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AIR EMISSIONS FROM THE  
TREATMENT OF SOILS CONTAMINATED  
WITH PETROLEUM FUELS AND OTHER SUBSTANCES

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## **ABSTRACT**

This report updates a 1992 report that summarizes available information on air emissions from the treatment of soils contaminated with fuels. Soils contaminated by leaks or spills of fuel products, such as gasoline and jet fuel, are a nationwide concern. Air emissions during remediation are a potential problem because of the volatile nature of many of the fuel components and the remediation processes themselves, which may promote or result in contaminant transfer to the vapor phase. Limited information also is included on air emissions from the treatment of soils contaminated with hazardous wastes.

The report will allow staff from state and local regulatory agencies, as well as staff from EPA regional offices, to assess the different options for cleaning up soil contaminated with fuels. Seven general remediation approaches are addressed in this report. For each approach, information is presented about the remediation process, the typical air emission species of concern and their release points, and the available air emissions data. Control technologies for each remediation approach are identified and their reported efficiencies are summarized. Cost data are given for each remediation approach and for its associated control technologies. Emission estimation methods (EEMs) for each remediation approach are presented along with a brief case study. An uncertainty and sensitivity analysis was also prepared for each EEM.

A 1992 report was initially revised in 1995 in fulfillment of EPA Contract No. 68-D2-0160, Work Assignment 2-62, by Radian Corporation. The 1992 report also was prepared by Radian Corporation.

This second revision to the 1992 report was prepared in 1996 in fulfillment of EPA Contract No. 68-D3-0035, Work Assignment II-92, by E.H. Pechan & Associates, Inc., 2880 Sunrise Boulevard, Suite 220, Rancho Cordova, CA 95742.

## EXECUTIVE SUMMARY

This document summarizes the available information on air emissions from the treatment of soils contaminated with fuels. It is intended to guide State and local air pollution control agencies in the evaluation of the air emission potential of treatment of contaminated soil and the cost-effectiveness of applicable emission control technologies. The scope was limited to the emissions of volatile organic compounds (VOCs); however, because of the limited data that were available, information was also included for the emissions of other organic compounds. This additional information is primarily from the treatment of soils contaminated with hazardous wastes.

Seven general approaches for the disposal or treatment of soils contaminated with gasoline, oil, or diesel fuel were identified:

- Excavation and removal;
- Thermal desorption;
- Soil vapor extraction (SVE);
- In-Situ biodegradation;
- Ex-Situ biodegradation;
- Incineration; and
- Soil washing/solvent extraction/soil flushing.

Each general approach may include several specific options. For example, thermal desorption may be performed in portable units designed specifically for soil treatment or in rotary drum aggregate dryers that are part of asphalt plants or other industrial facilities.

Literature pertaining to the emissions of volatile organic compounds (VOCs) for each remediation approach was identified and reviewed. The summarized information was organized into the same ten part format for each approach:

- Process description;
- Identification of air emission points;
- Identification of typical air emission species of concern;
- Summary of published air emissions data;
- Identification of applicable control technologies;
- Cost data for the overall remediation approach;
- Cost data for the emission controls;
- Equations and models for estimating VOC emissions;
- Case study of the use of the remediation approach; and
- References.

For most of the technologies examined, VOC emission estimates or measured data were found. Emission factors, in grams per hour, were identified or developed that are based on available data as well as assumed "typical" operating conditions for the remediation of relatively large sites. Cost data, in dollars per ton or cubic yard of soil treated, were obtained from a variety of sources, but data prior to 1986 were generally avoided because of the changes in remediation technology, standard operating practices, and regulations in recent years. All cost data for years prior to 1991 were converted to 1991 dollars using a 5% annual escalation factor. Cost data for years subsequent to 1991 are given on an as-is basis.

Certain limitations of the data presented in this document should be considered before extrapolations are made to a specific site under consideration. Any generalized guidance has inherent limitations due to the variety of site-specific and process-specific factors that may be encountered. Many of the cleanup processes are emerging technologies and have short operating histories. For these technologies, data on air emissions, treatment effectiveness, and costs are very limited. Furthermore, each site has its own unique obstacles to cleanup that may force modifications to the cleanup hardware or operating conditions. The development of typical air emission rates and emission factors applicable to the maximum number of site conditions and site locations required assumptions regarding the rate and scope of the cleanup effort, the type of fuel being treated, the number and nature of emission release points, and so on. The more a specific site differs from the assumed conditions, the less likely the generalized air emissions data will be applicable.

In general, only limited information was found for air emissions from the treatment of contaminated soil. The need for more data is greatest for emerging technologies and those that are area sources of VOC emissions. The general needs are for more emissions data, more control cost and effectiveness data, and data for the development of accurate emission estimation methods (EEMs). The most important research needs that were identified during this study were:

- VOC emission rate data for excavation;
- Improved EEMs to estimate VOC emissions from excavation; and
- Fate studies for VOCs in biotreatment systems.

## METRIC CONVERSIONS

Non-metric	Multiplied by	Yields Metric
MMBtu/hr	1054.35	MJ/hr (megajoule per hour)
°F	0.555556 (°F - 32)	°C
ft	0.3048	m
acfm	0.028317	acmm
dscfm	0.028317	dscmm
gal	3.78541	L
hp	746	J/sec
in	2.54	cm
lb	0.453592	kg
mil	0.0254	mm
mile	1609.344	m
ton	0.907185	Mg (megagram), metric ton, or 1,000 kg
yd <sup>3</sup>	0.76455	m <sup>3</sup>
yd <sup>2</sup>	0.8361	m <sup>2</sup>

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## LIST OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
BTU	British Thermal Unit
BTX	Benzene, Toluene, and Xylenes
CO	Carbon Monoxide
CSTR	Continuously-Stirred Tank Reactor
CTC	Control Technology Center
DAVES	Desorption and Vapor Extraction System
DOD	Department of Defense
EEM	Emission Estimation Method
EPA	Environmental Protection Agency
FTIR	Fourier-Transform Infrared
GAC	Granular Activated Carbon
HCl	Hydrochloric acid
HEPA	High Efficiency Particulate Air
IC	Internal Combustion
ICE	Internal Combustion Engine
LEL	Lower Explosive Limit
LTTA	Low-Temperature Thermal Aeration
LTTD	Low-Temperature Thermal Desorption
LUST	Leaking Underground Storage Tank
NA	Not Applicable
ND	Not Determined
NO <sub>x</sub>	Nitrogen Oxides
OUST	Office of Underground Storage Tanks
PAH	Polynuclear Aromatic Hydrocarbons
PCB	Polychlorinated Biphenyls
PCDD	Polychlorinated Dibenzodioxins
PCDF	Polychlorinated Dibenzofurans
PM	Particulate Matter
PNA	Polynuclear Aromatic
PVC	Polyvinyl Chloride
RCRA	Resource Conservation and Recovery Act
SVE	Soil Vapor Extraction
SVOC	Semi-Volatile Organic Compound
TCDD	Tetrachlorodibenzodioxin
TCE	Trichloroethylene
TEQ	Toxic Equivalent Quantity
THC	Total Hydrocarbons
TNMHC	Total Non-Methane Hydrocarbons
TPH	Total Petroleum Hydrocarbons
TTSD	Technology Transfer and Support Division (former CERI)
TVH	Total Volatile Hydrocarbons

LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

UST	Underground Storage Tank
UV	Ultraviolet
VOC	Volatile Organic Compound





## 1.0 INTRODUCTION

### 1.1 Background

The Control Technology Center (CTC) at the U.S. Environmental Protection Agency (EPA) is responsible for supporting State and local air pollution control agencies in the implementation of their programs. As part of this support, the CTC provides assessments of the control technologies available for reducing emissions from a particular type of source. The CTC typically provides expertise and information not otherwise available to the State or local agency.

The CTC has received requests from State and local regulatory agencies, as well as from EPA regional offices, regarding how to assess the different options for cleaning up contaminated soil. The requests have addressed a number of specific remediation techniques, such as the clean-up of soils using rotary drum dryers. Information is needed for estimating the potential air emissions from various types of processes and for determining what control options may be appropriate. While some guidance is currently available, it is dispersed among multiple documents.

The purpose of this project was to develop a procedure and guidance document for use by State and local regulatory agencies for evaluating the air emission potential and applicable control technologies for the treatment of contaminated soil. Radian Corporation assisted the CTC in this effort. The original document was prepared in 1992 under EPA Contract Number 68-DO-0125, Work Assignment 25 and Contract Number 68-D1-0117, Work Assignment 31. The document was revised in 1995 under EPA Contract Number 68-D2-0160, Work

Assignment 2-62. Existing guidance for how to assess both potential air emissions and available control technologies was identified. Examples of different clean-up operations were identified for soils contaminated with gasoline, diesel fuel, or fuel oil. In addition, information on the kind of control technologies that are available and their expected range of capital and operating costs was obtained.

### 1.2 Objectives

The specific objectives of this program were to:

- Identify options for the disposal/treatment of soils contaminated with gasoline, oil, or diesel fuel;
- Review the available literature pertaining to the emissions of volatile organic compounds (VOCs) for each clean-up option and emissions of dioxins/furans from the thermal treatment options;
- Summarize suggested approaches for estimating the VOC emissions from the various clean-up options;
- Identify applicable control technologies and compile ranges of capital and operating costs for each technology; and
- Summarize the information in a guidance document.

The clean-up options addressed in this document are:

- Excavation and removal;

- Thermal desorption (includes asphalt plants);
- Soil vapor extraction (SVE);
- In-Situ biodegradation;
- Ex-Situ biodegradation;
- On-site incineration; and
- Soil washing/solvent extraction.

### 1.3 Approach

The general approach was to perform a literature search and telephone survey of researchers and regulators. Several hundred publications were reviewed and evaluated. Contacts were made with researchers active in the field to identify any new or emerging information. Contacts also were made with regulatory staff in California, Florida, Louisiana, Maryland, Michigan, and Texas to obtain any air emissions measurement data submitted as part of permit applications. These states were thought the most likely to have such data, but no data were found in this search.

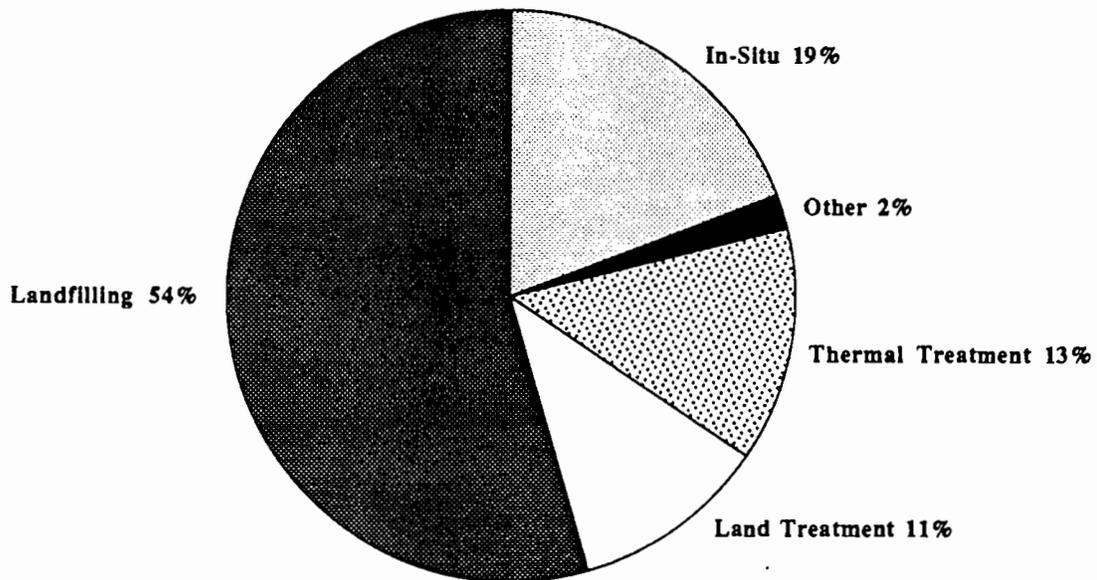
For each of the identified remedial options, the literature was reviewed to develop a process flow diagram and identify emission points, as well as to analyze available air emissions data. For most of the technologies examined, VOC emission estimates or measured data were found. Where VOC data were limited, data for other types of organic compounds were compiled. EEMS were identified or developed based on available data as well as assumed "typical" operating conditions for the remediation of relatively large sites.

Cost data were obtained from a variety of sources, but data from prior to 1986 were generally avoided due to the changes in remediation technology, standard operating practices, and regulations in recent years. All cost data prior to 1991 were converted to 1991 dollars using a 5% annual escalation factor. All cost data published after 1991 are reported with no correction.

### 1.4 Frequency of Use of Various Remediation Options

The remediation options addressed in this document are all potentially suitable for use as part of the remediation process for soils contaminated with fuels. The various options, however, are not necessarily all equally cost-effective nor is their use equally widespread. EPA's Office of Underground Storage Tanks (OUST) has surveyed state agencies responsible for the cleanup of leaking underground storage tank (UST) sites to ascertain the frequency of use of various remediation options. The information is primarily derived from the remediation of UST sites contaminated with gasoline and dates from 1991. This information is summarized in Figures 1-1 and 1-2.

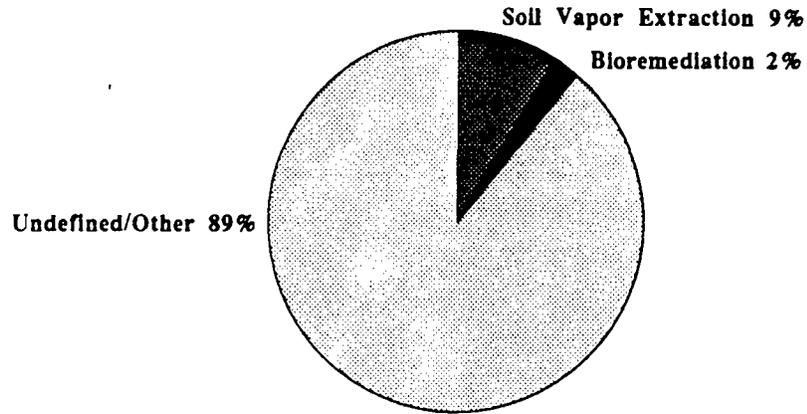
Figure 1-1 shows the relative frequency of use of the major classes of remediation options. Land filling (excavation and removal) is used somewhat more than half the time, with in-situ methods, thermal treatment, or land treatment also frequently used. Figure 1-2 provides more detail as to the type of in-situ, land treatment, and thermal treatment methods employed. For sites employing in-situ remediation, the exact technology used is undefined the majority of the time. It is



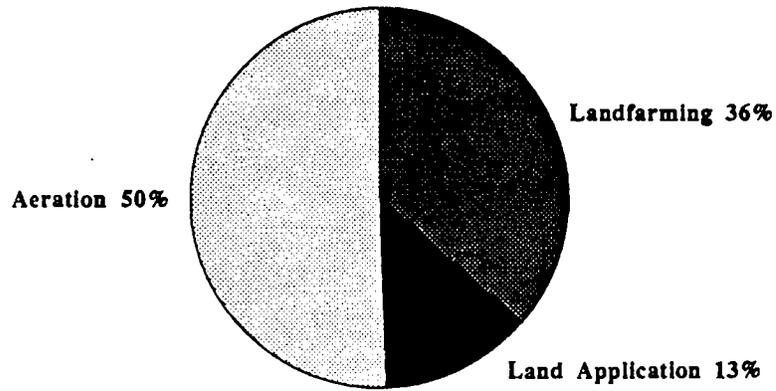
**Figure 1-1. Relative Frequency of Use of Remediation Technologies at UST Sites.**

Source: EPA-OUST (Due to rounding, figure may not total to 100%)

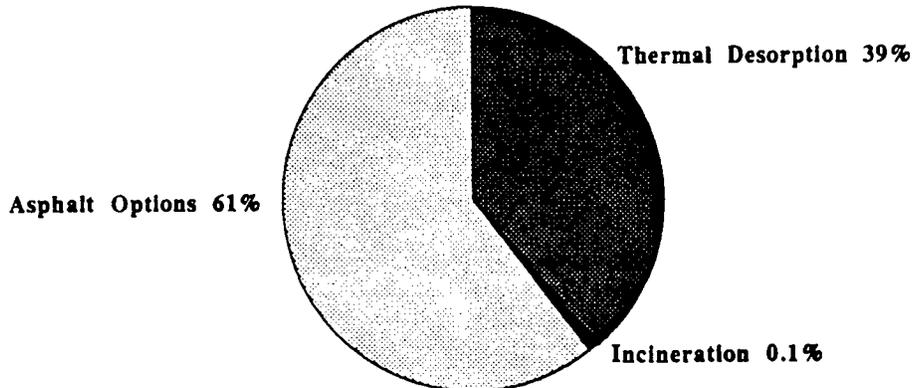
**In-Situ Technologies**



**Land Treatment Technologies**



**Thermal Treatment Technologies**



**Figure 1-2. Relative Frequency of Use at UST Sites by Specific Technology.**

Source: EPA-OUST (Due to rounding, figures may not total to 100%)

assumed that soil vapor extraction is probably used in most of these cases. For applications of thermal treatment, thermal desorption is almost always employed and incineration is only very rarely used.

The frequency with which various treatment methods have been proposed for use at Superfund sites is shown in Figure 1-3. Superfund sites may be contaminated with a number of pollutants instead of or in addition to petroleum fuels, such as heavy metals, polychlorinated biphenyls (PCBs), asbestos, and pesticides. Therefore, it is not surprising that the frequency with which various remedies are proposed for Superfund sites differs from that for UST sites.

### **1.5 Limitations of the Document**

The review of the available information showed that the amount of data is more limited than originally expected. There is not adequate data on VOC air emissions from remediation to assess the importance of fuel type, spill volume, the age of the spill, and the soil type as they relate to the combination of remediation and control technologies that are applied. Therefore, there is insufficient data to develop empirical step-by-step estimation procedures and to assess the uncertainty associated with such estimates.

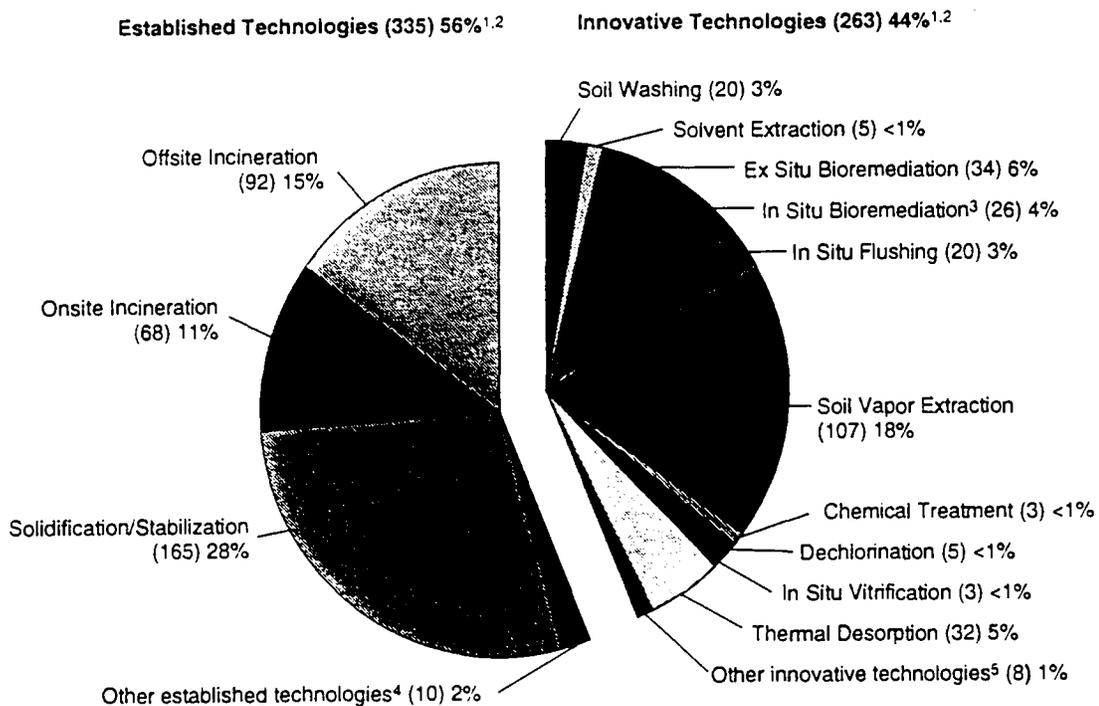
In this document, the limited existing information was compiled to provide users with a summary of air emissions data. Information is included for VOC air emissions from the treatment of both soils contaminated with petroleum fuels and the treatment of hazardous waste to fill as many data gaps as possible.

Generalized guidance for the remediation of soils contaminated with fuels

has inherent limitations. Many of the cleanup processes are “developing technologies” and therefore have short operating histories. For these technologies, data on air emissions, treatment effectiveness, and costs are very limited. Furthermore, each site was its own unique obstacles to cleanup that may force modifications to the cleanup hardware or operating conditions.

The development of typical air emission rates and emission factors applicable to the maximum number of site conditions and site locations required assumptions regarding the rate and scope of the clean-up effort, the type of fuel being treated, the number and nature of emission release points, and so on. Assumptions were based on what is “typical” and “reasonable” for the remediation of relatively large sites. Obviously, the diverse nature of sites with fuel contamination will result in the information presented here being more applicable to some sites than others. A limited data set must be used to generalize about a wide-spectrum of process conditions.

The VOC air emissions data compiled in this document can be used for planning purposes and for comparison to permit applications, but the user must take into account the inherent limitations of the data and the limitations in extrapolating the data to fit the specific remediation scenario under consideration.



<sup>1</sup>Based on 504 RODs specifying a total of 598 treatment applications.

<sup>2</sup>The number of times a technology was selected is shown in parentheses.

<sup>3</sup>Includes 11 in situ ground-water treatment remedies.

<sup>4</sup>"Other" established technologies are soil aeration, in situ flaming, and chemical neutralization.

<sup>5</sup>"Other" innovative technologies are air sparging, contained recovery of oily wastes, limestone barriers, and fuming gasification.

**Figure 1-3. Alternative Treatment Technologies Specified in Superfund Remedial Action RODs from FY 1982 Through FY 1992.**

Source: The Hazardous Waste Consultant: May/June 1994.

(Reprinted by permission of the publisher from "Use of Innovative Treatment Technologies Is Increasing at Superfund Sites", The Hazardous Waste Consultant, May/June 1994, p. 1.15, Copyright 1994 Elsevier Science Inc.)

## 2.0 SUMMARY OF RESULTS

Information was compiled and evaluated for six categories of remediation technologies. Information about each remediation technology is summarized in Table 2-1. The remediation technologies can be categorized as follows:

### *in-situ* approaches

soil vapor extraction  
*in-situ* biodegradation  
soil flushing

### *ex-situ* approaches

thermal desorption  
*ex-situ* biodegradation  
incineration  
soil washing  
solvent extraction

Information on excavation also is included because the *ex-situ* approaches all require that the contaminated soil be excavated and fed to the treatment unit. The fugitive emissions from the materials handling operations for *ex-situ* processes often are overlooked or ignored, but they may represent a significant fraction of the total emissions from the remediation effort.

A variety of control devices may be employed with each of the remediation technologies. The most commonly used controls for each technology are shown in Table 2-2.

Air emission data for each remediation technology were compiled. The reported data primarily are measured concentrations in the exhaust gas or offgas (i.e. mass/volume of air), but measured emission rate data (mass/time) also are

available. There was not sufficient data to develop meaningful VOC emission factors based on starting soil contamination levels for the remediation technologies of interest.

Typical treatment cost data are given in Table 2-3 for treatment operations with and without emission controls. The emission factors are based on "reasonable" operating conditions for the remediation of sites contaminated with petroleum fuels, but these estimates may not be applicable to some clean-up programs. A range of costs are given in most cases and these estimates are considered to be the best available information in the literature. The cost estimates are not all based on the same remediation scenario, so the data for a given remediation technology may not be directly comparable to the data for another remediation technology because the underlying assumptions of the volume of contaminated soil, the types and mass of contaminants that are present, the rate of treatment, the type of controls employed, etc. may vary.

**Table 2-1  
Summary of Information for Remediation Technologies**

<b>Remediation Technology</b>	<b>Emission Points</b>	<b>Typical Air Emission Species of Concern</b>	<b>Amount of Air Emissions Data</b>	<b>Frequency of Use of Controls</b>	<b>Comments</b>
Excavation	Soil surface	VOCs, PM	Very limited	Seldom	Often overlooked, Potential to be major air emission source
Thermal Desorption	Stack, Waste feed	VOCs, SVOCs	Extensive	Always	Usually performed with mobile units
Soil Vapor Extraction	Stack	VOCs	Some	>50% of systems	May be converted to bioventing after initial period
<i>In-situ</i> Bioremediation	Stack, Soil surface	VOCs, Degradation products	Very limited	Seldom (rarely needed)	Being used/proposed with increasing frequency
<i>Ex-situ</i> Bioremediation	Open tanks, Waste feed	VOCs, Degradation products, PM from waste feed	Very limited	Seldom	
Incineration	Stack, Waste feed	Metals, PM, NO <sub>x</sub> , CO, Dioxins/furans	Very extensive	Always	Seldom first choice for soils contaminated with fuels
Soil Washing	Process unit, Waste feed	VOCs	None	Not known	Developing technology
Solvent Extraction	Process unit, Waste feed	VOCs, solvent	None	Not known	Developing technology
Soil Flushing	Soil surface, Water recovery system	VOCs	None	Seldom (rarely needed)	Developing technology

**Table 2-2  
Typical Control Technologies Used for Remediation Technologies**

<b>Emission Source</b>	<b>VOCs/SVOC*s</b>	<b>Particulate Matter and Metals</b>	<b>Acid Gases</b>
Materials Handling			
Excavation	Operational Controls Foams Enclosure	Water Sprays	NA
Storage Piles	Polymer Sheeting	Cover Wind Screen	NA
Transport Vehicles	Cover Foam	Cover	NA
Roadways	NA	Gravel/Paving Water Sprays Water Sprays w/Additives	NA
Thermal Desorption	Condensers Thermal Incineration Carbon Adsorption	Cyclone Venturi Scrubber Fabric Filter HEPA Filter	Wet Scrubber Dry Scrubber
Soil Vapor Extraction	Carbon Adsorption Catalytic Incineration Thermal Incineration Internal Combustion Engine	NA	NA
<i>In-situ</i> Bioremediation	Carbon Adsorption	NA	NA
<i>Ex-situ</i> Bioremediation	Carbon Adsorption	NA	NA
Incineration	NA	Cyclone Venturi Scrubber Ionizing Wet Scrubber Wet ESP Fabric Filter	Wet Scrubber Dry Scrubber
Soil Washing	Carbon Adsorption	NA	NA
Solvent Extraction	Thermal Incineration	NA	NA
Soil Flushing	Carbon Adsorption	NA	NA

<sup>a</sup> SVOC = Semi-Volatile Organic Compound

**Table 2-3**  
**Summary of Cost Information for the Treatment of Contaminated Soil**

Technology	Estimated Treatment Cost, \$/Mg (\$/ton)	
	Controlled	Uncontrolled
Excavation and Removal	ND	68 - 454 (75 - 500)
Thermal Desorption	32 - 113 (35 - 125)	NA
Soil Vapor Extraction	47/Mg of VOC (52/ton of VOC)	24/Mg of VOC (26/ton of VOC)
<i>In-situ</i> Biodegradation	NA	91 (100)
<i>Ex-situ</i> Biodegradation	ND	64 - 118 (70 - 130)
On-Site Incineration	354 - 925 <sup>a</sup> (390-1020 <sup>a</sup> )	NA
Soil Washing	NA	48 - 195 (53 - 215)
Solvent Extraction	NA	95 - 476 (105 - 525)
Soil Flushing	NA	ND

<sup>a</sup>Assumes incineration of hazardous waste (as opposed to incineration of soil contaminated with petroleum fuels) and a relatively small site.

ND = Not determined

NA = Not applicable

### 3.0 EXCAVATION AND REMOVAL

#### 3.1 Process Description

Excavation and removal of soils contaminated with fuels is a common practice. If removal is the selected remedy, the excavated soil typically is transported off site for subsequent disposal in a landfill. Excavation activities also are typically part of on-site treatment processes such as incineration, thermal desorption, *ex-situ* biotreatment, and certain chemical and physical treatment methods. The soil is excavated and transported to the process unit, treated, and the treated soil may be used as fill at the site. The information presented in this section for excavation and removal is generally applicable to other soils handling operations such as dumping, grading, short-term storage, and sizing and feeding soil into treatment processes.

The magnitude of volatile organic compound (VOC) emissions depends on a number of factors, including the type of compounds present in the waste, the concentration and distribution of the compounds, and the porosity and moisture content of the soil. The key operational parameters are the duration and vigorousness of the handling, and the size of equipment used. The longer or more energetic the moving and handling, the greater likelihood that organic compounds will be volatilized. The larger the volumes of material being handled per unit operation, the lower the percentage of VOCs that are stripped from the soil, because the surface area to volume ratio is minimized.

The success of excavation and removal for a given application depends on numerous factors with the three key criteria being: 1) the nature of the contamination;

2) the operating practices followed; and 3) the proximity of sensitive receptors. Each of these criteria is described below.

As previously discussed, spills or leaks of fuels typically involve liquids containing dozens of different constituents. Excavation and removal is generally a viable option, except for those cases where air emissions potentially pose an unacceptable risk. For example, soil containing percent levels of benzene or other volatile carcinogens would likely pose a large risk to on-site workers and the surrounding populace if it were to be excavated. In-situ remediation methods, such as soil vapor extraction, would be preferable for such a site, either in lieu of excavation or prior to excavation to reduce the emissions potential.

The magnitude of emissions from soils handling operations will vary with the operating conditions. The rate of excavation and dumping, the drop height, the amount of exposed surface area, the length of time that the soil is exposed, the shape of the storage piles, and the dryness of the surface soil layers will all influence the levels of VOC emissions. Add-on control technologies are available for minimizing emissions, but they are relatively ineffective and costly to implement compared with controls for point sources. VOC emission control also can be achieved by controlling the operating conditions within preset parameters. Large reductions in emissions can be achieved by identifying and operating within acceptable ranges of conditions.

Some release of volatile contaminants is inevitable during excavation and removal unless unusual measures are taken (e.g., enclose the remediation within a dome), so the proximity of downwind receptors (i.e. people) will influence whether

or not excavation is an acceptable option. Excavation of contaminated areas that abut residential areas, schoolyards, etc. may require more extensive controls, relocation of the affected population, or remediation only during certain periods (e.g., summertime for school sites).

The relative advantages of excavation and removal over other remediation approaches are that:

- Earth-moving equipment and trained operators are widely available;
- Large volumes of soil can be quickly moved in a cost-effective manner; and
- Residual contamination remaining at the site is minimal.

The major disadvantages of excavation and removal versus other remediation approaches are that:

- The magnitude of air emissions may be high;
- Air emissions from excavation are difficult to control; and
- The contaminants are only removed, they are not destroyed.

### **3.2 Identification of Air Emission Points**

VOC emissions from handling operations result from the exchange of contaminant-laden soil-pore gas with the atmosphere when soil is disturbed and from diffusion of contaminants through the soil. There are several potential emission points involved in excavation as shown in Figure

3-1; all are considered to be fugitive area sources. For excavation, the main emission points of concern are emissions from:

- exposed waste in the excavation pit;
- material as it is dumped from the excavation bucket; and
- waste/soil in short-term storage piles.

In addition, the earth-moving equipment will be additional sources of emissions of VOC, particulate matter, nitrogen oxides, etc.

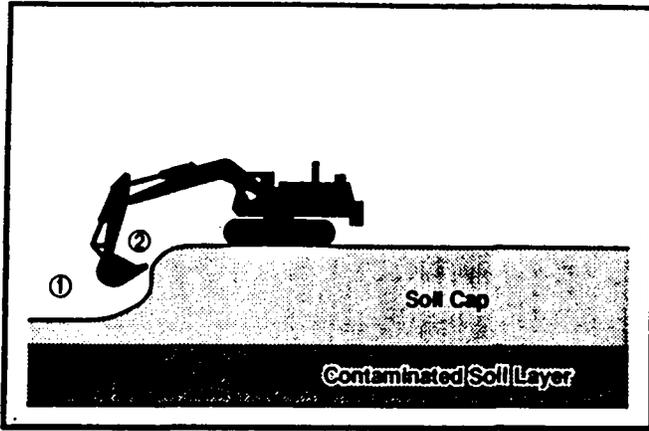
### **3.3 Typical Air Emission Species of Concern**

The emissions of concern from soils handling operations such as excavation can be any contaminant that is present in the soil. Relatively large amounts of VOCs may be released from soil during handling, so VOCs are typically the emissions of most concern. Emissions of particulate matter and associated metals and semi-volatile compounds may be of concern at some sites.

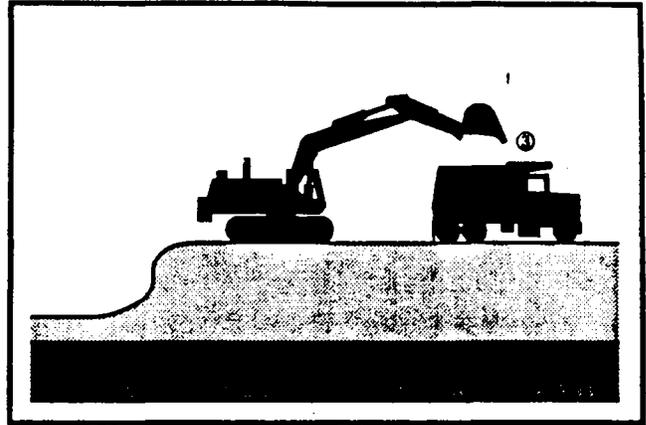
### **3.4 Summary Of Air Emissions Data**

Given the frequency with which excavation of contaminated soils is employed, surprisingly little air emissions or emission rate data for excavation has been published. The measurement of emission rates from dynamic processes, such as excavation, is difficult and relatively expensive, and so has rarely been attempted.

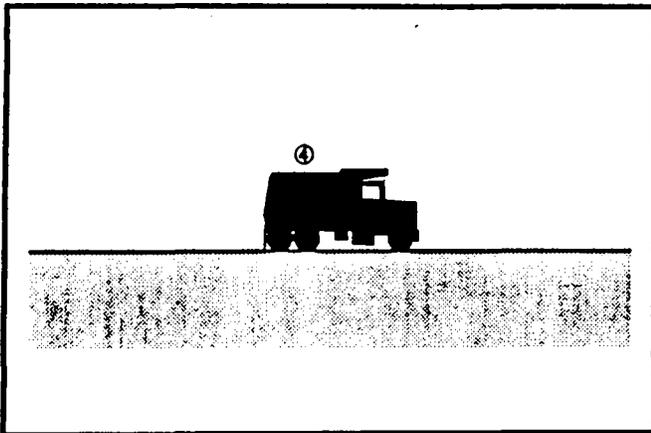
Volume III of the Series of Air-Superfund Guidance Manuals (Eklund, et al., 1989) for estimating clean-up emissions indicates that soils handling operations such as excavation increase VOC emission rates



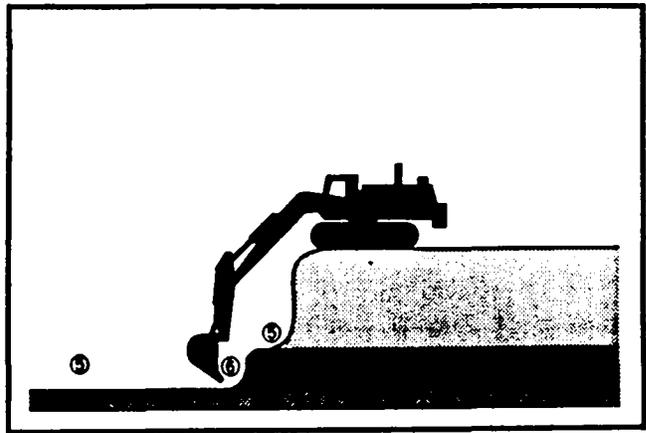
**I. Emissions from soil cap removal**  
 ① Emissions from soil cap excavation  
 ② Emissions from soil cap in bucket



**II. Emissions from truck filling with soil cap ③**



**III. Emissions from transport of soil cap ④**



**IV. Excavation of contaminated soil zone**  
 ⑤ Emissions from exposed contaminated soil zone  
 ⑥ Emissions from excavation of contaminated soil  
 ⑦ Emissions from excavator engine

**Figure 3-1. Summary of Air Emission Points For Excavation and Removal.**

Source: Saunders, 1990.

from contaminated soil over baseline rates. The increase in emissions is typically a factor of ten or more, and the increased emission rate decays exponentially back to near the baseline rate over short time periods (e.g. 4 days). A database of baseline emission rate measurement data (Eklund, et al., 1991) is available.

Emission rate measurements were made at two sites for EPA's Superfund program (Eklund, 1990). Measured emission rates from combined excavation and dumping operations were as high as 4 g/min for specific compounds. Most of the mass of VOCs present in the soil was stripped from the soil during excavation, based on a comparison of measured total emissions versus the mass of these same contaminants in the soil (calculated from soil concentration data). This was true for both sites, despite differences in soil concentrations and soil type. Excavation was found to decrease the soil moisture content by 35% to 56% and tended to somewhat decrease (e.g. -13%) the dry bulk density of the soil.

A few additional studies have been performed using open path monitoring with a Fourier-Transform Infrared (FTIR) instrument to measure ambient concentrations downwind of excavation activities. Under certain meteorological conditions, these measurements can be used to calculate emission rates.

FTIR measurements were performed at the Gulf Coast Vacuum Superfund site during pilot-scale excavation activities (Scotto, et al., 1992). Results were obtained for total C8+ branched-chain and for C8+ straight-chained hydrocarbons, as shown in Table 3-1. No individual VOCs were identified [the detection limit for benzene,

toluene, ethylbenzene, and xylenes (BTEX) was about 10 g/sec]. Emission rate measurements were made every one to two minutes over a 30-minute period when excavation was underway. The emission rates were found to vary by about a factor of two over both the full 30-minute period and from one minute to the next (Kagann, et al., 1993).

FTIR measurements also were performed during the excavation of trenches at the Westminster Superfund site (Kagann, et al., 1993). The site contained acidic sludges. Data were reported only for sulfur dioxide; these results are given in Table 3-2.

Theoretical models for estimating emissions (Eklund, et al., 1992a) indicate that about 70% of the mass of a volatile compound such as xylene is emitted during excavation of soil with a starting contaminant concentration of 1 ppm under the assumed typical conditions. Another theoretical study (Saunders, 1990) of soils handling emissions estimated that relative to excavation, other soils handling operations would have the following emissions: 1) Truck Filling - 0.58; 2) Transport - 5.23; and 3) Exposed soil - 1.47 (emissions/excavation emissions).

Field experience indicates that actual emissions may be substantially lower than the stripping percentages discussed above. For dry, porous soils containing low ppb levels of contaminants it can be assumed that most or all of the more volatile VOCs will be lost to the atmosphere during soils handling. For sites with moist soils and ppm levels of contaminants, however, a reasonable assumption may be that only 5 to 10% of the VOCs are emitted to the atmosphere during each handling step.

**Table 3-1**  
**Results of Emission Measurements at Gulf Coast Vacuum Site**

<b>Activity</b>	<b>Sludge Volume in m<sup>3</sup> (yd<sup>3</sup>)</b>	<b>Exposed Surface Area in m<sup>2</sup> (yd<sup>2</sup>)</b>	<b>C8+ Hydrocarbon Emission Rate in g/sec</b>
Sludge Disturbance	25 - 27 (33 - 35)	45 - 125 (54 - 150)	1.33
Sludge Excavation	26 - 48 (34 - 63)	125 - 261 ( 150 - 312)	7.76
Sludge Dewatering	1.7 (2.2)	3.3 (4.0)	1.24
Post- Disturbance	26 (34)	91 (109)	1.11

Source: Scotto, et al., 1992.

**Table 3-2  
Emission Rates Measured at the Westminster Superfund Site**

Activity in Trenches	Measurement Time		Sulfur Dioxide (SO <sub>2</sub> ) Emission Rate (g/sec)
	Start	End	
Excavate First Trench, Apply Foam	13:30	13:35	0.55
Apply Foam	13:45	13:50	0.92
Foam in Place	14:05	14:10	0.45
	14:20	14:25	0.73
	14:25	14:30	0.54
Refill Trench	14:30	14:35	1.1
Remove Topsoil from 2nd Trench	16:05	16:10	0.07
Encounter Waste Material	16:20	16:25	1.0
Apply Foam	16:35	16:40	0.42
Remove 60 Buckets of Material	16:50	16:55	0.41

Source: Kagann, et al., 1993.

More measurement data are needed to support these assumptions.

No valid emission factors were found. A theoretical study of the emissions from the clean-up of leaking underground storage tank sites (U.S. EPA-OUST, 1989) estimated that emissions from storage piles of contaminated soil with a surface area of 186 m<sup>2</sup> (2,000 ft<sup>2</sup>) were:

Average Benzene Emission Rate = 1 lb/hr  
Total Benzene Emissions = 336 lb  
Average VOC Emission Rate = 50 lb/hr  
Total VOC Emissions = 16,800 lb

The total emissions are based on a two-week time period. Emissions from the actual excavation process, as opposed to soils storage, were not estimated.

### **3.5 Identification of Applicable Control Technologies**

A number of methods are available for controlling VOC and particulate matter emissions from soils. In general, any method designed primarily for particulate control will also reduce VOC emissions and vice versa. Compared to point source controls, VOC emission controls for excavation and other area sources are difficult to implement and only moderately effective. The choice of controls also can affect treatment and disposal options. For example, controls such as water sprays or foams will alter the percent moisture, bulk density, and average heating value of the soil and may in some cases make thermal treatment infeasible.

VOC emission controls for soil area sources are described below including:

- Covers and physical barriers;

- Temporary and long-term foams;
- Water sprays;
- Operational controls;
- Complete enclosures; and
- Wind Barriers.

Additional information is given in Eklund, et al., 1992b.

#### **3.5.1 Covers and Physical Barriers**

The most commonly used VOC control approach for area sources is the use of covers to provide a physical barrier to vapor transport. The simplest barrier is the use of relatively clean soil as a cover for contaminated soil. The soil layer increases the necessary transport distance for vapor diffusion and thus greatly reduces, at least temporarily, the emission rate. Soil covers are widely used at sanitary landfills to control the emissions of odorous compounds and to control wind-borne pollution. The effectiveness of soil covers will depend on the depth of the cover and the percent of contaminated soil that can be covered. Measured emission rates may be substantially reduced (e.g., >95%) by the addition of compacted soil (Suder and Schmidt, 1992); however, lateral migration of VOCs may still occur. Soil covers will be less effective over long time periods and their use will tend to increase the total volume and mass of material that must be treated.

Synthetic covers are typically used to control VOC emissions from excavated soil in short-term storage piles. Synthetic covers are also widely used to control VOC emissions during transport by rail or truck. The cover may be thin (4-6 mil) plastic sheeting or relatively thick (30-40 mil) plastic sheeting or geotextile material. The resistance of various polymers to chemicals,

weather, gas permeability, and tears is documented (Landeeth, et al., 1983). The barrier material is available in large rolls and can be quickly applied to even large soil piles. The synthetic cover must be secured against wind.

The barrier can be left in place indefinitely, though physical and photodegradation of the polymer will tend to limit the effective lifetime of thin barriers to a few weeks. The effectiveness of the cover will depend on its permeability to the vapors that are present and the percentage of the soil pile that is adequately covered. Laboratory measurements of a 20 mil PVC membrane showed relatively poor performance for limiting vapor diffusion (Springer, et al., 1986). The PVC membrane proved to be only as effective as a covering of a few inches of porous soil.

Numerous mulch materials, such as sawdust, wood chips, straw, and wood fibers can also be used as a cover for soil undergoing long-term storage (U.S. EPA, 1991). The mulch acts primarily to control diffusion by insulating the soil surface and thereby lowering the soil temperature. The mulch material also limits diffusion somewhat if it is used as a cover, but if mixed in with the contaminated soil the mulch will generally increase the porosity of the soil and thereby increase the emission rate. The mulch also increases the volume and mass of contaminated material to be treated or disposed.

### **3.5.2 Temporary and Long-Term Foam Covers**

Modified fire-fighting foams are commonly used to control VOC emissions during the remediation of hazardous waste sites containing volatile toxic compounds.

At least six types of foam products are available (Evans and Carroll, 1986) from vendors such as Rusmar and 3M. The different foams vary in their compatibility and effectiveness for various classes of contaminants. Specialized equipment is available for applying foams over large areas. The foam is applied to a depth of 6-18 inches and coverage rates of 100 m<sup>2</sup>/min are possible. The liquid foam concentrate is applied via an air-aspirating nozzle or chute. The degree of expansion (how many gallons of foam produced from a gallon of liquid concentrate) can be high (250:1), low (20:1), or medium.

Two general types of foams are used: temporary and long-term. The temporary foams provide coverage for up to an hour, at which time 25% or more of the liquid incorporated in the foam will have been released. Long-term foams contain a stabilizing additive to extend the useful life of the foam to days or even weeks. The effectiveness of foams is quite high for the areas that are covered. Short-term emission reductions of 75% to 95% (for total paraffins and total aromatics, respectively) have been measured in the field over 20 minute time periods (Alm, et al., 1987). Emission reductions for total VOCs of 99% to 100% using stabilized foam have been measured in the field over 24-hour time periods (Alm, et al, 1987).

The two primary advantages of foams are that they can be highly effective and they can be applied directly to the backhoe bucket and the exposed contaminated soil. There are several disadvantages of foams to consider. The thick layers of foam required for emissions control can be applied more effectively to horizontal surfaces than to vertical surfaces such as the sides of the excavation pit.

Incomplete coverage of the emitting surfaces will markedly decrease the effectiveness of the controls. The foam concentrates are usually over 90% water and the addition of this water increases the weight of the soil, makes it more difficult to handle, and makes it less amenable to thermal treatment. The foam is difficult to apply on windy days and, under any conditions, frequent application or re-application of the foam may be necessary.

### **3.5.3 Water Sprays**

Water sprays are a commonly used control method for particulate matter (PM) emissions. The addition of dust control chemicals such as polymers or acrylics to the water increases the effectiveness of the spraying. The water added to the soil will decrease the air-filled porosity of the soil and will also tend to cool the surface soil temperature. The reduction in vapor transport will diminish VOC emissions, though the effectiveness of water sprays for VOC control is not documented. Water sprays are certainly much less effective than water-based foams, and they have essentially the same limitations as those listed above for foams.

