix. Soil excavation and disposal is dependent on the site conditions, depth to ground water and contaminant levels.	Landfarming operations are required to meet certain design and operation standards. Landfarms and landfills are permitted operations.	N/A	On-site storage requirements are based in part on the depth to ground water. Typically require storage of PCS on an impervious layer in a bermed area.

Table A-1 (continued)^a
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TESTING REQUIREMENTS		CLEANUP STANDARDS	REGULATORY STATUS OF PCS
	SAMPLING	ANALYSIS		
New York (II)	Guidelines are site-specific for sampling from the tank pit, stockpile, processed soils and non-excavated soils.	EPA Method 8020 for gasoline, EPA Method 8270 Base/Neutrals for fuel contaminated soils. Hazardous waste determination regarding ignitability and toxicity from lead. Proposed guidance provides both TCLP extract analysis and direct sample analysis by the above methods.	Proposed cleanup standards are compound specific, being protective of human health, fish and wildlife, groundwater quality, and aesthetics.	PCS regulated as industrial solid wastes. Proposed guidance: PCS are unregulated if they pass a TCLP test based on the state's water quality standards, or if contaminant levels are below maximum values set by the Water-Soil Partition model.
Oregon (X)	Sampling requirements are site specific and based on site complexity. Samples should represent soils remaining on site. No composite samples are allowed.	Gasoline contaminated soils, DEQ Lab Method TPH-G; Diesel or non-gasoline fraction hydrocarbons, DEQ Lab Method TPH-D. For all soils: Hydrocarbon identification (DEQ Lab Method TPH-HCID). Waste oil contaminated soils: analysis for volatile chlorinated solvents and volatile aromatic solvents. TCLP analysis for metals. PCBs by method 8080; DEQ Lab Method TPH-418.1 Modified.	Site specific numeric clean-up criteria, based on depth to ground water, mean annual precipitation, nature of soil and rock, sensitivity of uppermost aquifer, and potential receptors.	Specified waste under Oregon Administrative Rules (OAR 340-61-060).
Tennessee (IV)	Number of samples dependent on the size of the excavation and tanks removed. Grab samples in pit. Samples are required from the stockpiled soil to determine disposal options.	Benzene in TCLP extracts: EPA Method 8020 or 8240 or equivalent tests. TPH in TCLP extract: California GC Method. Lead concentration in TCLP extract: EPA Method 6010, 7240, 7421 or equivalent.	BTX levels < 10 ppm.	Special waste approvals required before waste with BTX between 10 and 100 ppm can be disposed of in landfills.
Texas (VI)	In general, minimum requirements dictate 1 sample must be collected from each wall of the excavation, 1 from the pit bottom, 1 from under the dispensing islands and 1 from any stockpiled soils.	Unleaded gasoline contaminated soils: TPH and BTEX analysis; leaded gasoline contaminated soils: TPH, BTEX, EP Tox for lead; Diesel contaminated soils: TPH and BTEX; Waste oil contaminated soils: EP Tox, total organic halogen scan and additional tests as deemed necessary. BTEX (EPA Method 8020 with EPA Method 5030 purge and trap). TPH (EPA Method 3540 or 3550 quantified using EPA Method 418.1 or ASTM d3328-78 Method B).	Goals are site specific and designed to prevent public exposure. A LUST Remediation Index has been established to set remediation goals when only soil is contaminated.	Have special regulatory status outside of Hazardous and Solid wastes rules unless they are deemed hazardous through ignitability.

Table A-1 (continued)^a
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TREATMENT/DISPOSAL RESTRICTIONS		TRANSPORTATION REQUIREMENTS	ON-SITE STORAGE REQUIREMENTS
	ON-SITE	OFF-SITE		
New York (II)	Non-excavated soils may be subject to the same standards as excavated soils, but are not regulated as solid or hazardous waste until after excavation (site specific parameters apply). Permitting required only for on-site treatment of hazardous PCS. Proposed: PCS must meet "clean" soil criteria for on-site disposal.	Hazardous PCS must be disposed of at a permitted hazardous waste facility. Non-hazardous PCS must be treated or landfilled at permitted facilities, except for fuel oil soils which may supply approved asphalt plants. Proposed: "clean" soil to be re-used, returned to excavation, or landfilled.	Hazardous PCS must be manifested to a permitted hazardous waste facility; none required for non-hazardous PCS. Appropriate transport permits are required for both types of soils. Proposed: "clean" soils to be transported without permits.	Excavated soils must be placed on and covered by impervious material with the sides banked to control/contain run-off. PCS cannot be stored on-site for more than 90 days without on-site treatment approval.
Oregon (X)	Regulated under UST permit modification.	For soils from regulated tank sites: landfilling only for specified wastes with authorization, one-time authorization and performance standards for off-site treatment of soils. Soil from non-regulated tanks subject to TCLP analysis and possibly restricted to hazardous waste disposal facilities.	Licensed by Oregon Public Utilities Commission for transportation of general commodities if soils are non-hazardous; special license required for hazardous waste transportation.	Permit required ensuring that soils are managed to prevent fire hazards and runoff contamination.
Tennessee (IV)	On-site or in-situ remedial activities must submit the results of periodic sampling.	Disposal and treatment options are based on concentration levels.	N/A	Contaminated soils stored separately from non-contaminated during excavation.
Texas (VI)	On-site aeration allowed if air pollution would not result. Permits and approval may be required in order to perform on-site remediations.	Currently landfills can not accept soils with BTEX levels > 500 ppm or TPH levels > 1000 ppm. Soon landfills will not be allowed to accept PCS.	N/A	On-site storage is regulated to prevent public exposure. PCS must be stored on an impervious material, have run-off and run-on protection and be covered if on-site aeration is not allowed.