### **3.5.4 Operational Controls**

Operational controls can be effective in minimizing VOC emissions. These controls may involve controlling the rate of excavation, the amount of contaminated soil area that is exposed, and the duration that soil piles are left uncovered. The timing of excavation can also be important. Scheduling excavation during times of the day or seasons of the year when wind speeds and temperatures are low can reduce emissions. Stagnant wind conditions, however, may lead to unacceptable ambient air concentrations at the work site. The

work can also be scheduled to avoid seasons with dry soil conditions to further minimize emissions.

### **3.5.5 Complete Enclosures**

If warranted, complete enclosure of the excavation-site can be accomplished to minimize VOC emissions. The enclosure acts to collect any emissions, which can then be vented to some type of control device suitable for point sources (see Section 5.5). The enclosure may be either air supported or self supported. Self-supported domes are more practical if trucks or other heavy equipment must regularly enter and leave the structure. If properly designed and operated, the enclosure may reduce VOC emissions to negligible levels.

There are severe limitations that limit the use of complete enclosures to the few sites where other control options are not acceptable. The capital cost of the structure is relatively high. Operating costs also can be very high if large volumes of air must be treated and exhausted to keep the concentrations of contaminants in the atmosphere within the dome at levels that are safe for the workers. Air temperatures within the structure may be high enough to affect worker productivity and safety. The added safety requirements along with the added time needed for getting trucks in and out of the structure likely will extend the time to complete the excavation and thereby increase the cost.

The U.S. EPA conducted a feasibility study of excavation with an enclosure (Dosani and Aul, 1992). Even with a gas exhaust system in operation, ambient concentrations of sulfur dioxide and other pollutants within the structure made it necessary for workers to wear Level B or

Level A personal protective equipment (PPE).

### 3.5.6 Wind Barriers

For small work areas, the use of wind barriers can reduce VOC emissions by lowering the effective wind speed at the soil surface. Commercial, porous wind fence material that is typically used for dust control has been found to be more effective than solid fence material (Springer, et al., 1986). For larger working areas, fencing is less practical.

VOC (and PM) emissions from storage piles can be minimized by controlling the placement and shape of the piles. When feasible, the piles can be placed in areas shielded from the prevailing winds at the site. The amount of surface area can be minimized for the given volume of soil by shaping the pile. The orientation of the pile will affect the wind velocity across the pile with the lowest windspeed occurring when the length of the pile is perpendicular to the prevailing wind direction.

### 3.6 Costs For Remediation

The total costs for the treatment of contaminated soil by excavation and removal will be the sum of the costs for excavation, transport, and treatment or disposal. The total costs will vary widely and are primarily dependent on the disposal or treatment costs. Total costs per ton may range from \$75 to \$500 or more, for excavation and off-site disposal. All costs shown below for years prior to 1991 have been converted to 1991 dollars using a 5% annual escalation factor. The cost per cubic yard will tend to increase for smaller levels

of effort such as the cleanup of a typical LUST site.

Standard costs for earth-moving activities are available (Means, 1991). Estimates of excavation costs for petroleum contaminated soils are in the range of \$2.50 to \$6.00 per ton (Troxler, 1992). The costs of excavation will depend the level of personal protective equipment required by the operator and on-site workers. Costs to excavate soil contaminated with hazardous wastes for different safety levels are (Lippitt, et al., 1986):

Hazard Level	Cost per m <sup>3</sup> (yd <sup>3</sup> )
No Hazard	\$22 ±19 (\$29±25)
Level D	\$75 ±56 (\$95±73)
Level C	\$91 ±84 (\$119±110)
Level B	\$117 ±86 (\$153±113)
Level A	\$133 ±96 (\$148±126)

Published cost estimates for excavation of soil contaminated with hazardous wastes vary widely. The estimated cost to excavate and load sixteen million cubic yards at the Rocky Mountain Arsenal was only \$6/yd<sup>3</sup> (U.S. GAO, 1986). The cost to excavate large volumes of soils contaminated with explosives has been estimated to be \$11.14/ton, or about \$13.92/yd<sup>3</sup> (Tennessee Valley Authority, 1990). This cost comprised 79% labor, 7% operating expenses, 10% equipment expense, and 4% for site reclamation. The cost to excavate large volumes of soils at another DOD site were estimated per cubic yard to be (Cullinane, et al., 1986):

Activity	Cost per m <sup>3</sup> (yd <sup>3</sup> )
Dry excavation	5.36 (7.02)
Wet excavation	10.72 (14.03)
Site grading and revegetation	1.66 (2.17)
Site grading	1.15 (1.51)
Backfilling with clean soil	25.84 (33.82)

If high-levels of volatile pollutants are present in the material to be excavated, it may be necessary to perform the removal within an enclosure. For the McColl site, in Fullerton, CA, the cost for excavation of soils contaminated with hydrocarbons and sulfur dioxide was estimated to be \$593/ton of in-place waste (Dosani and Aul, 1992). Cost for post-excavation treatment are not included. The \$593/ton cost includes the following components: labor (22%), supplies and consumables (21%), equipment (12%), and utilities (11%).

Cost estimates for transportation of petroleum contaminated soils range from \$0.08 to \$0.15 per ton per mile (Troxler, 1992). Vendor quotes for off-site transportation of soil contaminated with hazardous wastes typically range from \$2.50 to \$5/yd<sup>3</sup> per mile, though they may be higher under some site-specific conditions. Costs for transporting soil will be lower for on-site work and will be lower for off-site transport if it is not necessary to follow the procedures typically employed for transporting soils contaminated with hazardous wastes. Published cost estimates for off-site transport include an estimate of about \$3.80/yd<sup>3</sup> per mile (Cullinane, et al., 1986) and an average from ten sites of

\$0.25/ton per mile (Yang, et al., 1987). A cubic yard of soil can be assumed to weigh about 2500 pounds.

Disposal costs are highly dependent on the amount and nature of contamination present in the soil. Vendor quotes for disposal are typically \$250 to \$350/yd<sup>3</sup> of soil. Published estimates (Cullinane, et al., 1986) include costs of \$38/yd<sup>3</sup> for disposal in a sanitary landfill and \$160/yd<sup>3</sup> for disposal in a RCRA landfill.

### 3.7 Costs For Emission Controls

Costs for VOC controls for excavation are not widely available in the literature. Available data are summarized in Table 3-3.

### 3.8 Equations and Models For Estimating VOC Emissions

The factors that govern excavation emissions are very complex. During excavation, the physical properties of the soil that control the vapor transport rate (e.g. air-filled porosity) are changing with time and the concentration of contaminants may be rapidly decreasing. Predictive equations for estimating VOC emissions from excavation have been developed by the U.S. EPA. The predictive equations require assumptions about the size of each scoop of soil, the dimensions of the soil scoops and the excavation pit, and the shape of the soil after it is dumped. Further assumptions are required about the air and soil temperatures and the length of time that dumped soil is exposed before it is covered with more soil or with an emissions barrier.

Since it is rarely feasible or efficient to dig soil and immediately transfer the soil directly to transport vehicles or treatment

systems, any estimation procedure must account for each event in which the soil is handled. In most cases, soil will be excavated and placed into a temporary holding area and then handled one to two more times on-site. Elevated levels of VOC emissions are possible each time the soil is handled. When estimating emissions from sequential soil handling steps, it is important to adjust the starting concentrations for each step to account for contaminants emitted during prior steps.

The equations used are shown below. The average emission rate (g/sec) from excavation is equal to the sum of emission rates from the soil pore space and from diffusion:

The total mass of contaminants in a given volume of soil, or for an entire site, can be estimated as follows:

$$M = S_v C \beta 1.0 \quad (\text{Eq. 3-1})$$

where:

M = total mass of contaminants in soil (g);

S<sub>v</sub> = total volume of contaminated material (m<sup>3</sup>);

C = concentration of species i in bulk soil (μg/g);

β = bulk density of soil (g/cm<sup>3</sup>); and

1.0 = constant (g/10<sup>6</sup> μg/g \* 10<sup>6</sup>cm<sup>3</sup>/m<sup>3</sup>).

A simple check of the potential total emissions from remediation of a given volume of soil, or for the entire site, can be made by dividing the total mass of

contaminants by the projected duration of activity:

$$ER = M / t_{sv} \quad (\text{Eq. 3-2})$$

where:

ER = emission rate of species i (g/sec); and

t<sub>sv</sub> = time to excavate a given volume of soil (sec).

For the remediation of an entire site, t<sub>sv</sub> is the duration of remediation (sec). The emission rate from equation 3-2 is the theoretical maximum value for the average long-term emission rate for the remediation activities assuming all contamination is transferred to the atmosphere. As a sanity check, it should be demonstrated that any short-term emission rate estimates do not predict a greater mass of contamination being emitted over some time period than the total mass of contamination present in the soil.

A model to estimate the short-term emission rate from the excavation of soil has been developed by the U.S. EPA (Eklund, et al., 1992a). The model is presented below; example calculations are given in Appendix C to this report. The derivation of the excavation model is given in Appendix D. Tabulated physical property data is given in Eklund and Albert, 1993.

$$ER = ER_{PS} + ER_{DIFF} \quad (\text{Eq. 3-3})$$

$$ER_{PS} = \frac{P M_w 10^6 E_a Q ExC}{R T} \quad (\text{Eq. 3-4})$$

**Table 3-3  
Summary of Costs for Emission Controls for Area Sources**

<b>Control</b>	<b>Material Cost (\$/m<sup>2</sup> except as noted)</b>	<b>Comments</b>
Clay	\$4.15	Covers, mat, and membrane
Soil	\$1.33	Assume 6" deep; does not include soil transport
Wood chips, plastic net	\$0.50	Chip costs vary with site
Synthetic Cover	\$4.40	Assume 45 ml thickness
Short-term foam	\$0.04	Assume 2.5" thick, \$0.7/M <sup>3</sup> foam
Long-term foam	\$0.13	Assume 1.5" thick, \$3.3/M <sup>3</sup> foam
Wind screen	\$40/m	Per linear meter
Water Spray	\$0.001 (varies)	Assuming municipal water cost of \$1/\$1,000 L. Water requires constant re-application. Water truck rental: \$500/week.
Additives:		
Surfactant	\$0.65	Costs vary with chemical use
Hygro Salt	\$2.58	
Bitu/Adhes.	\$0.02	

Source: Eklund, et al., 1992b.

$$ER_{DIFF} = \frac{(C_s)(10,000)(A)}{\left(\frac{E_a}{K_{eq} k_g}\right) + \left(\frac{\pi t}{D_e K_{eq}}\right)^{\frac{1}{2}}}$$

(Eq. 3-5)

All variables are defined in Table 3-4. Also shown in Table 3-4 are the units of each variable and a typical default value to use if valid field data are not available. Soil concentration data typically are available as  $\mu\text{g/g}$  (ppm). This type of value can be multiplied by the bulk density of the soil ( $\text{g/cm}^3$ ) and by a conversion factor of  $10^{-6}$  ( $\text{g}/\mu\text{g}$ ) to yield units of  $\text{g/cm}^3$ :

$$C_s = (C)(\beta)(10^{-6}) \quad (\text{Eq. 3-6})$$

Equation 3-4 is based on the assumption that the soil pore gas is saturated with the compound of interest. If this is not the case, then Equation 3-4 may over predict the emission rate. The output from Equation 3-4 should be multiplied by the duration of excavation (i.e.,  $ER_{PS} * t_{sv}$ ) and the result compared to the total mass of contaminants present in the soil calculated from Equation 3-1 or the following (depending on what units of concentration data are available):

$$M = C * S_v * \frac{10^6 \text{ cm}^3}{\text{m}^3} \quad (\text{Eq. 3-7})$$

If  $ER_{PS} * t_{sv} > 0.33M$ , Equation 3-4 is giving a value that is far too conservative (i.e., is biased high). In such cases,  $ER_{PS}$  should be calculated using the following equation instead of Equation 3-4:

$$ER_{PS} = M * \frac{0.33}{t_{sv}} \quad (\text{Eq. 3-8})$$

### 3.9 Case Study

No suitable case study exists for excavation. Studies that have valid data for emissions, control efficiencies, and costs are referenced above in the applicable subsections.

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**Table 3-4**  
**Input Variables for Emission Equations**

Variable	Definition	Units	Default Value
A	Emitting surface area	m <sup>2</sup>	290
$\beta$	Bulk density	g/cm <sup>3</sup>	1.5
C	Concentration of species I in bulk soil	$\mu\text{g/g}$	--
C <sub>s</sub>	Mass loading in bulk soil	g/cm <sup>3</sup>	1.35 x 10 <sup>-4</sup>
C <sub>v</sub>	Concentration in soil gas	$\mu\text{g/m}^3$	--
D <sub>e</sub>	Effective diffusivity in air	cm <sup>2</sup> /sec	0.0269
E <sub>a</sub>	Air-filled porosity	Dimensionless	0.44
ER	Total emission rate	g/sec	--
ER <sub>PS</sub>	Emission rate due to soil pore space gas	g/sec	--
ER <sub>DIFF</sub>	Emission rate due to diffusion	g/sec	--
ExC	Soil-gas to atmosphere exchange constant	Dimensionless	0.33
K <sub>eq</sub>	Equilibrium coefficient	Dimensionless	0.613
M <sub>w</sub>	Molecular weight	g/g-mol	100
M	Total mass of contaminant	g	--
P	Vapor pressure	mm Hg	35
$\pi$	Pi	Dimensionless	3.14
Q	Excavation rate	m <sup>3</sup> /sec	0.042
R	Gas constant	mm Hg-cm <sup>3</sup> /g-mol <sup>o</sup> K	62361
S <sub>v</sub>	Volume of soil moved	m <sup>3</sup>	150
T	Temperature	Degrees Kelvin	298
t	Time to achieve best curve fit (use default value)	sec	60
t <sub>sv</sub>	Time to excavate a given volume of soil	sec	72 (per m <sup>3</sup> )
10,000	Conversion factor	cm <sup>2</sup> /m <sup>2</sup>	--
10 <sup>6</sup>	Conversion factor	cm <sup>3</sup> /m <sup>3</sup>	--

(Continued)

**Table 3-4  
(Continued)**

Variable	Definition	Units	Default Value
Other Variables Required to Calculate Certain Variables Listed Above			
$k_g$	Gas-phase mass transfer coefficient	cm/sec	0.15
$\rho$	Particle density	g/cm <sup>3</sup>	2.65
$D_a$	Diffusivity in air	cm <sup>2</sup> /sec	0.1
U	Wind speed	m/sec	2
$\mu_a$	Viscosity of air	g/cm-sec	1.81 x 10 <sup>-4</sup>
$\rho_a$	Density of air	g/cm <sup>3</sup>	0.0012
$d_e$	Diameter of emitting area	m	24

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## 4.0 THERMAL DESORPTION

This section contains information about mobile and stationary process units that employ thermal desorption to remediate soil and the use of asphalt aggregate dryers for soil remediation. Data are included for the treatment of soil contaminated with petroleum fuels and soil contaminated with hazardous wastes.

Key references are two studies that include summarized information about existing soil vapor extraction (SVE) systems in use at field sites (Hutzler, et al., 1989; and PES, 1989), an evaluation conducted under EPA's SITE program (Michaels, 1989a), and an overview paper (Johnson, et al., 1990). The Johnson, et al., paper is given as Appendix E of this report and EPA's Engineering Bulletin on SVE is contained in Appendix F of this report.

### 4.1 Process Description

In the thermal desorption process, volatile and semi-volatile contaminants are removed from soils, sediments, slurries, and filter cakes. Typical operating temperatures are 350°-700°F, but temperatures from 200° to 1,200°F may be employed. The process often is referred to as low-temperature thermal desorption to differentiate it from incineration, which is a thermal treatment process employing higher temperatures (see Section 8). Thermal desorption promotes physical separation of the components rather than combustion.

Contaminated soil is removed from the ground and transferred to treatment units, making this an *ex situ* process. Direct or indirect heat exchange vaporizes the organic compounds producing an offgas that

is typically treated before being vented to the atmosphere (Vatavuk, 1990). The best single source of information on thermal desorption is contained in a recent EPA Guidance Document (Troxler, et al., 1992). The engineering bulletin prepared by the U.S. EPA (U.S. EPA, 1991) for this technology also contains useful information and is included as part of Appendix F to this report.

After it is excavated, the waste material is screened to remove objects greater than 1.5" to 3.0" in diameter (de Percin, 1991a). In general, any one of four desorber designs are used: rotary dryer, asphalt plant aggregate dryer, thermal screw, and conveyor furnace. The treatment systems include both mobile and stationary process units designed specifically for treating soil, and asphalt aggregate dryers that can be adapted to treat soils. Mobile systems are most often used, due to reduced soil transportation costs and to allow for backfilling of the treated soil. However, stationary systems also are available and may be feasible to provide regional services. Typical specifications for thermal desorption systems are shown in Table 4-1.

The effectiveness of thermal desorption is related to the final soil temperature that is achieved, which in turn is a function of residence time and heat transfer. The temperatures and residence times effective in bench-scale systems also have proved to be effective in pilot-scale systems. Such findings support the use of a bench-scale test to determine the suitability of thermal desorption and the best residence time and temperature to use (de Percin, 1991a). The typical treatment temperature range for petroleum fuels from leaking underground storage tank (LUST) sites is

**Table 4-1**  
**Comparison of Features of Thermal Desorption**  
**and Offgas Treatment Systems**

	Rotary Dryer	Asphalt Plant	Thermal Screw	Conveyor Furnace
Estimated number of system	40-60	100-150	18-22	1
Estimated number of contractors	20-30	No estimate	9	--
Mobility	Fixed and mobile	Fixed	Mobile	Mobile
Typical site size, Mg (tons)	450-23,000 (500-25,000)	0-9,000 (0-10,000)	450-4,500 (500-5,000)	450-5,000 (500-5,000)
Soil throughput, Mg/hour (tons/hour)	9-45 (10-50)	23-90 (25-100)	3-14 (3-15)	5-9 (5-10)
Maximum soil feed size, cm (inches)	5-8 (2-3)	5-8 (2-3)	3-5 (1-2)	3-5 (1-2)
Heat transfer method	Direct	Direct	Indirect	Direct
Soil mixing method	Shell rotation and lifters	Shell rotation and lifters	Auger	Soil agitators
Discharge soil temperature, °C (°F)	150-300 <sup>a</sup> (300-600 <sup>a</sup> ) 300-650 <sup>b</sup> (600-1,200 <sup>b</sup> )	300-600	150-250 <sup>c</sup> (300-500 <sup>c</sup> ) 300-250 <sup>d</sup> (600-900 <sup>d</sup> ) 500-850 <sup>e</sup> (1,000-1,600 <sup>e</sup> )	300-800
Soil residence time (minutes)	3-7	3-7	30-70	3-10
Thermal desorber exhaust gas temperature, °C (°F)	250-450 <sup>a</sup> (500-850 <sup>a</sup> ) 400-500 <sup>b</sup> (800-1,000 <sup>b</sup> )	250-450 (500-850)	150 (300)	500-650 (1,000-1,200)
Gas/solids flow	Co-current or counter-current	Co-current or counter-current	Not applicable	Counter-current
Atmosphere	Oxidative	Oxidative	Inert	Oxidative
Afterburner temperature, °C (°F)	750-1,000 (1,400-1,800)	750-1,000 <sup>f</sup> (1,400-1,800 <sup>f</sup> )	Generally not used	750-1,000 (1,400-1,800)
Maximum thermal duty, Mj/hr (MMBtu/hr) <sup>g</sup>	10,500-105,000 (10-100)	5,300-105,000 (50-100)	7,400-10,500 (7-10)	10,500 (10)
Heatup time from cold condition (hours)	0.5-1.0	0.5-1.0	Not reported	0.5-1.0
Cool down time from hot condition (hours)	1.0-2.0	1.0-2.0	Not reported	Not reported
Total Petroleum Hydrocarbons				
Initial concentration (mg/kg)	800-35,000	500-25,000 <sup>h</sup>	60-50,000	5,000
Final concentration (mg/kg)	<10-300	<20 <sup>h</sup>	ND-5,500	<10.0
Removal efficiency (%)	95.0-99.9	Not reported	64-99	>99.9
BTEX				
Initial concentration (mg/kg)	NR	Not reported	155	Not reported
Final concentration (mg/kg)	<1.0	Not reported	<1.0	<0.01
Removal efficiency (%)	NR	Not reported	>99	Not reported

<sup>a</sup>Carbon steel materials of construction

<sup>b</sup>Alloy materials of construction

<sup>c</sup>Hot oil heat transfer system

<sup>d</sup>Molten salt heat transfer system

<sup>e</sup>Electrically heated system

<sup>f</sup>Not used on all systems

<sup>g</sup>Total duty of thermal desorber plus afterburner

<sup>h</sup>Vendor information: Soil Purification, Inc.

Source: Troxler, 1991.

400°F to 900°F. For the treatment of soils containing pesticides, dioxins, and polychlorinated biphenyls (PCBs), temperatures should exceed 850°F (de Percin, 1991c). The distillation temperature range will vary with the type of fuel contamination, as shown in Figure 4-1.

Thermal desorbers effectively treat soils, sludges, and filter cakes and remove volatile and semi-volatile organic compounds. Some higher boiling point substances such as PCBs and dioxins may also be removed (if present). Inorganic compounds are not easily removed with this type of process, although some relatively volatile metals such as mercury may be volatilized. Temperatures reached in thermal desorbers generally do not oxidize metals (de Percin, 1991a).

The soil is most effectively treated if its moisture level is within a specified range due to the cost of treating waste with a high water content. The typical acceptable moisture range for rotary dryers and asphalt kilns is 10-30%, (Troxler, 1991 and SPI, 1991), while thermal screw systems can accommodate higher water loadings of 30-80%. For removal of VOCs, the soils ideally should contain 10-15% moisture because the water vapor will carry out some of the VOCs (de Percin, 1991c).

High-molecular-weight organic compounds may foul or plug baghouses or condenser systems. Therefore, the types of petroleum products that can be treated by specific technologies may be limited. Rotary dryers typically can treat soils that have an organic content of less than two percent. Thermal screw units may treat soils that contain up to 50% organics. (Troxler, 1991).

Thermal desorbers may operate near or above 1000°F, so some pyrolysis and oxidation may occur in addition to the vaporization of water and organic compounds. Collection and control equipment such as afterburners, thermal oxidizers, fabric filters, activated carbon, or condensers prevent the release of the contaminants to the atmosphere (de Percin, 1991a). Various types of thermal desorption systems can produce up to nine residual process streams: treated soil, oversized media rejects, condensed contaminants, water, particulate control dust, clean off-gas, phase separator sludge, aqueous-phase spent carbon, and vapor- phase spent carbon (de Percin, 1991b).

Thermal desorption has the following advantages over other treatment processes:

- A wide range of organic contaminants can be treated; and
- The systems can be mobile.

There are a number of advantages compared with incineration. Thermal desorbers operate at lower temperatures, so significant fuel savings may result (Vatavuk, 1990). They also produce smaller volumes of off-gases to be treated. Thermal desorption also differs from incineration with regards to the regulatory and permitting requirements and the partitioning of metals within the process residual streams. Perhaps most importantly, thermal desorption enjoys more public acceptance than other thermal treatment methods (de Percin, 1991a).

Potential limitations of the treatment process exist as well. Thermal desorption does not destroy contaminants; it merely

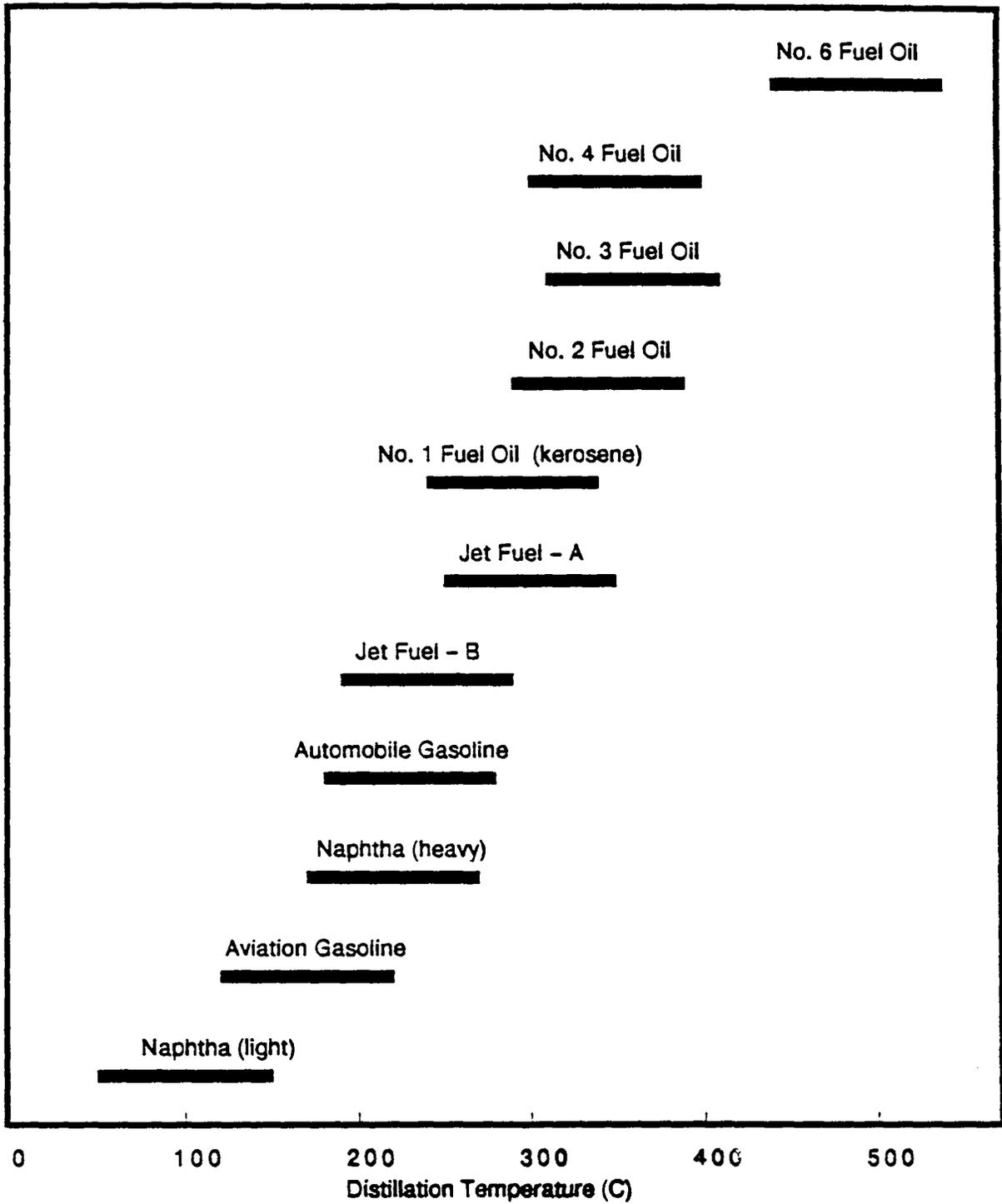


Figure 4-1. Soil Treatment Temperature Guide.

Source: Troxler, et al. 1992

strips them from the solid or liquid phase and transfers them to the gas phase. Therefore, devices to control VOC emissions are necessary. The efficiency of the thermal desorption process will vary with the chemical and physical properties of the specific contaminants. Metals (e.g., lead) tend to remain in the soil after treatment, so additional soil processing or treatment may be required (e.g., stabilization).

A generalized schematic diagram of a thermal screw, thermal desorption process is shown in Figure 4-2; the system shown most closely resembles Weston's LT<sup>3</sup> system. Other designs may use different types of control technology. Information about specific vendor designs is given below. The information is based primarily upon the use of portable remediation units, but the information should be generally applicable to other types of thermal desorption, such as rotary drum aggregate dryers.

#### **4.1.1 X\*TRAX™ by Chemical Waste Management, Inc.**

The X\*TRAX™ system is a transportable, indirectly heated rotary dryer, that treats up to 100 tons per day of soil and sediment contaminated with hazardous wastes. Propane fires an outer shell, which then heats the soil to 300°-900°F. Nitrogen gas sweeps the water and organic vapor to gas treatment and mitigates explosion hazards. Gas treatment consists of condensation, refrigeration, and carbon adsorption. The liquid water is separated from the liquid organic compounds and used for dust control (de Percin, 1991b).

#### **4.1.2 Taciuk by SoilTech, Inc.**

The Taciuk system is a two-zone, double-shell rotary dryer that treats up to 25 tons per hour of soil and sediments contaminated with hazardous wastes. The solids enter the first zone of the inside shell where temperatures of 300°F vaporize water and VOCs. Entry into the second zone of the inside shell enables additional organic compounds to be volatilized and pyrolyzed at temperatures of 1000° F.

The high temperature solids enter the outer shell where they transfer heat to the inner shell. Fired natural gas or propane heats the annulus between the shells. A cyclone, baghouse, caustic scrubber, and carbon adsorber treat the combustion gases while a condenser liquefies gases from both zones. Non-condensable gases from pyrolysis help to heat the system (de Percin, 1991b).

#### **4.1.3 LT<sup>3</sup> by Roy F. Weston, Inc.**

The Low Temperature Thermal Treatment, or LT<sup>3</sup> system, treats up to 20 tons per hour of soil and sediment using two banks of four heated screws. The process primarily is used for treating hazardous wastes. The combustion of propane heats transfer oil, which is pumped through the screws, heating the shell to 600°F. The combustion gases sweep the water and organic vapor to the gas treatment system (de Percin, 1991b).

#### **4.1.4 DAVES by Recycling Sciences, Inc.**

The Desorption and Vapor Extraction System (DAVES) treats contaminated material in a fluidized bed where it is fed along with hot air. Gas-fired

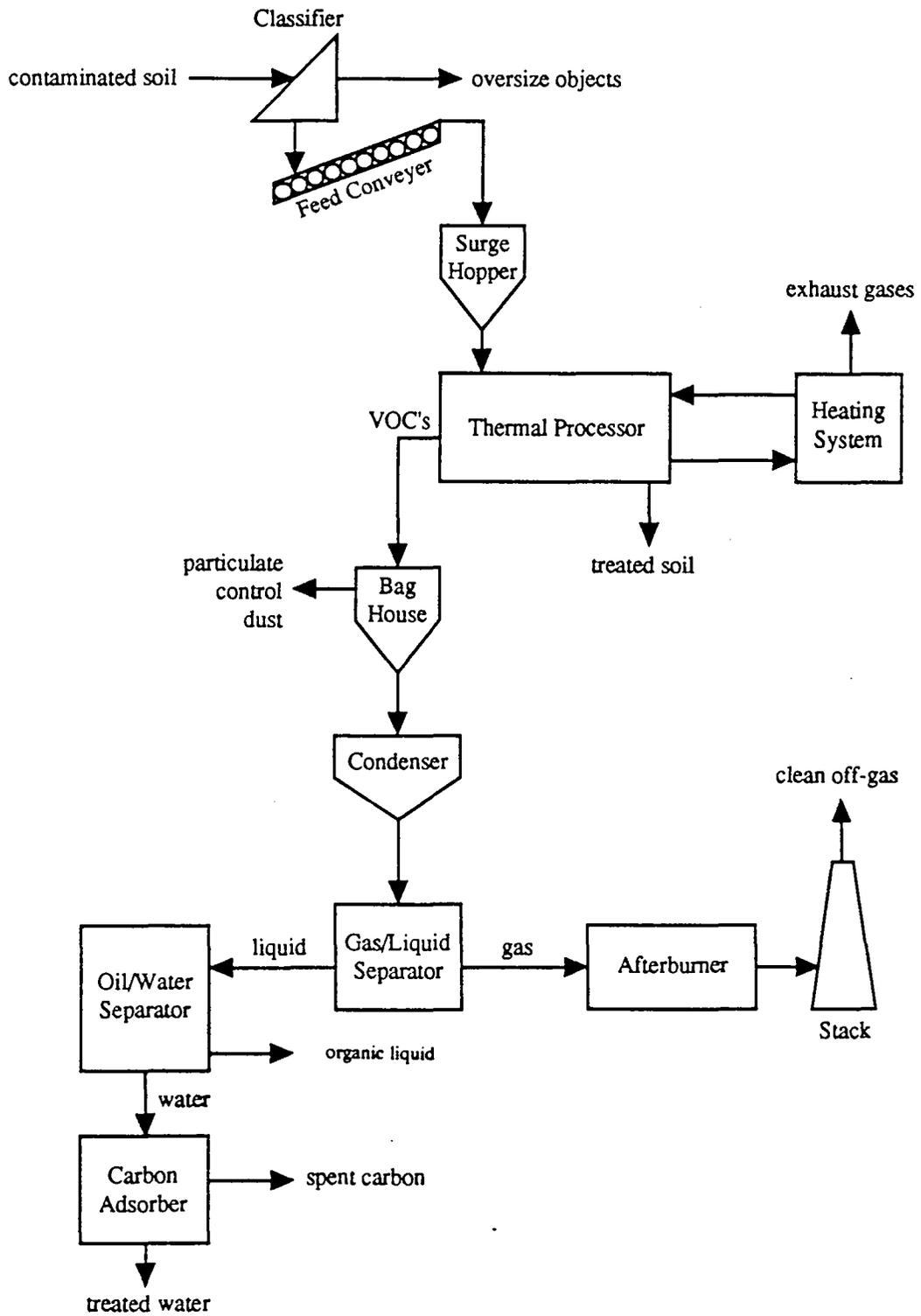


Figure 4-2. Generalized Process Diagram for Thermal Screw-Based Thermal Desorption.

heaters heat the air to 1000°-1400° F. The hot air vaporizes water and organic compounds and carries them to the gas treatment system. Gas treatment consists of a cyclone, baghouse, venturi scrubber, chiller, and carbon adsorber (de Percin, 1991b).

#### **4.1.5 ReTec by Remediation Technologies, Inc.**

The ReTec thermal desorption system operates at capacities of 0.5-3.5 tons per hour and is designed to treat soils contaminated with organic compounds and oily sludges. If the waste material has a high moisture content, the process begins with a dewatering step. Dewatered filter cakes from the press are fed to storage hoppers and then transported to the dryer by a covered conveyer.

The Holo-Flite Processor consists of a jacketed trough, which houses a double-screw mechanism. The heat-transfer fluid (thermal oil or steam) is circulated through the trough jacket can. The material enters and exits the dryer through rotary air-locks to prevent leakage of ambient air into the processor. The gas flow from the dryer, which is designed to remove moisture and the organic compounds with low boiling points, passes through a particle removal system, quench chamber, condenser, and activated carbon beds (Abrishamian, 1991).

The partially treated soil leaves the dryer and enters the processor, where the soil is subjected to temperatures between 500 and 900° F and shorter residence times (relative to the drying step) to remove the organic compounds with high boiling points. Molten salt, heated by an electric or fuel-fired heater, is used as the heating medium

for the processor. The molten salt does not produce off-gases, and it is non-toxic, non-flammable, and easily cleaned up if spilled. Inert gas added to the processor inhibits oxidation and enhances vaporization of contaminants. Off-gases from the processor undergo treatment with cyclones, a semi-volatile organic separator, chilled condenser, and activated carbon beds. A solids cooler lowers the temperature of the solids to less than 180° F for safe handling (Abrishamian, 1991).

#### **4.2 Identification of Air Emission Points**

The air emissions associated with thermal desorption come from several sources. The point sources of air emissions vary widely with each process. The stack of an afterburner vents combustion products, as does a fuel-fired heating system if the combustion gases are not fed into the desorber. The fuel-fired heating system typically operates with propane, natural gas, or fuel oil. If the VOC emission controls consist of a baghouse, scrubber, and vapor phase carbon adsorber, the offgas will contain small concentrations of the original contaminants, as well as products of any chemical reactions that might occur.

The volume of off-gas from a thermal desorption unit depends on the type of processor. Devices that are heated indirectly have offgases composed of volatilized VOCs and water from the soil being treated and, possibly, some sweep gas used to carry the contaminants out of the device. This volume of gas is typically 1,000 to 5,000 acfm (Troxler, 1991). In directly heated units, the off-gas contains volatilized contaminants and water, but also the combustion gases used to heat the soil.

The result is a much larger volume of off-gas that needs to be treated, around 10,000 to 50,000 acfm (Troxler, 1991). Therefore, off-gases from indirectly heated units, i.e. thermal screws, can be treated with smaller chemical/physical systems, such as a baghouse or a condenser, followed by an afterburner.

Fugitive emissions from area sources may contribute significantly to the total air emissions from a remediation site. Probably the largest source is excavation of the contaminated soil. Other sources may include the classifier, feed conveyor, and the feed hopper. Fugitive emissions from the components of the thermal desorption system and controls are possible as well. Emissions also may emanate from the waste streams such as exhaust gases from the heating system, treated soil, particulate control dust, untreated oil from the oil/water separator, spent carbon from liquid or vapor phase carbon adsorber, treated water, and scrubber sludge.

#### **4.3 Typical Air Emission Species of Concern**

The volatile and semi-volatile contaminants under remediation are the species emitted if no destruction or other chemical treatment has taken place.

Combustion products such as particulate matter, nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), and acid gases may be emitted if a destructive control device, such as an afterburner, is used or if the heating system is fuel-fired. In some cases, pyrolysis occurs to a certain degree in the dryer, so products from these reactions also may be emitted.

#### **4.4 Summary of Air Emissions Data**

Air emissions from thermal desorption systems are influenced by the waste characteristics, the desorption process, and the emissions control equipment. As noted above, pyrolysis may occur at the elevated temperatures in the desorber. Dioxins, furans, and phenol concentrations have been reported to increase with temperature (Foster, et al., 1992). The emissions data presented below are divided into two categories: emissions for asphalt aggregate dryers and emissions for other mobile units.

##### **4.4.1 Air Emissions Data for Asphalt Aggregate Dryers**

The VOC emissions from asphalt aggregate dryers will vary by several orders of magnitude depending on whether afterburners are used as a control device. These treatment systems typically do not employ VOC controls, unless they have been modified for soil remediation.

Soil Purification, Inc. (SPI), a subsidiary of a leading manufacturer of asphalt plants, has estimated the typical emissions for soil treatment in a modified asphalt aggregate dryer. This system consists of a direct-fired rotary drum operating at 550-1000° F. A primary cyclonic tube collector and pulse-jet baghouse are used to control particulate emissions. A thermal oxidizer (i.e., afterburner) destroys organic compounds in the off-gas stream (99-99.99% efficiency). Based on a processing rate of 35-60 tons per hour, typical emissions from this type of unit are:

- Particulate: 0.02-0.03 gr/dscf; and

- Total VOC: 0.1-5 lb/hr.

Data are given for three asphalt plants that were modified for the treatment of petroleum contaminated soils. Summaries of the soil properties and emission characteristics at these plants are presented in Tables 4-2a and 4-2b. Afterburners were not used on any of these systems. Each site is discussed in more detail below.

Soil contaminated with diesel fuel and gasoline were treated at an asphalt plant with a 450 tons/hour capacity at 5% moisture (Barr, 1990). Soil enters the dryer opposite of the burner and flows countercurrent to the combustion gases. This configuration allows the VOCs which desorb from the soil in the upper portion of the dryer to exit the system without exposure to the burner flame. The results presented for this plant represent worst-case conditions because all of the VOCs volatilized from the soil may not be destroyed and no additional VOC control device is present (Barr, 1990). The hot exhaust gases are routed to a wet scrubber and a cyclonic demister. The gas is then emitted to the atmosphere through the stack.

The feed rate for the diesel fuel and gasoline contaminated soils for the test runs were 280 and 255 tons/hour, respectively. The air pollution control equipment accommodates 80,000 acfm at 300°F (Barr, 1990). The soil headspace concentrations and removal efficiencies are reported for the remediation tests. Measured total hydrocarbon (THC) emission rates for these tests were 254 and 310 lb carbon per hour (i.e., about ten times the typical emission rate during asphalt production). Emission

rates of particulate matter were 64 and 67 lbs/hour.

A second trial burn was performed on a soil contaminated with petroleum hydrocarbons. The plant treats up to 120 tons/hour of soil at temperatures around 350-400°F (Batten, 1987). The exhaust gas from the system contained 129 and 175 ppmv of THC above background. THC's were emitted at a rate between 30.4 and 47.7 lb/hr. The estimated emission factor for total non-methane hydrocarbons was 0.21 to 0.26 lbs per ton of soil treated. Based on the results, Batten (1987) concluded that hydrocarbon controls would be necessary in order for the system to meet air pollution control requirements.

The Soil Cleanup System (SCS, from Earth Purification Engineering, Inc.) was demonstrated in the treatment of diesel-contaminated soil from a leaking underground fuel tank in Kingvale, California. The SCS is an asphalt recycling unit modified to treat contaminated soils. The offgas from the rotary kiln is routed to dual cyclones, an exhaust cooler, and a baghouse. The soil exits the system at 775°F. The emission rates for non-methane VOCs and semi-volatile organics were 1.04 and 1.57 lb/hour, respectively, or 0.44 and 0.67 lb/ton assuming 1.25 ton/yd<sup>3</sup> (SCS, 1990).

#### **4.4.2 Air Emissions Data for Mobile Units**

Thermal desorption has been used at many sites for the treatment of soils contaminated with various materials. Examples are described below. Additional data are given in the case studies in Section

**Table 4-2  
Characteristics of Asphalt Aggregate Dryers**

**Table 4-2a. Typical Soil Properties<sup>a</sup>**

Parameter	Initial Concentration (ppm)	Final Concentration (ppm)	Removal Eff. (%)
Benzene	0.11-39.5	<0.01-0.06	84.5-99.9
Toluene	0.27-<2	<0.01-0.1	NA
m,p-Xylenes	<0.8-<3	0.2-1.2	<75
o-Xylenes	3.1-15.6	<0.01	99.7-99.9
Total Xylenes	13.1	0.1	99.2
Ethylbenzene	0.11	<0.01	>90
THC	39-393	5.7-9.5	85-97.5
Diesel	1875	<1	>99.9

<sup>a</sup>Based on two or three installations depending on the parameter.

**Table 4-2b. Typical Offgas Characteristics<sup>b</sup>**

Parameter	Stack Concentration	Units
Benzene	4.3-8.6	ppmd
Toluene	0.6-0.8	ppmd
m,p-Xylenes	0.42-3.5	ppmd
THC	129-2,800	ppm
Naphthalene	5,136-6,757	$\mu\text{g}/\text{Nm}^3$
Acenaphthylene	634-901	$\mu\text{g}/\text{Nm}^3$
Acenaphthene	317-638	$\mu\text{g}/\text{Nm}^3$
Fluoranthene	405-763	$\mu\text{g}/\text{Nm}^3$
Phenanthrene	385-645	$\mu\text{g}/\text{Nm}^3$
Anthracene	<1.4-427	$\mu\text{g}/\text{Nm}^3$
Fluoranthene	24-135	$\mu\text{g}/\text{Nm}^3$
Pyrene	32-111	$\mu\text{g}/\text{Nm}^1$

<sup>b</sup>Based on two installations. Emission control equipment consists of a wet scrubber and cyclonic demister.

4.9, including data on dioxin and furan emissions.

According to Weston Services, Inc., the use of their full-scale LT<sup>3</sup> system on the Springfield, Illinois cleanup of gasoline and No. 2 fuel oil-contaminated soils produced stack emissions that were in compliance with federal and state regulations, including VOCs, HCl, CO, and particulates (Nielson and Cosmos, 1989). The emission rate of BTEX was 1079 grams/hour before controls and 21 grams/hour after the control devices.

ReTec's thermal adsorption unit was used in the remediation of coal tar-contaminated soil. Molten salt in a thermal screw was used to indirectly heat the soil to approximately 450°F. The soil was treated at a rate of 100 pounds per hour. The controlled emissions of BTEX were 0.26 grams per hour or 0.011 lb/ton (U.S. EPA, 1991).

At the McKin Superfund Site in Gray, Maine, soil containing primarily trichloroethylene (TCE) was treated by Canonie Environmental Services Corporation. Temperatures varied between 150 and 380°F, and the capacity was 1-4 cubic yards per batch. To achieve 0.1 ppm TCE concentration in the treated soil, the temperature was adjusted to 300°F for 6-8 minutes (Webster, 1986). The total reported emission rates were 24 g/hr.

The Thermotech Systems Corporation's Portable Soil Remediation Unit was used to treat petroleum contaminated soils in Washington, D.C. and Grand Rapids, MN. The unit has air pollution controls for particulate matter (dust collector) and organics (thermal oxidizer). For the Washington, D.C. site,

the particulate, BTEX, and TPH emissions were 5.0, 0.13, and 0.42 pounds per hour, respectively. The emission rate for particulates from the Grand Rapids site was 2.4 lb/hr (Thermotech, 1990-1991).

U.S. Waste Thermal Processing's Mobile Thermal Processor, Model 100, was used to treat gasoline- and diesel-contaminated soils. The transportable treatment unit consists of a primary furnace with an afterburner to incinerate the combustibles. The offgas from the afterburner is routed to a wet scrubber for particulate removal. The soil exit temperature is maintained between 300 and 650°F, and the afterburner operates at 1800°F, with a minimum residence time of 0.5 seconds. The scrubber is a dual-venturi collision scrubber. The test was performed on soil at 5000 and 5500 mg/kg contamination levels of gasoline and diesel fuel, respectively. The particulate emission rates were 4.2 and 2.7 lb/day (Remedial Technology Unit, 1990).

The Todds Lane Soil Remediation Plant handles soils contaminated with petroleum hydrocarbons. Pollution control devices include a cyclone, multiclones, a baghouse, and an afterburner. The maximum anticipated concentrations of certain VOCs in the soil were used to estimate the emission rates of the compounds after the afterburner, assuming 99% efficiency. The total emission rate for BTEX was determined to be 2.1 pounds per hour (United Engineers and Constructors, 1991).

The Soil Remediation Unit (SRU) 202 consists of a rotary kiln, an afterburner, and a baghouse. This unit was used to treat contaminated soil, and the emissions were

reported as follows: particulate - 1.7 to 2.5 lb/hr and VOC - 0.1 to 0.74 lb/hr (Air Consulting and Engineering, 1991).

The pilot-scale X\*TRAX system uses an externally-fired rotary kiln for the treatment of soils contaminated with hazardous wastes. The offgas is first treated in a liquid scrubber where particulate matter is removed. The gas is then cooled further to allow for condensation of the contaminants. The gas is routed through a particulate filter and to a carbon adsorber where most of the remaining organics are removed. The VOC emissions ranged from 0.01-0.08 lb/day for the treatment of clay and sandy soils (U.S. EPA, 1991).

A pilot-scale test was performed by IT Corporation for the treatment of creosote-contaminated soils at the Burlington Northern Superfund Site. The thermal desorption unit was operated at 1025° F and a residence time of 10 minutes. The treatment unit consists of a rotating desorber tube partially enclosed within a gas-fired furnace shell. Nitrogen is introduced into the system to flush out desorbed contaminants and to maintain an atmosphere that does not support combustion. The offgas is treated with a cyclone, a primary scrubber, a condenser, a demisting filter, a particulate filter, and an activated carbon unit. Finally, the offgas is scrubbed in a secondary scrubber and then discharged to the atmosphere. These values represent the average of six samples (IT, 1991). The IT system was also used to treat PCB contaminated soils at a rate of 40 to 70 pounds per hour. The results of these tests are presented in Table 4-3; the operating temperature and residence time varied for each run.

#### **4.5 Identification of Applicable Control Technologies**

Control of volatile organic emissions is crucial to the overall success of thermal desorption remediation of contaminated soils. The process uses physical separation driven by heat, so the vaporized contaminants would simply be transferred from one medium (soil) to another (air) if no emission controls were employed.

The types of controls available include both destruction and separation technologies. Typically two to six types of controls are used in series; they are chosen to suit the specific VOC contaminants present and the other pollutants of concern. Liquid-phase and solid-waste streams usually are treated on site or stored for subsequent off-site treatment. Depending on the types of contaminants present and their concentrations, it may be feasible to recover and reuse the volatilized contaminants. The offgas stream often is routed to the burner that provides heat to the dryer.

Typical VOC controls for point sources are briefly described below; Section 5.5 contains additional information. More detailed information is available in a recent EPA report (Eklund, et al., 1992). Asphalt kilns will have similar air emission control devices as mobile thermal desorption units, except that no VOC controls are typically employed and the air flowrates are higher, requiring some differences in design parameters.

Many low-temperature thermal desorption (LTTD) control devices use an off-gas treatment system consisting of a cyclone, afterburner, quench, and baghouse (fabric filter). The cyclone is used to reduce

**Table 4-3**  
**Estimated Emissions of Selected Compounds for the Cleanup**  
**of PCB-Contaminated Soil Using the IT Process**

Contaminant	Residence Time (minutes)	Temperature °F	Initial Concentration	Final Concentration	Units	Rate of Uncontrolled Emissions g/hr	Overall Estimated Percent Efficiency	Estimated Emissions Rate g/hr
PCB's	19	1022	37.5	2	ppm	1.14	95%	5.68e-02
2,3,7,8-TCDD	40	1040	260	0.018	ppb	0.00832	95%	4.16e-04
2,3,7,8-TCDD	19	1040	236	0.018	ppb	0.00755	95%	3.78e-04
2,3,7,8-TCDD	10.5	1040	266	0.018	ppb	0.00851	95%	4.26e-04
2,3,7,8-TCDD	24	860	233	0.5	ppb	0.00744	95%	3.72e-04
2,3,7,8-TCDD	5.6	1022	48	0.084	ppb	0.00153	95%	7.67e-05
2,3,7,8-TCDD	20	1031	56	0.23	ppb	0.00178	95%	8.92e-05

the particulate loading on downstream devices. The baghouse may be placed before or after the afterburner; it efficiently removes particulates to low levels. The afterburner oxidizes organics and CO by thermal destruction. Some LTDD systems use an afterburner followed by a quench chamber and a venturi wet scrubber. This system is capable of controlling acid gases if they are a concern. Some systems collect the organic contaminants, as shown in Figure 4-2, rather than destroying them.

#### **4.5.1 Particulate Removal**

Off-gases from the desorber typically pass first through a particulate control device. Particles that become entrained in the off-gas stream may be removed with cyclones, venturi scrubbers, or fabric filters. Collected particulates are usually returned to the incoming waste stream and retreated with the soil.

Cyclone collectors remove particles by creating a vortex from the inlet gas stream velocity. Centrifugal acceleration forces entrained particles outward where they collide with the wall and fall to a collection point. Cyclones efficiently remove the bulk of larger particles, however, venturi scrubbers or baghouses are required to remove smaller particles.

Venturi scrubbers are sometimes used to treat desorber off-gas, and efficiently remove particles greater than 0.5  $\mu\text{m}$  in diameter using an aqueous stream. The performance is not affected by corrosive, sticky, or flammable particles, but high collection efficiencies require a higher pressure drop and thus are more costly to operate (Sink, 1991). The scrubber may also

serve as the initial condensation stage for water and organic compounds.

The fabric filter may be a series of fine-mesh synthetic fabric bags similar to the type used in asphalt batch plants. An induced draft fan can be used to draw the exhaust gas through a filter. The filter may be a jet-pulse design such that high-pressure (80 psig) air periodically removes accumulated particulates to collection bins. Dust from the bins may then be combined with the contaminated soil for reprocessing. The maximum allowable pressure drop across the filter may be 15 inches of water (Weston, 1990), though 3 to 8 inches of water is typical.

#### **4.5.2 Condenser**

Condensers can be used to remove VOCs from a vapor stream if the design is efficient for removing the specific contaminants that are present. This physical separation process operates on the basis of the contaminants' vapor pressures, which vary widely. By reducing temperature or increasing pressure until the saturation vapor pressure is reached, the vapor condenses to a liquid phase and is treated accordingly. Contaminants with high vapor pressures require correspondingly low condensation temperatures. In these situations, a quencher that removes a large portion of the moisture present often precedes the condenser to prevent icing. The coolant may be air, ambient water, brine, chilled water, or refrigerants. A separator directs the vapor/gas and liquid streams to appropriate control systems.

#### **4.5.3 Liquid Phase Treatment**

The liquid from the condenser is sometimes partially treated on-site. The liquid is separated by a gravity oil/water separator. The insoluble light organic fraction is skimmed off the top, placed into 55-gallon drums and stored for off-site treatment. The contaminated water from the separator is passed through carbon adsorption columns and then typically recycled on-site. Potential water uses include dust control, service makeup, and cooling of the treated soil.

#### **4.5.4 VOC Control by Afterburner**

Fume incinerators (i.e., afterburners) often are used for the control of VOC emissions from thermal desorption systems, especially for systems used for treating underground storage tank sites. An afterburner used in one system identified in the literature is a 3.5 million-BTU/hr (MMBTU/hr) gas-fired fume incinerator, but afterburners may fire gas at up to 40 MMBTU/hr.

Afterburners typically operate at 1400-1800°F and have a residence time of 0.5-2 seconds. The air that carries the vaporized contaminants serves as the combustion air. The flame vortex exposes the VOCs to temperatures and turbulence necessary for complete combustion. A combustion air (offgas) fan maintains a minimum of three percent excess oxygen exiting the afterburner. Exhaust gases leaving the afterburner are sometimes mixed with ambient air to be cooled and then passed through a scrubber (Weston, 1990). Hot gases typically are quenched with water prior to entering a baghouse.

#### **4.5.5 VOC Control by Carbon Adsorption**

Often used as a polishing process after other treatments, carbon adsorption works on the principle that contaminants are physically adsorbed onto the activated carbon. No chemical change or reduction of the waste amount occurs. Adsorption processes can occur in either the liquid or vapor phase. Regeneration or disposal of spent carbon may also produce emissions, though this is very rarely done on-site.

Liquid-phase carbon adsorption usually treats water containing low contaminant concentrations with a two-stage system. Clean water is often used to cool discharge solids from the desorber and suppress dust formation (Nielson and Cosmos, 1989).

#### **4.5.6 Scrubber**

Exhaust gases from thermal destruction processes may be treated in a scrubber to remove particulates or neutralize acid gases. Wet scrubbers use a liquid to absorb pollutants from a waste gas stream; the process is enhanced through a large liquid/gas contact surface area. Wet scrubbers operate by either chemical absorption (reaction between pollutant and liquid), or physical absorption (pollutant trapped by liquid). Dry scrubbers operate by chemical absorption. Acid gases are not typically a concern when processing petroleum-contaminated soils because of low concentrations of halogenated compounds (Troxler, 1991). Particulate scrubbers (venturis) can be employed to capture the particles by impingement and agglomeration with liquid droplets. If a wet scrubber is used to treat the off-gases, a liquid separator is needed downstream of the scrubber, such as a cyclone or mist eliminator.

#### **4.5.7 Miscellaneous System Adaptations and Control Approaches**

Other emissions-control techniques include using treated water for dust control and using ultraviolet light. Ultraviolet rays have been used to destroy dioxin in the condensate from the thermal desorption of contaminated soils.

While conducting a pilot study of the McKin Superfund site in Gray, Maine, Canonie Environmental Services Corporation made efforts to control VOC and dust emissions from excavation and aeration processes. The soil was contaminated with trichloroethylene (TCE). Excavation down to 40 feet was conducted with a Kelly bar caisson rig fitted with a digging bucket and attached to a 100-foot crane. Soils discharged from the digging bucket entered a front-end loader equipped with a removable plastic cover. Cylindrical steel caissons were augered into the deep excavation holes to prevent further volatilization (Webster, 1986).

#### **4.6 Capital and Operating Costs for Remediation**

Because thermal desorption is virtually never used without controls, the costs reflect emission controls as well as remediation. Most thermal desorption units offered by vendors are predesigned systems with VOC and particulate controls already installed. This is especially true for mobile systems, which are typically housed on flat bed trailers. Asphalt plants do not typically have VOC controls, but if they have been modified to treat soils, the organic control device may already be added.

The costs for thermal desorption (exclusive of emission control costs) for treatment of soils contaminated with petroleum hydrocarbons typically range from \$50 - 125/ton for low temperature thermal screw units and from \$35 - 100/ton for rotary dryers (Troxler, 1991).

IT Corporation performed a pilot study for cleanup of PCBs on the Rosemount Research Center site of the University of Minnesota. IT estimated that direct operating costs for a full-scale system would be about \$80/ton based on a 10 ton/hour system treating soil with 20 percent moisture. This figure includes \$60/ton for labor, utilities, fuel, materials and supplies, and administrative costs, as well as \$20/ton for depreciation. These are hopper-to-hopper treatment costs; total costs are likely to be \$175 to \$350 per ton (Troxler, 1991). Costs depend on the contaminants present and site conditions. Cost estimations should take into consideration planning and procurement, permitting, site preparation, equipment mobilization, equipment erection/startup, operations, equipment decontamination and demobilization, and site closure (Fox, et al., 1991).

Soil contaminated with Herbicide Orange at the Naval Construction Battalion Center (NCBC) in Gulfport, Mississippi was treated with the IT Corporation's pilot-scale thermal desorption/ultraviolet apparatus (TD/UV). The costs for treating the dioxin-contaminated soil are summarized below and include the cost of ultraviolet destruction technology, which is not typically a part of the thermal desorption process (Helsel and Thomas, 1987):

Amount of Soil, Mg (tons)	Total Cost, million \$	Cost Per Mg, \$ (ton, \$)
9,071 (10,000)	6.0	544 (600)
18,143 (20,000)	8.0	365 (402)
36,287 (40,000)	11.8	268 (295)

Remediation Technologies, Inc. estimates the cost of treating oily soils and sludges to be in the range of \$100-\$300/ton of feed. The costs depend on quantity of waste, term of the contract, and moisture and organic content of the contaminated soil. Estimated costs for some other systems are presented in Table 4-4.

#### 4.7 Capital and Operating Costs for Emission Controls

Costs for emission controls are included in the remediation costs given in Section 4.6. The installed cost of complete thermal desorption systems that include treatment of offgases and condensates usually is about 2-4 times the cost of the thermal units themselves (Abrishamian, 1991).

Cost estimates were determined for thermal oxidizers and fabric filters used with thermal desorption units (See Tables 4-5 and 4-6). The cost estimates were calculated from procedures outlined in various U.S. EPA documents. These values were also compared with vendor quotes. The estimation was performed for gas flow rates of 5,000, 15,000, and 40,000 acfm. The total capital investment was determined for both mechanical shakers and pulse-jet fabric filters and includes equipment and installation costs. Site preparation and construction costs are not included in this

Figure. The results are presented in Table 4-6.

The cost estimate for an afterburner, or thermal oxidizer, was based on similar flow rates (5,000, 15,000, and 40,000 scfm). Two cases were considered for each flow rate: a) no heat exchanger (no heat recovery from the thermal oxidizer) and b) 50% heat recovery. The cost estimates and vendor information are summarized in Table 4-5. As stated earlier, thermal desorption units are typically sold as a predesigned unit that already incorporates the control devices into the total cost of the system.

#### 4.8 Equations/Models for Estimating Emissions

Theoretical models based on fundamental principles have been proposed for predicting the evolution of volatile compounds from soil in the thermal desorption process (Lighty, et al., 1990). Both particle desorption and bed desorption were examined. The models are partial differential equations based on mass and energy balances and on the Freundlich isotherm equation. In practice, an assessment of the applicability of thermal desorption for a given site is not based on modeling calculations, but instead on the types of contaminants present in the soil, the physical properties of the soil, and the results of any bench-, pilot- or full-scale test runs. In most cases, the process conditions, such as temperature and residence time, can be modified to yield the desired removal efficiency, though heavier weight petroleum fuels, such as No. 6 fuel oil, may present problems for systems with relatively low operating temperatures. The cost to operate at these process conditions, however, will

**Table 4-4**  
**Costs Including Emission Controls for Various Thermal Desorption Units**

System	Cost, \$/Mg feed (\$/ton feed)	Soil Characteristics	Soil Feed Rate, Mg/hr (tons/hr)
X*TRAX™, Chemical Waste Management	136-318 (150-350)	30% moisture; <10% organics	--
LTTA, Canonie Environmental Services, Corp.	73-136 (80-150)	---	27-45 (30-50)
LT <sup>3</sup> , Roy F. Weston	91-109 (100-120)	20% moisture; 10,000 ppm organics	9 (10)

SOURCE: Johnson and Cosmos, 1989

**Table 4-5**  
**Cost Information for Thermal Oxidizers**

Heat Recovery (%)	Flow Rate (scfm)	Estimated Capital Cost <sup>a</sup> (1992 \$)	Vendor Estimates <sup>b</sup>
0	5,000	156,000	100,000 <sup>c</sup>
	15,000	209,000	300,000 <sup>c</sup>
	40,000	304,000	--
50	5,000	304,000	150,000 <sup>c</sup>
	15,000	437,000	450,000 <sup>c</sup>
	40,000	580,000	--

<sup>a</sup>Estimated capital costs based on correlations given in the OAQPS Control Cost Manual (Vatavuk, 1990).

<sup>b</sup>Typical cost from Soil Purification, Inc. given as \$75-300,000 for a thermal oxidizer for a "typical" size system.

<sup>c</sup>Conversion Technology, Inc.

**Table 4-6  
Cost Information for Fabric Filters**

Filter Type	Flow Rate (acfm)	Estimated Capital Cost <sup>a</sup>	Vendor Estimates <sup>b</sup>
		(1992 \$)	
Mechanical Shaker	5,000	159,000	24,000 <sup>c</sup>
	15,000	298,000	36,400 <sup>c</sup>
	40,000	509,000	--
Pulse-Jet Fabric Filter	5,000	124,000	30,000 <sup>c</sup>
	15,000	205,000	52,000 <sup>c</sup>
	40,000	456,000	--

<sup>a</sup>Estimated capital costs based on correlations given in the OAQPS Control Cost Manual (Vatavuk, 1990).

<sup>b</sup>Typical cost from Soil Purification Inc. given as \$250-350,000 for a pulsed-jet fabric filter for a "typical" size portable system.

<sup>c</sup>Dustex Corporation.

Note: Cost difference may reflect differences in installed versus delivered costs.

dictate whether or not thermal desorption is competitive with other remediation options.

Using removal efficiencies obtained from test runs, a mass balance yields the following equation to estimate an emission rate for a volatile compound leaving the desorber. This estimate does not include emissions from excavation or other handling of contaminated soil nor does it include fugitive emissions from the desorber system or from liquid and solid phase waste streams. Combustion gases from the heating system and exhaust gases from afterburners produce additional emissions not taken into account by this estimation method.

$$ER_i = (C_i/1000)(F)(V_i/100)(1 - CE_i/100)$$

where:

$ER_i$  = emission rate for contaminant  $i$  (g/hr);

$C_i$  = concentration of species  $i$  in contaminated soil (mg/kg);

1000 = conversion factor (mg/g);

$F$  = mass rate of soil treated (kg/hr);

$V_i$  = percentage of contaminant  $i$  volatilized; and

$CE_i$  = percent efficiency of control devices.

Default values have been published by the U.S. EPA (Eklund, et al., 1993). The default value for the mass feed rate is 27,200 kg/hr, with a range of 2,700 to 90,800 kg/hr. The default value for the percent volatilized is

dependent on the desorber temperature. For 200 to 600 °F, the values are:

VOCs/BTEX	99.00%
SVOCs/PNA <sup>a</sup> s	90.00%
THC	95.00%
PCBs	50.00%

<sup>a</sup> PNA = Polynuclear Aromatic

For desorber temperatures of 600 to 1,000 °F, the values are:

VOCs/BTEX	99.99%
SVOCs/PNAs	99.00%
THC	99.90%
PCBs	99.00%

#### 4.9 Case Studies on Remediation and Air Emissions

Thermal desorption has been used at a number of sites in recent years. However, little performance data from these full-scale operations have been published. Results from five EPA-sponsored projects are presented in this section. These results include thermal desorption effectiveness and air emissions for soil contaminants, VOCs, SVOCs, dioxins, and furans.

##### 4.9.1 Use of LT<sup>3</sup> on Pesticides

The Low Temperature Thermal Aeration (LT<sup>3</sup>) system of Canonic Environmental Services Corporation was used at an abandoned pesticides mixing facility in Arizona. The waste consisted of soil contaminated with toxaphene, DDT, DDD, DDE, and others at a total concentration of 5 to 120 mg/kg.

Contaminated soil was heated counter currently to 730°F in a rotating cylinder, with heat provided by propane or fuel oil. Residence time was 9-12 minutes and the process throughput was 34 tons/hour. The emission controls included cyclones, baghouse, venturi scrubber, and carbon adsorbers. The scrubber liquid blowdown was treated by carbon adsorbers and reused as a wetting agent for the treated soil.

Performance is summarized in Table 4-7 (Peck, 1995). Process streams were sampled for VOCs and SVOCs. Although specific results were not available, stack emissions included acetonitrile, acrylonitrile, chloromethane, benzene, and toluene. The study concluded that these compounds were formed within the process, but dioxins and furans were not formed.

##### 4.9.2 Use of LT<sup>3</sup> to Treat Lagoon Sludge Contaminated with VOCs and SVOCs

The Low Temperature Thermal Treatment (LT<sup>3</sup>) process of Roy F. Weston, Inc. was used to treat a sludge primarily contaminated with 4,4'-methylenebis (2-chloroaniline) (MBOCA) in Michigan. The MBOCA concentration in the sludge ranged from 43.6 to 860 mg/kg. The process equipment consisted of two troughs, each with two hollow-screw conveyors. Hot oil flowed through the screws, heating the sludge to 500-530°F. Residence time was 90 minutes and process capacity was 2.1 tons/hour. The emission controls included a baghouse, air-cooled condenser, refrigerated condenser, and carbon adsorber. Condensed liquids were routed to an oil-water separator, a paper filter, carbon adsorber, and sent to off-site disposal. Process performance is summarized in Table 4-8.

**Table 4-7**  
**Results for Use of LT<sup>2</sup>A System on Pesticide-Contaminated Soil**

<b>Parameter</b>	<b>Untreated Soil (ppb)</b>	<b>Treated Soil (ppb)</b>	<b>Off-gas to GAC (ppb)</b>	<b>Stack Gas (ng/dscm)</b>
Toxaphene	18,300	<20	<50	<98.6
DDT	18,700	<1.06	<2.0	8.2
DDD	220	<0.39	<1.0	<1.97
DDE	6,980	677	79	1,980
Total PCDD	ND	ND	ND	0.057
Total PCDF	0.1	ND	ND	0.017

**Table 4-8**  
**Results for Use of LT<sup>3</sup> System on Lagoon Sludge**

<b>Parameter</b>	<b>Untreated Soil</b>	<b>Treated Soil</b>	<b>Off-gas to Adsorber</b>	<b>Stack Gas</b>
MBOCA	43.6-860 mg/kg	3-9.6 mg/kg	NA	ND
VOCs:				
Toluene	1-25 mg/kg	<30 µg/kg	8-10 ppmv	"effectively removed"
PCE	690-1900 mg/kg	<30 µg/kg	210-220 ppbv	"effectively removed"
SVOCs:				
3- and 4-methylphenol	3100-20,000 µg/kg	540-4000 µg/kg	ND	ND
bis(2-ethyl hexyl)phthalate	1100-7900 µg/kg	<820 µg/kg	<28 ppbv	ND
TNMHC	--	--	--	6.7-11 ppmv
Total PCDD	0.21 ng/kg	1.52 ng/kg	0.483 µg/dscm	0.0606 µg/dscm
Total PCDF	ND	2.49 ng/kg	0.33 µg/dscm	0.0699 µg/dscm

#### **4.9.3 Use of X\*TRAX to Treat PCB Contaminated Soil**

The RUST Remedial Services, Inc. X\*TRAX Model 200 Thermal Desorption System was used to remove PCBs and other organic contaminants from soil at a site in Massachusetts. The soil was treated in a rotating cylinder which was heated by hot flue gases flowing in an annular region outside the treatment cylinder. The soil was heated in five zones, to an average temperature of 850-928° F. Residence time was about 2 hours and the equipment capacity was 4.9 tons/hour. A nitrogen carrier gas and the off-gases were treated by a concurrent spray scrubber, air-cooled condenser, refrigerated condenser (40° F), and mist eliminator. Most gas was then returned to the process heater, but 5-10% was vented after passing through a 10 µm filter, a high efficiency particulate air (HEPA) filter, and carbon adsorbers. Condensates were separated into water, organic, and sludge streams, with the sludge then mixed with the contaminated soil feed. Separated water was used for scrubber makeup and for wetting the treated soil. The organic stream was sent to off-site treatment. System performance is summarized in Table 4-9.

#### **4.9.4 Use of ATP to Treat PCB Contaminated Soil**

The SoilTech ATP Systems, Inc. Anaerobic Thermal Processor was used to remove PCBs and other organic contaminants from soil at two sites, one in New York and one in Illinois. The process was essentially the same at both sites. In a four-step process, the soil is heated to 500° F, 1100° F, 1300° F, and then cooled to 600° F, with a total treatment time of about

30-40 minutes. The soil is indirectly heated in an anaerobic environment. Dehalogenation reagents (sodium hydroxide and polyethylene glycol) are added to the contaminated soil prior to its entering the ATP. The process capacity was 10 tons/hour. Off-gases were treated by a cyclone, scrubber, condenser, and a three-phase separator, which produced gas, water, and organic streams. The treated gas was returned to the combustion zone of the ATP. Organics were mixed with inlet soil and water was treated on-site. Performance for the two sites is summarized in Table 4-10. Some SVOCs were present in the soil in low concentrations. However, the SVOCs were either not detectable or were below the practical quantitation limit in both the treated solids and the stack gas. Likewise, some VOCs were also present in low concentrations in the contaminated soil and most were below detection limits in the treated soil samples. Stack gas samples were not analyzed for VOCs.

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**Table 4-9**  
**Results for Use of X\*TRAX System to Treat PCB-Contaminated Soil**

<b>Parameter</b>	<b>Untreated Soil</b>	<b>Treated Soil</b>	<b>Stack Gas</b>
Total PCBs	318 mg/kg	0.863 mg/kg	ND
VOCs:			
Chloromethane	--	--	369.9 µg/m <sup>3</sup>
Methyl chloride	--	--	17.6 µg/m <sup>3</sup>
Toluene	--	--	3.2 µg/m <sup>3</sup>
Total VOCs	--	--	396.6 µg/m <sup>3</sup>
SVOCs:			
Hexanedionic acid ester	--	--	70.7 µg/m <sup>3</sup>
9-Octadecen-1-ol	--	--	33.7 µg/m <sup>3</sup>
Total SVOCs	--	--	188.2 µg/m <sup>3</sup>
Total PCDD	310 ng/kg	74.1 ng/kg	0.0304 ng/m <sup>3</sup>
Total PCDF	597 ng/kg	93.7 ng/kg	0.0158 ng/m <sup>3</sup>
Total 2,3,7,8-TCDD TEQ <sup>a</sup>	28.8 ng/kg	3.47 ng/kg	0.000323 ng/m <sup>3</sup>

<sup>a</sup> TCDD = Tetrachlorodibenzodioxin  
TEQ = Toxic Equivalent

**Table 4-10**  
**Results For Use of ATP Process to Treat PCB-Contaminated Soil**

PCB Contaminated Soil Treatment in New York

<b>Parameter</b>	<b>Untreated Soil</b>	<b>Treated Soil</b>	<b>Stack Gas</b>
Total PCBs	28.2 mg/kg	0.043 mg/kg	23.1 µg/dscm
Total PCDD	3.2 µg/kg	ND	3.86 ng/dscm
Total PCDF	0.16 µg/kg	ND	5.66 ng/dscm
Total 2,3,7,8-TCDD TEQ	--	--	0.707 ng/dscm

PCB Contaminated Soil Treatment in Illinois

<b>Parameter</b>	<b>Untreated Soil</b>	<b>Treated Soil</b>	<b>Stack Gas</b>
Total PCBs	9761 mg/kg	2 mg/kg	0.837 µg/dscm
Total PCDD	ND	ND	ND
Total PCDF	104 µg/kg	6.05 µg/kg	0.0787 ng/dscm
Total 2,3,7,8-TCDD TEQ	--	--	0

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## 5.0 SOIL VAPOR EXTRACTION

### 5.1 Process Description

Soil vapor extraction (SVE) is a commonly-used method for treating soil contaminated with volatile hydrocarbons. The process is sometimes referred to as soil venting, vacuum extraction, aeration, or in-situ volatilization. A closely related remediation technology—bioventing is described in Section 6. In general terms, soil vapor extraction removes volatile organic constituents from contaminated soil by creating sufficient subsurface air flow to strip contaminants from the vadose (unsaturated) zone by volatilization. As the contaminant vapors are removed, they may be vented directly to the atmosphere or controlled in a number of ways.

Soil vapor extraction has been widely used to remediate sites contaminated with gasoline or chlorinated solvents (e.g., TCE). It also is sometimes used to minimize migration of vapors into structures or residential areas during other types of remediation. By its nature, SVE is an on-site, in-situ treatment method.

Complete removal may not be possible unless the source of vapors (e.g., hydrocarbon lens on groundwater) also is removed, so SVE often is used in conjunction with or following other remedial measures such as excavation of subsurface waste bodies, removal (pumping) of any hydrocarbon lens that is present, or air stripping of contaminated ground water. Combined two-phase treatment of both ground water and soil gas has been used successfully for several years (Welshans, et al., 1991), and increasingly is employed.

The success of SVE for a given application depends on numerous factors with the three key criteria being: 1) the nature of the contamination; 2) the behavior of subsurface vapor flow at the site; and 3) regulatory requirements.

Spills or leaks of fuels typically involve liquids containing dozens of different constituents. For removal by SVE to be effective, the contaminants generally must have vapor pressures greater than 1.0 mm Hg at 20°F. A simplified decision guide for judging the applicability of SVE is shown in Figure 5-1.

The tendency of the organic contaminants to partition into water or to be adsorbed onto soil particles also affects SVE effectiveness, so the compound's water solubility, Henry's Law constant, and soil sorption coefficient are of interest. The soil temperature affects each of these variables and hence, the rate of vapor diffusion and transport.

The concentrations of contaminants that are initially present affect their relative partitioning between vapor and liquid phases, and the amount that is solubilized or adsorbed. The time that the contamination has been present also is an important factor, as mixtures of contaminants will generally become depleted of their more volatile components over time through volatilization. This process, referred to as weathering, will tend to cause SVE to become progressively less applicable as the site ages. It also affects the operation of the SVE system, as the more volatile components are typically removed first and the composition of the vapors collected and treated varies over time.

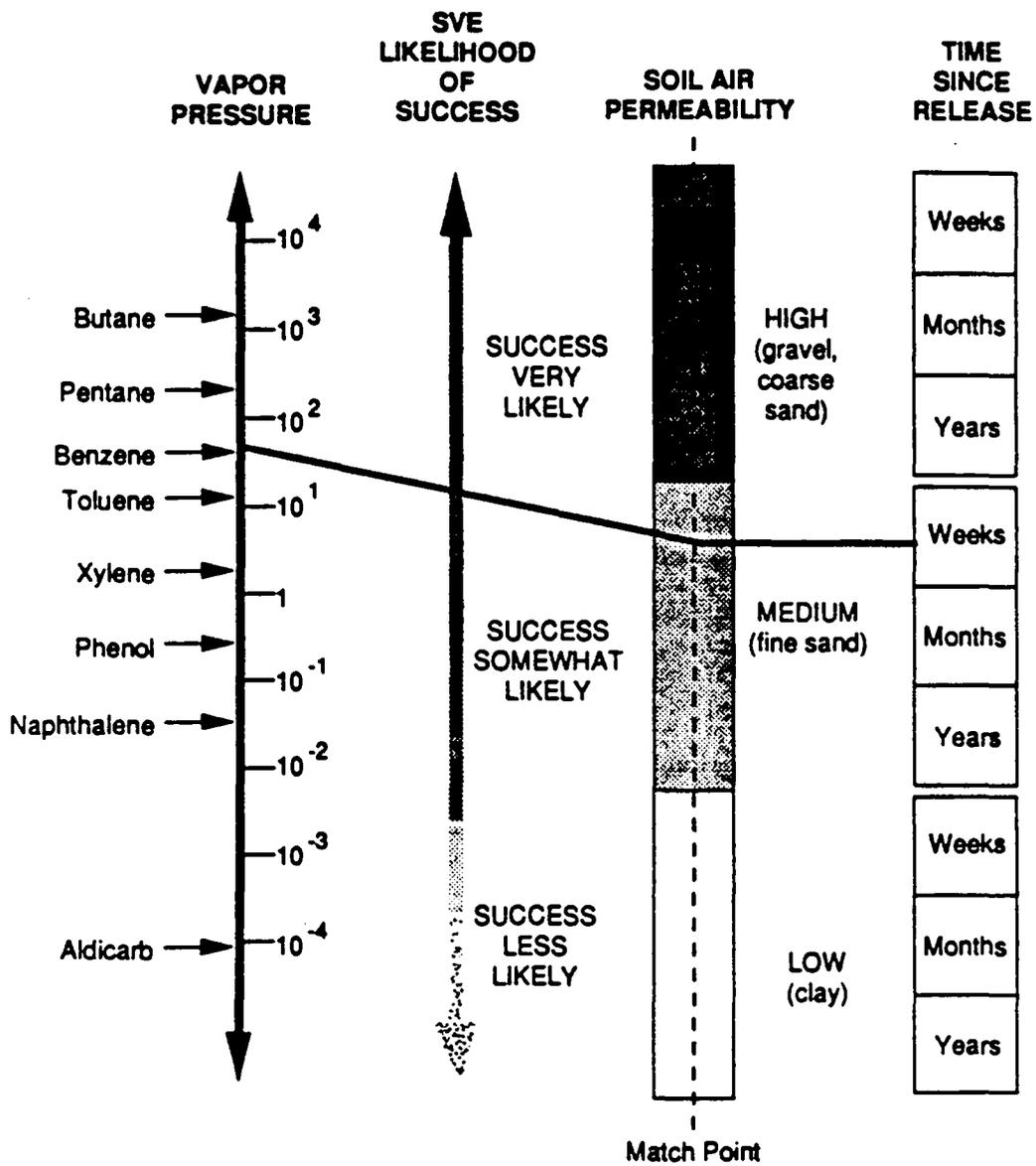


Figure 5-1. Simplified Guide to Applicability of Soil Vapor Extraction.

Source: (Pedersen and Curtis, 1991)

As mentioned above, soil temperature is an important variable in the effectiveness of SVE. Increasing the soil temperature is one option commonly considered for enhancing SVE performance. Soil can be heated in one of three ways: 1) introduction of heated air or steam, 2) input of electromagnetic energy through the soil, or 3) heat release through chemical reaction (HWC, 1994a). The use of heated air or steam appears to be the most widely used approach to full-scale thermally enhanced remediation (HWC, 1992). Approaches such as microwave, radio frequency, and electrical heating have been tested at the pilot scale (George, et al., 1992); (HWC, 1993); and (HWC, 1994b), but full-scale results are not yet available.

Although SVE may be used in a variety of soil types, the effectiveness will depend on the ability of air to flow through the soil. The ability of vapors to flow through a porous media such as soil is usually defined as the air permeability. Any factors that influence the air permeability of the soil, such as soil porosity, grain size, moisture content, depth to ground water, and stratification must be taken into consideration when planning this type of remediation. The presence of cracks, inadequately grouted boreholes, or other subsurface conduits will alter the subsurface flow patterns. The goal is to direct the air flow through the contaminated zone and minimize short-circuiting through bypasses. SVE may not be practical for sites where the source of vapors is deep underground (e.g., >100 feet), in areas with shallow groundwater tables (e.g., <10 feet) or at sites where the groundwater level fluctuates greatly over time. It has been suggested that SVE is not effective for the fraction of organic pollutants that are trapped inside the soil matrix (Travis and Macinnis, 1992).

The types of contaminants present and the clean-up criteria will affect the cost-effectiveness of SVE versus other remediation options. The final cleanup level for contaminants in the soil will dictate whether or not SVE is a viable option. Very stringent cleanup levels may dictate excavation of the soil and further on-site treatment. Air emission regulations may require the use of controls to reduce the level of contaminants in the SVE exhaust gas. The cost of such emission controls may influence the overall selection of a remediation approach.

Figure 5-2 shows a generalized process flow diagram for the SVE process. Typical systems include extraction wells, monitoring wells, air inlet wells, vacuum pumps, vapor treatment devices, vapor/liquid separators, and liquid-phase treatment devices. Wells are generally 4 to 8 inches in diameter. An option sometimes employed is to introduce the air at the air inlet well into the saturated zone (i.e., groundwater table). This technique, referred to as air sparging, acts to strip some of the volatile and semi-volatile compounds from the ground water.

A number of potential problems may arise in implementation of soil vapor extraction, but effective solutions exist for most problems. If there is concern that contaminant vapors from other sources may be drawn in by the vacuum system, air inlet wells may be placed around the perimeter of the site to limit remediation to the site under treatment. To avoid channelized flow, butterfly or ball valves may be placed on the monitoring or extraction wells so that they may be shut down if necessary.

The extent of short circuiting through other wells can be determined using a tracer gas (Olschewski, et al., 1995). If

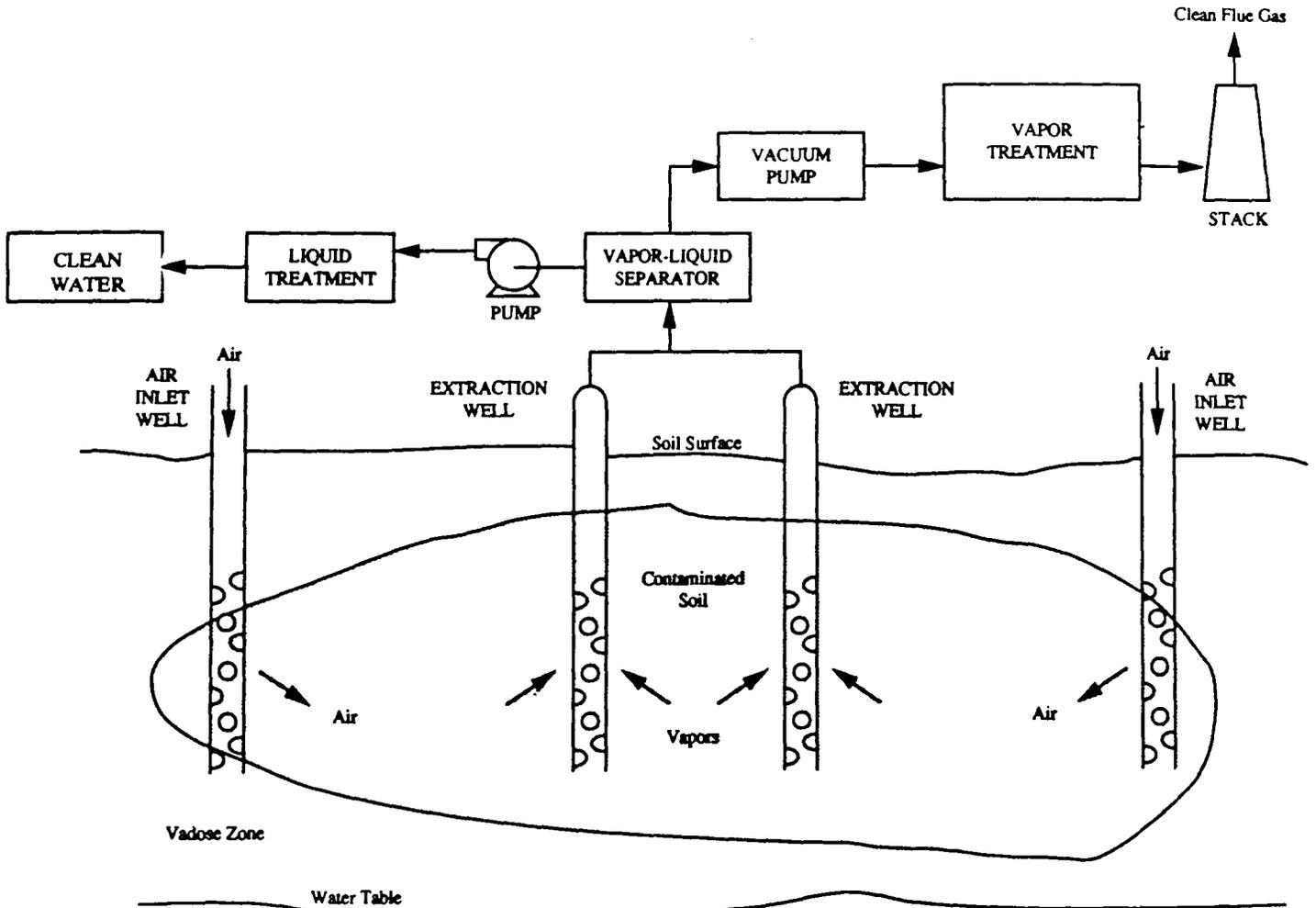


Figure 5-2. Generalized Process Flow Diagram for Soil Vapor Extraction.

contaminated water is extracted in the process, a liquid phase treatment system is usually installed. The oxygen introduced by SVE can promote the growth of iron-utilizing bacteria and lead to decreased pump efficiencies for groundwater extraction; this problem can be minimized by a chlorination program (McCann, et al., 1994).

In bioventing (see Section 6), the rate of vapor extraction is relatively low and the primary objective is to introduce oxygen into the subsurface to promote microbiological activity. This is not the primary goal for SVE, but introduction of oxygen into the subsurface during SVE may, as a side benefit, enhance biodegradation and thereby improve the overall remediation efficiency. Evidence of unusually high carbon dioxide levels indicates that some sites may experience enhanced subsurface biodegradation that may be partially or wholly a result of soil vapor extraction. At one site, carbon dioxide concentrations in the soil gas were 8.5%; much higher than the 0.03% or 0.04% typically present in the atmosphere, though co-disposed municipal waste could have been partially responsible for the high levels. Rough calculations indicated that up to 40% of the gasoline was destroyed by degradation.

The relative advantages of SVE over other remediation approaches are:

- the equipment is readily available and simple to install and operate;
- large volumes of soil can be treated in a cost-effective manner;
- remediation can proceed in many cases without disrupting on-going commercial activities at the site; and

- air emissions are released from a point source and, thus, can readily be controlled.

The major disadvantages of SVE versus other remediation approaches are that:

- The method is not applicable for saturated soils or soils with low air-permeabilities;
- the success of the method varies with the volatility (vapor pressure) of the contaminants present; and
- significant residual contamination may remain in the soil after treatment under some remediation scenarios.

A number of reports and articles have been published that provide useful information regarding SVE systems. The best single source of information is an EPA report (Pedersen and Curtis, 1991). Much of the information in this section was drawn from that report and a second EPA report (Thompson, et al., 1991). Other key references are two studies that include summarized information about existing SVE systems in use at field sites (Hutzler, et al. 1989; and PES, 1989), an evaluation conducted under EPA's SITE program (Michaels, 1989a), and an overview paper (Johnson, et al., 1990). The Johnson, et al., paper is given as Appendix E of this report and EPA's Engineering Bulletin on SVE is contained in Appendix F of this report.

## **5.2 Identification of Air Emission Points**

The air emissions associated with SVE systems come primarily from the stack. Stack heights are typically 10-30 feet and

usually only one stack is used (Eklund, et al., 1992a). Additional releases of volatile organics may occur from the treatment of any contaminated water that is extracted. Fugitive emissions are considered negligible due to the negative pressure throughout most of the system.

### **5.3 Typical Air Emission Species of Concern**

Emissions include untreated volatile organics from the extraction process. Removal and emissions of semi-volatile organic compounds will also occur, though with less efficiency than for VOCs. Lesser amounts of air emissions associated with the control system may also occur. Due to the variety of technologies used for vapor treatment, stack emissions may include products of incomplete combustion, NO<sub>x</sub>, particulate matter, CO, and acid gases. Of primary concern, however, are the volatile organics emitted from the point sources.

### **5.4 Summary Of Air Emissions Data**

Air emissions data for several SVE systems are summarized in Table 5-1. The data are from a variety of soil vapor extraction systems. Overall, there is little detailed published information about air emissions from SVE systems, making it difficult to assess the representativeness of this sample.

The emission rate of VOC compounds over time from continuously operated SVE systems tends to show an exponential-type decay curve. If the system is stopped and then restarted, however, the VOC emission rate returns to near the original rate unless the remediation is nearing completion. Shutting off the vacuum allows the soil-gas equilibrium to

become re-established. Due to this behavior, the most efficient method of operation often is to run the SVE system only for a part of each day or week, i.e., operate in a "pulsed" mode.

Published emission factors for SVE systems based on typical operating conditions (Thompson, et al., 1991) are:

- Uncontrolled Emissions: 25,000 g/hr or 250 kg/day (based on 10 hours of operation).
- Controlled Emissions: 1,250 g/hr or 0.05 g/g VOC in soil.

### **5.5 Identification of Applicable Control Technologies**

As the vapors are removed from the soil, they are either discharged to the atmosphere or treated to reduce air emissions. Direct combustion is theoretically possible if the hydrocarbon content of the exhaust gas is high enough, but the concentration typically drops significantly during removal. Therefore, natural gas or some other fuel would be needed to maintain combustion. Also, for safety reasons, dilution air typically is added to maintain the VOC concentration below the lower explosive limit (LEL).

For lower levels of hydrocarbons, catalytic oxidation may be effective. Carbon adsorption systems often are used, but they may be costly to implement and are generally not acceptable for high-humidity gas streams. An EPA survey from the late 1980s indicates that the exhaust from about 50% of SVE systems is vented directly to the atmosphere with no controls (PES, 1989). The trend, however, is for VOC

**Table 5-1  
Summary of Emissions Data for SVE Systems**

Source	No. of Systems Surveyed	Parameter	Units	Range or Value	Approximate Average
Crow (1987)	13	Flow Rate Per Well	cmm (cfm)	0.2-8 (5.3 - 300)	2 (80)
		Removal	kg/day (lb/day)	0.9-113 (2 - 250)	27 (60)
		Exhaust Gas Concentration	ppmv	20 - 350	100
Hutzler, et al. (1989)	19	Total Flow Rate	cmm (cfm)	0.1-161 (3 - 5,700)	23 (800)
		Treatment: - None - Carbon - Catalytic Incineration - Combustion	# systems	9 6 1 1	NA
		Removal Rate	kg/day (lb/day)	2-195 (4 - 430)	45 (100)
		Total Flow Rate	cmm (cfm)	0.7-318 (25 - 11,300)	62 (2,200)
PES (1989)	17	Pollutant Concentration	ppmv	150 - 38,000	4,000
		Control Efficiency	%	90 - 99	95

controls to be required. For those systems requiring controls, the most viable options are:

- 1) activated carbon adsorption;
- 2) catalytic oxidation;
- 3) thermal incineration;
- 4) internal combustion engine; and
- 5) miscellaneous control approaches.

The first three treatment options are the most commonly used for large SVE systems such as those used at Superfund sites or refineries. Internal combustion

engines (ICE) are a common choice for control of emissions for small systems such as those used at Leaking Underground Storage Tank (LUST) sites. Removal efficiencies of 95-99% for VOCs should be theoretically achievable with any of these control options.

No single control method is preferred. Each has advantages and disadvantages that must be considered for each specific application. Control options are discussed below. Further information is available from EPA's Technology Transfer

and Support Division (TTSD) (Eklund, et al., 1992b).

### **5.5.1 Carbon Adsorption**

Carbon adsorption using GAC is the most common control method for SVE systems. VOCs are removed by being physically trapped on the surface of the GAC or by chemical reactions with the carbon. The efficiency of GAC is due to its very large surface area per unit mass. Two options for GAC systems are available: 1) "throw away" systems, and 2) fixed bed regenerable systems. In the first option, canisters of GAC are used and disposed of or reactivated off-site. In regenerable systems, steam or hot air is used to strip contaminants from the GAC in place. The contaminants are recovered as a liquid. The cost-effectiveness of regenerable systems will increase as the treatment time and the mass of contaminants to be treated increase.

Modular, skid-mounted treatment systems are available from numerous vendors. Prefabricated GAC units containing up to a ton of carbon are available. Flow rates over 1,000 scfm can be accommodated.

The primary advantage of carbon adsorption over other control options is that the control efficiency of GAC systems is not significantly affected by the changes in air flow rate and VOC concentration that typically occur at SVE sites. It is applicable to most contaminants having molecular weights between 50 and 150; lighter compounds tend to pass through the GAC unadsorbed, and heavier compounds tend to bind permanently to the carbon and cannot be desorbed. GAC tends to be the control method of choice for SVE systems with low VOC concentrations in the exhaust gas (e.g.

less than 500-1000 ppmv). Removal efficiencies can exceed 99% under optimal conditions, which include adequate residence time, moderate temperature (100-130°F), and no fouling compounds present in the gas stream.

Carbon adsorption has several limitations that may be significant for SVE applications as shown below. One, water vapor will occupy adsorption-sites and reduce the removal capacity. It is usually recommended that the gas to be treated has a relative humidity of less than 50% for GAC to be effective. Two, carbon tends to not retain organics at temperatures exceeding 150°F. This temperature is well below the temperatures of 200 to 800°F in the exhaust gas that can be caused by compression of offgas in the removal pump. The air can be cooled or pumps used that do not add much heat to the system (e.g., liquid ring seal pumps). Three, high mass loadings of VOCs in the exhaust gas will cause the carbon to be exhausted quickly and result in high costs to replace or regenerate the carbon. The first two limitations can be offset through modifications to the system design, but these modifications will increase the cost of remediation.