Table A-1 (continued)*
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TESTING REQUIREMENTS		CLEANUP STANDARDS	REGULATORY STATUS OF PCS
	SAMPLING	ANALYSIS		
Utah (VIII)	Minimum of 4 samples are required per excavation.	TPH (California modified 8015 or approved equivalent). Oil and waste oil contaminated soils are analyzed for total oil and grease (EPA Method 413.1). Samples for grain size analysis must also be collected.	Established on a site by site basis.	Various local Department of Health ordinances apply.
Virginia (III)	Composite samples (minimum number based on volume), if intend to excavate and dispose in landfill. Must have discrete samples for on-site disposal.	BTEX, free liquid, TOX, TPH (EPA Method 418.1); EP Toxicity and Ignitability (if applicable). Additional testing requirements applied on a site-specific basis.	Standards are site specific and are based on risk and technology.	Status is determined by analytical results, and may fall either under the Solid or Hazardous Waste Management Program.
Washington (X)	Sampling requirements are being developed.	TPH analysis (Dept. Lab Method) is required of all excavated soils. BTEX analysis is required for all gasoline contaminated soils.	100 ppm TPH for gasoline 200 ppm TPH for diesel 0.5 ppm for benzene 20 ppm ethylbenzene 40 ppm toluene 20 ppm xylenes 250 ppm lead	Defined as "problem wastes" under state's solid waste regulation; specific requirements are lacking. New guidance is being developed.
Wyoming (VIII)	A single representative grab sample is required from location of maximum potential contamination.	No laboratory analysis of gasoline, diesel fuel or crude oil is required. Analysis required for waste oil or other petroleum products.	Interim standards are based on depth to ground water. TPH > 100 ppm must be mitigated. TPH > 10 ppm and GW < 50 ft. must be mitigated.	Soils contaminated with gasoline, diesel, fuel oil or crude oil are regulated. Soil contaminated with waste oil or any other petroleum product needs specific authorization for disposal.

Note: "N/A" means that either there are no specific requirements for petroleum contaminated soils, or that information regarding such requirements was not available to EPA.

Table A-1 (continued)^a
Summary of State Requirements for Management of Petroleum Contaminated Soils

STATE (REGION)	TREATMENT/DISPOSAL RESTRICTIONS		TRANSPORTATION REQUIREMENTS	ON-SITE STORAGE REQUIREMENTS
	ON-SITE	OFF-SITE		
Utah (VIII)	Local health departments may restrict on-site activity.	At the state level, landfills are not regulated as to what they can accept. Regulation and permitting is controlled by the local agencies.	N/A	Excavated PCS should be stored on plastic and comply with air emission standards.
Virginia (III)	A hazardous waste management permit is required for the on-site treatment or disposal of hazardous PCS. If the soil is a solid waste, treatment may be performed under direction of the State Water Control Board.	Off-site disposal/treatment of hazardous soils must be performed at authorized hazardous waste management facilities. Off-site treatment is available at approved thermal treatment units.	Hazardous PCS must be transported by a Virginia-permitted transporter under a manifest. There are no specified requirements for non-hazardous PCS.	Stockpiling of soils is strongly discouraged until waste has been properly characterized. Soils should be stored in containers or tanks. Non-putrescible solid wastes are required to be disposed at intervals less than thirty days.
Washington (X)	N/A	Currently no specific guidelines in place that dictate ultimate disposal options. Proposed guidance will probably indicate a number of disposal options based on contamination levels.	N/A	Stockpile management requirements are being developed.
Wyoming (VIII)	On-site treatment is permitted only in case of emergencies, provided certain restrictions are met. Air quality permits are required for soil vapor treatment operations.	Soils contaminated with gasoline, diesel, fuel oil or crude oil may be routinely accepted for landfill disposal at permitted facilities. Soils contaminated with waste oil or other petroleum products need special approval before acceptance and only after certain requirements are met by the disposal facility.	N/A	PCS are usually loaded directly into a dump truck. PCS stockpiled on site required to be stored on a liner and covered.

The table provides a snapshot of the state requirements based on examples provided by states through the first quarter of 1991. It is not intended to be a comprehensive compilation of all current requirements that could affect selection of corrective action technologies.

Table A-2
Corrective Action Technologies Used in States Contacted During this Study

STATE	LANDFILLING	LANDFARMING	AERATION	LAND APPLICATION	ASPHALT OPTIONS	INCINERATION	LTTS	SOIL VAPOR EXTRACTION	BIOREMEDIATION
Arizona	X	X						X	
Colorado	X	X				X	X		X
Connecticut	X		X					X	
Delaware	X	X	X		X		X	X	
Florida	X	X			X	X	X	X	
Indiana	X	X			X			X	
Iowa	X	X	X					X	X
Kentucky	X	X	X			X			
Louisiana	X		X						
Maine	X	X	X	X	X			X	
Maryland	X				X			X	
Massachusetts	X				X				
Minnesota					X		X		
Missouri	X			X				X	
Montana	X			X					
New Jersey	X						X		
New Mexico	X	X	X					X	
New York	X				X		X	X	X
Oregon	X	X	X				X		X
Tennessee	X		X		X			X	X
Texas	X	X	X			X	X	X	
Utah	X	X	X						
Virginia	X	X		X			X		X
Washington	X	X	X					X	
Wyoming	X	X			X				