### **5.5.2 Thermal Incineration**

Thermal incineration can be used to destroy vapor-phase contaminants. Contaminant-laden vapors are heated to temperatures above 1000°F via a direct flame or a combustion chamber. The method is applicable to a wide range of compounds and over a large range of concentrations. It is not, however, widely used for SVE applications except for large-scale, long-term cleanups. For the flame to be self-sustaining, the VOC concentration needs to be at percent levels that may be

above the lower explosive limit for the contaminant of concern. For lower VOC levels, auxiliary fuel such as methane or propane must be added. The cost of this fuel can be prohibitive. The efficiency of the method is also affected by changes in the flow rate. As the flow rate varies from design conditions, the mixing and residence times in the incinerator will vary and decrease the destruction efficiency. Design efficiency typically is 98% or higher.

### **5.5.3 Catalytic Oxidation**

Catalytic oxidation, also called catalytic incineration, is similar in design and operation to thermal incineration except that a catalyst is present that enhances combustion. The catalyst is usually palladium or platinum in a metallic mesh, ceramic honeycomb, or catalyst-impregnated beads in a packed bed. The catalyst allows destruction to occur at lower temperatures than for thermal incineration (600-900°F). There is therefore less auxiliary fuel required and commensurate lower fuel costs.

Design efficiencies of 95 to 99% percent are typical. The catalyst can be damaged by overheating, so the air stream must be diluted, if necessary, to a VOC concentration below about 3000 ppmv, to maintain acceptable operating temperatures. Maintenance of this VOC level raises the capital and operating cost of the system since accurate monitoring of the gas stream is needed, as is the ability to control the dilution of the gas stream. As for thermal incinerators, catalytic oxidation systems function best when the flow rate is constant.

The catalyst will become less effective over time and can be adversely affected by trace contaminants in the gas stream. Depending on the type of catalyst

employed, it can be damaged by chlorinated hydrocarbons, mercury, phosphorus, or heavy metals.

### **5.5.4 Internal Combustion Engines (IC)**

Industrial or automotive engines have been widely used to control VOC emissions from SVE systems. Depending on the engine size, air flows of 30 to 100 scfm have been treated. The effective flow rate is reduced, however, if ambient air must be added to the air stream to add sufficient oxygen to support combustion. As with other thermal treatment methods, supplemental fuel is needed.

Destruction efficiencies of 99+% have been reported for the most common components of gasoline (Pedersen and Curtis, 1991). Advantages of IC engines as controls are that the systems are portable, they can handle very concentrated air streams without the need for dilution, and the engine can provide power to operate the SVE system. Disadvantages are that the systems can only treat small flow rates and that manual supervision is required for a period during start-up to set the flow rates and operating conditions. Emissions of NO<sub>x</sub> from the engine may be a concern in some locales.

### **5.5.5 Miscellaneous Control Approaches**

A number of additional control devices may be applicable for controlling VOC emissions from SVE systems, including condensers, packed bed thermal processors, and biofilters. Condensers using chilled water or other refrigerants can remove anywhere from 50 to 90% of VOCs from concentrated streams (>5000 ppmv VOCs). Packed bed thermal processors consist of a bed of ceramic beads heated to

1800°F that is used to destroy organics and chlorinated hydrocarbons. Biofilters consist of soil beds that trap VOCs in a manner analogous to GAC and then are regenerated by biological action. Biotreatment requires time to establish an active culture of microbes and careful control of soil moisture, temperature, and air flow patterns to maintain the efficiency of the microbial action.

## **5.6 Costs For Remediation**

The costs to install and operate an SVE system will vary from site to site. A typical cost to install and start up a small system is less than \$100,000 (Newton, 1990). Total capital costs for equipment range from \$65,000 to \$135,000, excluding the cost of each vapor-recovery well (Cochran, 1987). Typical capital costs for the major components of the system (Pedersen and Curtis, 1991) are \$2,000 to \$4,000 per well, \$10,000 or more for a vacuum pump (25 hp positive displacement blower), \$2,500 for an air/water separator, and \$10,000 for a structure to house the system. A major variable is the cost of any monitoring and control system needed to maintain the VOC level in the exhaust stream within preset limits. VOC control costs are discussed in the next subsection.

Typical operation and maintenance costs are \$6,000 to \$26,000 per year (Cochran, 1987). The major operating costs (Pedersen and Curtis, 1991) are for power, VOC controls, monitoring, and labor. Power costs for a 10 hp system are estimated to be about \$600 per month. Monitoring and labor costs are highly variable. In general, operating costs in these areas can be minimized through the use of automated monitoring and control equipment. The optimal split for this trade-off between

capital and operating costs will depend on the duration of the remediation and the proximity of the site to the labor source.

Remediation costs often are reported in terms of cost per volume of soil treated. Typical operating costs for SVE at a site with no off-gas treatment and no wastewater generated range from \$11 per ton at a large site with sandy soil to \$55 per ton at a small site with clay soil (Michaels, 1989b).

As discussed in Section 5.1, soil heating can enhance SVE performance. One option, hot air injection, is most cost-effective using electric immersion heaters for 50-kW or smaller systems. Natural gas burners are used for larger systems. The installed cost of a 50-kW hot air injection system, with stainless steel injection wells, is about \$15,000 to \$22,000; electricity cost is about \$3,600 per month. A 200-kW steam injection system burning natural gas will cost about \$35,000 to \$45,000 installed, with operating costs of gas and water of about \$7,500 per month (HWC, 1994a).

## **5.7 Costs For Emission Controls**

Equations for predicting the costs of emission controls based on system design parameters are available (PES, 1989). Typical costs for various types and sizes of treatment systems are given in Table 5-2. The cost estimates are drawn from a number of vendors and, therefore, a range is shown in most cases. The costs from different vendors may not be directly comparable since the cost basis may vary. For example, regenerable carbon adsorption systems cost from \$22,000 (one bed) to \$55,000 (six beds) for manually regenerated systems and

**Table 5-2**  
**Summary of Capital Costs to Control VOC Emissions From SVE Systems**

<b>Treatment</b>	<b>Maximum Flow scmm (scfm)</b>	<b>Capital Cost (\$)</b>
Carbon Adsorption (Regenerable)	3 (105)	20,000 <sup>a</sup>
	7 (250)	24,000 <sup>a</sup>
	14 (500)	33,000 <sup>a</sup>
	31 (1100)	12,000 <sup>b</sup>
Carbon Canisters	3 (100)	700
	14 (500)	8,000 <sup>c</sup>
	28 (1000)	6,000
	113 (4000)	23,000 <sup>c</sup>
Thermal Incineration	2 (70)	13,000 <sup>d</sup>
	3 (100)	25,000 <sup>d</sup>
	16 (570)	44,000 <sup>d</sup>
Catalytic Oxidation	3 (100)	25,000 <sup>e</sup>
	6 (200)	31,000 - 69,000 <sup>e</sup>
	14 (500)	44,000 - 86,000 <sup>e</sup>
	28 (1000)	77,000 <sup>f</sup>
	142 (5000)	140,000 <sup>g</sup>
Internal Combustion Engine	2 (60)	62,000
	3 (100)	50,000

Source: Adapted from Pedersen and Curtis, 1991.

<sup>a</sup> Includes blower, demister, controls, gauges, valves, and flow ammeter.

<sup>b</sup> Includes blower, flexible connector, and damper.

<sup>c</sup> Deep bed units.

<sup>d</sup> Includes blower, sampling valves, and controls. Heat recovery systems are not included

<sup>e</sup> Includes burner, blower, flame arrestor, gauges, filters, knockout pot, sampling port, controls, and skid mounting.

<sup>f</sup> Dilution system available for an additional \$22,000.

<sup>g</sup> Source: Eklund, et al., 1992b.

about \$165,000 for a fully-automated equivalent system (Pedersen and Curtis, 1991). The cost data are intended to show the general level of costs likely to be incurred for various types of control options.

Maintenance costs will vary depending on the type of system and may include power, fuel, activated carbon, and the associated labor. The costs will vary with the size of the system and the operating rates. Electricity cost to run a 10-hp blower motor is about \$600 per month. Fuel costs for thermal incineration and catalytic oxidation depend on the VOC concentration of the influent air. Typical costs are \$500 to \$1,000 per month. Auxiliary fuel costs for IC engines are also about \$500 to \$1,000 per month. Activated carbon will cost from \$1 to \$2 per pound. However, an additional consideration is that an IC engine can power a generator, thus reducing electrical costs to operate pumps and blowers. Typical carbon costs are about \$25 per pound of hydrocarbons removed (about \$160 per gallon).

In terms of costs per volume of soil treated, one source estimates the cost of activated carbon can range from \$16 per ton to \$28 per ton (Michaels, 1989b). The cost of wastewater treatment or disposal (if required) is site-specific and may vary widely.

## **5.8 Equations and Models For Estimating VOC Emissions**

The factors that govern vapor transport in the subsurface are very complex, and no theoretical models for predicting emissions or recovery rates for SVE systems exist that are considered accurate and reliable due to limitations in obtaining adequate input data. During operation of

SVE systems, the vacuum that is applied to the soil and the resulting pressure gradient is the dominant factor in determining the flow rate of vapors. The induced vacuum in the soil decreases with distance from the extraction well, and a radius of influence exists that defines the extent to which vapors can be drawn to the well. The length of this radius depends on the strength of the vacuum source; the screened interval of the well; soil properties such as porosity, permeability, and moisture content; and site properties such as surface coverings.

In practice, field tests are typically performed to evaluate the potential effectiveness of SVE for a given site. The field tests may be either pilot-scale demonstrations of SVE or tests of the air permeability. This information is used to determine the number of wells required to remediate the site and the spacing of the wells.

Subsurface vapor flow equations based on Darcy's Law have been published that predict the flow rate of vented gas (Johnson, et al., 1990). The key inputs are the air permeability of the soil, the air-filled porosity of the soil, the thickness of the soil layer, the density of the vapor, and the gradients of pressure and vapor concentration. Methods for measuring the air permeability are based on measuring the difference between the ambient atmospheric pressure and the air pressure in the soil during vapor transport.

Johnson, et al., (see Appendix E) describe a test where air is withdrawn from a well at a constant flow rate while the draw-down (vacuum) pressure is measured in a monitoring well some distance away. The pressure is plotted versus the log of time, and the slope of this equation is the air

permeability. Measurements at several monitoring well locations are needed. Similar test methods may also be employed such as air injection tests and oil field tests including pressure buildup and draw-down tests (Pedersen and Curtis, 1991).

Various computer models are available for evaluating the feasibility, design, and performance of SVE systems. The U.S. EPA recently has evaluated some of the more commonly used models (Jordan, Mercer, and Cohen, 1995). The available models are described in Table 5-3.

For rough estimates of air emissions from SVE systems, data from pilot-scale tests at the site can be used with the following mass balance equation (Eklund and Albert, 1993):

$$ER = (C_g) \left( \frac{Q}{60} \right) (10^{-6})$$

where:

ER= Emission rate (g/sec);

$C_g$ = Conc. in extracted vapors ( $\mu\text{g}/\text{m}^3$ );

Q= Vapor extraction rate ( $\text{m}^3/\text{min}$ );

1/60= Conversion factor (min/sec); and

$10^{-6}$ = Conversion factor (g/ $\mu\text{g}$ ).

The extraction rate, Q, can be estimated from the results of pilot-scale tests at the site if any changes in pump size and number of wells between the pilot- and full-scale systems are taken into account. If no pilot-scale data are available, results of field tests of soil-air permeability can be used to estimate Q. If these too are not available, a default value can be used for the extraction rate. Typical flow rates for Q at Superfund sites range from 14  $\text{m}^3/\text{min}$  (500 cfm) to 425

$\text{m}^3/\text{min}$  (15,000 cfm), with a typical default value being  $Q = 85 \text{ m}^3/\text{min}$  (3,000 cfm).

The contaminant concentration in the extracted vapors,  $C_g$ , can also be estimated from the results of pilot-scale tests at the site. The next best approach is to estimate  $C_g$  by collecting samples of the headspace vapors above the contaminated soil and measuring the concentration of the compound(s) of interest. These equilibrium soil-gas samples can be collected using ground (soil-gas) probes or by transferring soil samples from split-spoon samplers (to minimize VOC losses) to sealed containers and allowing the headspace to equilibrate.

Field data are required to get an accurate value for  $C_g$ . If no field data are available, however, a very conservative value for  $C_g$  can be estimated by assuming that the soil-gas is saturated. The maximum vapor concentration of any compound in the extracted vapors is its equilibrium or "saturated" vapor concentration, which is calculated from the compound's molecular weight, vapor pressure at the soil temperature, and the ideal gas law:

$$C_g = \frac{(P_{\text{vap}})(MW * 10^9)}{(R)(T)}$$

where:

$C_g$ = Estimate of contaminant vapor concentration ( $\mu\text{g}/\text{m}^3$ );

$P_{\text{vap}}$  = Pure component vapor pressure at the soil temperature (mm Hg);

MW = Molecular weight of component (g/mole);

R = Gas constant = 62.4 L-mm Hg/mole- $^{\circ}\text{K}$ ;

T = Absolute temperature of soil ( $^{\circ}\text{K}$ ); and

$10^9$  = Conversion factor ( $\mu\text{g}-\text{L}/\text{g}-\text{m}^3$ ).

**Table 5-3  
Summary of SVE Models Evaluated by the U.S. EPA**

<b>Model</b>	<b>Type</b>	<b>Capabilities</b>	<b>Advantages</b>	<b>Limitations</b>	<b>Hardware/Software Requirements</b>	<b>Availability</b>
Hyper-Ventilate, v2.0 (IBM PC) v1.01 (Apple MacIntosh)	Screening	Calculates air permeability, well flow rates, mass removal rate, mass removal from several idealized diffusion-limited scenarios  Calculates contaminant concentrations over time for multiple constituents	Provides rapid estimates for determination of the potential feasibility of SVE  Provides rapid estimates of contaminant concentrations in extracted gas, allows comparison of removal rates of different constituents	Analytical air flow solution  Should not be used to design SVE systems	IBM PC or Compatible: 80386/80387 coprocessor or 80486, 4 MB RAM, DOS 3.1 or higher, Microsoft Windows 3.x and runtime version of Object PLUS  Apple MacIntosh (Plus, SE, SE/30, II, IIX, or portable): 1 MB RAM, Apple HyperCard Software (v2.0 or greater)	Available from EPA as EPA/600/R-93/028 (EPA ORD Publications, 513-569-7562) <sup>1</sup>  Object PLUS available from Object PLUS Corp., 125 Cambridge Park Dr. Cambridge, MA 02140 <sup>2</sup>
VENTING, v3.01	Screening	Calculates contaminant concentrations over time for multiple constituents	Provides rapid estimates of contaminant concentrations in extracted gas, allows comparison of removal rates of different constituents	User supplies flow rate to extraction well  Simplistic one-dimensional representation of mass transport  Should not be used to design SVE systems	IBM PC/AT or Compatible, DOS, 512 KB RAM, math coprocessor	Environmental Systems & Technologies, Inc. 2608 Sheffield Drive, Blacksburg, VA 24060-8270 703-552-0685

(Continued)

<sup>1</sup>From NTIS: Report with disk (PB93-502664/AS)  
Report only (PB93-134880/AS)

<sup>2</sup>From NTIS: IBM PC Disk (S/N 055-000-00427-7)  
MacIntosh Disk (S/N 055-000-00403-0)

**Table 5-3  
(Continued)**

<b>Model</b>	<b>Type</b>	<b>Capabilities</b>	<b>Advantages</b>	<b>Limitations</b>	<b>Hardware/Software Requirements</b>	<b>Availability</b>
AIRFLOW <sup>EM</sup> v2.07	Air flow	Calculates pressure distribution in a radial domain, calculates air flow pathlines and velocities	<p>Easy-to-use 'CAD-type' graphical user interface which simplifies model input and setup</p> <p>Rapid setup aids in hypothesis testing for simple problems</p> <p>Many sample problems included with the code</p>	<p>Only allows for one extraction well</p> <p>No mass transport</p>	IBM PC or compatible, 80386/80486, 4 MB RAM, DOS 2.0 or higher, mouse and math coprocessor for 80386-based machines recommended	Waterloo Hydrogeologic Software 19 McCauley Drive (RR#2) Bolton, Ontario, Canada L7E SR8 905-880-2886
CSUGAS	Air flow	Calculates vacuum distribution in the subsurface in inches of water	<p>Allows full, three-dimensional analysis of heterogeneous, multi-well air flow problems</p> <p>Text-based input/output is flexible and up to the user</p>	<p>Lack of easy-to-use input/output interface may intimidate beginners</p> <p>No steady-state solution option</p> <p>No mass transport</p>	IBM PC AT/XT or compatible, 640 KB RAM, DOS 2.0 or higher	Dr. James W. Warner Department of Civil Engineering Colorado State University Fort Collins, CO 80523 303-491-5048

(Continued)

**Table 5-3  
(Continued)**

<b>Model</b>	<b>Type</b>	<b>Capabilities</b>	<b>Advantages</b>	<b>Limitations</b>	<b>Hardware/Software Requirements</b>	<b>Availability</b>
AIR3D	Air flow	Calculates pressure distribution in the subsurface	Easy-to-use 'CAD-type' graphical user interface which simplifies model setup and input  Allows three-dimensional analysis of complex problems	Users need an awareness of the operation and limitations of the MODFLOW code  No mass transport	IBM PC or compatible, DOS 3.3 or higher, 4 MB RAM, VGA card and color monitor, mouse is highly recommended	American Petroleum Inst. 1220 L Street Northwest Washington, DC 20005  The original version of AIR3D (without the GUI) is available free of charge from: USGS Book and Open File Reports BLDG 810, Box 25425 Denver, CO 80225
VENT2D/ VENT3D	Air flow and multi-component contaminant transport	Calculates pressure distribution in the subsurface, multi component contaminant constituent concentrations over time in the subsurface	Only readily available compositional flow and transport code  Source code is available  Text-based input/output is flexible and up to the user	Grid size limited to 25 x 25 cells (can be increased with a different version available from the author)	IBM PC or compatible, 80X86 with math coprocessor, DOS 3.0 or higher, 525 KB RAM	David A. Benson 524 Claremont Street Reno, NV 98502 702-322-2104

Source: Jordan and Mercer, 1995.

Values of molecular weight, vapor pressure at 25°C, and saturated vapor concentration at 25°C are given in Eklund and Albert, 1993. It is important to note that the above equation gives the theoretical maximum value of  $C_g$ . It will overpredict  $C_g$  for any compound present in the soil at relatively low concentrations. It will also overpredict the long-term average value of  $C_g$  since the concentration of contaminants in the gas extracted using a SVE system will tend to drop over time. It can drop by more than 95% in the first two days of operation, though pulsed operation will allow the soil-gas concentration to be periodically re-established at levels near the initial concentration.

The above equation assumes that an infinite source of vapors exists and that the contaminants are present in the soil or ground water at relatively high concentrations (e.g., total hydrocarbons of 500 ppm in the soil). Therefore, the vapor-phase concentration for a given compound is assumed to be independent of the concentration of that same compound in the soil/liquid matrix.

Removal rates can be 500-600 kg/day or higher, and control efficiencies (when applicable) range from 60-99%. As previously mentioned, only about half of the sites listed used any VOC control equipment.

## 5.9 Case Study

### **Process Description**

Terra Vac Incorporated has developed a vacuum extraction system designed to remove volatile organic contaminants from the vadose zone. At the Groveland, Massachusetts Superfund site, the contaminated air stream was treated with

two sets of activated carbon canisters (Michaels, 1989a and Michaels, 1989b). Due to weather conditions, liquid water was extracted as well, so a vapor-liquid separator was included to remove contaminated water to a holding tank. The process design is shown in Figure 5-3. Air inlet wells were not used at this site.

Because no biodegradation was taking place in this case, the compounds released to the atmosphere were the same as those found in the soil. By far the most predominant contaminant removed was trichloroethylene, although 1,1,1-trichloroethane, trans-1,2-dichloroethylene, and tetrachloroethylene were also extracted.

### **Emission Factors**

Table 5-4 shows emissions factors for each of the four contaminants. The estimated total VOC peak emission factor is 18 g/hr. Based on the field data, the carbon adsorption control device had an efficiency of better than the 99% assumed in these calculations. In addition to stack emissions from vapor treatment, there would be evaporative emissions from contaminated water stored on-site in a holding tank. These emissions would add an estimated 3 g/hr to the total emissions. The removal efficiency for the total mass of contaminants present at the site was not demonstrated, nor was the associated control efficiency.

### **Costs**

The equipment fabrication and construction costs were estimated to be \$55,000 (in 1991 dollars). The total cost to treat 6,000 tons of contaminated soil (removing 1,300 pounds of VOCs) at the site was estimated to be \$310,000 or \$52 per ton. Of this, costs for activated carbon were \$14 per ton and for liquid waste disposal were \$8 per ton. Including power and labor

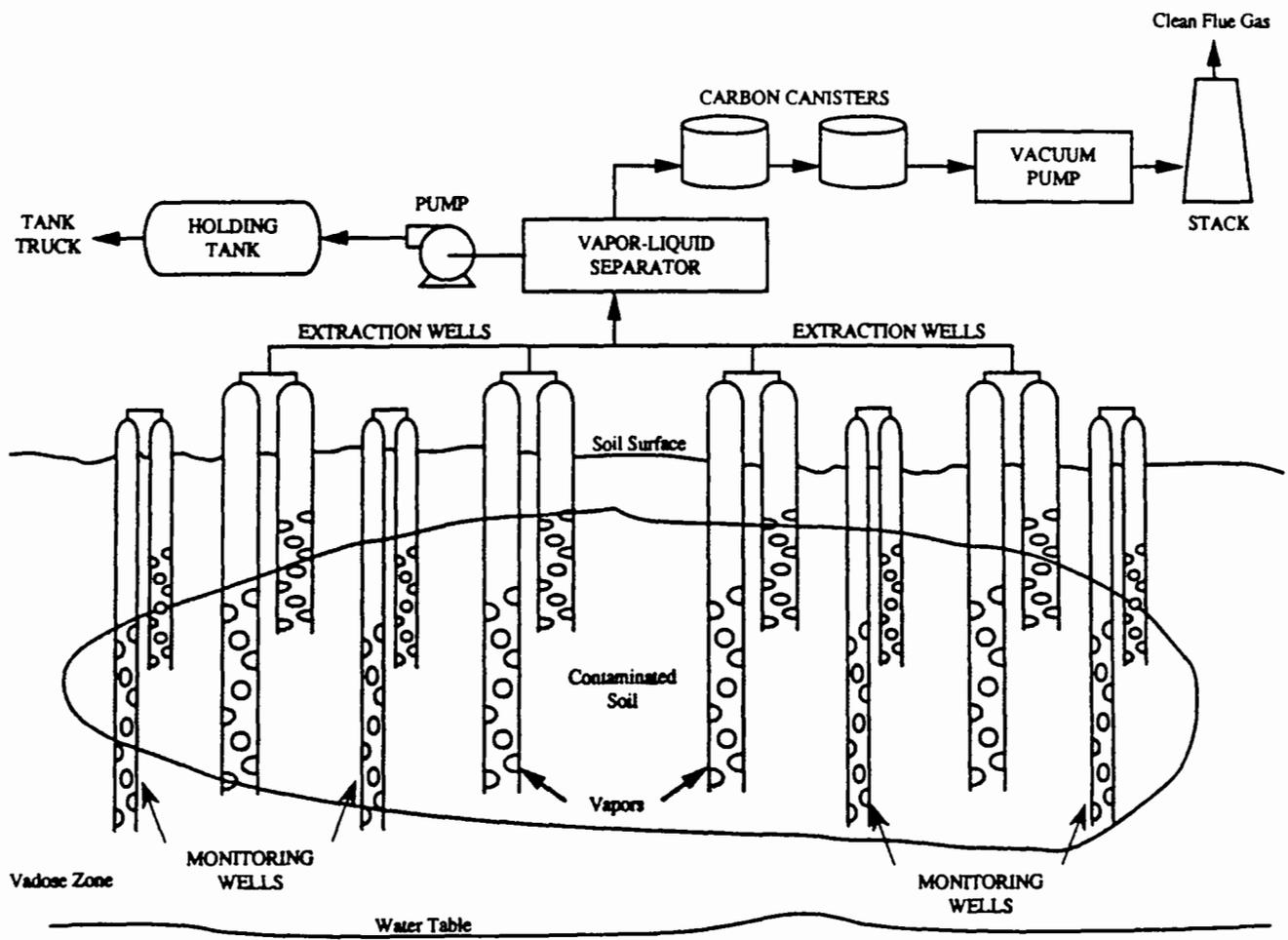


Figure 5-3. Process Flow Diagram for Terra Vac In Situ Vacuum Extraction System.

**Table 5-4**  
**Estimated Emissions for Terra Vac's In-Situ Vacuum Extraction System**

Pollutant	Molecular Weight g/mol	Peak Uncontrolled Stack Emissions g/hr <sup>a</sup>	Peak Controlled Stack Emissions g/hr <sup>b</sup>
Trichloroethylene (TCE)	131.29	1,712	17.1
trans-1,2-Dichloroethylene (DCE)	96.94	99.4	0.99
1,1,1-Trichloroethane (TCA)	133.41	13.6	0.14
Tetrachloroethylene (PCE)	165.83	3.18	0.03
Totals		1,830	18.3

<sup>a</sup> Uncontrolled emissions equal removal rate of each contaminant.

<sup>b</sup> Based on estimated 99% overall control efficiency for two carbon adsorption canisters in series.

of better than the 99% assumed in these calculations. In addition to stack emissions from vapor treatment, there would be evaporative emissions from contaminated water stored on-site in a holding tank. These emissions would add an estimated 3 g/hr to the total emissions. The removal efficiency for the total mass of contaminants present at the site was not demonstrated, nor was the associated control efficiency.

### **Costs**

The equipment fabrication and construction costs were estimated to be \$55,000 (in 1991 dollars). The total cost to treat 6,000 tons of contaminated soil (removing 1,300 pounds of VOCs) at the site was estimated to be \$310,000 or \$52 per ton. Of this, costs for activated carbon were \$14 per ton and for liquid waste disposal were \$8 per ton. Including power and labor costs, the VOC control system represents about one-half of the total remediation cost.

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## 6.0 IN-SITU BIODEGRADATION

### 6.1 Process Description

*In-situ* biodegradation is the term for biological treatment processes that are performed in place and therefore do not require excavation and removal of the contaminated soil. Biodegradation of contaminants in soils is most often accomplished through bioventing, which employs subsurface addition of oxygen through air injection or soil gas extraction to promote the biodegradation of contaminants. Other *in-situ* bioremediation approaches include the infiltration of nutrients, electron acceptors (such as oxygen), and microorganisms to enhance the microbial activity and remediation of contaminants.

The main purpose of *in-situ* treatment is to stimulate the natural microbiological activity of soil to decompose organic constituents into carbon dioxide and water. Systems that work to enhance this natural biological activity typically use injection wells to provide an oxygen source (such as air, pure oxygen, or hydrogen peroxide) to stimulate aerobic degradation. In bioventing systems, oxygen is added to the subsurface through air injection wells within the contaminated soil or through vapor extraction wells at the perimeter of the contaminated zone. Nutrients may also be needed to support the growth of waste-consuming microorganisms. In some cases, microorganisms that have the ability to metabolize specific contaminants of interest may be added to the soil.

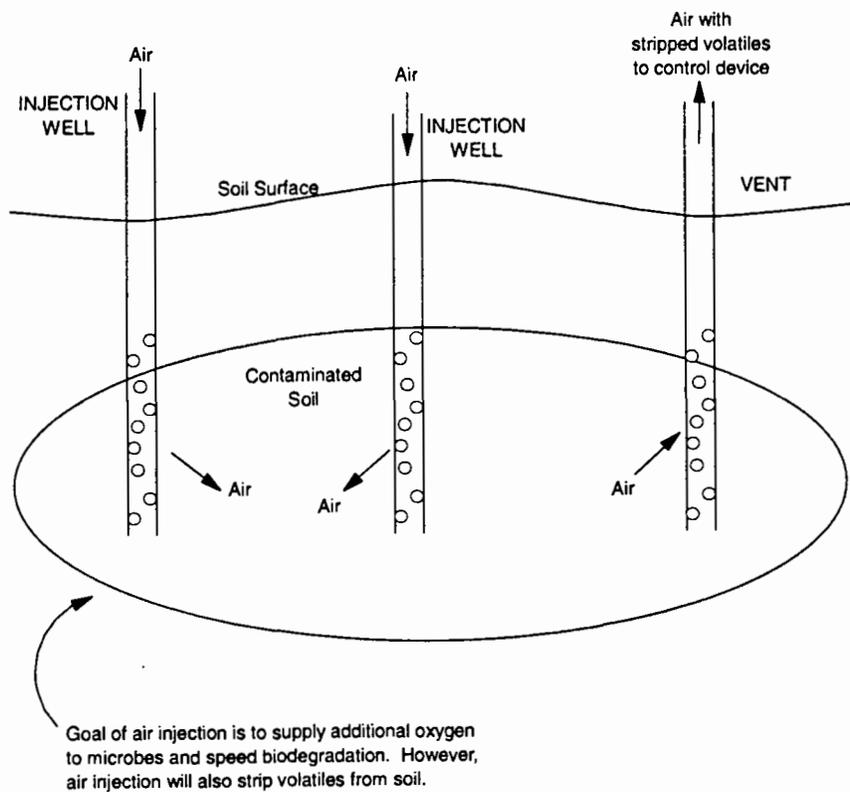
During *in-situ* biotreatment, biodegradation is actually only one of several competing mechanisms. The contaminants may also be leached,

volatilized, undergo chemical degradation, or be adsorbed onto the soil particles. The overall removal achieved by *in-situ* biotreatment processes represents the combined impact of all of these mechanisms. Field studies have shown that volatilization may account for the majority of VOCs that are removed (Dupont, 1993; HWC, 1993; Downey et al., 1994; van Eyk, 1994). Recent bioventing studies, however, have shown that volatilization can be minimized by optimizing the air flow rate so that volatilization accounts for less than 20% of the total hydrocarbon removal for these systems (Miller et al., 1991; Dupont, 1993; Downey et al., 1995). In addition, the vent gas can be recycled to further increase the fraction of contaminants biodegraded (HWC, 1993).

Like all biotreatment processes, *in-situ* treatment is not applicable for the remediation of non-biodegradable contaminants such as heavy metals and other inorganic compounds. Some halogenated organic wastes also are not amenable to biotreatment or may require substrates to biodegrade these contaminants. Test data from 137 sites have shown that bioventing has almost universal application for remediating hydrocarbon-contaminated soils, including gasoline, JP-4, diesel fuel, heating oils, and waste oils (AFCEE, 1994).

In many instances, sites are remediated initially using SVE to remove the more volatile constituents, and then the air flow rate is decreased and bioventing is used to biodegrade the remaining constituents.

Figure 6-1 shows a general schematic of an *in-situ* biodegradation process. Air injection wells are installed within the zone of contamination to



**Figure 6-1. Flow Diagram for Off-Gas Treatment System For In-Situ Biodegradation**

provide oxygen to stimulate the natural microbiological activity of the soils. An extraction or vent well can alternatively be used to provide oxygen to the subsurface, but this configuration may require off-gas treatment.

The primary factor affecting the volatilization of contaminants is the rate of air flow through the subsurface. The lower air flows used in bioventing, relative to soil vapor extraction systems, enhance biodegradation while minimizing volatilization. Other site factors, such as the temperature and soil moisture, can significantly affect the biodegradation rate for a site. As a result, competing mechanisms such as volatilization may predominate.

For an *in-situ* biotreatment process, the time required to treat the contaminated soil will vary greatly depending on a number of factors including the:

- Physical and chemical properties of the soil matrix;
- Physical and chemical properties of the contaminant;
- Initial concentration of the contaminant in the soil; and
- Biodegradability of the contaminants (i.e., biodegradation rate constants).

Hydrocarbon degradation rates have been measured from 300 to 7300 mg/kg TPH per year at numerous bioventing sites (Fredrickson, 1993; HWC, 1993). One site showed 99.5% removal as measured by soil TPH concentrations after 9 months of soil vapor extraction and 14 months of bioventing treatment. The average and

maximum initial TPH concentrations were <1000 mg/kg and 15,000 mg/kg, respectively. Biodegradation accounted for 44% of the total TPH removal.

The primary advantages of *in-situ* treatment, especially bioventing, are simplicity and low-cost. The equipment and operating costs for this type of treatment are very low compared to other technologies. The mechanical equipment required is simply a blower to inject or extract air.

The primary disadvantages of *in-situ* treatment are that only certain compounds are amenable to degradation, the removal efficiency may vary across a site, and the treatment may be relatively slow.

## 6.2 Identification of Air Emission Points

The specific point source of air emissions from bioventing systems is the off-gas collected by the extraction system. These vapors typically are collected through an extraction system and released through a short stack. Because the flow rate of bioventing systems is low and much of the contaminants are biodegraded in the subsurface, the off-gas from these systems often does not require treatment.

In some *in-situ* bioremediation systems, air injection wells are used to supply oxygen and no gas extraction system is employed. In such systems, area-wide emissions can occur, but the flow rates are typically low enough that emissions at the surface are thought to be minimal.

### 6.3 Typical Air Emission Species of Concern

Typical emissions from *in-situ* biotreatment process are a result of the volatilization of VOCs in the soil. The primary air emission species of concern are the specific volatile contaminants present in the soil. The air emissions may be biased towards the lighter molecular weight VOCs that make up the contamination. In addition, products of partial biodegradation are possible.

### 6.4 Summary of Air Emissions Data

Although *in-situ* biodegradation has been used to remediate numerous sites contaminated with petroleum hydrocarbons, few data on air emissions are available in the literature. Most bioventing studies have measured the concentration of contaminants in the system off-gas to estimate the fraction of total petroleum hydrocarbons volatilized versus bioremediated. As previously mentioned, sites may first be remediated using SVE to remove the more volatile constituents followed by bioventing to biodegrade the remaining constituents. Depending on the type and volatility of the contaminant, biodegradation can contribute from 50% to 90% to the total removal of petroleum hydrocarbons. Table 6-1 presents a summary of these data.

Source emission rates were determined at two sites, as shown in Table 6-2. Although the volatilization was in the range of 20 to 30 lb/day, the contribution of volatilization to the total removal was only 10% to 20%. To achieve this ratio of biodegradation to volatilization and minimize

air emissions, the bioventing system usually must be optimized.

The Hill AFB site is a good example of the difference in operating SVE systems versus bioventing systems and the amount of volatilization that can occur. Initially, the site was remediated by SVE and the volatilization and biodegradation rates were 200-400 lb/day and 70 lb/day, respectively. After 9 months of operation, the operating scheme was modified for bioventing. The bioventing volatilization and biodegradation rates were 20 lb/day and 100 lb/day, respectively.

Flux testing was conducted at five sites utilizing bioventing systems to measure the potential surface emissions during remediation. These results are summarized in Table 6-3. The maximum surface emission observed during the study was 2.5 mg/day/m<sup>2</sup>. Rates of biodegradation are typically 100 times greater than the rates of volatilization observed at these sites (AFCEE, 1994).

### 6.5 Identification of Applicable Control Technologies

As the vapors are removed from the soil, they are either discharged to the atmosphere or treated to reduce air emissions. Bioventing utilizes low air flow rates to provide only enough oxygen to sustain biological activity, so off-gas treatment is rarely needed. Off-gas treatment is most likely to be needed at sites contaminated with VOCs that have vapor pressures greater than 1 atm because they will be more likely to volatilize rather than biodegrade (Cookson, 1995).

**Table 6-1**

**Summary of Removal Rates for Bioventing Systems**

Site	Contaminant	Initial Soil Concentration	Removal Due to Volatilization	Removal Due to Biodegradation	Notes	Ref.
Burlington Northern RR, NE	No. 2 diesel fuel	20,000 to 50,000 mg/kg TRPH	<10%	>90%	2-yr bioventing test; Overall TRPH reduction: 55-60%	Downey et al., 1995
Eglin AFB, FL	gasoline	1200 mg/kg TRPH 500 mg/kg BTEX	35%	65%	Biodegradation exceeded volatilization as main removal mechanism after 30 days.	Downey et al., 1994
Retail gas station	gasoline	100 to 20,000 mg/kg BTEX 100 to 57,000 mg/kg mineral oil	800 kg hydrocarbons (1,764 lb hydrocarbons)	572 kg hydrocarbons (1,261 lb hydrocarbons)	Initially performed SVE; reduced air flow after week 67 for bioventing; 2 years of operation	van Eyk, 1994
Tyndall AFB, FL	jet fuel	NA	26 kg HC (45%) (57 lb HC)	32 kg HC (55%) (71 lb HC)	7-mo. test; Under optimal air-flow conditions, 82% HC removal by biodegradation (18% by volatilization) was achievable	Miller et al., 1991
Hill AFB, UT	JP-4	max. 15,000 mg/kg TPH avg. >1000 mg/kg TPH	53,600 kg (56%) (118,200 lb)	42,100 kg (44%) (92,900 lb)	Total removal: SVE for 9 mo. and bioventing for 14 mo. 99.5% overall contaminant removal	Dupont, 1993

**Table 6-2**

**Summary of Source Emission Rates for Bioventing Systems**

<b>Site</b>	<b>Emission Rates</b>	<b>Total Emissions</b>	<b>Notes</b>	<b>Reference</b>
Burlington Northern Railroad, NE	0.3 kg/day BTEX (0.7 lb/day BTEX) 14.7 kg/day diesel (32 lb/day diesel)	10,700 kg (23,600 lb) over 2 years	Equivalent to 600 mg/kg TRPH concentration reduction; <10% of removal by volatilization	Downey et al., 1995
Hill AFB, UT	9 kg/day (20 lb/day)	53,600 kg (118,200 lb) over 2 years (includes 9-month SVE test)	Biodegradation rate of 45 kg/day (100 lb/day); <20% of removal by volatilization (during bioventing test)	Dupont, 1993

**Table 6-3**

**Summary of Surface Emissions at Bioventing Sites**

<b>Base</b>	<b>Site Type</b>	<b>Air Injection Rate, scmm (scfm)</b>	<b>TVH Flux Estimate (g/day)</b>	<b>Initial Soil Gas TVH (ppmv)</b>
Plattsburg AFB, NY	Fire training pit	0.4 (13)	200	8400
Beale AFB, CA	Fire training pit	0.8 (30)	70	4800
Bolling AFB, D.C.	Diesel fuel spill	0.6 (20)	200	860
Fairchild AFB, WA	JP-4 fuel spill	0.4 (15)	150	29000
McClellan AFB, CA	Diesel fuel spill	1.4 (50)	30	380

Source: AFCEE, 1994

TVH = Total volatile hydrocarbons

AFB = Air Force Base

Although most bioventing systems do not contain VOC control systems, the most viable options when controls are necessary are similar to those for soil vapor extraction systems. These options include:

- Activated carbon;
- Catalytic oxidation; and
- Internal combustion engine.

Removal efficiencies of 95% to 99% should be theoretically achievable with any of these control options. A final option are biofilters which capture VOCs on soil beds and biodegrade the contaminants.

## 6.6 Costs for Remediation

Costs to perform *in-situ* bioremediation are low. The major capital investments are the blower and the treatment wells. Operating requirements are minimal and consist mainly of electricity and routine maintenance. The total costs for bioventing are in the range of \$10 to \$60 per cubic yard (AFCEE, 1994). The unit cost for bioventing is typically lower than SVE because off-gas treatment is not needed (Cookson, 1995). Unit costs are much lower than for low temperature thermal desorption and excavation/landfarming treatment processes (HWC, 1993; AFCEE, 1994).

The cost of a full-scale bioventing system for the remediation of 5,000 cubic yards of soil with an average concentration of 3,000 mg/kg of JP-4 would be \$90,300. This estimate includes pilot testing and 2 years of remediation (AFCEE, 1994).

## 6.7 Costs for Emissions Controls

Typically, emission controls are not required for bioventing systems. When controls are required, the cost is likely small,

on the order of \$20,000 to \$60,000. However, this cost can be a significant portion of the total remediation cost for bioventing systems.

## 6.8 Equations and Models for Estimating VOC Emissions

Vapor transport and biodegradation in contaminated soil are complex and competing processes. No practical, accurate theoretical models for predicting emissions or recovery rates are known to exist for bioventing systems. The pressure gradient (and related flow rate) and the biodegradation rate are the dominant factors in determining the mass rate of vapors.

Using data from pilot or full-scale tests at the site, air emissions can be estimated from the following mass balance equation (Eklund, et al., 1993):

$$ER = C_g (Q/60) 10^{-6}$$

where:

ER = Emission rate for contaminant of interest (g/sec);

$C_g$  = Concentration of the contaminant in the soil gas ( $\mu\text{g}/\text{m}^3$ );

Q = Exhaust gas flow rate ( $\text{m}^3/\text{min}$ );

1/60 = Conversion factor (min/sec); and

$10^{-6}$  = Conversion factor (g/ $\mu\text{g}$ ).

This equation does not address surface emissions.

If the extraction rate is not available from pilot tests, it can be estimated from the following:

$$Q = (1.0/1440) S_v E_a$$

where:

1.0 = Estimated flow rate for maximum biodegradation and minimum volatilization (pore volume/day);

1/1440 = Conversion factor (day/min);

$S_v$  = Volume of soil ( $m^3$ ); and

$E_a$  = Air-filled porosity (fraction).

Bioventing systems typically operate at flow rates that are equivalent to 0.25 to 2.0 pore volumes per day. A flow rate of 1.0 pore volumes per day is thought to maximize the amount of biodegradation and minimize the amount of volatilization (Eklund, et al., 1993). Typically, flow rates for bioventing systems are between 10 and 50 acfm (Dupont, 1993).

Field data, such as field measurements from pilot tests, provide the most accurate values for the contaminant concentration. If field data are not available, a very conservative estimate can be made by assuming that the soil gas is saturated. The maximum vapor concentration is its equilibrium or saturated vapor concentration:

$$C_g = P_{vap} \frac{MW}{R T} 10^9$$

where:

$P_{vap}$  = Pure contaminant vapor pressure at the soil temperature (mm Hg);

MW = Molecular weight of contaminant (g/gmol);

R = Gas constant (62.4 L-mmHg/gmol-°K);

T = Absolute temperature of soil (°K); and

$10^9$  = Conversion factor ( $\mu\text{g-L/g-m}^3$ ).

This equation will overpredict the long-term average value since the soil gas concentration tends to drop exponentially over time (Downey et al., 1994). This calculation also does not account for biodegradation of contaminants, which is the primary removal mechanism in bioventing processes.

## 6.9 Case Study

No suitable case study was found for the *in-situ* bioremediation of soils contaminated with petroleum hydrocarbons.

## 6.10 References

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## 7.0 EX-SITU BIODEGRADATION

### 7.1 Process Description

*Ex-situ* biodegradation is the general term for treatment processes in which the contaminated soil or sludge is excavated and remediated through biological processes. *Ex-situ* bioremediation technology most often involves slurry-phase bioremediation where an aqueous slurry is created by combining contaminated soil or sludge with water and then the contaminants are biodegraded in a self-contained reactor or in a lined lagoon. *Ex-situ* biodegradation also encompasses solid-phase bioremediation, such as landfarming, composting, and biopiles. In these processes, the contaminated soil is excavated, and oxygen, nutrients, water, or microorganisms are added to enhance the natural biodegradation of the contaminants.

#### 7.1.1 Slurry-Phase Bioremediation

There are two main objectives behind using slurry-phase bioremediation: to destroy the organic contaminants in the soil or sludge, and, equally important, to reduce the volume of contaminated material. This process can be the sole treatment technology in a complete cleanup system, or it can be used in conjunction with other biological, chemical and physical treatment. Slurry biodegradation has been shown to be effective in treating highly contaminated soils that have fuel or other organic contaminant concentrations ranging from 2,500 mg/kg to 250,000 mg/kg. The slurry process has also shown potential for treating a wide range of contaminants including pesticides, creosote, pentachlorophenol, PCBs, and other halogenated organics. The effectiveness of slurry biodegradation for

certain general contaminant groups is shown in Table 7-1.

Figure 7-1 shows a general schematic of the slurry biodegradation process. However, the design of slurry processes may vary significantly among vendors. Furthermore, each vendor's process may be capable of treating only certain types of contaminants. Treatability studies to determine the biodegradability of the contaminants and the solids/liquid separation that occurs at the end of the process typically are necessary before final selection of *ex-situ* biodegradation as a remedy for a given site.

As shown in Figure 7-1, waste preparation is required before applying slurry biodegradation. The preparation may include excavation and handling of the waste material as well as screening to remove debris and large objects. Particle size reduction, water addition, and pH and temperature adjustment also may be required to meet feed specifications. Table 7-2 shows the desired feed characteristics for a typical slurry biodegradation process.

After appropriate pretreatment, the wastes are suspended in a slurry form and mixed in a tank to maximize the contact between contaminants and microorganisms capable of degrading those contaminants. From the mix tank, the slurry is pumped (using special slurry pumps) to the bioreactor system. The bioreactor system can either be an above-ground continuously stirred tank reactor (CSTR) or a lined lagoon. Since aerobic treatment is the most common mode of operation for slurry biodegradation, aeration must be provided to the bioreactors by either floating or submerged aerators or by compressors or purgers. Nutrients and neutralizing agents

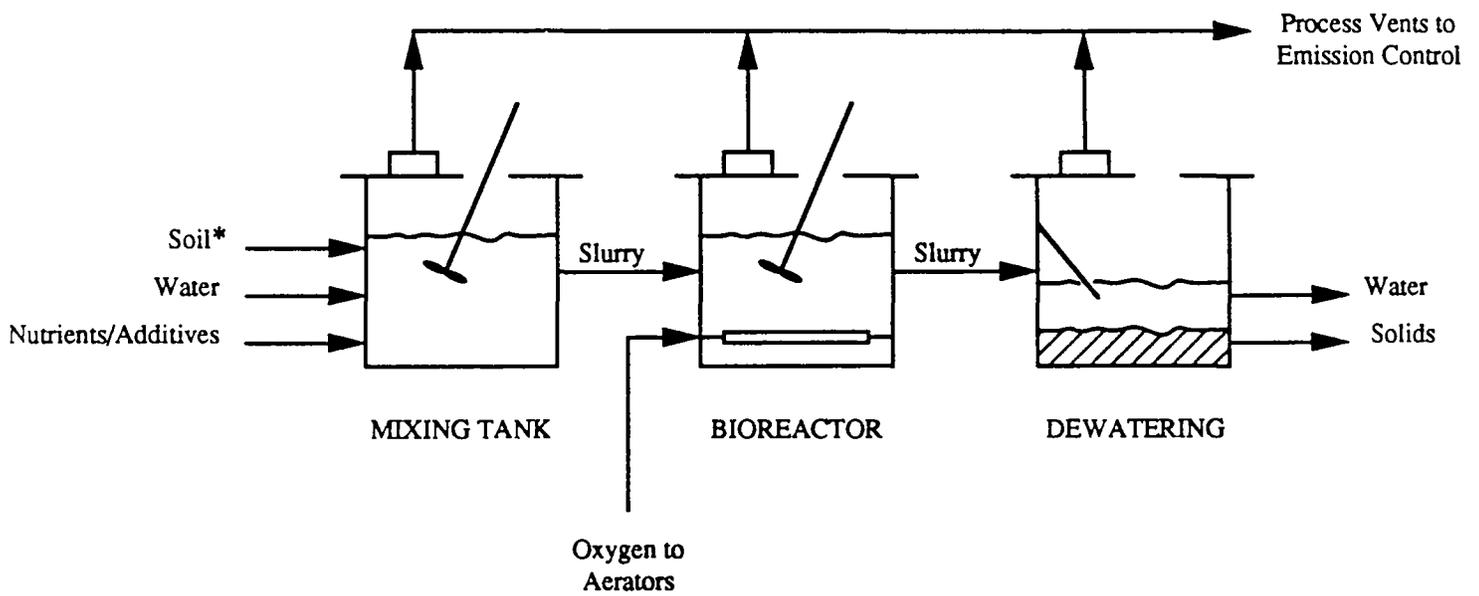
**Table 7-1**  
**Applicability of Slurry Biodegradation for Treatment of**  
**Contaminants in Soil, Sediments, and Sludges**

Contaminant	Applicability
<b>ORGANIC CONTAMINANTS:</b>	
Halogenated volatiles	1
Halogenated semivolatiles	2
Nonhalogenated volatiles	1
Nonhalogenated semivolatiles	2
PCBs	1
Pesticides	2
Dioxins/Furans	0
Organic Cyanides	1
Organic Corrosives	0
<b>INORGANIC CONTAMINANTS:</b>	
Volatile metals	0
Nonvolatile metals	0
Asbestos	0
Radioactive materials	0
Inorganic corrosives	0
Inorganic cyanides	1
<b>REACTIVE CONTAMINANTS:</b>	
Oxidizers	0
Reducers	0

Source: U.S. EPA, 1990.

**KEY:**

- 2 = Demonstrated Effectiveness; Successful treatability test at some scale has been completed.
- 1 = Potential Effectiveness; Expert opinion is that the technology will work.
- 0 = No Expected Effectiveness; Expert Opinion is that the technology will not work.



\* Waste preparation may be required. This includes excavation as well as other pretreatment to remove metals & other inorganics.

Figure 7-1. Slurry Bioremediation Process Flow Diagram

**Table 7-2**  
**Desired Inlet Feed Characteristics for Slurry Biodegradation Processes**

<b>Characteristic</b>	<b>Desired Range</b>
Organic Content	0.025 - 25 wt %
Solid Content	10 - 40 wt %
Water Content	60 - 90 wt %
Solids Particle Size	< 1/4 in. diameter
Feed Temperature	15 -35 deg C
Feed pH	4.5 - 8.8

also are supplied to remove any chemical limitations for microbial activity. Other materials, such as surfactants and dispersants, may be used to improve the material's handling characteristics.

In the bioreactor, microorganisms may be added initially to seed the reaction, or they may be added continuously to maintain the correct concentration of biomass. The required residence time for the waste in the bioreactor will depend on a number of factors including:

- The physical and chemical properties of the soil or sludge matrix;
- The physical and chemical properties of the contaminant, including its concentration in the waste; and
- The biodegradability of the contaminants.

A typical residence time may be as short as several days (e.g., 10) or as long as 8 to 9 weeks, depending on-site conditions.

Once the biodegradation of the contaminants is completed, the treated slurry is sent to a separation/dewatering system. A clarifier for gravity separation can be used to remove the water from the soil.

Slurry bioreactors are generally transportable units that can be brought on-site by trailer. Typically, commercial units require a set-up area of 0.5 to 1 acre per million gallons of reactor volume. Water needs at the site can be high since the waste must be put in slurry form. Large quantities of wastewater also may have to be stored on-site prior to discharge to allow time for analytical tests to verify that the discharge standard for the site has been met.

Limited performance data on slurry biodegradation systems are currently available. Some of the data presented in this report are based on information supplied by vendors. The validity of these results has not been evaluated.

Table 7-3 shows performance data for a full-scale slurry biodegradation system designed by Remediation Technologies, which was used to treat wood preserving sludges at a site in Sweetwater, Tennessee (U.S. EPA, 1990). The system achieved an overall removal efficiency of greater than 95%, but the breakdown of the removal efficiency between biodegradation and volatilization is not available.

Another full-scale test of a slurry biodegradation system was conducted by ECOVA Corporation (U.S. EPA, 1990). In this cleanup effort, more than 750 yd<sup>3</sup> of soil contaminated with pesticides was treated. Soil pesticide levels were reduced from 800 mg/kg to less than 20 mg/kg (>97.5% efficiency) in 13 days using a 26,000-gallon bioreactor. Residuals of the process were treated further by land application.

Under the Superfund Innovative Technology Evaluation (SITE) program, a pilot-scale demonstration of slurry-phase bioremediation was performed for creosote-contaminated soil. During a 12-week test, greater than 87% of the total polynuclear aromatic hydrocarbons (PAHs) were removed from the contaminated soil (U.S. EPA, 1993). Other case studies evaluated in the SITE report showed similar removal efficiencies. The slurry bioremediation of petroleum sludge from an impoundment yielded >90% removal of PAHs by both volatilization and biodegradation processes. Another study performed at a waste disposal services site in Texas resulted in 80%

**Table 7-3**  
**Performance Results for Slurry Biodegradation Process**  
**Treating Wood Preserving Wastes<sup>(a)</sup>**

Compound	Initial Concentration		Final Concentration		Removal <sup>(b)</sup>	
	Solids (mg/kg)	Slurry (mg/kg)	Solids (mg/kg)	Slurry (mg/kg)	Solids (%)	Slurry (%)
Phenol	14.6	1.4	0.7	< 0.1	95.2	92.8
Pentachlorophenol	687	64	12.3	0.8	98.2	92.8
Naphthalene	3,670	343	23	1.6	99.3	99.5
Phenanthrene & Anthracene	30,700	2,870	200	13.7	99.3	99.5
Fluoranthene	5,470	511	67	4.6	98.8	99.1
Carbazole	1,490	139	4.9	0.3	99.7	99.8

- (a) Treatment done using a 50,000 gallon reactor supplied by Remediation Technologies.  
(b) Includes the combined effect of volatilization and biodegradation

removal of most contaminants and 100% removal of some contaminants (U.S. EPA, 1993).

### **7.1.2 Solid-Phase Bioremediation**

Solid-phase bioremediation involves the excavation and preparation of contaminated soil to enhance the bioremediation of contaminants in the soil. Land treatment (land farming) refers to the placement of the soil in an above-ground treatment system and tilling the soil at regular intervals to improve aeration and contact between the microorganisms and the contaminants. Nutrients and microorganisms may be added to the soil.

Composting involves the storage of biodegradable waste with a bulking agent to increase the porosity of the soil material. Oxygen is supplied through tilling or forced aeration. The moisture, temperature, and nutrients may need to be amended to successfully biodegrade the contaminants. Soil heap (or biopile) bioremediation is similar to composting in that the contaminated soil is piled in large mounds. However, for these processes air is usually provided by pulling a vacuum through the pile.

Table 7-4 gives a summary of the performance data available for biopile processes. Generally, the removal efficiencies of biopiles are similar to that of slurry-phase bioremediation systems. At the McClellan AFB site, both a biopile and a slurry phase process were tested. The removal efficiencies were 76% and 88%, respectively (Stefanoff and Garcia, 1995).

## **7.2 Identification of Air Emission Points**

As shown in Figure 7-1, there are three primary waste streams generated in slurry-phase bioremediation processes: the treated solids (sludge or soil), the process water, and air emissions. The solids are dewatered and may be further treated if they still contain organic contaminants. Also, if the solids are contaminated with inorganics or heavy metals, they can be stabilized before disposal. Some portion of the process water can be recycled, with the remainder treated in an on-site treatment system prior to discharge.

The air emissions from slurry biodegradation processes can either be area or point sources. For processes using open lagoons, emissions come from the exposed surface of the lagoon. In systems using above-ground self-contained reactors, the primary source of emissions usually is a process vent. The air emissions from composting and land treatment systems usually are area emissions, whereas the emissions from biopiles can be area or point sources depending on the air delivery system.

## **7.3 Typical Air Emission Species of Concern**

In *ex-situ* bioremediation processes, the emissions of concern are usually VOCs. The soils-handling steps required to deliver the contaminated soil to the treatment unit may also emit significant amounts of PM. Emissions from soils handling are addressed in Section 3 of this document.

**Table 7-4**  
**Summary of Performance Data for Biopile Systems**

<b>Site</b>	<b>Contaminants</b>	<b>Initial Contaminant Concentration</b>	<b>TPH Removal</b>	<b>Notes</b>	<b>Reference</b>
Distribution facility in Tustin, CA	Gasoline	85 to 8900 ppm TPH; average = 1296 ppm	TPH below action levels (50 ppm) in 100% of the treated soil	80 days remediation	Autry and Ellis, 1992
Unknown	Petroleum	1100 to 3300 mg/kg TPH; average = 1187 mg/kg	>90%	Typical final concentration: 48 mg/kg	Hater et al., 1994
Refinery	Refined products and crude oil	NA	55%	Contamination is very weathered	Hayes et al., 1995
McClellan AFB, CA	Fuel and oil disposal site	3900 mg/kg TPH	76%	Final concentration: 920 mg/kg	Stefanoff and Garcia, 1995
Glass bottle manufacturing facility	Fuel oil	Up to 20,000 mg/kg TPH	90% HC 100% gasoline components	Off-gas recirculated through soil pile	Miller 1995

#### **7.4 Summary of Air Emissions Data**

Little information exists on volatile losses from *ex-situ* bioremediation processes. Table 7-5 summarizes the data available for both slurry-phase and biopile systems. Although these data are limited, volatilization appears to be a small component of the overall removal of hydrocarbons in these processes.

In open lagoons and composting and land treatment processes, the primary environmental factors which influence air emissions, in addition to the biodegradability and volatility of the waste, are process temperature and wind speed. Emissions tend to increase with an increase in surface turbulence due to wind or mechanical agitation. Temperature affects emissions through its influence on microbial growth. At temperatures outside the band for optimal microbial activity, volatilization will increase (U.S. EPA, 1989a). Emissions from self-contained reactors are also determined by reactor design parameters such as the amount of air or oxygen used to aerate the slurry. Higher gas flow will strip more volatiles out of solution and increase air emissions.

#### **7.5 Air Emissions Controls**

When the air emissions from slurry biodegradation or biopiles processes are released through a process vent, standard VOC air pollution control technologies can be applied. Common alternatives for controlling VOC vent emissions include carbon adsorption as well as thermal and catalytic oxidation. The vent stream will likely contain dilute amounts of VOCs, so auxiliary fuel must be used in either thermal or catalytic oxidizers. For the relatively low VOC levels and low gas flows from

bioreactors and biopiles, carbon-based VOC emission controls are generally the best choice for point source emissions. For biopiles, the off-gas stream can be recirculated to the heap to reduce VOC emissions further through biodegradation.

When the air emissions from *ex-situ* bioremediation processes are area emission sources, applying air pollution control technologies is more difficult. Two control options are commonly used. The first alternative is to use a vapor collection hood to capture any VOC emissions and then route those emissions to a standard control device. A second, generally less favorable, alternative is to use an oil film or foam on top of the slurry to suppress evaporative losses. Typically, the air emissions from area sources are small and do not require controls.

#### **7.6 Costs for Remediation**

Presently there are little cost data available on slurry biodegradation processes because of limited experience with this type of remediation. The cost for slurry-phase bioremediation is estimated at \$50 to \$250/yd<sup>3</sup> (U.S. EPA, 1993). One vendor estimates the cost of full-scale operation to be \$85-160/yd<sup>3</sup> of soil, depending on the initial contaminant concentration and the total amount of soil to be treated. The process cost will also vary depending on the need for additional pre- and post-treatment of the soil and on the type of air emissions control equipment. Labor costs for materials handling and operation can account for one-half of the cost of these systems (U.S. EPA, 1993).

The cost of biopiles and other solid-phase bioremediation processes are less known. One study found that a biopile was

**Table 7-5  
Summary of Emissions Data for Ex-Situ Bioremediation Systems**

Site	Contaminants	Emission Rate	Total Emissions	Biodegradation/ Volatilization	Notes	Reference
<b>Slurry-phase bioremediation</b>						
Burlington Northern Superfund site, MN	Creosote	0.014 lb/hr THC max (day 1); 0.00015 lb/hr THC (day 6)	NA	NA	Off-gas concentrations peaked during day 1 and decreased to near baseline by day 5.	U.S. EPA, 1991
Refinery	Petroleum sludge	NA	910 kg HC	NA	425,000 kg of soils were treated. Emissions reduced to background by day 6.	U.S. EPA, 1993
Sheridan disposal services site, TX	Petroleum sludge	NA	10-20 kg/yr; 1.5 kg dredging 30 kg storage tank; 4 kg pond	NA	A full-scale system is estimated to have 500 to 2,000 kg of VOC emissions.	U.S. EPA, 1993

(Continued)

**Table 7-5  
(Continued)**

Site	Contaminants	Emission Rate	Total Emissions	Biodegradation/ Volatilization	Notes	Reference
<b>Biopile</b>						
Distribution facility in Tustin, CA	Gasoline	NA	NA	99%/1%	Air emissions measured for the stockpiling/handling, mixing, and curing operations. Mixing component accounted for 96% of contaminants lost. 73% of VOCs lost were trapped in carbon units.	Autry and Ellis, 1992
Unknown	Petroleum	0.021 lb/hr HC once through; 0.067 lb/hr HC after treatment (carbon)	NA	NA	Off-gas was also recycled back to the biopiles to further reduce emissions.	Hater et al., 1994
Refinery	Petroleum	16 ppb BTEX startup; 5 ppb BTEX (day 8); <1 ppb BTEX (day 35)	NA	>99%/<1%		Hayes et al., 1995

more cost-effective than a slurry-phase system because the biopile was more robust with respect to varying soil characteristics and because of the difficulties in dewatering slurries (Stefanoff and Garcia, 1995).

The materials handling component is consistent across all types of *ex-situ* bioremediation processes, so most of the cost differences would occur in the treatment and post-treatment portions of these processes.

### **7.7 Costs for Emissions Controls**

Equations for predicting the costs of emission controls based on system design parameters are available (PRE, 1989). Section 5 of this document provides typical costs for various types and sizes of treatment systems which could be applied to an *ex-situ* biodegradation process. As mentioned in Section 5, the cost estimates are drawn from a number of vendors and, therefore, a range is shown in most cases. The cost data are intended to show the general level of costs likely to be incurred.

### **7.8 Equations and Models for Estimating Air Emissions**

Although no models have been explicitly developed for estimating emissions from *ex-situ* bioprocesses used to treat contaminated soil, there are currently, several public-domain PC models available for estimating air emissions from a variety of other biotreatment options, principally surface impoundments. The two most commonly used models are CHEMDAT-7 (U.S. EPA, 1989b) and the Surface Impoundment Modeling System (SIMS). Both CHEMDAT-7 and SIMS are based on mass transfer and biodegradation models developed by the U.S. EPA. The mass

transfer model uses two-film resistance theory, along with the characteristics of the impoundment, to estimate overall mass transfer coefficients for each pollutant. The biodegradation model assumes Monod kinetics to estimate a biodegradation rate.

The accuracy of estimating emissions from *ex-situ* biotreatment processes, though, is limited by the assumptions inherent in both CHEMDAT-7 and SIMS. Both models perform all calculations at 25°C and rely on physical property and kinetic data that are not always readily available for the modeled contaminants. Furthermore, both models rely on a simple thermodynamic analysis and are only valid in the Henry's Law regime. Henry's Law is applicable to dilute solutions and may not be applicable to bioslurries. In addition, neither CHEMDAT-7 nor SIMS use thermodynamic models that can predict the presence of two liquid phases.

The validity of CHEMDAT-7 and SIMS for modeling emissions from *ex-situ* biotreatment processes will depend on the process used and the operating parameters. Their validity must be evaluated on a case-by-case basis. If these models prove to be unacceptable for a given application, emissions can be estimated using a simple mass balance approach. For continuous-flow slurry systems, the following simple correlation is applicable (Thompson, et al., 1991):

$$ER_i = (C_i/1,000)(M_i)(V_i/100)$$

where:

$ER_i$  = emission rate for contaminant i (g/hr);

$C_i$  = concentration of species i in contaminated soil (mg/kg);

$M_t$  = mass rate of soil treated (kg/hr); and

$V_i$  = percentage of contaminant  $i$  volatilized (%).

The percentage of each contaminant that is volatilized will vary greatly depending on the physical properties of the contaminant and the design of the treatment system. Based on field studies of an aerated impoundment treating contaminated water, as much as 20% of each compound may be volatilized depending on its volatility and biodegradability (Eklund, et al. 1988).

For batch slurry biotreatment systems, a similar expression can be used to estimate air emissions:

$$ER_i = (C_i/1,000)(M)(\%V_i/100)/(t)$$

where:

$ER_i$  = emission rate for contaminant  $i$  (g/hr);

$C_i$  = concentration of species  $i$  in contaminated soil (mg/kg);

$M$  = mass of soil treated (kg);

$V_i$  = percentage of contaminant  $i$  volatilized (%); and

$t$  = residence time in treatment system.

Again, volatilization may be 20% or higher, depending on the properties of the compound of interest. This equation can also be used to estimate the emissions from solid-phase bioremediation processes.

Emissions will also occur when excavating the contaminated soil, while transporting it to the treatment unit, during any soil preparation steps, and when feeding

the soil into the treatment process. These fugitive emissions are not addressed in either the PC-based models or in the mass balance equations discussed above. Fugitive VOC emissions from soils handling operations are addressed in Section 3.

## 7.9 Case Study

No suitable case study was found for the *ex-situ* bioremediation of soils contaminated with petroleum hydrocarbons.

## 7.10 References

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## 8.0 INCINERATION

Thermal treatment processes include those designed to destroy the contaminants, such as incineration, and those designed to effect transfer of the contaminants to the gas phase, such as thermal desorption (see Section 4). Incineration is seldom used to remediate soils contaminated with fuel products because of economic considerations, and it is much less commonly employed for this purpose than thermal desorption, excavation and removal, and other treatment technologies.

### 8.1 Process Description

A broad range of technologies can be categorized as thermal destruction/incineration. The most common incineration technologies include liquid injection, rotary kiln, and multiple hearth (Lee, et al., 1986; Cheremisinoff, 1986). However, for remediation of fuel-contaminated soils, rotary kilns are most often used. In general, soil remediation by thermal destruction can be classified under two general categories: 1) on-site treatment using a transportable incinerator, or 2) shipment of contaminated soils off-site to a larger, permanent incinerator. For the treatment of soils contaminated with petroleum fuels, on-site incineration using mobile or transportable units is much more common than off-site incineration. Although incineration is a well-established technology, the evolution of mobile or transportable incinerators is a more recent development.

The literature on incineration is very extensive. The best source of information on air emissions from incineration is a recent review (Dempsey and Oppelt, 1993), which is contained in Appendix G to this report.

In broad terms, thermal destruction of hazardous waste is an engineered process in which controlled combustion is used to reduce the volume of an organic waste material and render it environmentally safe. Thermal treatment is a flexible process capable of being used for many waste types including solids, gases, liquids, and sludges.

Figure 8-1 shows a generalized process flow diagram for incineration systems. A typical system includes the waste feed system, primary and (in most cases) secondary combustion chambers, and exhaust gas conditioning system.

At the front-end of a hazardous waste incineration system is the waste feed process. The configuration of the waste feed system is determined by the physical characteristics of the waste. Contaminated soil is introduced to the combustion chamber by means of screw augers or belt feeders. If liquids are to be treated as well in the incinerator, they are usually injected into the unit by means of an atomization nozzle(s), which uses steam or compressed air as an atomization fluid. Liquids with entrained solids may require screening to prevent clogging of the atomizer nozzle.

The largest part of the waste destruction usually takes place in the primary combustion chamber. As mentioned earlier, for contaminated soils this chamber is usually a rotating kiln. Gases formed in the primary combustion chamber are then routed to a secondary combustion chamber, or afterburner, where any unburned hydrocarbons or products of incomplete combustion such as CO can be fully oxidized. Temperatures typically will be 1200-2300°F in the primary chamber and 2000-2500°F in the after burner.

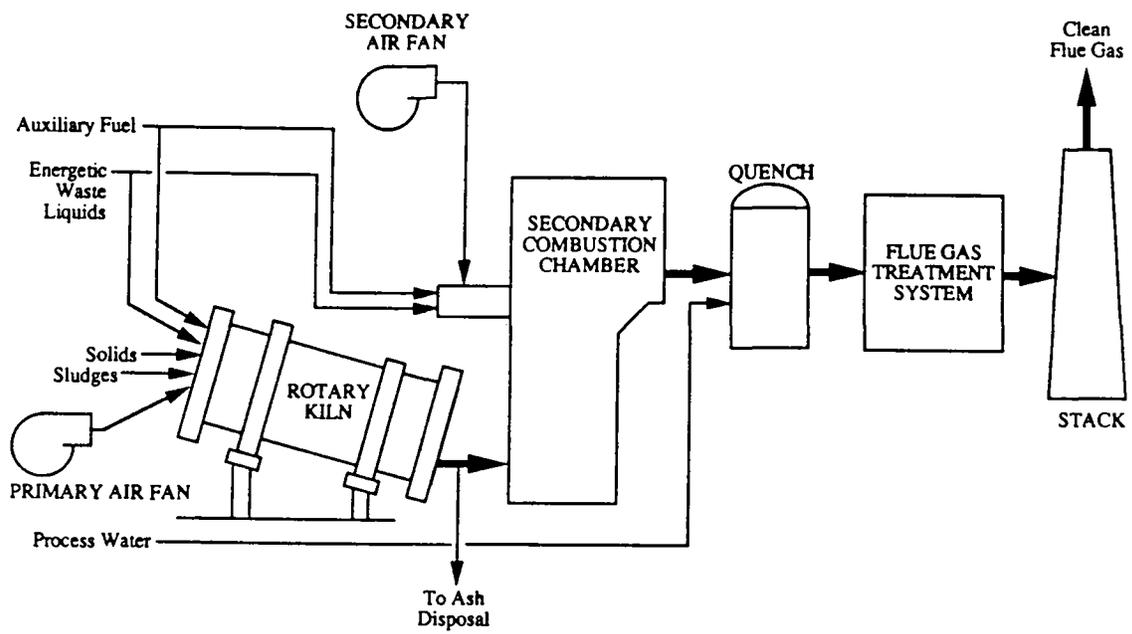


Figure 8-1. Process Flow Diagram for Commercial Rotary Kiln Incinerator.

After the combustion gases leave the incinerator, they may be routed through a variety of air pollution control devices including gas conditioning, particulate removal, and acid gas removal units. Gas conditioning is accomplished with equipment such as waste heat boilers or quench units. Typical particulate removal devices include venturi scrubbers, wet electrostatic precipitators, ionizing wet scrubbers, and fabric filters. Acid gas removal units include packed-, spray-, or tray-tower absorbers; ionizing wet scrubbers; and wet electrostatic precipitators.

The advantages of thermal treatment include the following:

- Demonstrated effectiveness;
- Applicability to a wide range of wastes (can be used on most contaminant and soil types); and
- High commercial availability.

However, thermal treatment also has a number of significant disadvantages such as:

- High cost;
- Public resistance to the construction and permitting of incinerators; and
- The need to meet stringent treatment requirements for process residuals.

## **8.2 Identification of Air Emission Points**

The air emissions associated with full-scale thermal treatment are primarily stack emissions of combustion gas. There may, however, be some additional

evaporative emissions from equipment leaks and waste handling. Full-scale, off-site incineration units may vent all emissions from waste handling and transfer activities to the combustion chamber as make-up air. The air emissions for on-site incinerators are similar to off-site units, except that waste handling activities have a greater likelihood of being uncontrolled. For off-site units, typical incinerator stacks will be 100-200 ft high. For transportable units, stack heights range from 40-100 ft. The fugitive emissions sources associated with thermal treatment will likely be ground-level.

As previously discussed, fugitive emissions from excavation and other area sources may be a significant fraction of the total air emissions.

## **8.3 Typical Air Emission Species of Concern**

Emissions from both on-site and off-site incinerators include: undestroyed organics, metals, particulate matter, NO<sub>x</sub>, CO, and acid gases. The cause of each of these pollutants is discussed below. Fugitive emissions associated with excavation, storage, and handling of the feed material must also be considered when assessing potential air impacts from incineration (see Section 3).

### **8.3.1 Unburned Hydrocarbons**

In general, incinerators treating wastes must achieve a required destruction and removal efficiency of at least 99.99% for RCRA wastes and 99.9999% for PCB- or dioxin surrogate wastes. The remaining 0.01% or 0.0001% of the waste can be assumed to pass through the system uncombusted (Eklund, et al., 1989). However, in addition to unburned

hydrocarbons there may be some additional reactions in the combustion process that may produce a number of other organic compounds, called products of incomplete combustion (PICs). PICs may include dioxins, formaldehyde, and benzo(a)-pyrene and other PAHs. PIC formation is not restricted to the combustion chamber; the reactions which produce PICs may continue to occur in the combustion gases as they travel through the incineration system and out of the exhaust system (Eklund, et al., 1989; Treholm and Oberacker, 1985).

Studies indicate that PIC emissions are a natural consequence of the kinetically-limited thermal degradation of hazardous wastes. Comparison of PIC formation/destruction rates based on theory and nominal incineration conditions indicate that PIC emissions can be several orders of magnitude higher than predicted based on equilibrium (Dellinger, et al., 1991). This finding suggests that temporal or spatial excursions from these nominal conditions are occurring, which lead to PIC formation. Possible causes of PIC emissions include low temperatures due to quenching, residence-time short circuits due to nonplug flow and/or unswept recesses, and locally high waste/oxygen concentration ratios due to poor microscale mixing.

Dioxins and furans are potential PICs. Dioxins are three-ringed compounds of the chemical family dibenzo-p-dioxins. Furans are three-ringed structures of the chemical family dibenzofurans that are similar in structure to dioxins. "Dioxin" and "furan" usually refer to the chlorinated congeners of dibenzo-p-dioxin and dibenzofuran. Dioxins and furans are considered to be potent carcinogens. These compounds may be present in incinerator exhaust gas as a result of incomplete

combustion or the recombination of exhaust products from the burning of mixtures containing chlorinated compounds (Dempsey and Oppelt, 1993). The total dioxin/furan emissions tend to correlate with the chlorine content of the waste feed (Helble and Hlustick, 1994). Thus, dioxin and furan emissions should not be a concern for the treatment of soils containing petroleum fuels with no chlorinated compounds present.

### **8.3.2 Metals**

The metals introduced to the incinerator via the waste feed stream are not destroyed. Depending on their boiling point, they can either be volatilized or remain as solids. Volatilized metals will exit the stack as a gas or they will condense or adsorb onto particles in the stack gas stream. Metals associated with particulate matter (PM) will be captured in the PM control device. Non-volatilized metals can be fluidized and swept up into the combustion gas or leave the incinerator in the bottom ash.

### **8.3.3 Particulate Matter**

The waste feed, auxiliary fuel, and combustion air can all serve as sources for particulate emissions from an incineration system. Particulate emissions may result from inorganic salts and metals that either pass through the system as solids or vaporize in the combustion chamber and recondense as solid particles in the stack gas. High-molecular-weight hydrocarbons may also contribute to particulate emissions if oxidation is not complete. RCRA requirements for particulate emissions call for a limit of 0.08 grains/dscf corrected to 7% O<sub>2</sub>. A number of potential PM control devices can be used, including venturists, wet

electrostatic precipitation, ionizing wet scrubbers, and fabric filters.

### 8.3.4 Nitrogen Oxides

Achieving high levels of destruction of organic wastes is directly related to combustion chamber temperature: the higher the temperature, the greater the destruction and removal efficiency (DRE) of organics. Unfortunately, the fixation of nitrogen and oxygen to form  $\text{NO}_x$  also increases with combustion temperatures.  $\text{NO}_x$  emissions caused by this mechanism are referred to as thermal  $\text{NO}_x$ . Also, if there are bound nitrogen atoms in the waste (e.g. amines), additional  $\text{NO}_x$  emissions, called fuel  $\text{NO}_x$ , will be formed. In such cases, two-stage combustion or emissions controls may be needed.

### 8.3.5 Carbon Monoxide

Carbon monoxide emissions are generally low (<100 ppmv) in incinerators because of the high operating temperatures and excess oxygen maintained in the process.

### 8.3.6 Acid Gases

Hazardous waste incineration will also produce acid gases. These include oxides of sulfur ( $\text{SO}_x$ ) and halogen acids (HCl, HF, and HBr). The sulfur, chlorine, fluorine, and bromine contents of the waste and fuel feed determine the emission levels of their respective acid gases. The concentrations of these elements range widely amongst different wastes; consequently, the resulting acid gas emissions will also show wide variability. Acid gas emissions are usually not a concern for the incineration of soils contaminated by petroleum fuels. Most incinerators are

equipped with some type of flue gas treatment system to control acid gas emissions. Control efficiencies typically range from 85-99%. Units treating soil contaminated with halogenated solvents generally are required to meet RCRA requirements governing HCl emissions.

## 8.4 Summary of Air Emissions Data

The wide variety in design and operation of incinerators makes it difficult to generalize about air emissions. However, extensive research has been done to determine the range of unburned hydrocarbon and PIC emissions that can be expected from full-scale incinerators. Table 8-1 shows the range of PIC concentrations found in testing of several different full-scale incinerators. Given the volume flowrate of the incinerator off-gas, these concentrations can be used to estimate the range of emissions from a particular incinerator system. The data in Table 8-1 are not necessarily based on the incineration of fuel-contaminated soils, and therefore, may overestimate emissions from the treatment of fuel-contaminated soils.

A summary of dioxin and furan emissions from incinerators and other thermal destruction facilities is given in Table 8-2. Emissions of dioxins and furans from hazardous waste incinerators generally are below detection limits. Reasonable worst-case emission rates of polychlorinated dibenzo-p-dioxin (PCDD) and tetrachlorodibenzofuran (TCDF) are 102 and 1.41  $\text{ng}/\text{m}^3$ , respectively (Dempsey and Oppelt, 1993). Results of recent dioxin/furan emissions tests are summarized in Table 8-3.

**Table 8-1  
PICs Found in Stack Effluents of Full-Scale Incinerators<sup>1</sup>**

<b>PIC</b>	<b>Number of Sites</b>	<b>Concentrations (ng/L)</b>
Benzene	6	12 - 670
Chloroform	5	1 - 1,330
Bromodichloromethane	4	3 - 32
Dibromochloromethane	4	1 - 12
Bromoform	3	0.2 - 24
Naphthalene	3	5 - 100
Chlorobenzene	3	1 - 10
Tetrachloroethylene	3	0.1 - 2.5
1,1,1-Trichloroethane	3	0.1 - 1.5
Hexachlorobenzene	2	0.5 - 7
Methylene chloride	2	2 - 27
o-Nitrophenol	2	25 - 50
Phenol	2	4 - 22
Toluene	2	2 - 75
Bromochloromethane	1	14
Carbon disulfide	1	32
Methylene bromide	1	18
2,4,6-Trichlorophenol	1	110
Bromomethane	1	1
Chloromethane	1	3
Pyrene	1	1
Fluoranthene	1	1
Dichlorobenzene	1	2 - 4
Trichlorobenzene	1	7
Methyl ethyl ketone	1	3
Diethyl phthalate	1	7
o-Chlorophenol	1	2 - 22
Pentachlorophenol	1	6
2,4-Dimethyl phenol	1	1 - 21

<sup>1</sup>Data from Trenholm, Gorman, and Junglaus, 1984.

**Table 8-2**  
**Dioxin/Furan Emissions from Thermal Destruction Facilities**  
**(ng/dscm @ 7% O<sub>2</sub>)**

Facility Type <sup>a</sup>	Sample (Waste) <sup>b</sup>	2378- TCDD	PCDD	PCDF	I-TEQs/89 <sup>c</sup>	
					ng/dscm	g/yr <sup>d</sup>
HWI (Commercial, Rotary Kiln, Liquid Injection)	FG <sup>c</sup> (HW)	ND <sup>f</sup>	ND	ND	ND	ND
HWI (Confidential)	FG/FA (HW)	ND	22	70	17.7	1.95
HWI (On-site Liquid Injection)	FG (HW)	ND	ND	7.3	0.93	0.02
HWI (On-Site Liquid Injection)	FG (HW)	ND	ND	ND	ND	ND
HWI (Commerical, Two Chamber, Liquid Injection and Hearth)	FG/FA (HW)	ND	ND	1.7	0.57	0.02
HWI (On-site Kiln and Liquid Injection in Parallel)	FG (HW)	ND	ND	ND	ND	ND
HWI (Liquid Injection Incinerator Ship)	FG/FA (PCB)	ND	ND	ND	0.3	0.16
HWI (Fixed Hearth)	FG/FA (PCP)	ND	ND	ND	ND	ND
HWI (Liquid Injection)	FG/FA (PCB)	ND	0.64	9.9	1.63	0.81
HWI (Rotary Kiln/Liquid Injection)	FG/FA (PCB)	0.003	0.108	3.18	0.073	0.001
HWI (Pilot-scale Rotary Kiln)	FG/FA (PCB)	0.003	0.108	3.18	.073	0.001
Cement Kiln	FG (HW)	ND	ND	ND	ND	ND
Cement Kiln	FG (HW)	ND	ND	ND	ND	ND
Lime Kiln	FG/FA (HW)	ND	ND	ND	ND	ND
Industrial Boiler/A (Watertube Stoker)	FG/FA (PCP)	ND	75.5	NR <sup>g</sup>	10.5	0.84
Industrial Boiler/D (Converted Stoker)	FG/FA (HW)	ND-0.002	0.64-0.8	0.24-5.5	0.45	0.12
Industrial Boiler/E (Packaged Watertube)	FG/FA (HW)	ND	ND	0.14	0.01	0.0026

(Continued)

**Table 8-2  
(Continued)**

Facility Type <sup>a</sup>	Sample (Waste) <sup>b</sup>	2378- TCDD	PCDD	PCDF	I-TEQs/89 <sup>c</sup>	
					ng/dscm	g/yr <sup>d</sup>
Industrial Boiler/M (Tangentially Fired Watertube)	FG/FA (HW)	ND	ND	0.81	0.11	NA <sup>h</sup>
Industrial Boiler/L (Packaged Watertube)	FG/FA (HW)	ND	1.1	2.5	0.336	NA

<sup>a</sup>HWI = Hazardous Waste Incinerator.

<sup>b</sup>Information in parentheses describes waste feed; HW = hazardous waste; PCB = polychlorinated biphenyls; PCP = pentachlorophenol waste.

<sup>c</sup>Calculated by the International Toxicity Equivalency Factor/89 (I-TEF/89) method. If isomer specific data were not available, homologue data were considered to be composed of the most toxic isomers.

<sup>d</sup>Assumes 8160 operating hours per year.

<sup>e</sup>FG = flue gases analyzed; FA = flue gas particulate analyzed.

<sup>f</sup>ND = not detected.

<sup>g</sup>NR = not reported.

<sup>h</sup>NA = Not available.

<sup>i</sup>SDA/FF = spray dryer absorber/fabric filter.

<sup>j</sup>ESP = electrostatic precipitator.

Source: Dempsey and Oppelt, 1993.

**Table 8-3  
Recent Dioxin/Furan Emissions Data**

<b>Trial</b>	<b>Total Dioxins ng/dscm</b>	<b>Total Furans ng/dscm</b>	<b>TEQ ng/dscm</b>	<b>Reference</b>
Plant A	4.34-7.12	1.48-2.86	0.06-0.133	Santolero, 1994
Plant B	3.43	66.63	0.054	
Plant C <sup>a</sup>	0.403-0.76	1.95-4.35	4.83-5.72	
Plant D	2.71-23.25	4.23-12.57	0.126-0.415	
EPA Research Facility	0.081-0.130	2.53-4.42	--	Waterland and Venkatesh, 1994
Trial Burn		3.6-210 <sup>b</sup>	0.056-2.45	Canter, 1995
Performance Tests		0.7-39 <sup>b</sup>	0.010-0.27	

<sup>a</sup>Level of chlorinated organics in waste feed was 22%.

<sup>b</sup>Dioxins + furans.

## **8.5 Identification of Applicable Control Technologies**

Unlike other soil remediation technologies, incineration does not require additional add-on VOC controls because it converts organics into carbon dioxide and water. However, additional controls are usually required to reduce emissions of acid gases, particulate matter (PM), and metals.

The two primary alternatives for controlling acid gas and PM emissions are wet or dry scrubbing systems. Wet scrubbing systems typically use a packed- or spray-tower scrubber with a caustic scrubbing solution to remove acid gases and a venturi scrubber or wet electrostatic precipitator to remove particulate matter. Dry scrubbing systems typically use a spray dryer absorber or dry sorbent injection to remove acid gases from the waste gas stream. The calcium-based alkali absorbent is usually in the form of slaked lime. Semi-dry systems inject the alkali as a slurry with water which is then evaporated. Dry ESPs or fabric filters are used to remove particulate matter from the gas stream. Table 8-4 shows typical ranges of emissions and estimated removal efficiencies for acid gas and PM control systems. The efficiency of PM control systems depends on the particle-size range present in the flue gas.

Pollutants of special concern from incinerators include mercury and dioxins/furans. Recent tests by the EPA have demonstrated mercury control efficiencies averaging 87% using a wet scrubber (Carroll, Thurnau, and Fournier, 1995). Dioxins/furans typically are present in the vapor-phase (70-80% of the total), so particulate matter controls are of limited effectiveness for these compounds (Williamson, 1994). Emissions of dioxins

and furans can be controlled through the use of activated carbon. Dioxin and furan emissions have been reduced to  $<0.1 \text{ ng/m}^3$  using an activated carbon filter (Steinhaus and Dirks, 1994) and have been reduced over 90% using process control and carbon injection (Sigg, 1994).

## **8.6 Costs for Remediation**

The costs to use thermal destruction to remediate fuel-contaminated soil will vary from site to site and depend on whether on-site or off-site treatment is used. The choice between off-site and on-site incineration is usually determined by the volume of soil to be treated and the proximity of full-scale off-site hazardous waste incinerators. The cost of using a transportable on-site incinerator will only be justified if the volume of contaminated soil to be remediated is large and/or the expense of off-site incineration is excessive because of transportation costs or other factors.

Table 8-5 shows approximate costs for off-site incineration. As the table shows, the estimated cost for incinerating contaminated soil is \$540 - \$1,070 per ton including transportation costs. It should be emphasized that this costs will vary with type of contamination and the volume of soil to be remediated (Cochran, et al., 1987).

Table 8-6 shows approximate costs for on-site incineration (U.S. EPA 1990). As indicated in the table, costs may range from \$180 to \$1,580 per ton depending on the volume of soil being remediated. Also, as the table shows, on-site incineration is most economical when a large volume of waste must be treated. The cost of remediation per ton falls significantly as the volume increases. For large-scale on-site

**Table 8-4  
Characteristics of Off-Gas from On-Site Incineration Systems**

**Table 8-4a. Typical Properties of Off-Gas from Combustion Chamber<sup>a</sup>**

Parameter	Units	Value
Air flow rate	ACFM	30,000 - 50,000
Temperature of Exit Gas	°C (°F)	760 - 982 (1,400 - 1,800)
Oxygen Content	%	3
System Pressure Drop	In. H <sub>2</sub> O	10 - 15

<sup>a</sup>Based on a limited number of designs.

**Table 8-4b. Typical Emissions**

	EPA <sup>b</sup> Conservative Estimated Efficiencies	Typical Actual Control Efficiencies	Typical Range of Emission Rates
Particulate Matter	99+%	99.9+%	0.005-0.02 gr/dscf
Hydrogen chloride (HCl)	--	99+	10-50 mg/Nm <sup>3</sup>
Sulfur dioxide (SO <sub>2</sub> )	--	95+	30-60 mg/Nm <sup>3</sup>
Sulfuric acid (H <sub>2</sub> SO <sub>4</sub> )	--	99+	2.6 mg/Nm <sup>3</sup>
Arsenic	95	99.9+	1-5 µg/Nm <sup>3</sup>
Beryllium	99	99.9	<0.01-0.1 mg/Nm <sup>3</sup>
Cadmium	95	99.7	0.1-5 mg/Nm <sup>3</sup>
Chromium	99	99.5	2-10 mg/Nm <sup>3</sup>
Antimony	95	99.5	20-50 mg/Nm <sup>3</sup>
Barium	99	99.9	10-25 mg/Nm <sup>3</sup>
Lead	95	99.8	10-100 mg/Nm <sup>3</sup>
Mercury	85 - 90	40 - 90+	10-200 mg/Nm <sup>3</sup>
Silver	99	99.9+	1-10 mg/Nm <sup>3</sup>
Thallium	95	99+	10-100 mg/Nm <sup>3</sup>
PCDD/PCDF <sup>c</sup>	--	90-99+	1-5 ng/Nm <sup>3</sup>

<sup>b</sup> Based on spray dryer fabric filter system or 4-field electrostatic precipitator followed by a wet scrubber.

<sup>c</sup> Total of all congeners.

SOURCE: Donnelly, 1991.

**Table 8-5**  
**Estimated Range of Costs for Off-Site Incineration<sup>a</sup>**

<b>Types of Waste</b>	<b>Cost Range, \$/Mg (\$/ton)</b>
Drummed Waste	154 - 490 (170 - 540)
Liquids	64 - 490 (70 - 540)
Clean Liquids with High Btu Value	18 - 64 (20 - 70)
Soils and/or Highly Toxic Liquids	490 - 971 (540 - 1,070)

<sup>a</sup>Data from Cochran, R., et al., 1987.

**Table 8-6**  
**Estimated Range of Costs for On-Site Incineration<sup>a</sup>**

<b>Site Size (Tons)</b>	<b>Cost Range, \$/Mg (\$/ton)</b>
Very Small (<5,000)	481 - 1,433 (530 - 1,580)
Small (5,000 - 15,000)	354 - 925 (390 - 1,020)
Medium (15,000 - 30,000)	236 - 617 (260 - 680)
Large (>30,000)	163 - 481 (180 - 530)

<sup>a</sup>Data from Engineering Bulletin: Mobile/Transportable Incineration Treatment (U.S. EPA/540/2-90-014) 1990. Data are for the treatment of hazardous waste.

incineration, capital costs are on the order of \$5,000,000—\$15,000,000. Operating costs, which consist primarily of fuel and labor, will also be substantial. Additional costs will also be incurred for the disposal of the incinerator ash, unless the treated soil can be backfilled on-site.

### 8.7 Costs for Emissions Controls

Costs for controlling acid gas and particulate emissions are substantial. Depending on the volume of gas treated, the installed cost for a wet scrubbing system on a full-scale (i.e., fixed base) incinerator could be \$1,000,000-\$3,000,000. Costs for wet scrubber controls for a mobile system are likely to be on the order of \$200,000-\$1,000,000. Similar costs would be expected for dry scrubbing systems.

### 8.8 Equations and Models for Estimating VOC Emissions

A simple mass approach (Thompson, et al., 1991) can be used to estimate emissions from incineration. Separate correlations for each pollutant of concern are presented below.

#### 8.8.1 Unburned Hydrocarbons

An emission rate for unburned hydrocarbons can be generated from a mass balance on the incinerator system:

$$ER_i = [1 - (DRE_i/100)](C_i)(m_w)$$

where:

$ER_i$  = emission rate for pollutant i (g/hr);

$DRE_i$  = destruction efficiency (assume 99.99% if not known);

$m_w$  = total mass flow rate of waste feed (kg/hr); and

$C_i$  = waste feed concentration for pollutant i (g/kg).

Typical feed rates for soils are 5,900 kg/hr, with a range from 900 to 24,000 kg/hr (Eklund and Albert, 1993).

#### 8.8.2 Products of Incomplete Combustion

Emissions of PICs, both the amount and the type, will vary greatly from unit to unit depending on design and waste feed. Data is currently unavailable to generate a single emission factor.

#### 8.8.3 Metals

Metals are not destroyed in the incineration process. They leave the system via either the bottom ash, are captured in the air pollution control system, or exit with the stack gas. There are currently no correlations available for determining the partitioning of metal emissions in incineration systems. If stack data is available for the incinerator in question, metals emissions rates can be estimated from:

$$ER_i = (C_i)(m_w)(\%ME_i/100)$$

where:

$ER_i$  = emission rate for metal i (g/hr);

$C_i$  = concentration of metal i in the feed (g/kg);

$m_w$  = mass flow rate of waste (kg/hr); and

ME<sub>i</sub> = metal emitted to air expressed as a percentage of metal fed (%) (See Dempsey and Oppelt, 1993 - Appendix G, Table XV).

#### 8.8.4 Acid Gases

The production of acid gases (HCl, SO<sub>2</sub>, and HF) is determined by the respective chlorine, sulfur, and fluorine contents in the waste and fuel feed streams. A conservative approach to calculating the air emissions of these acid gases is to assume complete conversion of Cl, S, and F into their respective acid gas products and apply a typical removal efficiency for the air pollution control system. These equations follow the form:

$$ER_i = (C_j)(R_{ij})m_w(1-\%CE_i/100)$$

where:

ER<sub>i</sub> = emission rate for acid gas i (g/hr);

C<sub>j</sub> = concentration of element (Cl, S, or F) in waste (g/kg);

R<sub>ij</sub> = stoichiometric ratio of acid gas to (g/g);

m<sub>w</sub> = mass flow rate of waste (kg/hr); and

CE<sub>i</sub> = control efficiency of acid gas treatment system (%).

#### 8.8.5 Nitrogen Oxides and Carbon Monoxide

In general, incinerator systems are not considered significant sources of NO<sub>x</sub> emissions. NO<sub>x</sub> is usually only a concern for wastes with high nitrogen content. Typical NO<sub>x</sub> emissions for an incinerator may be on

the order of 100-200 ppmv (dry basis), or expressed on a fuel basis, 0.12-0.33 lbs NO<sub>x</sub> per MMBtu. If a low-NO<sub>x</sub> burner is used, the emissions may be on the order of 0.05 lbs of NO<sub>x</sub> per MMBtu.

CO emissions from incinerators are also not considered a major problem. Most systems are designed to be fired with excess air (i.e., oxygen rich) to ensure complete combustion of organic material to carbon dioxide. Vendors typically guarantee CO emissions less than 100 ppmv (dry basis). Actual measured CO levels are often lower.

#### 8.9 Case Study: On-Site Incineration

No suitable case study was found for the incineration of soils contaminated with petroleum fuels.

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## **9.0 SOIL WASHING, SOLVENT EXTRACTION, AND SOIL FLUSHING**

### **9.1 Process Description**

Three remediation technologies are described below: soil washing, solvent extraction, and soil flushing. These are all primarily separation processes designed to decrease the volume of contaminated soil, and further treatment of the collected contaminants typically will be required. While these separation processes may be more effective in treating soils contaminated with petroleum fuels, generally they are employed to treat soils containing metals or heavy organic compounds.

Additional information about each of these three remediation technologies is contained in the engineering bulletins contained in Appendix F.

#### **9.1.1 Soil Washing**

Soil washing is an *ex situ* process in which contaminated soil is excavated and fed through a water-based washing process. It operates on the principle that contaminants are associated with certain size fractions of soil particles and that these contaminants can be dissolved or suspended in an aqueous solution or removed by separating out clay and silt particles from the bulk soil. Additives such as surfactants or chelating agents sometimes are used to improve the separation efficiency (treatment using additives may be referred to as chemical extraction). The aqueous solution containing contaminants is treated by conventional wastewater treatment methods (U.S. EPA, 1990).

Most organic and inorganic contaminants bind chemically or physically to clay or silt soil particles, which in turn adhere to larger sand and gravel particles primarily by the relatively weak forces of compaction and adhesion. Typically, 99% of the contaminants in soil are associated with particles of less than 60  $\mu\text{m}$  in diameter (Leggiere and Wehner, 1995). Particle-size separation by washing enables the contaminated clay and silt particles (and the bound contaminants) to be concentrated. Separating the sand and gravel from the small contaminated soil particles significantly reduces the volume of contaminated soil, making further treatment or disposal more economical. The larger particles may be returned to the site (U. S. EPA, 1990).

Soil washing is effective for a wide range of organic and inorganic contaminants, including petroleum and fuel residues (Anderson, 1993). Removal efficiencies range from 90-99% for volatile organic compounds (VOCs) and from 40-90% for semi-volatile compounds. Compounds with low water solubilities such as metals and pesticides sometimes require acids or chelating agents to assist in removal (U.S. EPA, 1990). If soil washing lowers contaminant concentrations in the soil to acceptable levels, the only additional treatments to be considered are emission controls for any water or air discharge. In many cases, however, further soil treatment is required and soil washing serves as a cost-effective pre-processing step.

Soil washing potentially can be effective for the remediation of soils with a small amount of clay and silt particles, but large amounts of clay and silt particles mitigate the effectiveness of soil washing. Soil washing is reported to be cost-effective

for soils containing up to 40% fines, but it is most applicable to soil with 20% or less fines (HWC, 1993). Particle size distribution is a key parameter in determining the feasibility of soil washing. The relative effectiveness of soil washing for various soil types is shown below.

<b>Particle Size Distribution (mm)</b>	<b>Relative Effectiveness</b>
>2	Requires pretreatment of oversized particles
0.25-2	Effective soil washing
0.063-0.25	Limit soil washing
<0.063	Clay and silt fraction: not amenable to soil washing

Bench-scale and pilot-scale treatability tests are recommended before undertaking full-scale operation. Further concerns about feasibility include the fraction of hydrophobic contaminants that require surfactants or organic solvents for effective removal, how the complexity and stability of the contamination affect washing-fluid formulation, and the effect of washwater additives on wastewater treatment (U.S. EPA, 1990).

Figure 9-1 shows a process diagram of a soil washing process. Excavation and removal of debris and large objects precedes the soil washing process. Sometimes water is added to the soil to form a slurry that can be pumped. After the soil is prepared for soil washing, it is mixed with washwater and extraction agents are sometimes added. At this point, three separation processes occur:

- 1) water-soluble contaminants are transferred to the washwater;
- 2) contaminants are suspended in the washwater; and
- 3) clay and silt particles to which contaminants are adhered are separated from larger soil particles.

After separation from the washwater, the soil is rinsed with clean water and may be returned to the site. The suspended soil particles are removed by gravity from the washwater as sludge. Sometimes flocculation is used to aid in sludge removal. This sludge is more highly contaminated than the original soil and undergoes further treatment or secure disposal. The spent washwater from which the sludge is removed is treated and recycled. Residual solids from the recycle process may require further treatment (U.S. EPA, 1990).

Soil washing generates four waste streams:

- 1) contaminated solids separated from the washwater;
- 2) wastewater;
- 3) wastewater treatment sludge and residual solids; and
- 4) air emissions.

There are a number of treatment options that may be feasible for the contaminated clay fines and solids: incineration, low-temperature thermal desorption, solidification and stabilization, and biological or chemical treatment. It is recommended that as much blowdown water be recycled as possible. Blowdown water released to local wastewater treatment plants

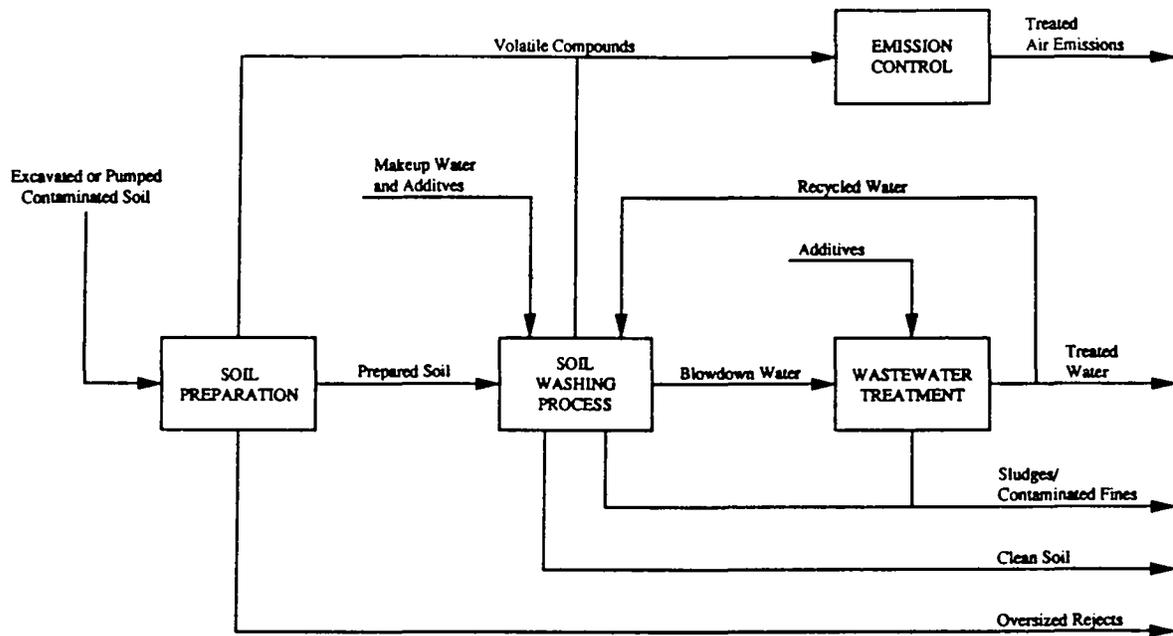


Figure 9-1. Schematic Diagram of Aqueous Soil Washing Process.

must meet local discharge standards. Sludge and solids from wastewater treatment require appropriate treatment and disposal. Collected air emissions from the waste site or soil-washing unit can be treated using carbon filters (Banerjee, et al., 1993).

Advantages of the soil washing process include:

- Applicability to a wide variety of organic and inorganic compounds;
- High removal efficiencies for certain soil types; and
- Minimal fire and explosion hazards.

Some disadvantages are that soil washing:

- Is only suitable for certain soil types;
- Does not destroy contaminants; and
- May require additives that improve removal but compromise treatment of the waste streams.

### 9.1.2 Solvent Extraction

Solvent extraction differs from soil washing in that it employs organic solvents rather than aqueous solutions to extract contaminants from the soil. Like soil washing, it is a separation process that does not destroy the contaminants. The contaminants will have greater solubility in the solvent than in the soil. The equilibrium concentration gradient drives the mass transport process such that the contaminant transfers from the soil to the solvent. When the soil is separated from the solvent, the soil contaminant concentrations are

presumably lower than before contact with the solvent. "Solvent extraction" treats organic compounds much more effectively than inorganic compounds and metals. It can be used in conjunction with other processes to reduce remediation costs (U.S. EPA, 1994).

Sediments, sludge, and soils contaminated with volatile organic compounds (VOCs), petroleum wastes, PCBs, and halogenated solvents can be effectively treated with solvent extraction. The removal of inorganic compounds such as acids, bases, salts, and heavy metals is limited, but these types of compounds usually do not hinder the remediation process. Metals may undergo a chemical change to a less toxic or leachable form but their presence in the waste streams may also restrict disposal and recycle options (U.S. EPA, 1994).

Figure 9-2 shows a process diagram of the solvent extraction process. The remediation process begins with excavating the contaminated soil and feeding it through a screen to remove large objects. In some cases, solvent or water is added to the waste in order to pump it to the extraction unit. In the extractor, solvent is added and mixed with the waste to promote dissolving of the contaminants into the solvent. Laboratory testing can determine which solvent adequately separates the contaminants from the soil (U.S. EPA, 1992). Generally, the solvent has a higher vapor pressure than the contaminants (i.e., it has a lower boiling point) so that with an appropriate pressure or temperature change, the solvent may be separated from the contaminants, compressed, and recycled to the extractor (U.S. EPA, 1994).

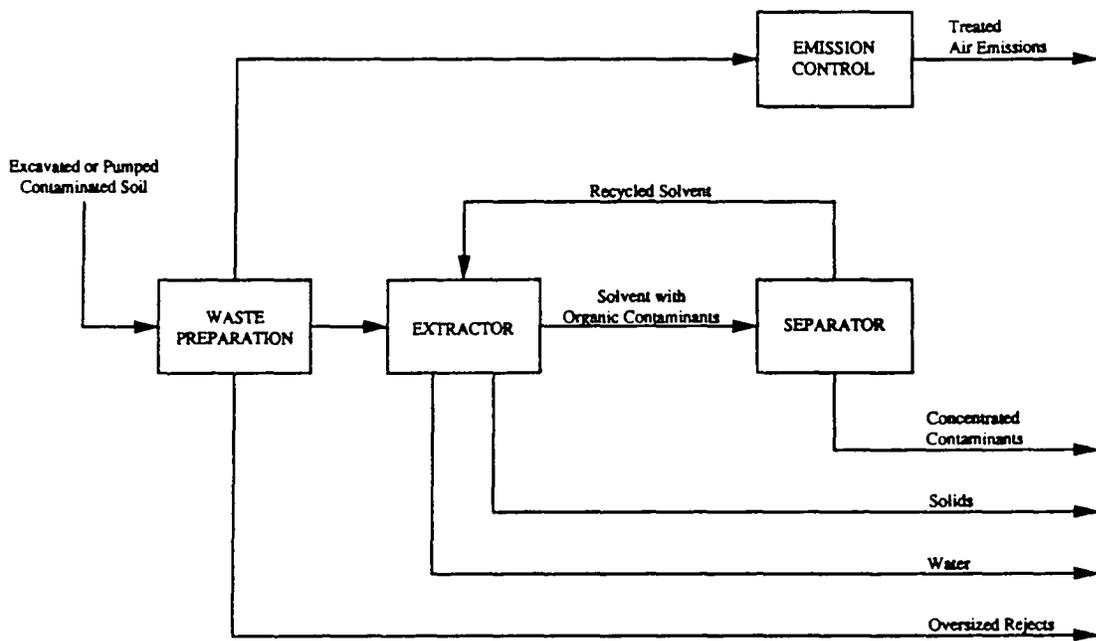


Figure 9-2. Schematic Diagram of Solvent Extraction Process.

Up to five waste streams may result from the solvent extraction process:

- 1) Concentrated contaminants;
- 2) Solids;
- 3) Wastewater;
- 4) Oversized rejects; and
- 5) Treated air emissions.

The concentrated contaminants may be analyzed and subsequently designated for further treatment, recycle, or reuse before disposal. While solvent extraction presumably improves the condition of the solids, they often still need dewatering, treatment for residual organic compounds, additional separation, stabilization, or other treatment. The water from the dewatering process, the solids, and the water from the extractor will need to be analyzed to aid in the choice of the most appropriate treatment and disposal.

The solvent-extraction units are a closed-loop design in which the solvent is recycled and reused. Typically, solvent extraction units are designed to produce negligible air emissions, but solvents have been detected in the off-gas vent system (U.S. EPA, 1994). In addition, significant levels of emissions (both vapor-phase and particulate matter) may occur during waste preparation activities such as excavation and materials handling.

The primary advantage of solvent extraction is the treatability of a wide variety of media. This capability is in contrast to soil washing, the success of which is heavily dependent on the particle size distribution.

Some disadvantages of the process are that solvent extraction:

- Does not destroy the contaminants;

- May not be appropriate for contaminants with high vapor pressures because these compounds may be removed with the solvent in the separation process instead of remaining with the concentrated contaminant stream;
- Is compromised by the presence of detergents and emulsifiers which compete with the solvent in dissolving the contaminants;
- May leave residual solvent and contaminant concentrations in the treated waste;
- Is not effective for high molecular weight or hydrophilic compounds; and
- May use flammable or mildly toxic solvents.

A variety of solvent extraction systems have been developed to treat several types of contamination (see Appendix F for further information). Four systems where full-scale or pilot-scale performance data are available are described below.

### **CF Systems**

Probably the most widely used solvent extraction system is the CF Systems, which uses liquified hydrocarbons such as propane and butane as the solvent to treat soil and sludge, and carbon dioxide to treat wastewater. Water is added to the waste to enable pumping of the material through the extraction process. Particles greater than 1/8 inch in diameter are removed. In some cases, oversized particles are reduced in size for subsequent processing. The pH is adjusted in the feed to minimize corrosion of

metallic components of the treatment system. CF Systems has used a 25-tons/day-capacity unit to remediate refinery sludge and achieved extraction efficiencies greater than 99% for benzene, toluene, and xylenes (BTX) and PAH compounds (U.S. EPA, 1994).

#### **RCC B.E.S.T.<sup>TM</sup>**

RCC's B.E.S.T.<sup>TM</sup> system does not need a pumpable waste and uses aliphatic amines (often triethylamine) as the solvent. Feed pH is adjusted to alkaline conditions, and objects over one inch in size are removed. The process operates at near ambient temperature and pressure. Due to its high vapor pressure and low boiling point azeotrope formation, triethylamine is removed with steam stripping. The full-scale system has treated refinery waste streams, heavy metals, PAHs, and PCBs.

#### **Terra-Kleen**

The Terra-Kleen solvent extraction system has been used at three Superfund sites to remediate soils containing PCBs. Removal efficiencies of 90% or better were achieved.

#### **Dehydro-Tech**

The Carver-Greenfield (C-G) Process<sup>®</sup>, developed by Dehydro-Tech Corporation, was evaluated in a pilot-scale test to remediate 640 pounds of contaminated drilling mud. About 90% of the oil and essentially 100% of the total petroleum hydrocarbons were removed from the material.

### **9.1.3 Soil Flushing**

Soil flushing differs from soil washing and solvent extraction in that it is an *in-situ* process in which the solvent is injected into or sprayed over the

contaminated area, percolates through the soil and dissolves the contaminants (it is sometimes referred to as *in-situ* soil washing). A process diagram for soil flushing is shown in Figure 9-3. Water is introduced and allowed to percolate down into the soil. The applied solution may contain fertilizer or other additives designed to promote microbiological activity in the subsurface. Elutriate is collected in a series of wells and drains. If possible, the collected liquid is recycled. Standard pump-and-treat methods are employed to remove and treat the ground water.

Flushing solutions may include the following:

- 1) Water for water-soluble contaminants;
- 2) Acidic aqueous solutions for metals and basic organic contaminants;
- 3) Basic aqueous solutions for some phenols, complexing and chelating agents for metals such as zinc, tin, and lead; and
- 4) Surfactants.

Soil flushing is generally used in conjunction with other treatment technologies such as activated carbon, *in-situ* biodegradation, or chemical precipitation to treat the contaminated ground water that is collected (U.S. EPA, 1991). The method is theoretically suitable for a wide range of contaminants. Soil flushing is most effective for permeable soils ( $K > 1.0 \times 10^{-3}$  cm/sec).

The advantages of soil flushing (Rizvi and Nayyar, 1995) are that it:

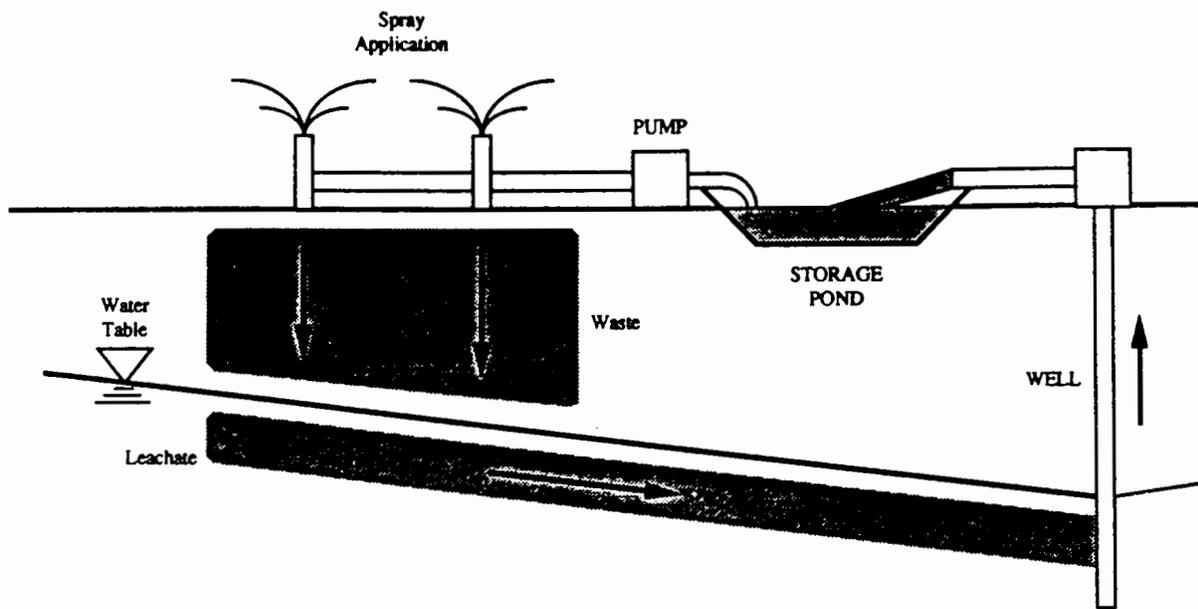


Figure 9-3. Generalized Soil Flushing Process Flow Diagram.

- Can be used to remove contamination from areas inaccessible to excavation or other treatment;
- Can be used to provide oxygen and nutrients to enhance natural biodegradation; and
- Entails minimal disturbance to any on-going operations at the site.

The disadvantages of the method include:

- Soil flushing is limited to medium-to-coarse grained soils so that the reinjected water can readily flow through the soil;
- The depth to groundwater must not be too shallow (or surface flooding may occur) nor too deep (or recovery will be affected); and
- Solvents and contaminants may migrate into uncontaminated areas and also be resistant to removal due to soil heterogeneity (Chambers, C.D., et al., 1990).

Laboratory tests are recommended to determine the best flushing solution for the types of soil and contaminants present. The flushing solution may affect the soil such that removal is hindered and it may also alter the soil's physical and chemical properties after remediation. The suitability of the site to soil flushing should be determined by a groundwater injection test and/or a ground water pumping test.

## 9.2 Identification of Air Emission Points

In the soil-washing process, the greatest potential for emissions of volatile contaminants occurs in the excavation, materials handling, feed preparation, and extraction processes. Air emissions from the excavation and pretreatment steps typically are uncontrolled. Air emissions from the batch soil-washing process may be collected and, if so, typically are treated by carbon adsorption or incineration (U.S. EPA, 1990). The waste streams also have the potential to be sources of VOC emissions.

Solvent extraction may also produce emissions during excavation and soil transport and from contaminated oversize rejects (U.S. EPA, 1994). The solvent recovery process involves vaporization of the solvent, so fugitive emissions are possible from this as well as other stages of the solvent process. The waste streams also have the potential to be sources of VOC emissions to the extent that any VOCs are present.

Emissions from soil flushing may emanate from the soil surface, solvent storage vessels and spray system, and from locations where the contaminant-laden flushing solution is recovered and treated.

## 9.3 Typical Air Emission Species of Concern

For petroleum-contaminated soils, the primary air emission species of concern are volatile and semi-volatile organic compounds. For solvent extraction processes, emissions of the solvent itself also may be cause for concern. For soil flushing, products of aerobic and anaerobic

decomposition are possible, but these tend to be predominantly carbon dioxide and methane.

#### **9.4 Summary of Air Emissions Data**

No data were identified for the air emissions from soil washing, solvent extraction, and soil flushing. Information on emissions from excavation may be found in Section 3.

#### **9.5 Identification of Applicable Control Technologies**

Carbon adsorption and incineration are typical controls used to treat collected emissions. In solvent extraction, volatile solvents are recovered and recycled. These control technologies are described in Section 5.5.

#### **9.6 Capital and Operating Costs for Remediation**

Recent data on operating costs for specific soil washing and solvent extraction processes are summarized in Table 9-1. Capital cost data generally are very limited, though some data may be found in the SITE program reports given in the references.

Cost for remediating contaminated soil by soil washing range from \$53 to \$215 per ton of feed soil, according to information from vendors of the equipment. The more expensive processes included in the cost range cover disposal of soil residue (U.S. EPA, 1990).

Solvent extraction costs are most influenced by waste volume, number of extraction stages, operating parameters, and lost time resulting from delays in equipment

operation. Operating parameters include labor, maintenance, setup, decontamination, and demobilization. The choice of solvent, solvent/waste ratio, feed rate, extractor residence time, and number of passes through the extractor determine the efficiency of the process. Estimated costs range from \$50 to \$900 (U.S. EPA, 1994).

No cost data are available on soil flushing, although costs are expected to be moderate if inexpensive flushing solutions are used and the network of extraction wells is relatively simple.

#### **9.7 Capital and Operating Costs for Emission Controls**

No cost data for emission controls for these treatment processes were found. General costs for controlling point source emissions are given in Section 5.7.

#### **9.8 Equations/Models for Estimating Emissions**

No equations or models for predicting the air emissions from these processes were identified.

#### **9.9 Case Studies of Remediation and Air Emissions**

Given the lack of air emissions data, no suitable case studies showing emissions were found for these processes. Remediation performance data, however, were available and Tables 9-2 through 9-4 show selected results of treatments at several sites. Further information may be obtained from the relevant documents listed below.

**Table 9-1**  
**Summary of Costs for Soil Washing and Solvent Extraction**

<b>Treatment Method</b>	<b>Type of Contamination<sup>a</sup></b>	<b>Process Rate, Mg/hr (tons/hr)</b>	<b>Operating Cost, \$/Mg (\$/ton)<sup>b</sup></b>	<b>Reference</b>
Soil Washing	--	--	68-113 (75-125)	HWC, 1994
Soil Washing	TPH, metals, etc.	5-91 (5-100)	24-120 (27-132)	HWC, 1994
Soil Washing	Fuel oil	53 Mg/day (58 tons/day)	109 (120)	Leggiere and Wehner, 1995
Soil Washing	TPH, metals, etc.	68 Mg/day (75 tons/day)	181 (200)	Leggiere and Wehner, 1995
Soil Washing	Crude oil	454-1,814 total Mg (500-2,000 total tons)	67-145 (74-160)	Banerjee, et al., 1993
Soil Washing	Lead	2-4	150 (165)	Gaire, 1995
Solvent Extraction	TPH	1.4	200 (221)	Raptis, et al., 1992
Solvent Extraction	PCBs	50 tons/day	136-408 (150-450)	Valentinetti, 1990a and 1990b

<sup>a</sup>TPH = total petroleum hydrocarbons

<sup>b</sup>Does not include cost of excavation

**Table 9-2a.**  
**Summary of Performance Data on Soil Washing**

<b>Process</b>	<b>Contaminants</b>	<b>Range of Removal Efficiencies</b>	<b>Residual Concentrations, ppm</b>
Soil Cleaning of America	oil and grease	50 - 83%	250 - 600
Biotrol Soil Treatment System	Pentachlorophenol	90 - 95%	<115
	other organics	85 - 95%	<1
EPA's First Generation Pilot	oil and grease	90 - 99%	<5 - 2400
MTA Remedial Resources	volatile organics	98 - 99+%	<50
	semi-volatile organics	98 - 99+%	<250
	most fuel products	98 - 99+%	<2200
Bodemsandering Nederland BV	aromatics	>81%	>45
	crude oil	97%	2300
Harbauer of America	total organics	96%	159 - 201
	PAH	86 - 90%	91.4 - 97.5
Heidemij Froth Flotation	oil	>99%	20
Klockner Umweltechnik	hydrocarbons	96.3%	82.05
	chlorinated hydrocarbons	>75%	<0.01
	aromatics	99.8%	<0.02
	PAHs	95.4%	15.48

Source: U.S. EPA, 1990.

**Table 9-2b.**  
**Results of Remediation of Soil Containing Fuel Oil Using Soil Washing**

<b>Test Run</b>	<b>TPH in Untreated Soil (mg/Kg)</b>	<b>TPH in Treated Soil (mg/Kg)</b>	<b>Removal Efficiency</b>
#1	7,666	2,650	65%
#2	7,567	2,033	73%
#3	9,933	2,833	72%

Source: Banerjee, et al., 1993.

**Table 9-3a.**  
**Results of Remediation of API Separator Sludge by Solvent Extraction**

<b>Compound</b>	<b>Initial Concentration (µg/g)</b>	<b>Final Concentration (µg/g)</b>	<b>Percent Removal</b>
Benzene	30.2	0.18	99%
Toluene	16.6	0.18	99%
Ethylbenzene	30.4	0.23	99%
Total Xylenes	13.2	0.98	93%
Anthracene	28.3	0.12	99%
Benzo(a)pyrene	1.9	0.33	83%
Bis-(2-ethylhexyl)phthalate	4.1	1.04	75%
Chrysene	6.3	0.69	89%
Naphthalene	42.2	0.66	98%
Phenanthrene	28.6	1.01	96%
Pyrene	7.7	1.08	86%

Source: Valentinetti, 1990b.

**Table 9-3b.**  
**Results of Remediation of Drilling Mud Waste Using Solvent Extraction**

<b>Test Run</b>	<b>Removal Efficiency of Indigenous Oil</b>	<b>Removal Efficiency of Indigenous TPH</b>
#1	92.1%	100%
#2	88.3%	100%

Source: Raptis, et al., 1992.

**Table 9-4  
Results of Remediation Using Soil Flushing**

<b>Site</b>	<b>Compound</b>	<b>Peak Ground Water Concentration (µg/L)</b>	<b>Ending Ground Water Concentration (µg/L)</b>	<b>Reduction</b>
Gasoline station Well #1 <sup>1</sup>	Benzene	7	ND	100%
	Toluene	76	ND	100%
	Ethylbenzene	140	ND	100%
	Xylenes	1,300	5	99.6%
	Naphthalene	81	ND	100%
Bus garage Well #4 <sup>2</sup>	Benzene	1,800	690	62%
	Toluene	9,000	1,400	84%
	Ethylbenzene	2,300	1,500	35%
	Xylenes	10,000	5,600	44%
	Naphthalene	270	369	-37%

Source: Rizvi and Nayyar, 1995.

Notes:

1. Data for gasoline station are from June 1992 to February 1995
2. Data for bus garage are from June 1993 to February 1995

## 9.10 References

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## 10.0 UNCERTAINTY AND SENSITIVITY ANALYSIS

### 10.1 Introduction

An analysis of the uncertainty associated with the EEMs presented in Chapters 3 through 8 was performed and the results are presented in this chapter. Every method that is used to estimate air pollutant emissions, whether it is an emission factor or a more complex emissions model, carries a certain level of uncertainty. There are two sources of uncertainty associated with EEMs:

- Uncertainty of the EEM itself: this refers to the ability of the method to accurately predict real-world emissions. In other words, if each value for all of the parameters in the method are precisely known, how accurate is the EEM (in terms of precision and bias) in predicting actual emissions?
- Uncertainty in the values of the EEM variables: in many cases, the values for the EEM parameters will not be precisely known and must be estimated. In addition, where the parameter may have a measured value, there is variability associated with this value. Often a sensitivity analysis is performed in order to gain an understanding of which variables have the largest impact on the predicted result (i.e., which contribute the most to the variability in the prediction).

Ideally, an analysis of uncertainty would address both sources and present the results as a combined result. However, in order to analyze method uncertainty (as

described under the first bullet), field data are needed for comparison against the EEM-predicted results. These data are very rarely available and were not available for use in this uncertainty analysis. Limited EEM predictions compared against field data have shown that the EEMs can be expected to yield conservatively-biased (i.e., high) predictions within a factor of 3 to 10 (see Table A-7 in Appendix D).

A description of the approach and results obtained for the uncertainty analysis of EEM variables is given in the sections that follow. A sensitivity analysis is also performed for each EEM in order to determine which variable(s) contribute the most to the variability in the predicted results.

### 10.2 Approach

Monte Carlo simulations of each EEM were performed using a commercially-available software (Crystal Ball Version 4.0). Monte Carlo simulation is an efficient technique for analyzing real-world problems that have a large number of possible outcomes based on the potential values of associated variables. In a Monte Carlo simulation, random numbers for each variable are generated that conform to the real-world potential values. A large number of EEM trials are run (e.g., 10,000) using these randomly-generated values. Based on the results of this large number of trial simulations, a distribution and summary statistics are derived. These statistics can be used to gain an understanding of the variability associated with the EEM projections (e.g., mean, coefficient of variation, 95% confidence limits).

In order to perform the uncertainty/sensitivity analysis, assumptions

had to be derived for an example application. The same set of assumptions (e.g., soil properties and benzene concentration level) were used during the analysis of each EEM. It was assumed that there was a need to develop an emission rate for benzene from soil remediation activities. The soil had been contaminated with gasoline and moderate levels of benzene were present (10 ppm). No other physical data were available for the soil (e.g., moisture content, bulk density, temperature) which is common during these analyses. However, it was assumed that the remediation would occur during the summer months (ambient temperature of 25 degrees C) and that the soil was a fine-textured clay.

For each EEM, a spreadsheet was developed that contained the equation(s) for estimating emissions and the associated variables. For each variable, assumptions were assigned that described the range and distribution of potential values (e.g., normal, uniform, triangular). These assumptions are summarized in Table 10-1. Most of the information used to develop the variable distributions were taken directly from the text of this report. For example, the percentage of benzene that is anticipated to volatilize during thermal desorption was assumed to be 99.50% based on information given in Chapter 3. Further, based on the same information and engineering judgement, it was assumed that the minimum percentage of benzene volatilized would be 99.00% and that the maximum would be 99.99%. Using the minimum, maximum, and likeliest values, a triangular distribution was developed for input to the Monte Carlo simulations.

Using the assumptions listed in Table 10-1 and the equations given in Chapters 3 through 8, Monte Carlo

simulations were run for each EEM to develop distributions of the potential emission rates. Along with the distributions of potential emission rates, charts depicting the sensitivity of the EEM to the associated variables were developed.

### 10.3 Results

A summary of the uncertainty/sensitivity analysis is shown in Table 10-2. Monte Carlo modeling results are given in Appendix G. For each EEM, a point estimate of the emission rate is given. This value was derived by using the appropriate equation given in Chapters 3 through 8 and the mean or most likely values for the associated variables given in Table 10-1.

The mean of each Monte Carlo distribution is shown in Table 10-2 along with 95% confidence limits for the potential emission rate. In the final column, the variables which had the largest influence on the EEM predictions are listed along with the contribution to variance associated with each.

For excavation/removal, the total emission rate was influenced most by the soil bulk density variable. This variable is used to determine the air-filled porosity parameter ( $E_a$ ) which, in turn, is used during the estimation of both the emission rate from the pore space and the emission rate from diffusion. These results signify the importance of gathering and using site-specific data whenever possible. Based on the 95% confidence limits, the total emission rate could vary by a factor of more than 5.

For thermal desorption, the emission rate was shown to vary by a factor of about

8. The variability was driven almost exclusively by the uncertainty in the estimate of control efficiency.

For soil vapor extraction, the vapor extraction rate was only independent variable, and therefore was the only variable that contributed to quantifiable uncertainty in the emission rate estimate. The 95% confidence limits show that the range in potential emissions could span a factor of about 2.

The analysis for in-situ biodegradation revealed that again the bulk density of the soil contributed the most to variability in the emission rate. However, the estimate of the number of pore volumes extracted per day was also a high contributor. Potential emissions varied by a factor of nearly 8.

For ex-situ biodegradation, the EEM was shown to be most sensitive to the estimate given for V (the fraction of benzene volatilized). This situation is likely to persist, as there is scant data of this type available. Potential surrogate data for use here include from studies of VOC volatilization from sewage treatment plants and sewer systems.

As with thermal desorption, the variability in predicted emissions for incineration is driven by estimates of control efficiency. Specific vendor estimates or guarantees would likely improve upon the assumptions used here. Often a minimum control efficiency can be guaranteed (e.g., >99.90%) that would be high enough to tighten the assumed distribution. This would result in lower variability of the projected emissions.

Details of the Monte Carlo simulations are given in Appendix G. Each EEM begins with a print-out of the spreadsheet used to build the emission projections (forecasts). Charts that display the sensitivity of the EEM to each variable are shown. Figures are also shown that depict the distributions of each forecast (e.g., emission rates) and assumptions.

#### 10.4 References

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Fleischer, E.J., et al., "Evaluating the Subsurface Fate of Organic Chemicals of Concern Using the SESOIL Environmental Fate Model", *Proceedings of the Third Eastern Regional Groundwater Conference*, National Well Water Association, Springfield, MA, July 29-31, 1986.

Pechan, personal communication from staff of Weston, Inc., 1996.

**Table 10-1  
Scenario Development for the Uncertainty/Sensitivity Analysis**

<b>Variable</b>	<b>Value</b>	<b>Comments</b>
Benzene concentration (C)	10 ppm	Based on hypothetical representative sampling of the site. The distribution is assumed to be normal with a mean of 10 and a standard deviation of 1.0.
Soil moisture content (Mfrac)	15%	Mid-point of the typical range for clay soils [clay soil is characteristic of the site (Brady, 1984)]. Distribution is uniform with 12% as the minimum and 18% as the maximum.
Ambient temperature (Ta)	298K	Assumed that the remediation takes place during the summer months.
Soil temperature (Ts)	293K	The soil temperature will be about 5 degrees cooler than the assumed ambient temperature of 298K. Based on data from Brady (1984).
Soil bulk density (beta)	1.5 g/cm <sup>3</sup>	Soil assumed to be moderately compacted and finely-textured (Brady, 1984). The distribution is uniform with a minimum of 1.0 and a maximum of 2.0.
Particle density (p)	2.65 g/cm <sup>3</sup>	Assumed from information given in Chapter 3. Uniform distribution around a 2.65 g/cm <sup>3</sup> mean and a +/- 5% error.
Volatilized fraction during thermal desorption (V)	99.50%	From information presented in Chapter 2. Triangular distribution with a minimum of 99.00%, a maximum of 99.99%, and a likeliest value of 99.50%.
Soil feed rate into the thermal desorber (F)	27,200 kg/hr	Assumed from information given in Chapter 2. Uniform distribution around a mean of 27,200 kg/hr and a +/- 10% error.
Vapor extraction rate during soil vapor extraction (Q)	85 m <sup>3</sup> /min	Assumed from information given in Chapter 5. Uniform distribution around a 85 m <sup>3</sup> /min mean and a +/- 30% error.
Pore volumes per day for in-situ bioremediation (pv)	1.0	Based on information given in Chapter 5. Distribution is triangular with a minimum of 0.3, a maximum of 2.0, and the likeliest value of 1.0.
Fraction volatilized during continuous ex-situ bioremediation (V)	0.60 vol/vol	Based on limited data soil/water partitioning (Fleischer, et al., 1986). End-points of the uniform distribution derived from an error estimate of +/- 30%.
Mass feed rate of soil into the continuous ex-situ bioreactor (Mr)	600 kg/hr	Assumed based on information provided in Chapter 6. Distribution is uniform with 600 kg/hr the mid-point and the end points determined from a +/- 10% error estimate.
Mass feed rate of soil into the thermal incinerator (Mw)	4,500 kg/hr	Assumed based on information from Pechan (1996). Distribution is uniform with 4,500 kg/hr as the mid-point and end-points determined from a +/- error assumption of 10%.
Control efficiency (CE) during thermal desorption and thermal oxidation processes	99.50%	Based on engineering judgement. Distribution is assumed to be triangular with a minimum of 99.00%, a maximum of 99.99%, and a most likeliest value of 99.50%.
Contaminated area	2500 m <sup>2</sup>	Assumed.
Contaminated depth	5 m	Assumed.

**Table 10-2.  
Uncertainty/Sensitivity Analysis Results**

EEM No.	Remediation Process	Predicted Benzene Emissions, g/sec (g/hr)			EEM Parameters Contributing the Most to Emissions Variability (% Contribution to Variance)
		Point Estimate of Emissions	Monte Carlo Predictions		
			Mean	95% Confidence Limits	
1	Excavation/Removal:				ER pore space: excavation rate (Q) = 50%; bulk density (beta) = 32%; exchange constant (ExC) = 17%. ER diffusion: bulk density (beta) = 90% ER total: bulk density (beta) = 85% excavation rate (Q) = 6%
	Emissions from Pore Space	0.59	0.98	0.16 - 2.71	
	Emissions from Diffusion	3.26	3.19	1.10 - 5.23	
	Total Emissions	3.85	4.17	1.41 - 7.38	
2	Thermal Desorption	1.35	1.36	0.32 - 2.54	control efficiency (CE) = 93%
3	Soil Vapor Extraction	0.47	0.47	0.33 - 0.60	vapor extraction rate (Q) = 100% (this is the only independent variable)
4	In-Situ Biodegradation	0.017	0.018	0.005 - 0.039	bulk density (beta) = 58%; pore volumes extracted per day (pv) = 40%
5	Ex-Situ Biodegradation	3.72	3.60	1.80 - 5.82	fraction volatilized (V) = 89%; benzene concentration (C) = 6%
6	Incineration	0.23	0.23	0.052 - 0.42	control efficiency (CE) = 93%

## APPENDIX A

### PROPERTIES AND COMPOSITION OF VARIOUS FUEL TYPES

Brief descriptions are given below for liquefied petroleum gases, gasoline, diesel fuel, jet fuel, oil, and asphalt and bitumen.

**Liquefied Petroleum Gases (LPG)** comprise ethane ethylene, propane, propylene, normal butane, butylene, and isobutane and are typically produced at refineries or natural processing plants. Normal butane added to gasoline helps to regulate its vapor pressure and isobutane serves as an alkylation feedstock and is sold as LPG.

**Gasoline** is a petroleum derivative with over 100 components boiling from 90°F to 420°F. Additives that improve gasoline performance can change its physical properties significantly. Adding normal butane adjusts the Reid vapor pressure (RVP) so that it varies between about 9.5 psi in the winter and 23.5 psi in the summer<sup>1</sup>. Butane accounts for about 75% of the vapor pressure of gasoline with pentanes making up much of the remainder. Detergent additives acting as surfactants reduce the surface tension which in turn influences subsurface migration. Hydrophilic additives such as methyl-tert-butyl ether (MTBE), methanol, and ethanol boost octane numbers and considerably increase the solubility of gasoline in water<sup>2</sup>.

**Diesel Fuel** is used by trucks, railroads, stationary engines, and some automobiles. The three types of diesel most commonly used are No.1 and No.2 for automobiles and trucks; and No.4, which is heavier and used by large, slow-speed vehicles<sup>3</sup>. This middle distillate tends to be less volatile, less mobile in soil, and less water soluble than gasolines<sup>4</sup>.

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<sup>1</sup>Handbook of Energy Technology and Economics, Robert A. Meyer, ed. John Wiley and Sons, 1983, NY.

<sup>2</sup>David K Kreamer and Klaus J. Stetzenback, "Development of a Standard, Pure-Compound Base Gasoline Mixture for Use as a Reference in Field and Laboratory Experiments," Spring 1990, Ground Water Monitoring Review, p. 136.

<sup>3</sup>Handout of Energy Technology and Economics, Robert A. Meyer, ed. John Wiley and Sons, 1983, NY, pp.217-18.

<sup>4</sup>"A guide to the Assessment and Remediation of Underground Petroleum Releases," API Publication 1628, 2nd Ed., August 1989, p. 9.

**Jet Fuels** used by commercial and military aircraft resemble kerosene and have a similar boiling range to light diesel fuels and heating oils. Jet fuels contain no more than 20% aromatic compounds<sup>5</sup>. This middle distillate tends to be less volatile, less mobile in soil, and less water soluble than gasolines<sup>6</sup>.

**Oil** - Heating oils No.1 and No.2 are used to heat homes and businesses. The heavier oils, Nos. 4, 5, and 6, are used by shipping and industry and have higher viscosities and pour points<sup>7</sup>.

**Asphalt and Bitumen** are solid phase components of crude oil that remain virtually immobile in soil because shallow subsurface temperatures rarely rise above their melting points<sup>8</sup>.

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<sup>5</sup>Handbook of Energy Technology and Economics, Robert A. Meyer, ed. John Wiley and Sons, 1983, NY, pp. 217-18.

<sup>6</sup>"A guide to the Assessment and Remediation of Underground Petroleum Releases," API Publication 1628, 2nd Ed., August 1989, p. 9.

<sup>7</sup>Handbook of Energy Technology and Economics, Robert A. Meyer, ed. John Wiley and Sons, 1983, NY, pp. 217-18.

<sup>8</sup>"A guide to the Assessment and Remediation of Underground Petroleum Releases," API Publication 1628, 2nd Ed., August 1989, p. 9.

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<sup>7</sup>Handbook of Energy Technology and Economics, Robert A. Meyer, ed. John Wiley and Sons, 1983, NY, pp. 217-18.

<sup>8</sup>"A guide to the Assessment and Remediation of Underground Petroleum Releases," API Publication 1628, 2nd Ed., August 1989, p. 9.

**APPENDIX B**

STATE CLEANUP REQUIREMENTS

## State cleanup standards for hydrocarbon contaminated soil and groundwater

Summary of Alabama Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	602. 624	*	any amount	5 ppb	5 ppb
	Ethylbenzene		*	any amount	700 ppb	700 ppb
	Toluene		*	any amount	1000 ppb	1000 ppb
	Xylenes		*	any amount	10,000 ppb	10,000 ppb
Diesel	PAH	EPA Method 610. 625	*	any amount	Site Specific**	Site Specific**
Waste Oil	BTEX	EPA Method 602. 625	*	any amount	Same as Gasoline	Same as Gasoline
	PAH	EPA Method 610. 625	*	any amount	Same as Diesel	Same as Diesel

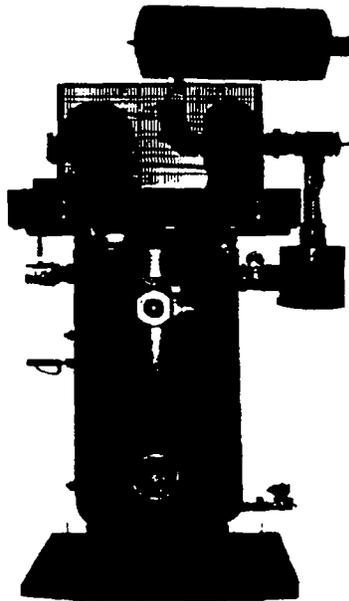
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of Environmental Management.  
205-270-5613

\* Dictated by Method.

\*\* Health Advisory Limits.

Note: Risk Assessment may be used to allow  
for a higher level.

These states do not have charts  
and ask that interested parties  
call for information:

Colorado: 303-692-3330

Connecticut: 203-566-5599

Rhode Island: 401-277-3872

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### Summary of Alabama Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	EPA Method 9071	*	any amount	100 ppm	100 ppm**
	TPH	Standard Method 5520	*	any amount	100 ppm	100 ppm**
	TPH	EPA 418.1	*	any amount	100 ppm	100 ppm**
Diesel	TPH	EPA Method 9071	*	any amount	100 ppm	100 ppm**
	TPH	Standard Method 5520	*	any amount	100 ppm	100 ppm**
	TPH	EPA 418.1	*	any amount	100 ppm	100 ppm**
Waste Oil	TPH	EPA Method 9071	*	any amount	100 ppm	100 ppm**
	TPH	EPA 418.1	*	any amount	100 ppm	100 ppm**

\* Dictated by Method

\*\* Risk Assessment may be used to allow for a higher level.

Contact: Dorothy Malaier, Alabama Department of  
Environmental Management 205-270-5613

### Summary of Alaska Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	GRPH (C <sub>6</sub> -C <sub>10</sub> )	EPA Method 8015M	1 mg/l	any amount	sheen	sheen
	Benzene	EPA Method 602	.005 mg/l	any amount	.005 mg/l	.005 mg/l
	Toluene	EPA Method 602	.005 mg/l	any amount	1 mg/l	1 mg/l
	Ethylbenzene	EPA Method 602	.005 mg/l	any amount	0.7 mg/l	0.7 mg/l
	Xylene	EPA Method 602	.005 mg/l	any amount	10 mg/l	10 mg/l
Diesel	DRPH (C <sub>10</sub> -C <sub>28</sub> )	EPA Method 8100M	1 mg/l	any amount	sheen	sheen
Waste Oil	All of the Above and TPH (>C <sub>29</sub> )	EPA Method 418.1	1 mg/l	any amount	sheen	sheen

Contact: Cynthia Pring-Ham, Alaska Department of  
Environmental Conservation 907-465-5200

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Summary of Alaska Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Gasoline Range Petro. Hydrocarbons C <sub>6</sub> -C <sub>10</sub>	EPA Method 8015M	1 mg/kg	any amount	Site Specific 50-1000 ppm	Site Specific/50-1000ppm
	BTEX	EPA Method 8020	0.05 mg/kg	any amount	Site Specific 10-100ppm	Site Specific/10-100ppm
	Benzene	EPA Method 8020	0.05 mg/kg	any amount	Site Specific .1-.5ppm	Site Specific/0.1-.5ppm
Diesel	Diesel Range Petro. Hydrocarbons C <sub>10</sub> -C <sub>24</sub>	EPA Method 8100M	10 mg/kg	any amount	Site Specific 100-2000ppm	Site Specific/100-2000ppm
Waste Oil	All of the Above and TPH (> C <sub>29</sub> )	EPA Method 418.1	25 mg/kg	any amount	2000 ppm	2000 ppm

Contact: Cynthia Pring-Ham, Alaska Department of Environmental Conservation 907-465-5200

Summary of Arizona Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline, Diesel, Waste Oil	TPH	EPA Method 418.1	lab dep.	any amount	X>Non-Det.	Not Applicable
	Benzene	EPA Method 502.2***	lab dep.	any amount	X>Non-Det.	X< 5ppb
	Toluene	EPA Method 502.2***	lab dep.	any amount	X>Non-Det.	X< 1000ppb
	Ethylbenzene	EPA Method 502.2***	lab dep.	any amount	X>Non-Det.	X< 700ppb
	Xylenes	EPA Method 502.2***	lab dep.	any amount	X>Non-Det.	X< 10,000ppb
	VOCs	EPA Method 502.2***	lab dep.	any amount	X>Non-Det.	****

\*\*\* All target compounds in addition to BTEX analyzed by these test methods must be reported. The first round of water samples from a newly completed well must be analyzed using EPA Method 502.2. Subsequent samples may be analyzed using 502.1 or 503.1 upon ADEQ approval. Contact: Sean McKenzie, Arizona Department of Environmental Quality 602-628-6708

\*\*\*\* Refer to most recent ADHS, HBGLs and/or MCL for information on specific compounds not given under AWQS

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### EPA wants advice to streamline permits

The EPA is holding five national roundtable discussions on how to improve the environmental permitting process by gathering advice from individuals on how to improve the quality, certainty and timeliness of the permit decision process. The EPA is considering recommendations to establish teams with states to review the permitting process, identifying statutes that prevent flexibility in permitting, and finding a multi-media approach to permits. Meetings are open to the public. Jeanne Fox is co-chair of the team and Lance Miller is executive director. ■

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Summary of Arizona Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	ADHS Method BLS-181	lab dependent	any amount	X>N.D.	X<100ppm but risk assessment option exists
	Benzene	EPA Method 8020	lab dependent	any amount	X>N.D.	X<0.13ppm but risk assessment option exists
	Toluene	EPA Method 8020	lab dependent	any amount	X>N.D.	X<200ppm but risk assessment option exists
	Ethylbenzene	EPA Method 8020	lab dependent	any amount	X>N.D.	X<68ppm but risk assessment option exists
	Xylenes	EPA Method 8020	lab dependent	any amount	X>N.D.	X<44ppm but risk assessment option exists
Kerosene	Identical with all the above gasoline categories.					
Diesel	TPH only	ADHS Method BLS-181	lab dependent	any amount	X>N.D.	X<100ppm but risk assessment option exists
Jet Fuel	Identical to all the above Gasoline categories.					
Heavy Oil	Identical to Diesel above.					
Solvents	TPH	ADHS Method BLS-181	lab dependent	any amount	X>N.D.	X<100ppm but risk assessment option exists
	VOCs	EPA Method 8010***	lab dep.	any amount	X>N.D.	****
	BTEX: Identical in all respects to BTEX for gasoline above.					
Waste Oil	TPH	ADHS Method BLS-181	lab dependent	any amount	X>N.D.	X<100ppm but risk assessment option exists
	BTEX <u>Not Required</u>					
	VOCs	EPA Method 8010	lab dep.	any amount	X>N.D.	****

BTEX: Benzene, Toluene, Ethylbenzene, Xylene; TPH: Total Petroleum Hydrocarbon. N.D.: Non Detect. ADHS: Arizona Department of Health Services. VOCs: Volatile Organic Compounds. N.A. Not Applicable (i.e. standards have not been established) MCL: Maximum Contaminant Level. \*\*\* All target compounds in addition to BTEX analyzed by these test methods must be reported. The first round of water samples from a newly completed well must be analyzed with EPA Test Method 502.2. Subsequent samples may be analyzed using 502.1 or 503.1 upon ADEQ approval. \*\*\*\* Refer to most recent ADHS, HBGLs and/or MCL for information on specific compounds not given under AWQS

Contact: Sean Mckenzie, Arizona Department of Environmental Quality 602-628-6708

Summary of Arkansas Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene/ Total BTEX	EPA Method 8020	1ppb	Not Used	5 ppb Benzene 100ppb BTEX	Site Specific*
	TPH	EPA Method 418.1	10ppm	Not Used	15 ppm	Site Specific*
Diesel	TPH	Modified 8015	10ppm	Not Used	15 ppm	Site Specific*
	TPH	EPA Method 418.1	10ppm	Not Used	15 ppm	Site Specific*
Waste Oil	TPH	Modified 8015	10ppm	Not Used	15 ppm	Site Specific*
	TPH	EPA Method 418.1	10ppm	Not Used	15 ppm	Site Specific*
May also require VOC scan (8240) under certain circumstances						

\* Based on Risk Assessment

Summary of Arkansas Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	EPA Method 418.1	10ppm	Not Used	100 ppm	Site Specific/100-1000ppm*
	TPH	Modified 8015	10ppm	Not Used	100 ppm	Site Specific/100-1000ppm*
	BTEX	EPA Method 8020	1ppm	Not Used	40 ppm	Site Specific/0-400ppm*
Diesel	TPH	EPA Method 418.1	10ppm	Not Used	100 ppm	Site Specific/100-1000ppm*
	TPH	Modified 8015	10ppm	Not Used	100 ppm	Site Specific/100-1000ppm*
Waste Oil	TPH	EPA Method 418.1	10ppm	Not Used	100 ppm	Site Specific/100-1000ppm*
	TPH	EPA Method 8015 Modified	10ppm	Not Used	100 ppm	Site Specific/100-1000ppm*
May also require VOC scan (8240) and TCLP for metals under some circumstances						

\* Based on Risk Assessment

Contact: James Atchley, Arkansas Department of Pollution Control & Ecology 501-562-6533

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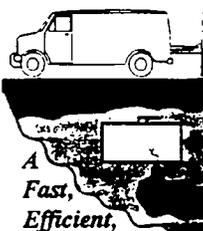
Summary of California Cleanup Goals for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA 602			0.7ppb DHS Action Level	
	Toluene	EPA 602			*State Action Level 100ppb DHS	
	Xylene	EPA 602			MCLs (1750ppb)	
	Ethylbenzene	EPA 602			MCLs (680ppb)	
	HVOs	EPA 601				
Diesel					Same as above	
Waste Oil					Same as above	

\* Health based guidance number, nonenforceable.

Summary of California Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	DHS Recommended	*	NA	**	
	***Benzene	EPA Method 8020	*	NA	NA to 1ppm	
	***Toluene	EPA Method 8020	*	NA	NA to 50ppm	
	***Ethylbenzene	EPA Method 8020	*	NA	NA to 50ppm	
	***Xylene	EPA Method 8020	*	NA	NA to 50ppm	
	HVOs	EPA Method 8010	*	NA	Site Specific	
Diesel	TPH	DHS Recommended	*	NA	10 to 1000ppm	
	TRPH	EPA Method 418.1	*	NA	100 to 10,000ppm	
	BTEX same as Gasoline above.					

\* Test Specific. \*\* There are three action levels associated w/ TPH & BTEX for sites which fall into categories low, medium and high.  
 \*\*\* If BTEX levels are detectable, even though TPH concentration is below 10ppm gas or 100ppm Diesel proceed from site investigation to the general risk appraisal. Note: California does not have state standard cleanup levels. Values shown are recommended action levels from the LUFT manual. Cleanup levels are site specific. California has 9 Regional Boards throughout the state and 105 local agencies. Notification is required for all unauthorized releases unless the operator is able to clean up the release within eight hours, it did not escape from a secondary containment, does not increase hazard of fire or explosion and did not deteriorate secondary containment of UST.

Contact: Paul Johnston, California  
 State Water Resources,  
 Central Board 916-227-4337



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Summary of Delaware Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	APHA 5520C, 503B	5 mg/l	any amount	*	Site Specific**
		EPA Method 418.1	5 mg/l	any amount	*	Site Specific**
		California Method GC-FID	5 mg/l	any amount	*	Site Specific**
	BTEX	EPA Method 5030, 8020, 8240	5 µg/l	any amount	*	Site Specific**
		EPA Method 602, 624 Equivalent Method	5 µg/l	any amount	*	Site Specific**
Diesel	TPH	Same As Gasoline		any amount	*	Site Specific**
Waste Oil	TPH	Same As Gasoline		any amount	*	Site Specific**
	BTEX	Same As Gasoline		any amount	*	Site Specific**

\* No established action levels, site specific. \*\* Drinking water standards to approximately 10ppm BTEX and 1ppm B.  
 Note: Water samples not required during tank removal activities. Water samples required as part of hydrogeologic investigation.

Contact: Patricia M. Ellis, Ph.D., Delaware Dept. of Natural Resources & Environmental Control 302-323-4588

Summary of Delaware Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level*	Cleanup Level*
Gasoline	TPH	Mod 8015, Mod 418.1 EPA Method 9071	40 mg/kg	any amount	100 ppm	Site Specific generally ≤ 100
		APHA Methods 5520E/ 5520C, 503B, 503E	40 mg/kg	any amount		Same As Above
	TPH	California Method GC-FD	10 mg/kg	any amount		Same As Above
	BTEX	EPA Method 3010/8020, 5030/8020	1 mg/kg	any amount	BTEX > 10ppm B > 1ppm	Site Specific generally ≤ 10 BTEX, 1 B
EPA Method 3810, 8240, 8240 purge & trap, Mod 602		1 mg/kg	any amount			
Diesel	TPH	as above	as above	any amount	1000 ppm	Site Specific generally ≤ 1000
Waste Oil	BTEX	as above	as above	any amount	BTEX > 10ppm B > 1ppm	Site Specific generally ≤ 10 BTEX, 1 B
	TPH	as above	as above	any amount	1000 ppm	Site Specific generally ≤ 1000ppm

\* Class B Site. Note: Class A sites—more sensitive, more stringent. Class B sites—average sensitivity. Class C sites—less sensitive, less stringent. Sites are rated by the DE DNREC as either A, B, or C. Factors influencing ratings include well locations, groundwater depth, residential, commercial or industrial settings, etc.

Contact: Patricia M. Ellis, Ph.D., Delaware Department of Natural Resources & Environmental Control 302-323-4588

Summary of Florida Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 602	NA	any amount		1ppb
	Total Volatiles Organic Aromatics	EPA Method 602	NA	any amount		50ppb
	1, 2 dichloroethane (EDB)	EPA Method 601	NA	any amount		3ppb
	1, 2 dichloroethane Lead	EPA Method 601	NA	any amount		.02ppb
	MTBE	EPA Method 239.2	NA	any amount		50ppb
	MTBE	EPA Method 602	NA	any amount		50ppb
Diesel	Same As Above	Plus				
	PAHs (Excluding Naphthalenes)	EPA Method 610	10ppb	any amount		Detection Level
	Total Naphthalenes	EPA Method 610	NA	any amount		100ppb
	TRPH	EPA Method 418.1	NA	any amount		5ppm
Waste Oil	Same As Diesel	Plus				
	Priority Pollutant Volatile Organics	EPA Method 624	NA	any amount	Site Specific	Site Specific
	Priority Pollutant Extractable Organics	EPA Method 625	NA	any amount	Site Specific	Site Specific
	Ar, Cd, Cr, Pb		NA	any amount	Site Specific	Site Specific

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Summary of Florida Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Organic Vapor Analysis	OVA with Flame Ionization		10ppm	>500 ppm*	VOA<100ppb** TRPH<10ppm**
Diesel	Organic Vapor Analysis	OVA with Flame Ionization Detector		10ppm	>50 ppm*	VOA<100ppb** TRPH<10ppm**

\* Soils with TPH readings greater than 500ppm (or 50ppm for Diesel) require remediation. Soils with vapor readings from 10-500 ppm may require cleanup depending on site factors. \*\* Soil cleanup criteria for thermal treatment. Contact: Thomas Conrady, Florida Department of Environmental Protection 904-488-0190

Summary of Georgia Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8020	1 µg/l	any amount	5 µg/l	Site Specific 5-71 µg/l
	Toluene	EPA Method 8020	1 µg/l	any amount	1000 µg/l	Site Specific 1000-200,000 µg/l
	Ethylbenzene	EPA Method 8020	1 µg/l	any amount	700 µg/l	Site Specific 700-28,718 µg/l
	Xylene	EPA Method 8020	1 µg/l	any amount	10,000 µg/l	Drinking water standards 10,000µg/l
Diesel/ Waste Oil	Benzo (a) Pyrene	EPA Method 550, 8270	.06/10 µg/l	any amount	.0311 µg/l	Site Specific .0311-.2 µg/l
	Anthracene	EPA Method 8270	10 µg/l	any amount	110,000 µg/l	* 110,000 µg/l
	Chrysene	EPA Method 8270	10 µg/l	any amount	.0311 µg/l	* .0311 µg/l
	Fluoranthene	EPA Method 8270	10 µg/l	any amount	370 µg/l	* 370 µg/l
	Fluorene	EPA Method 8270	10 µg/l	any amount	14,000 µg/l	* 14,000 µg/l
	Pyrene	EPA Method 8270	10 µg/l	any amount	11,000 µg/l	* 11,000 µg/l

\* Georgia in-stream water quality standards

Contact: Martin Gottschalk, Ph.D., Georgia Department of Natural Resources, 404-362-2687

Summary of Georgia Cleanup Standards for Hydrocarbon Contaminated Soil*						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	Modified California	0.1 mg/kg	any amount	100 mg/kg	Site Specific/100-500 mg/kg
BTEX	EPA Method 8020	0.001 mg/kg	any amount	20 mg/kg	Site Specific/20-100 mg/kg	
Diesel	TPH	Modified California Method	0.1 mg/kg	any amount	100 mg/kg	Site Specific/100-500 mg/kg
Waste Oil	TPH	Modified California	0.1 mg/kg	any amount	100 mg/kg	Site Specific/100-500 mg/kg

\* Amendments to the Georgia rules for underground storage tank management have been proposed - the amendments would significantly revise the soil clean-up standards, the amendments are expected to be adopted in January, 1995.

Contact: Martin Gottschalk, Ph.D., Georgia Department of Natural Resources, 404-362-2687

Summary of Hawaii Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Criteria Above The UIC / Below The UIC Line (Maui) / Line (Mauka)
Gasoline	TPH as Gasoline	EPA Method 5030, 8015 or LUFT Method		****		**** / ****
	Benzene	*		****		.005 / 1.7 ppm
	Ethylbenzene	*		****		.7 / .14 ppm
	Toluene	*		****		1 / 2.1 ppm
Diesel, Jet Fuel, Kerosene, Fuel Oil	TPH as Diesel	**		****		**** / ****
	Benzene	*		****		.005 / 1.7 ppm
	Ethylbenzene	*		****		.7 / .14 ppm
	Toluene	*		****		1 / 2.1 ppm
	Acenaphthene	***		****		NS / .320 ppm
	Naphthalene	***		****		NS / .78 ppm
	Fluoranthene	***		****		NS / .013 ppm
	Benzo (a) Pyrene	***		****		.0002 / NS ppm

\* 5030/ 8015 or 5030/ 8020 or 5030/ 8240 or 602 or 624. \*\* 3550/ 8015 or 3510/ 8270 or 3520/ 8270 or LUFT. \*\*\* 3510/ 8310 or 3520/ 8310 or 3510/ 8100 or 3520/ 8100 or 610. \*\*\*\* All spills over 25 gallons that cannot be contained and cleaned up within 24 hours. \*\*\*\*\* No Cleanup criteria based on TPH—however that does not preclude use as screening method. Note: NS=No Standard, Note: Standards are currently undergoing revisions. UIC=Underground Injection Control.

Contact: Kim Savage, Department of Health Underground Storage Tank Division 808-586-4226

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### Summary of Hawaii Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Criteria	
						Above The UIC Line (Maui)	Below The UIC Line (Maui)
Gasoline	TPH as Gasoline	EPA Method 5030, 8015, LUFT			****	**** / ****	
	Benzene	*		****		.05 / 1.7 ppm	
	Ethylbenzene	*		****		7 / 1.4 ppm	
	Toluene	*		****		10 / 21 ppm	
	TPH as Diesel	**		****		**** / ****	
	Benzene	*		****		.05 / 1.7 ppm	
	Ethylbenzene	*		****		7 / 1.4 ppm	
	Toluene	*		****		10 / 21 ppm	
	Naphthalene	***		****		100 / 100 ppm	
	Acenaphthene	***		****		100 / 100 ppm	
Fluoranthene	***		****		500 / 500 ppm		
	Benzo (a) Pyrene	***		****		1 / 1 ppm	

\* 5030/ 8015 or 5030/ 8020 or 5030/ 8240. \*\* 3550/ 8015 or 3540/ 8270 or 3550/ 8270 or LUFT Method.  
 \*\*\* 3540/ 8310 or 3550/ 8310 or 3540/ 8270 or 3550/ 8270. \*\*\*\* All spills over 25 gallons that cannot be  
 contained and cleaned up within 24 hours. \*\*\*\*\* No Cleanup criteria based on TPH—however that does not  
 preclude use as screening method. Note: NS=No Standard. Note: Standards are currently undergoing revisions.  
 UIC=Underground Injection Control.

Contact: Kim Savage, Department of Health Underground  
 Storage Tank Division 808-586-4226

### Summary of Idaho Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8020	1ppb	any level	5 µg/l	5 ppb (µg/l)
	Toluene		1ppb	any level	1000 µg/l	1000 ppb (µg/l)
	Ethylbenzene		1ppb	any level	700 µg/l	700 ppb (µg/l)
	Total Xylenes		1ppb	any level	10,000 µg/l	10,000 ppb (µg/l)
Diesel	PAH	EPA Method 8270			DWS	Drinking water standards
	BTEX	EPA Method 8020	1ppb	any level	Same As Gas	Same As Gas
Waste Oil	TPH	EPA Method 418.1			100ppm	100ppm
	VOCs	EPA Method 8240			Site Specific	Drinking water standards
	RCRA Metals	EPA Method 6010			Site Specific	Drinking water standards
	PAHs	EPA Method 8270			Site Specific	Drinking water standards

Note: Risk based assessments are allowed on a case by case basis.

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Summary of Idaho Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	EPA Method 8015 Modified as Gas	*	any amount	> 40ppm	Site Specific/40-200ppm
Diesel	TPH	EPA Method 8015 Modified as Diesel	*	any amount	> 100ppm	Site Specific/100-2000ppm
Waste Oil	Chlorinated Solvents	EPA Method 8010 or 8240	*	any amount	Site Specific	Site Specific
	TPH	EPA Method 418.1	*	any amount	> 100ppm	100ppm
	TCLP, RCRA Metals	EPA Method 6010	*	any amount	Site Specific	Site Specific/RCRA Criteria
	PCBs	EPA Method 8080	*	any amount	Site Specific	Site Specific

\* Dependent on sample matrix and concentration. 10 mg/kg target.  
 Note: Risk based assessments are allowed on a case by case basis.

Contact: Thomas Neace, Idaho Division of Environmental Quality 208-334-5860

Summary of Illinois Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	*****	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	*	.002mg/l	***	****	Site Specific
	BETX	*	.002-.005**	***	****	Site Specific
Other Petroleum	Benzene	*	.002mg/l	***	****	Site Specific
	BETX	*	.002-.005**	***	****	Site Specific
	Naphthalene	*	.010mg/l	***	****	Site Specific
	Acenaphthene	*	.018mg/l	***	****	Site Specific
	Anthracene	*	.0066mg/l	***	****	Site Specific
	Fluoranthene	*	.0021mg/l	***	****	Site Specific
	Fluorene	*	.0021mg/l	***	****	Site Specific
	Pyrene	*	.0027mg/l	***	****	Site Specific
	Total Carc. PNAs	*	.0013 - .0015**	***	****	Site Specific
	Total Non-Carc. PNAs	*	.00076 - .010**	***	****	Site Specific
Waste Oil	LUST Pollutants List	*	Compound Specific	***	*****	Site Specific

\* Any approved EPA SW-846 Method. \*\* Each constituent has unique ADL. \*\*\* Notification criteria based on any release of product, not specific contaminant levels. \*\*\*\* Any amount above the cleanup objectives. \*\*\*\*\* Any amount above the screening detection limits listed on LUST pollutants list. \*\*\*\*\* Acceptable Detection Limits.

Contact: G. Tod Rowe, Illinois Environmental Protection Agency 217-782-6761

Summary of Illinois Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	*****	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	*	.002mg/l	**	***	Site Specific
	BETX	*	.002-.005mg/l	**	***	Site Specific
Other Petroleum	Benzene	*	.002mg/l	**	***	Site Specific
	BETX	*	.002-.005mg/l	**	***	Site Specific
	Naphthalene	*	.660mg/l	**	***	Site Specific
	Acenaphthene	*	1.2mg/l	**	***	Site Specific
	Anthracene	*	.660mg/l	**	***	Site Specific
	Fluoranthene	*	.660mg/l	**	***	Site Specific
	Fluorene	*	.140mg/l	**	***	Site Specific
	Pyrene	*	.180mg/l	**	***	Site Specific
	Total Carc. PNAs	*	.0087 - .10mg/l	**	***	Site Specific
	Total Non-Carc. PNAs	*	.0051 - .660mg/l	**	***	Site Specific
Waste Oil	LUST Pollutants List	*	Compound Specific	**	****	Site Specific

\* Any approved USEPA SW-846 Method. \*\* Notification criteria based on any release of product, not specific contaminant levels. \*\*\* Any amount above the cleanup objectives. \*\*\*\* Any amount above the screening detection limits listed on LUST pollutants list. \*\*\*\*\* Acceptable Detection Limits.

Contact: G. Tod Rowe, Illinois Environmental Protection Agency 217-782-6761

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### Summary of Indiana Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Acceptable Methods	Detection Level	Notification Level	Action Level	Cleanup Level
Kerosene. Gasoline	Benzene, Toluene, Ethylbenzene, Xylene*	GC/PID 8020 or GC/MS 8240/60 or GC/MS 524.2	5ppb(ug/l)	any amount	Site Specific	Site Specific
	TPH (optional)	GC/FID 8015 - Modified (California)	500ppb(ug/l)			
Naptha. Diesel	Benzene, Toluene, Ethylbenzene, Xylene* and	GC/PID 8020 or GC/MS 8240/60 or GC/MS 524.2	5ppb	any amount	5ppb 1ppb 700ppb 10,000ppb	5ppb 1ppb 700ppb 10,000ppb
	Semi-Volatile Organics (SVOC)	GC/MS 8270 or GC/MS 525	10ppb	any amount	Site Specific	100ppb
	TPH (optional)	GC/FID 8015 - Modified (California)	500ppb	any amount	Site Specific	Site Specific
	Waste Oil	VOC*	GC/PID 8020 or GC/MS 8240/60	5ppb	any amount	Site Specific
	Total SVOC	GC/MS 8270	10ppb	any amount	Site Specific	MCLs
	TPH	418.1 IR	1000ppb	any amount	Site Specific	Site Specific
	PCB	GC/ECD 8080/8081	.5ppb(ug/l)**	any amount	Site Specific	MCLs
	Metals***	use the appropriate SW-846 method		set by the appropriate method	Site Specific	MCLs

\* This analysis also should include Methyl-tertiary-butyl-ether (MTBE). \*\* PCB Aroclor 1254 and 1260 detection limit must be 1.0 ppb. \*\*\* Metal scans must include: Barium, Cadmium, Chromium (total), Lead, Mercury, Nickel, and Zinc.

Contact: John Gunter, Indiana Department of Environmental Management 317-233-6412

### Summary of Indiana Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Acceptable Methods	Detection Level	Notification Level	Action Level	Cleanup Level
Kerosene, Gasoline	Total Petroleum Hydrocarbons (TPH)	GC/FID 8015 - Modified (California) or GC/MS 8240/60	20ppm	any amount	On-site ≥ 100 Off-site any amount	On-site ≤ 100 Off-site N.D.
Naptha. Diesel	TPH	GC/FID 8015 - Modified (California) or GC/MS 8270	20ppm	any amount	On-site ≥ 100 Off-site any amount	On-site ≤ 100 Off-site N.D.
Waste Oil	VOC* and	GC/PID 8020 or GC/MS 8240/60	20ppm	any amount	Site Specific	Site Specific
	SVOC and	GC/MS 8270	20ppm	any amount	Site Specific	Site Specific
	TPH and	418.1 IR	20ppm	any amount	Site Specific	Site Specific
	PCB and	GC/ECD 8080/8081	1ppm	any amount	Site Specific	Site Specific
	Metals**	use the appropriate SW-846 method		set by the appropriate method	any amount	Site Specific

\* This analysis also should include Methyl-tertiary-butyl-ether (MTBE). \*\* Metal scans must include: Barium, Cadmium, Chromium (total), Lead, Mercury, Nickel, and Zinc.

Contact: John Gunter, Indiana Department of Environmental Management 317-233-6412

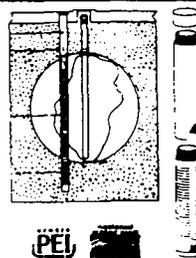


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Summary of Iowa Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	OA-1		any amount	5 ppb	Site Specific
	Toluene				2420 ppb	Site Specific
	Xylene				12000 ppb	Site Specific
Diesel	Ethylbenzene	OA-1		any amount	700 ppb	Site Specific
	same				same as Gasoline	Site Specific
Waste Oil	same	OA-1		any amount	same as Gasoline	Site Specific

Summary of Iowa Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	Iowa OA-1		any amount	100 mg/kg	Site Specific
Diesel	TPH	Iowa OA-2		any amount	100 mg/kg	Site Specific
Waste Oil	TPH	Iowa OA-2		any amount	100 mg/kg	Site Specific

Contact: Jim Humeston, Iowa Department of Natural Resources 515-281-8957

Summary of Kansas Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 502.2, 8020	.5ppb	.5ppb	5ppb	5ppb
	Ethylbenzene	EPA Method 502.2,503.1, 524.1, 524.2	68ppb	68ppb	680ppb	680ppb
	Toluene	EPA Method 502.2,503.1, 524.1, 524.2	100ppb	100ppb	1000ppb	1000ppb
	Xylene	EPA Method 502.2,503.1, 524.1, 524.2	44ppb	44ppb	440ppb	440ppb
	1-2 Dichloroethane	EPA Method 502.1,503.1 524.1,524.2,601,624,1624	5ppb	5ppb	5ppb	5ppb
Diesel	Napthalene		14.3ppb	14.3ppb	143ppb	143ppb

Summary of Kansas Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	*	10		100 ppm	100ppm
	Benzene	EPA Method 8020,8021, 8240, 8260	.14ppm		1.4 ppm	1.4ppm
	1-2 Dichloroethane	EPA Method 8010, 8021, 8240, 8260	.8ppm		8 ppm	8ppm
Diesel	TPH	*	10ppm		100 ppm	100ppm
Waste Oil	TPH	*	10ppm		100 ppm	100ppm

\*Purge and trap, Summation of peaks chromatograph

Contact: Thomas Winn, Department of Health & Environment, 913-296-1684

## Get on-line with EPA

The EPA Cleanup Information Bulletin Board System, CLU-IN, offers a wide range of information on line that can be downloaded to your computer via modem.

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### Summary of Kentucky Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8240, 8260 8020 or 8021	5ppb	5ppb	5ppb	5 to 400ppb
	Toluene	EPA Method 8240, 8260 8020 or 8021	1000ppb	1000ppb	1000ppb	1000 to 9400ppb
	Ethylbenzene	EPA Method 8240, 8260 8020 or 8021	700ppb	700ppb	700ppb	700 to 2400ppb
	Xylene	EPA Method 8240, 8260 8020 or 8021	10,000ppb	10,000ppb	10,000ppb	10,000ppb
Diesel*	PAH	EPA Method 8100, 8270 or 8310	5ppb	5ppb	5ppb	5ppb
Waste Oil*	Oil & Grease	EPA Method 9070	5ppm	5ppm or over background	>5ppm or over background	less than background
	Total Lead	EPA Method 7420, 7421 or 6010	15ppb	15ppb	15ppb	15ppb

\* Currently under review, numbers may change

Contact: Doyle Mills, Division of Waste Management 502-564-6716

### Summary of Kentucky Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline*	Benzene	EPA Method 8240, 8260, 8020 or 8021	0.006ppm	0.006ppm	0.006ppm	0.006 to 20ppm
	Toluene	EPA Method 8240, 8260, 8020 or 8021	0.7ppm	0.7ppm	0.7ppm	0.7 to 130ppm
	Xylene	EPA Method 8240, 8260, 8020 or 8021	7.0ppm	7.0ppm	7.0ppm	7.0 to 200ppm
	Ethylbenzene	EPA Method 8240, 8260, 8020 or 8021	0.35ppm	0.35ppm	0.35ppm	0.35 to 550ppm
Diesel	PAH	EPA Method 8100, 8270 or 8310	1ppm	1ppm	1ppm	1ppm
Waste Oil	Oil & Grease	EPA Method 9071	1ppm	10ppm or over background	>10ppm or over background	<10ppm or less than background
	Total Lead	EPA Method 7420, 7421 or 6010	1ppm	10ppm or over background or >10ppm	over background	less than background or < 20ppm

\* These values vary depending on facility classification, see 080E.

Contact: Doyle Mills, Division of Waste Management  
502-564-6716

### Summary of Louisiana\* Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline*	Benzene	EPA Method 8240 EPA Method 8020	5ppb 2ppb	any amount	MDL	Non-Detect/Background
	Toluene	EPA Method 8240 EPA Method 8020	5ppb 2ppb	any amount	MDL	Non-Detect/Background
	Ethylbenzene	EPA Method 8240 EPA Method 8020	5ppb 2ppb	any amount	MDL	Non-Detect/Background
	Xylene(Total)	EPA Method 8240 EPA Method 8020	5ppb 5ppb	any amount	MDL	Non-Detect/Background
Gasoline**	TPHG	CA DHS SW 846- 8015 Modified		any amount	1 ppm	>2.5ppm
	BTEX	EPA Method 8020		any amount	.25 ppm	2.5ppm
Diesel*	TPH-D	Modified 8015 California DHS	250ppb	any amount	MDL	Non-Detect/Background
Diesel**	TPH-D	CA DHS SW 8410, 8015 Modified		any amount	***	
Waste Oil**	Oil & Grease	EPA Method 5520F Standard Method		any amount	100 ppm	300ppm
	Volatile Organics	EPA Method SW846- M8260		any amount		10ppm

Note: Louisiana is currently revising cleanup levels to reflect risk based levels. \* Groundwater Protection Division \*\*  
Underground Storage Tanks Division. \*\*\* No values at present time. \*\*\*\* California DHS SW846-8015 Modified.

Contact: Department of Environmental  
Quality 504-765-0741

Summary of Louisiana* Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 8020		any amount		Site Specific/<100ppm
	TPHG	***				Site Specific/<300ppm
Diesel	TPHD, California Ap.A.	***		any amount		Site Specific/<300ppm
Waste Oil	TCLP (Heavy Metals)	SW846/1311		any amount		Substitute C HW Requirements

Note: Louisiana is currently revising their cleanup levels to reflect risk based levels. \* Underground Storage Tanks Division. Contact: Department of Environmental Quality 504-765-0741  
 \*\* Solid Waste Division- no definitive standard site specific determination. \*\*\* California DHS SW846-8015 Modified.

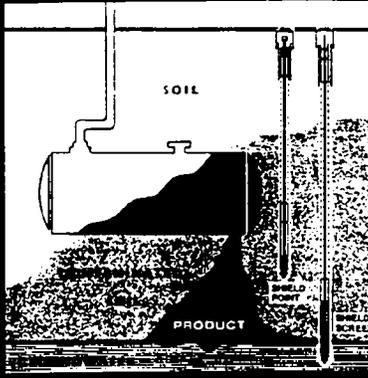
Summary of Maine Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene		5ppb			5ppb*
	MTBE		20ppb			50ppb*
	Total Gasoline	DEP 4.2.2	10ppb			50ppb*
Diesel	Total Fuel Oil	DEP 4.1.1	30ppb			50ppb*

\* Stringent sites only. Note: Maine DEP uses a decision tree approach to establish remediation standards. The three categories of LUST sites are baseline, intermediate and stringent, depending upon geologic vulnerability of site and availability of public water. An additional category is being considered. Contact: Fred Lavallee, Maine Department of Environmental Protection 207-287-2651

Summary of Maine Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Total Gasoline	DEP 4.2.3	1ppm	200ppm by Jar / Headspace		5mg/kg*
Diesel	Total Fuel Oil	DEP 4.1.2	5ppm	50ppm by Headspace		10mg/kg*

\* Intermediate and stringent sites only. Note: Maine DEP uses a decision tree approach to establish remediation standards. The three categories of LUST sites are baseline, intermediate and stringent, depending upon geologic vulnerability of site and availability of public water. An additional category is being considered. Contact: Fred Lavallee, Maine Department of Environmental Protection 207-287-2651

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### Summary of Maryland Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level (1)	Action Level	Cleanup Level (2)
Gasoline	BTEX and MTBE	EPA 602, 8020, 8240		Any Amount	>Background	Site Specific
Diesel/Fuel Oil	TPH Naphthalene	Modified 8015 EPA 8240		Any Amount	>Background	Site Specific or 10ppm
Used Oil	TPH TCLP	EPA 418.1 Modified 8015		Any Amount	>Background	Site Specific or 10ppm

There are no promulgated clean-up standards. All decisions on "how clean is clean" are made via site-specific risk characterization. **Note:** For groundwater there are no promulgated clean-up standards.

Contact: Herb Meade, Maryland Department of the Environment 410-631-3442

### Summary of Massachusetts Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level (1)	Action Level	Cleanup Level (2) A / B / C Site Specific
Gasoline	Benzene	NS	NS	5/2000µg/l	NS	5/ 2000/ 7000 µg/l
	Toluene	NS	NS	1000/6000ug/l	NS	1000/ 6000/50,000 ug/l
	Ethylbenzene	NS	NS	700/4000ug/l	NS	700/ 30,000/ 4000 ug/l
	Total Xylenes	NS	NS	6000/6000ug/l	NS	10,000/ 6000/ 50,000 ug/l
	MTBE	NS	NS	700/50,000ug/l	NS	700/ 50,000/ 50,000 ug/l
Diesel	TPH	NS	NS	1000/50,000ug/l	NS	1000/ NA/ 50,000 ug/l
	Naphthalene	NS	NS	20/6000ug/l	NS	20/ 6000/ 6000 ug/l
	Phenanthrene	NS	NS	50/50ug/l	NS	30/ NA/ 50 ug/l
Waste Oil	Benzene	NS	NS	5/2000ug/l	NS	5/ 2000/ 7000 ug/l
	TPH	NS	NS	1000/50,000ug/l	NS	1000/ NA/ 50,000 ug/l
	Various Metals Various PAHs	NS NS	NS NS	Metal/ area specific Compound/ area specific	NS NS	Metal/ area Specific Compound/ area Specific

Note: ug/l approximates ppb. NS= Not Specified in regulation. NA= Not Applicable (Non-volatile contaminants). (1) Two notification thresholds have been established depending upon potential use of groundwater. (2) Three cleanup values have been established depending upon potential groundwater use/ exposure: A-groundwater actual/ potential drinking water supply; B-where groundwater could be source of vapor emissions to building; C-everywhere. Alternative levels possible based upon site-specific Risk Characterization.

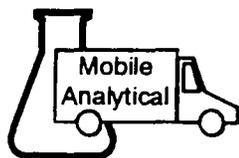
Contact: John J. Fitzgerald, Mass. Dept. of Environmental Protection 617-932-7702

### Summary of Massachusetts Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level (1)	Action Level	Cleanup Level (2)
Gasoline	Benzene	NS	NS	10/60 µg/g	NS	Site Specific/10-200µg/g
	Toluene	NS	NS	90/500 µg/g	NS	Site Specific/90-2500µg/g
	Ethylbenzene	NS	NS	80/500 µg/g	NS	Site Specific/80-2500µg/g
	Total Xylenes	NS	NS	500/500 µg/g	NS	Site Specific/500-2500µg/g
	MTBE	NS	NS	3/200 µg/g	NS	Site Specific/3-200µg/g
Diesel	TPH	NS	NS	500/2500 µg/g	NS	Site Specific/500-5000µg/g
	Naphthalene	NS	NS	4/1000 µg/g	NS	Site Specific/4-1000µg/g
	Phenanthrene	NS	NS	100/100 µg/g	NS	Site Specific/100-2500µg/g
Waste Oil	Benzene	NS	NS	10/60 µg/g	NS	Site Specific/10-200µg/g
	TPH Various Metals	NS NS	NS NS	500/2500 µg/g Metal/ Area specific	NS NS	Site Specific/500-5000µg/g Metal/ Area Specific

Note: µg/g=ppm mass/ mass dry weight basis. NS= Not Specified in regulation. (1) Two notification thresholds have been established for "high" and "low" exposure potential areas. (2) Nine cleanup values have been established depending upon exposure potential/ accessibility of soil, and use/ classification of underlying groundwater. Alternative cleanup levels are allowed based upon a site-specific risk characterization. **Note:** Please refer to Massachusetts regulations 310 CMR 40.0000 for complete details on cleanup numbers and requirements.

Contact: John J. Fitzgerald, Mass. Dept. of Environmental Protection 617-932-7702



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### Summary of Michigan Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Criteria A(ppb) / B(ppb) / C(ppb)
Gasoline	Benzene	502.2, 503.1, 524.1	1ppb	any amount	1.2ppb	1.2 / NA / 60
	Toluene	524.2, 602, 8020	1ppb	any amount	790ppb	1500 / 790 / 110
	Ethylbenzene	8021, 8240, 8260, CLP-Low	1ppb	any amount	74ppb	680 / 74 / 31
	Xylenes	All Above Except CLP-Low	3ppb	any amount	280ppb	13,000 / 280 / 59
Premium Gas	MTBE	502.2, 503.1, 524.1 524.2, 602, 8020 8021, 8240, 8260, CLP-Low	50ppb	any amount	230ppb	230 / NA / 380
Leaded Gas	Lead	200.8, 239.2, 1620, 6020, 7421	4ppb	any amount	4ppb	4 / NA / 6.6
Diesel	BTEX**	Same As Gasoline				
	PNA's	525, 550, 550.1, 610 8270, 8310, CLP-Low 8100*	5ppb	any amount	Varies By Component	Varies By Component
Waste Oil	BTEX and Lead**	Same As Gasoline				
	PNA's	Same As Gasoline				

A=Health based drinking water value. B=Aesthetic drinking water value. C=GSI value.

\* Acceptable methods for determining PNA compounds are below MDLs of OM#6 when neither petroleum hydrocarbons nor PNA's are present. If present other PNA methods such as 8270 or 8310 should be used.

Contact: Christine Flaga, Michigan Department of Natural Resources, Environmental Response Division 517-373-0160

### Summary of Michigan Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Criteria
Gasoline	Benzene	**	10ppb	any amount	24ppb	24ppb
	Toluene	**	10ppb	any amount	16,000ppb	16,000ppb
	Ethylbenzene	**	10ppb	any amount	1500ppb	1500ppb
	Xylenes	**	30ppb	any amount	5600ppb	5600ppb
Premium Gas	MTBE	**	100ppb	any amount	4600ppb	4600ppb
Leaded Gas	Lead	EPA Method 6020, 7420 and 7421	1000ppb	any amount	80ppb	80ppb
	PNA's	EPA Method 8270, 8310, CLP-RAS 8100	330ppb	any amount	*	*
Waste Oil	BTEX and Lead	BTEX in Diesel at same levels as in gasoline				
	PNA's	Same as in Diesel				

\* Varies by component. \*\*EPA Method 8020, 8021, 8240, 8260, CLP-RAS.

Note: Other metals and organic solvents of waste oils need to be tested for. Call MDNR for information.

Contact: Christine Flaga, Michigan Department of Natural Resources, Environmental Response Division 517-373-0160

### Summary of Minnesota Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	Wisconsin DNR GRO Method		any amount	Site Specific***	Site Specific***
	VOCs	Purge & Trap GC Procedure		any amount	Site Specific**	Site Specific**
Diesel	TPH	Wisconsin DNR DRO Method		any amount	Site Specific***	Site Specific***
	VOCs	Purge & Trap GC Procedure		any amount	Site Specific**	Site Specific**
Waste Oil*	TPH	Wisconsin DNR DRO Method		any amount	Site Specific***	Site Specific***
	VOCs	Purge & Trap GC Procedure		any amount	Site Specific**	Site Specific**

\* Defined as virgin oil that is discarded before use \*\* Based on risk assessment and Minnesota Department of Health Recommended Allowable Limits for drinking water. (and multiples thereof) \*\*\* In most cases, action and cleanup levels in groundwater are based on VOC levels

Contact: Minnesota Pollution Control Agency  
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Continues on page 38 →



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# Secrets of clay

*Why clay is so difficult to handle, and tips to minimize problems*

By Alfred Conklin, Ph.D.

Clay presents a challenge to anyone who wishes to work with soil. There are several reasons for the difficulties that clays pose. Several types of clays with different characteristics occur in most soils. Clays hold large amounts of water and attract and hold cations and organic matter. Also some are extremely sticky and plastic (able to hold a shape) while others are slippery. If worked when wet they become puddled—where particles act independently of each other—making them almost impervious to water. Frequent traffic compacts clay,

type of clay called bentonite that is used in oil drilling fields and environmental treatment wells. Other types of clay are used as fillers in paper and other consumer products. In the chemical industry, clay is used as a catalyst to increase the rate of certain chemical reactions. Some researchers have even suggested that soil clays acted as a catalyst for life on earth.

The soil scientist defines clay as inorganic particles less than 0.002 mm in diameter. Particles this small are colloidal, that is, they do not settle out of aqueous suspension. Clays can be

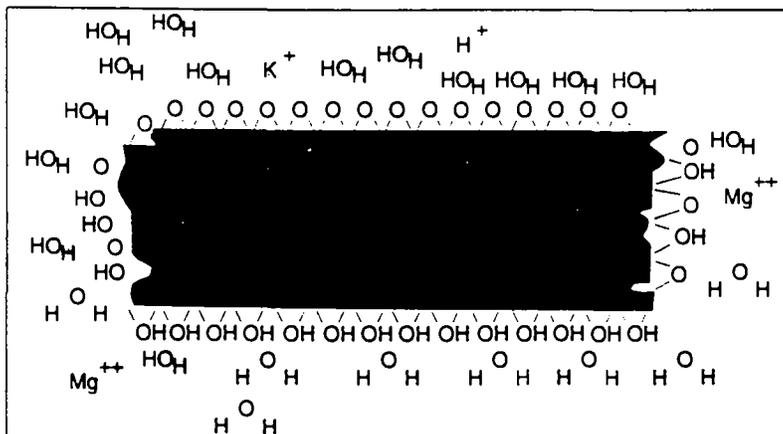


Figure 1

resulting in impervious layers. Proper handling can ameliorate some of these problems, but they cannot be totally reversed.

Clay is a common part of everyday life. Modeling clay comes to mind as a common product. Clay is used in many useful ways. Drilling mud is a

divided into two broad classes depending on their origin: clays that are unchanged from rock, primary minerals—and those that have been significantly changed, secondary minerals. In soil, secondary minerals are most common. Thus, in this discussion, we will only consider these secondary clay minerals, their characteristics and how they affect physical and chemical characteristics and remediation of contaminated soils.

Soil clays are constantly being synthesized and decomposed, so that

Continues on page 32 →

*Alfred Conklin Jr., Ph.D. is a professor in the agriculture department of Wilmington College, Wilmington, Ohio.*

State standards,  
from page 29

Summary of Minnesota Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	Wisconsin DNR GRO Method		any amount	40 ppm**	Site Specific****
	BTEX	*		any amount	40 ppm**	Site Specific****
	MTBE	*		any amount	40 ppm**	Site Specific****
Diesel	TPH	Wisconsin DNR DRO Method		any amount	10 ppm***	Site Specific****
	BTEX	*		any amount	10 ppm***	Site Specific****
Waste Oil	Same as Diesel					

\* All samples, unless specifically noted, should use an EPA approved method or equivalent. \*\* Soil Vapor headspace analysis  $\geq 40$ ppm. \*\*\* Visual evidence of contamination or soil vapor headspace  $\geq 10$  ppm. \*\*\*\* Additional investigation needed if base, sidewall soil samples are  $>50$ ppm TPH for sands.

Contact: Minnesota Pollution Control Agency  
612-296-6300 or 1-800-657-3864

Summary of Mississippi Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 602, 624, 8020, 8240, 8260	*	any amount	18 ppm or more	**
Diesel	TPH	EPA Method 418.1	.1ppm	any amount	18 ppm or more	**
Waste Oil	TPH	EPA Method 418.1	1ppm	any amount	18 ppm or more	**

\* Benzene-.09ppb, Toluene-.1ppb, Ethylbenzene-.05ppb, Meta & Para Xylene-.1ppb.  
\*\* 18ppm or less if no sensitive environmental receptors present.

Contact: Martha Martin, Mississippi Underground  
Storage Tank Division 601-961-5058

Summary of Mississippi Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 602, 624, 8020, 8240, 8260	*	any amount	100 ppm or over	**
Diesel	TPH	EPA Method 418.1	4ppm	any amount	100 ppm or over	**
Waste Oil	TPH	EPA Method 418.1	1ppm	any amount	100 ppm or over	**

\* Benzene-11.25ppb, Toluene-12.5ppb, Ethylbenzene-6.25ppb, Meta & Para Xylene-12.5ppb.  
\*\* 100ppm or less if no sensitive environmental receptors present.

Contact: Martha Martin, Mississippi Underground  
Storage Tank Division 601-961-5058

Summary of Missouri Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	EPA Method 418.1	5.0ppm	5.0ppm	Site Specific	Site Specific/5-10ppm
	Benzene	EPA Method 8020 or 8240	.005ppm	.005ppm	Site Specific	Site Specific/5-50ppb*
	Toluene	EPA Method 8020 or 8240	.005ppm	.005ppm	Site Specific	Site Specific/max 150ppb
	Ethylbenzene	EPA Method 8020 or 8240	.005ppm	.005ppm	Site Specific	Site Specific/max 320ppb
	Xylene	EPA Method 8020 or 8240	.005ppm	.005ppm	Site Specific	Site Specific/max 320ppb
	Total BTEX	EPA Method 8020 or 8240	.005ppm	.005ppm	Site Specific	Site Specific/max 750ppb
Diesel	Same as Gasoline					
Waste Oil	TPH	EPA Method 418.1	Same as Gasoline			
	BTEX	EPA Method 8240	Same as Gasoline			
	Heavy Metals	EPA Method 1311/ 6010 (TCLP)	TCLP	Contact the Environmental Services Program. Site specific.		

\* 5ppb for Drinking Water. Note: Regulatory levels in 40CFR 261.24  
Note: In January 1995 new regulations which will affect TPH methodology will be promulgated.  
contact Missouri Department of Natural Resources with questions.

Contact: John Crawshaw, Missouri Department of  
Natural Resources 816-795-8655

### Summary of Missouri Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	EPA Method 418.1 Modified	5.0ppm	25ppm	Site Specific	Site Specific/50-500ppm
	Benzene	EPA Method 8020 or 8240	.05ppm	.5ppm	Site Specific	Site Specific Min (Total BTEX<2ppm)
	Toluene	EPA Method 8020 or 8240	.05ppm	Total BTEX 1ppm	Site Specific	Max (Benzene 2ppm, Toluene 10ppm,
	Ethylbenzene	EPA Method 8020 or 8240	.05ppm	Total BTEX 1ppm	Site Specific	Ethylbenzene 50ppm, Xylene 50ppm)
	Xylene	EPA Method 8020 or 8240	.05ppm	Total BTEX 1ppm	Site Specific	
Diesel Waste Oil	Same as Gasoline					
	TPH	Same as Gasoline				
	BTEX	EPA Method 8240	Same as Gasoline			
	Heavy Metals	EPA Method 1311/6010 (TCLP)	40 mg/kg	Contact the Environmental Services Program. Site Specific		

Note: TCLP Regulatory levels in 40CFR 261.24

Note: In January 1995 new regulations which will affect TPH methodology will be promulgated. contact Missouri Department of Natural Resources with questions.

Contact: John Crawshaw, Missouri Department of Natural Resources 816-795-8655

### Summary of Montana Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	GRO**	Not Specified	any concentration	Not Specified	Site Specific
	Benzene	602, 624, 524.2	Not Specified	any concentration	5.0ppb	≥ MCL (Site Specific)***
	Toluene	602, 624, 524.2	Not Specified	any concentration	1000ppb	≥ MCL (Site Specific)
	Ethylbenzene	602, 624, 524.2	Not Specified	any concentration	700ppb	≥ MCL (Site Specific)
	Xylenes	602, 624, 524.2	Not Specified	any concentration	10,000ppb	≥ MCL (Site Specific)
Diesel	TPH	DRO**	Not Specified	any concentration	Not Specified	Site Specific
	BTEX	Same As Gasoline				
Waste Oil	TPH	DRO** with a used oil standard	Not Specified	any concentration	Not Specified	Site Specific
	VOCs*	624, 524.2	Not Specified	any concentration	Not Specified	See above for BTEX
	Cadmium, Chromium, Lead*	Not Specified	Not Specified	any concentration	5-10ppb Metal Spec.	5-10ppb Metal Spec.

\* Contamination from metals and halogenated VOCs is under the jurisdiction of another program.

\*\* Must be performed according to MDHES guidelines.

\*\*\* ≤5.0ppb for water used for domestic purposes

Contact: Michael Savka, Montana Department of Health and Environmental Sciences 406-444-5970

### Summary of Montana Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	GRO**	Non-specific Level Required	100 ppm	NA	Site Specific ≥100ppm
	Benzene	EPA Method 8020, 8260	Non-specific Level Required	1 ppm	NA	Site Specific ≥1ppm
	Total BTEX	EPA Method 8020, 8260	Non-specific Level Required	10 ppm	NA	Site Specific ≥10ppm
Diesel	TPH	DRO**	Non-specific Level Required	100 ppm	NA	Site Specific ≥100ppm
Waste Oil	TPH	DRO** with a used oil standard	Non-specific Level Required	100 ppm	NA	Site Specific ≥100ppm
	VOCs	EPA Method 8260	Non-specific		NA	See above for BTEX*
	Cadmium, Chromium, Lead	Not Specified	Non-specific Level Required		NA	*

\* Contamination from metals and halogenated VOCs is under the jurisdiction of another program.

\*\* Must be performed according to DHES guidelines.

Contact: Michael Savka, Montana Department of Health and Environmental Sciences 406-444-5970

Summary of Nebraska Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8021, 8020, 8240, 8260, 602, 624	≤ Cleanup Level	any amount	≥ Cleanup level	5ppb
	Toluene	EPA Method 8021, 8020, 8240, 8260, 602, 624	≤ Cleanup Level	any amount	≥ Cleanup level	1000ppb
	Ethylbenzene	EPA Method 8021, 8020, 8240, 8260, 602, 624	≤ Cleanup Level	any amount	≥ Cleanup level	7000ppb
	Xylenes	EPA Method 8021, 8020, 8240, 8260, 602, 624	≤ Cleanup Level	any amount	≥ Cleanup level	10,000ppb
	TRPH	EPA Method 418.1	≤ Cleanup Level	any amount	≥ Cleanup level	2000ppb
Diesel	Benzene	EPA Method 8021, 8020, 8240, 8260, 602, 624	≤ Cleanup Level	any amount	≥ Cleanup level	5ppb
	Toluene	EPA Method 8021, 8020, 8240, 8260, 602, 624	≤ Cleanup Level	any amount	≥ Cleanup level	1000ppb
	Ethylbenzene	EPA Method 8021, 8020, 8240, 8260, 602, 624	≤ Cleanup Level	any amount	≥ Cleanup level	7000ppb
	Xylenes	EPA Method 8021, 8020, 8240, 8260, 602, 624	≤ Cleanup Level	any amount	≥ Cleanup level	10,000ppb
	TRPH	EPA Method 418.1	≤ Cleanup Level	any amount	≥ Cleanup level	2000ppb
Waste Oil*	TRPH	EPA Method 418.1	≤ Cleanup Level	any amount	≥ Cleanup level	2000ppb

\* Other sampling, analysis and cleanup regulations established on a case by case basis.

Contact: Marc Fisher, Nebraska Department of Environmental Quality 402-471-4230



### Summary of Nebraska Recommended Cleanup Goals for Hydrocarbon Contaminated Soil

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8021, 8020 8240, 8260	≤ Cleanup Level	any amount	≥ Cleanup Level	Site Specific/.005-50ppm
	Total BTEX	EPA Method 8021, 8020 8240, 8260	≤ Cleanup Level	any amount	≥ Cleanup Level	Site Specific/1-10,000ppm
	TRPH	EPA Method 418.1	≤ Cleanup Level	any amount	≥ Cleanup Level	Site Specific/10-500ppm
Diesel	Benzene	EPA Method 8021, 8020 8240, 8260	≤ Cleanup Level	any amount	≥ Cleanup Level	Site Specific/.005-50ppm
	Total BTEX	EPA Method 8021, 8020 8240, 8260	≤ Cleanup Level	any amount	≥ Cleanup Level	Site Specific/1-10,000ppm
	TRPH	EPA Method 418.1	≤ Cleanup Level	any amount	≥ Cleanup Level	Site Specific/100-500ppm
Waste Oil*	TRPH	EPA Method 418.1	≤ Cleanup Level	any amount	≥ Cleanup Level	Site Specific/10-500ppm
	VOCs, SVOCs	EPA Method 8240/ 8260: 8270	≤ Cleanup Level	any amount	≥ Cleanup Level	Established Case-By-Case Level

\* Other sampling, analysis and cleanup regulations are established on a case by case basis.  
 Note: Soil levels are recommended and not stipulated by regulation.

Contact: Marc Fisher, Nebraska Department of Environmental Quality 402-471-4230

### Summary of Nevada Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 624*	1 µg/l	> 25 Gallons or 3 Cubic Yards	MCLs 5ppb	MCLs
	Toluene	EPA Method 624*	1 µg/l		MCLs 1ppm	MCLs
	Ethylbenzene	EPA Method 624*	1 µg/l		MCLs .7ppm	MCLs
	Xylene	EPA Method 624*	1 µg/l		MCLs 10ppm	MCLs
Diesel	Benzene	EPA Method 624*	1 µg/l	> 25 Gallons or 3 Cubic Yards	MCLs As Above	MCLs
	Toluene	EPA Method 624*	1 µg/l		MCLs	MCLs
	Ethylbenzene	EPA Method 624*	1 µg/l		MCLs	MCLs
	Xylene	EPA Method 624*	1 µg/l		MCLs	MCLs

\*Other EPA approved methods are also acceptable for use.



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Summary of Nevada Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	EPA Method 8015 Modified	10 mg/kg	> 25 Gallons or 3 Cubic Yards	100 ppm	100 ppm
Diesel	TPH	EPA Method 8015 Modified	10 mg/kg	> 25 Gallons or 3 Cubic Yards	100 ppm	100 ppm
Waste Oil	TPH	EPA Method 8015 Modified, TCLP Inorganics	10 mg/kg	> 25 Gallons or 3 Cubic Yards	100 ppm MCLs MCLs	100 ppm MCLs MCLs

Contact: Larry Woods, Nevada Department of Conservation and Natural Resources 702-687-4670

Summary of New Hampshire Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Standards
Gasoline	VOC	*	Test Specific	Same As Cleanup Level	Site Specific	Benzene 5ug/l Ethylbenzene 700ug/l MTBE 100ug/l Toluene 1000ug/l Xylenes 10,000ug/l
No's 2,4,5,6 Fuel Oil and Diesel	VOC PAH	**	Test Specific	Same As Cleanup Level	Site Specific	VOCs Same As Above Benzo(a)pyrene .2ug/l Naphthalene 20ug/l
Waste Oil and similar weight products	VOC PAH	Same as Above				

\* Initially 8260 plus MTBE all other samples 8020 plus MTBE or 8240 plus MTBE or 8260 plus MTBE

\*\* Initially 8260 and 8270/8310 all other samples 8020, 8240, 8260 or 8270/8310

Contact: George Lombardo, New Hampshire Department of Environmental Services 603-271-3503

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### Summary of New Hampshire Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level (ppm)	Cleanup Guidelines (ppm)
Gasoline	VOC and TPH (TPH as gasoline)	*	Test Specific	Same As Cleanup Level	Benzene>.2	.2
					1-2-Dichloroethane>.04	.04
					Ethylbenzene >75	75
					Isopropylbenzene>23	23
					MTBE>.6	.6
					Toluene>75	75
					Xylenes>750	750
TPH>10,000	10,000					
No's 2,4,5,6 Fuel Oil and Diesel	VOC, PAH and TPH (TPH as oil)	**	Test Specific	Same As Cleanup Level	VOCs and TPH Same As Above	
					Naphthalene >.66	.66
					Acenaphthene >.66	.66
					Benzo(a)pyrene >.66	.66
					Benzo(b)Fluoranthene >.66	.66
					Benzo(k)Fluoranthene >.66	.66
					Chrysene >.66	.66
					Dibenzo(a)anthracene >.66	.66
					Fluoranthene >.66	.66
					Indene(1,2,3-ed)pyrene >.66	.66
					2-methylnaphthalene >.66	.66
Total Non-Carcinogenic PAHs	>7800	>7800				
Waste Oil and similar products	Same as Above Plus TCLP			Site Specific	Site Specific	

\* Initially 8260 plus MTBE and P&T-GC/FID for TPH. All other samples 8020 plus MTBE or 8240 plus MTBE and P&T GC/FID for TPH.

\*\*Initially 8260, 8270/8310 and extraction GC/FID for TPH. All other samples 8020, 8240, 8260 or 8270/8310 and extraction GC/FID for PAH.

Contact: George Lombardo, New Hampshire Department of Environmental Services 603-271-3503

### Summary of New Jersey Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level*					
Gasoline	Benzene	EPA Method 524 (Drinking Water)	Test Specific	any amount	NS	1					
						Toluene	EPA Method 524 (Drinking Water)	Test Specific	any amount	NS	1000
						Ethylbenzene	EPA Method 524 (Drinking Water)	Test Specific	any amount	NS	700
						Xylene	EPA Method 524 (Drinking Water)	Test Specific	any amount	NS	40
						Anthracene	EPA Method 525	Test Specific	any amount	NS	2000
						Naphthalene	EPA Method 524.2	Test Specific	any amount	NS	—
						Lead	NS	Test Specific	any amount	NS	10
						Benzo (A) Pyrene	EPA Method 525	Test Specific	any amount	NS	NA
Diesel	Same As Above For Gasoline										

NS=Not Specified

\*Higher of Groundwater Quality Criteria or Practical Quantitation Limit.

Contact: New Jersey Department of Environmental Protection 609-984-3156

### EPA toughens landfill rules

EPA's new Phase II Land Disposal Restriction requires that soils contaminated with benzene and other organics must be treated prior to disposal in a Subtitle C or D landfill. New universal treatment standards for over 200 hazardous constituents have been identified. This restriction will increase the cost of landfilling contaminated soils.



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Summary of New Jersey Cleanup Criteria for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Criteria <small>Residential / Non-Feed / Impacted Groundwater</small>
Gasoline	Benzene	EPA Method SW 846	Test Specific	any amount	NS	3mg/kg / 13mg/kg / 1mg/kg
	Toluene	EPA Method SW 846	Test Specific	any amount	NS	1000mg/kg / 1000mg/kg / 500mg/kg
	Ethylbenzene	EPA Method SW 846	Test Specific	any amount	NS	1000mg/kg / 1000mg/kg / 100mg/kg
	Xylene	EPA Method SW 846	Test Specific	any amount	NS	<110mg/kg / 1000mg/kg / 10mg/kg
	Anthracene	EPA Method SW 846	Test Specific	any amount	NS	10,000mg/kg / 10,000mg/kg / 100mg/kg
	Naphthalene	EPA Method SW 846	Test Specific	any amount	NS	230mg/kg / 4200mg/kg / 100mg/kg
	Lead	EPA Method SW 846	Test Specific	any amount	NS	400mg/kg / 600mg/kg / NS
Diesel	Benzo (A) Pyrene	EPA Method SW 846	Test Specific	any amount	NS	.66mg/kg / .66mg/kg / 100
	Same As Above For Gasoline					

NS=Not Specified

Contact: N.J. Dept. of Environmental Protection 609-984-3156

Summary of New Mexico Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level ppm	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 602	0.001		.01 ppm	.01 ppm
	Toluene	EPA Method 602	0.075		.75 ppm	.75 ppm
	Ethylbenzene	EPA Method 602	0.075		.75 ppm	.75 ppm
	Xylenes (Total)	EPA Method 602	0.062		.62 ppm	.62 ppm
	MTBE	EPA Method 602	0.01		.1 ppm	.1 ppm
Diesel	Naphthalene	EPA Method 610	0.001		.03 ppm	.03 ppm
	Benzo (A) Pyrene	EPA Method 610	0.7ppb		.0007 ppm	.0007 ppm

Contact: Anna Richards, New Mexico Environmental Department 505-827-0173

Summary of New Mexico Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	EPA Method 8020			50 ppm	50ppm
	BTEX	EPA Method 8020	0.50ppm		*	*
Diesel	TPH	EPA Method 8015 Modified	25.0ppm		100 ppm	100ppm
		EPA Method 418.1 Modified 8015			100ppm	100ppm
Waste Oil	TPH	Same as Diesel +	25.0ppm		Per RCRA	Per RCRA

\* Total 50ppm and Benzene 10ppm

Contact: Anna Richards, New Mexico Environmental Department 505-827-0173

Summary of New York Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8021, 8020	1ppb	any amount	.7ppb	*
	Ethylbenzene	EPA Method 8021, 8020	1ppb	any amount	5ppb	*
	Toluene	EPA Method 8021, 8020	1ppb	any amount	5ppb	*
	Xylene	EPA Method 8021, 8020	2ppb	any amount	5ppb	*
	MTBE	EPA Method 8021, 8020	1ppb	any amount	50ppb	*
	Other Compounds Listed in STARS #1	EPA Method 8021	Compound Specific	any amount	Compound Specific	Action Level, or when not achievable, site specific
Diesel	Naphthalene	EPA Method 8021, 8020	1ppb or 6ppb	any amount	10ppb	*
	Anthracene	EPA Method 8270	8ppb	any amount	50ppb	*
	Fluorene	EPA Method 8270	8ppb	any amount	50ppb	*
	Pyrene	EPA Method 8270	8ppb	any amount	50ppb	*
	Other Compounds Listed in STARS #1	EPA Method 8021 or 8270	Compound Specific	any amount	Compound Specific	Action Level, or when not achievable, site specific
Waste Oil	PCBs	EPA Method 8270	Compound Spec.			

\* Action Level or, when not achievable, site specific.

Contact: Chris O'Neill, New York Department of Environmental Conservation 518-457-9412

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### Summary of New York Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8021 or 8020	2ppb	any amount	14ppb	Site Specific
	Ethylbenzene	EPA Method 8021 or 8020	2ppb	any amount	100ppb	Site Specific
	Toluene	EPA Method 8021 or 8020	2ppb	any amount	100ppb	Site Specific
	Xylene	EPA Method 8021 or 8020	2ppb	any amount	100ppb	Site Specific
	MTBE	EPA Method 8021 or 8020	1ppb	any amount	1000ppb	Site Specific
	Other Compounds Listed in STARS #1	EPA Method 8021	Compound Specific	any amount	Compound Specific	Site Specific
Diesel	Naphthalene	EPA Method 8021	1ppb	any amount	200ppb	Site Specific
	Anthracene	EPA Method 8270	330ppb	any amount	1000ppb	Site Specific
	Fluorene	EPA Method 8270	330ppb	any amount	1000ppb	Site Specific
	Pyrene	EPA Method 8270	330ppb	any amount	1000ppb	Site Specific
	Other Compounds Listed in STARS #1	EPA Method 8021 or 8270	Compound Specific	any amount	Compound Specific	Site Specific
	Waste Oil	PCBs	EPA Method 8270	Compound Specific	Compound Specific	Compound Specific

Contact: Chris O'Neill, New York Department of Environmental Conservation 518-457-9412

### Summary of North Carolina Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 602 or 502.2 & 524.2	MDL	>1ppb	>1ppb	>1ppb
	Ethylbenzene	EPA Method 602 or 502.2 & 524.2	MDL	>29ppb	>29ppb	>29ppb
	Toluene	EPA Method 602 or 502.2 & 524.2	MDL	>1000ppb	>1000ppb	>1000ppb
	Xylenes	EPA Method 602 or 502.2 & 524.2	MDL	>530ppb	>530ppb	>530ppb
	MTBE	Modified 602	MDL	>200ppb	>200ppb	>200ppb
	Lead	3030C	MDL	>15ppb	>15ppb	>15ppb
	EDC	601	MDL	>0.38ppb	>0.38ppb	>0.38ppb
	EDB	Modified 602 or 502.2 & 524.2	MDL	>0.0004ppb	>0.0004ppb	>0.0004ppb
	Diesel, Kerosene, etc.	BTEX	602 or 502.2 and 625 with 10 Largest Non- Target Peaks Identified	MDL	As Above	As Above

Note: MDL = Method Detection Limit.

Contact: Mike Cleary, North Carolina Division of Environmental Management, 919-733-1322



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#### Learn from the rule-maker

EPA offers a four-page *Guide for Alternative Technology Demonstrations Projects* that give information about how to set up demonstration projects for alternative cleanup technologies. EPA also offers *Technologies and Options for UST Corrective Actions: Overview of Current Practice* that summarizes experiences and outlines state requirements. Call 800-424-9346 for a free copy of either or both publications.

Summary of North Carolina Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline, Aviation Fuels, etc.	TPH	5030 sample prep. w/ modified 8015	MDL	10ppm	10ppm	Site Specific*
Diesel, Kerosene, etc.	TPH	5030 + 3550 sample prep. w/ modified 8015	MDL	5030-10ppm 3550-40ppm	10ppm 40ppm	Site Specific*
Heavy Fuels (Virgin Products)	TPH	9071	MDL	>250ppm	>250ppm	Site Specific*
Waste Oil	TPH	9071 and 8021, if 9071 > 250ppm or cmpds. are detected by 8021, then use 1311 (TCLP)	MDL	9071 (>250ppm) 8021 (>MDL) 1311 (>MDL)	9071 (>250ppm) 8021 (>MDL) 1311 (>MDL)	Site Specific*
Metals	Pb, Ba, As, Cd Cr, Ag, Hg, Se	1311(TCLP)	MDL	>Cleanup Level	>Cleanup Level	Naturally Occurring Background Concentrations

Note: MDL = Method Detection Limit. \* North Carolina uses a Site Sensitivity evaluation to rate sites. Cleanup criteria are based on evaluation.

Contact: Mike Cleary, North Carolina Division of Environmental Management, 919-733-1322

Summary of North Dakota Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 524.2	5ppb	any amount	5ppb	Site Specific/5ppb
	Toluene	EPA Method 524.2	5ppb	any amount	5ppb	Site Specific
	Ethylbenzene	EPA Method 524.2	5ppb	any amount	5ppb	Site Specific
	Xylenes	EPA Method 524.2	5ppb	any amount	5ppb	Site Specific
Diesel	TRPH	EPA Method 418.1	1 mg/l			Site Specific
Waste Oil	Lead	EPA Method 239.2	2µg/l			Site Specific
	Chromium	EPA Method 218.2	2µg/l			Site Specific
	Cadmium	EPA Method 213.2	2µg/l			Site Specific

Summary of North Dakota Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	EPA Method 418.1 or *DHS		any amount	100 ppm	Site Specific/100+ ppm
Diesel	TPH	EPA Method 418.1 or *DHS		any amount	100 ppm	Site Specific/100+ ppm
Waste Oil	BTEX	EPA Method 8020		any amount	5mg/l Benzene	
	Lead	EPA Method 239.2		any amount	5mg/l	
	Chromium	EPA Method 218.2		any amount	5mg/l	
	TOX	EPA Method 9020, 9022		any amount	1000mg/l	

\* California Department of Health Services Method.

Contact: Dave Glatt, State Department of Health and Consolidated Laboratories 701-221-5210

Summary of Ohio Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 602	Method Specific	any amount	.005 ppm	Site Specific
	Toluene	EPA Method 602	Method Specific	any amount	12 ppm	Site Specific
	Ethylbenzene	EPA Method 602	Method Specific	any amount	.700 ppm	Site Specific
	Total Xylenes	EPA Method 602	Method Specific	any amount	10 ppm	Site Specific
Diesel	TPH	None Specified	None Specified	None Specified	None Specified	None Specified
	Benzene	EPA Method 602	Method Specific	any amount	.005 ppm	Site Specific
	Toluene	EPA Method 602	Method Specific	any amount	12 ppm	Site Specific
	Ethylbenzene	EPA Method 602	Method Specific	any amount	.700 ppm	Site Specific
	Total Xylenes	EPA Method 602	Method Specific	any amount	10 ppm	Site Specific
	PNAs	EPA Method 610	Method Specific	any amount		Site Specific Site Specific
Waste Oil	TPH	None Specified	None Specified	None Specified	None Specified	None Specified
	VOAs	EPA Method 624	Method Specific	any amount	Site Specific	Site Specific

Contact: Raymond Roe, Ohio Department of Commerce 614-752-7941

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### Summary of Ohio Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8020	Method Specific	Action Level Based	.006 - 500 ppm	Site Specific
	Toluene	EPA Method 8020	Method Specific	Action Level Based	4-12 ppm	Site Specific
	Ethylbenzene	EPA Method 8020	Method Specific	Action Level Based	6-18 ppm	Site Specific
	Total Xylenes	EPA Method 8020	Method Specific	Action Level Based	28-85 ppm	Site Specific
Diesel	TPH	Modified Method 8015	Method Specific	Action Level Based	105-600 ppm	Site Specific
	Benzene	EPA Method 8020	Method Specific	Action Level Based	.006 - 500 ppm	Site Specific
	Toluene	EPA Method 8020	Method Specific	Action Level Based	4-12 ppm	Site Specific
	Ethylbenzene	EPA Method 8020	Method Specific	Action Level Based	6-18 ppm	Site Specific
	Total Xylenes	EPA Method 8020	Method Specific	Action Level Based	28-85 ppm	Site Specific
	PNAs	EPA Method 8100	Method Specific	Any Level	Site Specific	Site Specific
	TPH	EPA Method 418.1	Method Specific	Any Level	380-1156ppm	Site Specific

Contact: Raymond Roe, Ohio Department of Commerce 614-752-7941

### Summary of Oklahoma Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level 1 / 2 / 3 ppm
Gasoline, Diesel and Kerosene	TPH	*	1ppm	any amount above action level	TPH>2ppm B>.005ppm	TPH: 2 / 10 / 25 B: .005 / .05 / .5
	BTEX	*	1ppm	any amount above action level	T>1ppm E>.7ppm X>10ppm	T: 1 / 10 / 100 E: .7 / 7 / 70 X: 10 / 100 / 1000

### Summary of Oklahoma Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level 1 / 2 / 3 ppm
Gasoline, Diesel and Kerosene	TPH	*	1ppm	any amount above action level	TPH>50ppm B>.5ppm	TPH: 50 / 500 / 1000 B: .5 / 5 / 10
	BTEX	*	1ppm	any amount above action level	T>40ppm E>15ppm X>200ppm	T: 40 / 400 / 1000 E: 15 / 150 / 1000 X: 200 / 1000 / 1000

Note: Oklahoma uses a Remediation Index in determining cleanup standards on a site-by-site basis.

\* No methods are specified- Whatever method is specified must be able to detect the most stringent cleanup levels.

Contact: Oklahoma Corporation Commission, Underground Storage Tank Program 405-521-3107

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### EPA opens tank training center

The EPA, in cooperation with the University of Tennessee at Chattanooga, has developed the 4M Center for Underground Storage Tanks Training and Technology.

The center provides training in measurements, monitoring and mitigation. It also develops practical field experience on technologies to assess and clean up spills and leaks.

For more information call 615-785-2103.

Summary of Oregon Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 8020 or 8240	.5 ppb	any amount		B: 5ppb, T: 700ppb E: 1000ppb, X: 10,000ppb
	Additives	EPA Method 8010 or 8240	.5 ppb	any amount		1,2-Dibromoethane-1ppb 1,2-Dichloroethane-5ppb Lead-5ppb
Diesel	BTEX	Same As Gasoline Above				
	PAHs Carcinogenic	EPA Method 8310	.1 ppb	any amount		Benzo (A) Pyrene .2ppb Benzo(A)Anthracene .1ppb Benzo (b) Fluoranthene 0.2 Benzo (k) Fluoranthene 0.2 Chrysene 0.2 Dibenzo (a,b) Anthracene 0.3 Indenopyrene 0.4

Note: Oregon uses a site scoring matrix to determine petroleum cleanup standards in soil.

Contact: Michael Anderson, Department of Environmental Quality, 503-229-6764

Summary of Oregon Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	DEQ Method, TPH-G	10 mg/kg	any amount		Site Specific, Level 1=40ppm, Level 2=80ppm Level 3=130ppm
Diesel	TPH	DEQ Method, TPH-D or TPH-418.1	20 mg/kg	any amount		Site Specific Level 1=100ppm, Level 2=500ppm, Level 3=1000ppm.

Note: Oregon uses a site scoring matrix to determine petroleum cleanup standards in soil.

Contact: Michael Anderson, Department of Environmental Quality, 503-229-6764

Summary of Pennsylvania Cleanup Standards for Hydrocarbon Contaminated Groundwater							
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level	
Gasoline	Benzene	EPA Method 8020	.2 µg/l	any amount	None	Non-Detect	
	Toluene	EPA Method 8020	.2 µg/l	any amount	None	Non-Detect	
	Ethylbenzene	EPA Method 8020	.2 µg/l	any amount	None	Non-Detect	
	Total Xylene	EPA Method 8020		any amount	None	Non-Detect	
	PHC	API-GRO		.1 mg/l	any amount	None	Non-Detect
	Total Lead*	None Specified			any amount	None	Non-Detect
Diesel	PHC	API-DRO	.1 mg/l	any amount	None	Non-Detect	

\* When tank contained a leaded Gasoline.

Contact: Doug Cordell, Department of Environmental Resources 717-772-5835

Summary of Pennsylvania Cleanup Standards for Hydrocarbon Contaminated Soils							
Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level	
Gasoline	Benzene	EPA Method 8020	2 µg/l	0.2ppm	0.2ppm	0.2ppm	
	Toluene	EPA Method 8020	2 µg/l	0.5ppm	0.5ppm	0.5ppm	
	Ethylbenzene	EPA Method 8020	2 µg/l	1ppm	1ppm	1ppm	
	Total Xylene	EPA Method 8020		0.7ppm	0.7ppm	0.7ppm	
	PHC- Petroleum Hydrocarbons	API-GRO		5 mg/kg	200ppm	200ppm	200ppm
	Total Lead*	None Specified			any amount	N/A	Residential Areas 200 ppm Industrial Areas 600ppm
Diesel	PHC	API-DRO	4 mg/kg	200ppm	200ppm	200ppm	
Waste Oil	TPH	EPA Method 418.1		any amount	Site Specific	Site Specific	

\* When tank contained a leaded Gasoline.

Contact: Doug Cordell, Department of Environmental Resources 717-772-5835

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**Summary of South Carolina Cleanup Standards for Hydrocarbon Contaminated Groundwater**

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level (MCLs)
Gasoline	BTEX	EPA Method 8020	Test Specific	any amount	**	B: 5µg/l, T: 1000µg/l, E: 700µg/l, 10,000µg/l
	MTBE	EPA Method 8020	Test Specific	any amount	**	Recommended 40µg/l
	TPH	EPA Method 5030*	Test Specific	any amount	**	Not Established
Diesel	BTEX	EPA Method 8020	Test Specific	any amount	**	B: 5µg/l, T: 1000µg/l, E: 700µg/l, 10,000µg/l
	Naphthalene	EPA Method 8020	Test Specific	any amount	**	Not Established
Waste Oil	TPH	EPA Method 3510*	Test Specific	any amount	**	Not Established
	BTEX	EPA Method 8240	Test Specific	any amount	**	B: 5µg/l, T: 1000µg/l, E: 700µg/l, 10,000µg/l

\* California method or equivalent. \*\* Site Specific.

**Summary of South Carolina Cleanup Standards for Hydrocarbon Contaminated Soil**

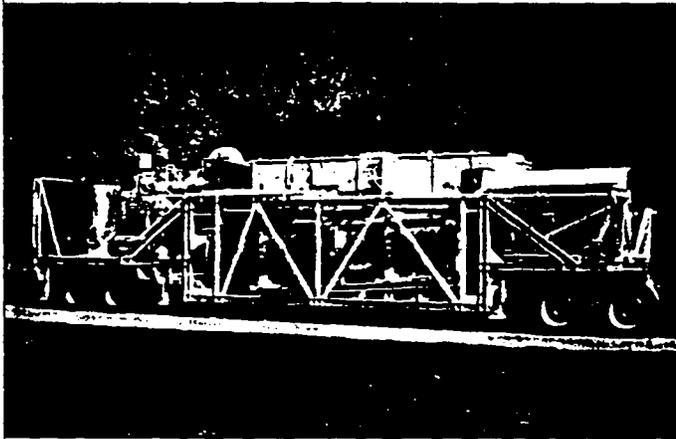
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 8020	1 mg/kg	any amount	**	Site Specific
	TPH	EPA Method 5030*	10 mg/kg	any amount	**	Site Specific
Diesel	BTEX	EPA Method 8020	1 mg/kg	any amount	**	Site Specific
	Naphthalene	EPA Method 8020	any amount	any amount	**	Site Specific
Waste Oil	TPH	EPA Method 3550*	10 mg/kg	any amount	**	Site Specific
	BTEX	EPA Method 8240	1 mg/kg	any amount	**	Site Specific
	Naphthalene	EPA Method 8240	any amount	any amount	**	Site Specific
	TPH	EPA Method 9071	10 mg/kg	any amount	**	Site Specific

\* California method or equivalent.  
\*\* Site Specific.

Contact: Read Miner, South Carolina Department of Health  
& Environmental Control 803-734-5331

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Summary of South Dakota Cleanup* Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Ethylbenzene	***	.7ppm	.7ppm	.7ppm	.7ppm
	Benzene	***	.005ppm	.005ppm	.005ppm	.005ppm
	Toluene	***	1ppm	1ppm	1ppm	1ppm
	Xylene	***	10ppm	10ppm	10ppm	10ppm
	TPH	***	1ppm	1ppm	1ppm	**
Diesel	TPH	***	1ppm	1ppm	1ppm	**
Waste Oil	TPH**	***	1ppm	1ppm	1ppm	

\* South Dakota does not specifically refer to the groundwater quality standards as "Cleanup Standards" but in a practical sense they are used as such. \*\* Compliance in the 1ppm level is required if the contamination is within the radius of influence of a well or within a delineated well head protection area, unless a variance is obtained. Otherwise the compliance level is 10ppm. \*\*\* No particular method is specified however, methods used must conform with "Standard Methods for Examination of Water and Waste Water" and "EPA Methods, Methods for Chemical Analysis of Waters and Wastes."

Contact: Doug Miller, Department of Environmental and Natural Resources 605-773-3296

Summary of South Dakota Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	*	10ppm	any amount	10-100 ppm	10-100 ppm**
Diesel	TPH	*				
Waste Oil	TPH	*				
	EPTOX Methods	*				

\* California/ USGS method or similar methods that can quantify TPH by integrating all detectable peaks within the time period in which 95% of the recoverable hydrocarbons are eluted. \*\* Action Levels/ Cleanup Levels are Site Specific and are based on the type of contaminant released, depth to an aquifer and the soil type present.

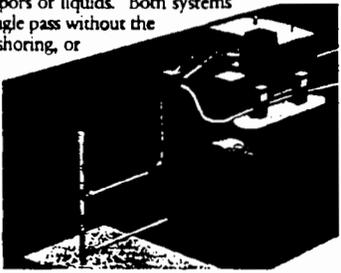
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### Summary of Tennessee Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	SW-846 5030 P&T/ 8020 GC	.002ppm	any amount	> 5ppb	Applic. CL based on GW Class, > 5ppb or >70ppb
	TPH	Tennessee Method for Gasoline Range Organics	.1ppm	any amount	> 100ppb	> 100ppb or >1000ppb
Diesel	TPH	Tennessee Method for Diesel Range Organics	.1ppm	any amount	> 100ppb	> 100ppb or >1000ppb
Waste Oil	TPH	503E or 418.1	1ppm	any amount	> 100ppb	> 100ppb or >1000ppb

Contact: Curtis Hopper, Tennessee Department of Environment and Conservation 615-532-0956

### Summary of Tennessee Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Total BTX	SW-846 5030 P&T/ 8020 GC	.002ppm	any amount	>10 ppm	Applic. CL based on GW Class. & Soil Perm. > 10ppm- >500ppm
	TPH	TN Method for Gasoline Range Organics	10ppm	any amount	>100 ppm	> 100ppm — >1000ppm
Diesel	TPH	TN Method for Diesel Range Organics	10ppm	any amount	>100 ppm	> 100ppm — >1000ppm
Waste Oil	TPH	503E or 418.1	100ppm	any amount	>100 ppm	> 100ppm — >1000ppm

Contact: Curtis Hopper, Tennessee Department of Environment and Conservation 615-532-0956

### Summary of Texas Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	Toluene	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	Ethylbenzene	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	Xylene	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	TPH	EPA Method 418.1	.5ppm	any amount	Site Specific	None***
Diesel	Benzene	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	Toluene	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	Ethylbenzene	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	Xylene	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	TPH	EPA Method 418.1	.5ppm	any amount	Site Specific	None***
	PAHs	EPA Method 8100, 8270, 8310	Chemical Specific	any amount	Site Specific	Site Specific/Risk-based**
Waste Oil	BTEX	EPA Method 8020	1ppb	any amount	*	Site Specific/Risk-based**
	TPH	EPA Method 418.1	.5ppm	any amount	Site Specific	None***
	VOCs PAH	EPA Method 8240 EPA Method 8100, 8270, 8310	Chemical Specific Chemical Specific	any amount any amount	Site Specific Site Specific	Site Specific/Risk-based** Site Specific/Risk-based**

\* EPA Maximum Contaminant Level.

\*\* No Range Available. Based on set procedures. \*\*\*Not used for establishing cleanup goals.

Contact: Chris Chandler, Texas Natural Resource Conservation Commission 512-239-2200

## EPA smiles at immunoassay

The Environmental Monitoring Systems Laboratory-Las Vegas (EMSL-LV) is investigating the usefulness of immunochemical techniques to monitor contamination in environmental and biological matrices. EMSL-LV believes immunoassay techniques hold great promise for the quantitative analysis

of target analytes.

EPA SITE studies indicate a strong correlation between field immunoassays, laboratory immunoassays and gas chromatography-mass spectrometry. Studies are underway in the use of antibody-coated, fiber-optic immunosensors.

Summary of Texas Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8020	.5mg/kg	any amount	*	Site Specific/Risk-based**
	Toluene	EPA Method 8020	.5mg/kg	any amount	*	Site Specific/Risk-based**
	Ethylbenzene	EPA Method 8020	.5mg/kg	any amount	*	Site Specific/Risk-based**
	Xylene	EPA Method 8020	.5mg/kg	any amount	*	Site Specific/Risk-based**
	TPH	EPA Method 418.1	10mg/kg	any amount	*	None***
Diesel	Benzene	EPA Method 8020	.5mg/kg	any amount	*	Site Specific/Risk-based**
	Toluene	EPA Method 8020	.5mg/kg	any amount	*	Site Specific/Risk-based**
	Ethylbenzene	EPA Method 8020	.5mg/kg	any amount	*	Site Specific/Risk-based**
	Xylene	EPA Method 8020	.5mg/kg	any amount	*	Site Specific/Risk-based**
	TPH	EPA Method 418.1	10mg/kg	any amount	*	None***
Waste Oil	PAHs	EPA Method 8100, 8270, 8310	Chemical Specific	any amount	*	Site Specific/Risk-based**
	BTEX	EPA Method 8020	.5mg/kg each	any amount	*	Site Specific/Risk-based**
	TPH	EPA Method 418.1	10mg/kg	any amount	*	None***
	VOCs PAH	EPA Method 8240 EPA Method 8100, 8270, 8310	Chemical Specific Chemical Specific	any amount any amount	*	Site Specific/Risk-based** Site Specific/Risk-based**

\* Product Specific/ Site Specific.

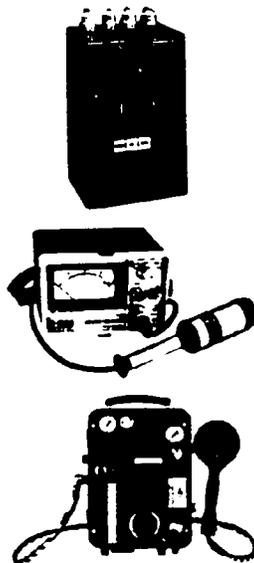
\*\* No Range Available. Based on set procedures. \*\*\*Not used for establishing cleanup goals.

Contact: Chris Chandler, Texas Natural Resource  
Conservation Commission 512-239-2200

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### Summary of Utah Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	TPH	CDHS Method 8015 Modified	500µg/l	any amount	500µg/l	*
	Benzene	EPA Method 602 or 624	2µg/l		5µg/l	*
	Toluene	EPA Method 602 or 624	2µg/l		1000µg/l	*
	Ethylbenzene	EPA Method 602 or 624	2µg/l		700µg/l	*
	Xylene	EPA Method 602 or 624	2µg/l		10,000µg/l	*
	Naphthalene	EPA Method 602 or 624	2µg/l		20µg/l	*
Diesel	TPH	CDHS Method 8015 Modified	500µg/l	any amount	500µg/l	*
	Benzene		2µg/l		5µg/l	*
	Toluene		2µg/l		1000µg/l	*
	Ethylbenzene		2µg/l		700µg/l	*
	Xylene		2µg/l		10,000µg/l	*
	Naphthalene		2µg/l		20µg/l	*
Waste Oil	TRPH	EPA Method 418.1	500µg/l	any amount		*
	Oil & Grease	EPA Method 413.1 BTEXN	10,000µg/l Same as Diesel BTEXN	any amount Above	10,000µg/l	10,000µg/l

\* Same as Action Level, but Site Specific

Note: Depends on level of environmental sensitivity and is determined on a case-by-case basis.

Contact: Robin Jenkins, Utah Department of  
Environmental Quality 801-536-4100

### Summary of Utah Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline**	TPH	CDHS Method 8015 Modified	10mg/kg	any amount	30mg/kg	*
	Benzene	EPA Method 8020	.2mg/kg	any amount	.2mg/kg	*
	Toluene	EPA Method 8020	.2mg/kg	any amount	100mg/kg	*
	Ethylbenzene	EPA Method 8020	.2mg/kg	any amount	70mg/kg	*
	Xylene	EPA Method 8020	.2mg/kg	any amount	1000mg/kg	*
Diesel	TPH	CDHS Method 8015 Modified	10mg/kg	any amount	100mg/kg	*
	Benzene	EPA Method 8020	.2mg/kg	any amount	.2mg/kg	*
	Toluene	EPA Method 8020	.2mg/kg	any amount	100mg/kg	*
	Ethylbenzene	EPA Method 8020	.2mg/kg	any amount	70mg/kg	*
	Xylene	EPA Method 8020	.2mg/kg	any amount	1000mg/kg	*
	Naphthalene	EPA Method 8020	.2mg/kg	any amount		*
Waste Oil	TRPH	EPA Method 418.1	100mg/kg	any amount	100mg/kg	*
	Oil & Grease	EPA Method 413.1 BTEXN	100mg/kg Same as Diesel BTEXN	any amount Above	300mg/kg	*

\* Same as Action Level, but Site Specific. \*\* Level I environmental sensitivity.

Note: Depends on level of environmental sensitivity and is determined on a case-by-case basis.

Contact: Robin Jenkins, Utah Department of  
Environmental Quality 801-536-4100

### Summary of Vermont Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8020	1ppb	any amount	5ppb	Site Specific
	Toluene	EPA Method 8020	1ppb	any amount	2420ppb	Site Specific
	Ethylbenzene	EPA Method 8020	1ppb	any amount	680ppb	Site Specific
	Xylenes	EPA Method 8020	1ppb	any amount	400ppb	Site Specific
	MTBE	EPA Method 8020	1ppb	any amount	40ppb	Site Specific
Diesel	Benzene	EPA Method 8020	1ppb	any amount	5ppb	Site Specific
	Toluene	EPA Method 8020	1ppb	any amount	2420ppb	Site Specific
	Ethylbenzene	EPA Method 8020	1ppb	any amount	680ppb	Site Specific
	Xylenes	EPA Method 8020	1ppb	any amount	400ppb	Site Specific
Waste Oil	VOCs	EPA Method 8240	1ppb	any amount	*	Site Specific

\* Compound specific groundwater enforcement standard

Contact: Chuck Schwer, Vermont Agency of  
Environmental Conservation 802-241-3888

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Summary of Vermont Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 8020	100ppb	any amount	*	Site Specific
Diesel	BTEX	EPA Method 8020	↓ 10ppm	any amount	*	Site Specific
	TPH	EPA Method 418.1 or Extended GC		any amount	1000 ppm	
Waste Oil	VOCs	EPA Method 8240	100 µg/kg	any amount	*	Site Specific

\* 20 times the groundwater enforcement standard for specific compounds. Contact: Chuck Schwer, Agency of Environmental Conservation 802-241-3888

Summary of Virginia Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 8020	*	any amount		Site Specific/Risk Based
	TPH	Cal Luft Method	.5 mg/l	any amount		Site Specific/Risk Based
Diesel	BTEX	EPA Method 8020	*	any amount		Site Specific/Risk Based
	TPH	Cal Luft Method	.5 mg/l	any amount		Site Specific/ Risk Based
Waste Oil	TPH	Cal Luft Method	.5 mg/l	any amount		Site Specific/Risk Based

Summary of Virginia Cleanup Standards for Hydrocarbon Contaminated Soil						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 8020	*	any amount		Site Specific/Risk Based
	TPH	Cal Luft Method	10 mg/kg	any amount		Site Specific/Risk Based
Diesel	BTEX	EPA Method 8020	*	any amount		Site Specific/Risk Based
	TPH	Cal Luft Method	10 mg/kg	any amount		Site Specific/ Risk Based
Waste Oil	TPH	Cal Luft Method	*	any amount		Site Specific/Risk Based

\* PQL for constituents as stated in SW846. Note: Methods above are required for remediation monitoring under permit. During Site Characterization, Closure, etc. all EPA approved methods and Cal Luft Method for TPH are acceptable.

Contact: Dave Chance, Virginia DEQ 804-527-5188

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### Summary of Washington Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	BTEX	EPA Method 8020 or 8260 *	*	any amount	NS	B: 5ppb, T: 40ppb E: 30ppb, X: 20ppb
	TPH	WTPH-G	*	any amount	NS	1000ppb
	Total Lead	EPA Method 7421	*	any amount	NS	5ppb
Diesel	TPH	WTPH-D	*	any amount	NS	1000ppb
Waste Oil	TCLP		*	any amount	NS	Analyte Specific
	PCB	EPA Method 8080	*	any amount	NS	.1 µg/l
	Total Metals	EPA Method 6010, 7000 Series	*	any amount	NS	Metal Specific
	Volatile Organics	EPA Method 8021, 8260	*	any amount	NS	Analyte Specific
	Phenols	EPA Method 8040 or 8270	*	any amount	NS	Analyte Specific
	PAHs	EPA Method 8100 or 8270 *	*	any amount	NS	.1 µg/l

\* Test Specific. NS=Not Specified.

Contact: Mary Ellen McKain, Washington Department of Ecology, 206-407-7218

### Summary of Washington Cleanup Standards for Hydrocarbon Contaminated Soil

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level Method A / Method B
Gasoline	Benzene	EPA Method 8020 or 8260 *	*	any amount	NS	.5mg/kg / .5mg/kg
	Ethylbenzene	EPA Method 8020 or 8260 *	*	any amount	NS	20mg/kg / 20mg/kg
	Toluene	EPA Method 8020 or 8260 *	*	any amount	NS	40mg/kg / 40mg/kg
	Xylenes	EPA Method 8020 or 8260 *	*	any amount	NS	20mg/kg / 20mg/kg
	TPH	WTPH-G	*	any amount	NS	100mg/kg / 100mg/kg
	Total Lead	EPA Method 6010, 7420 or 7421	*	any amount	NS	250mg/kg / 1000mg/kg
Diesel	TPH	WTPH-D	*	any amount	NS	200mg/kg / 200mg/kg
Waste Oil	TCLP	EPA Method 1311	*	any amount	NS	Analyte Specific
	PCBs	EPA Method 8080	*	any amount	NS	1mg/kg
	Volatile Organics	EPA Method 8021 or 8260	*	any amount	NS	Analyte Specific
	Phenols	EPA Method 8040 or 8270 *	*	any amount	NS	Analyte Specific
	PAHs	EPA Method 8100 or 8270 *	*	any amount	NS	1mg/kg
	Total Metals	EPA Method 6010 and 7000 series	*	any amount	NS	Metal Specific

\* Test Specific. NS=Non Specified. Note: Washington State has rating matrix for establishing cleanup standards. Method A = Routine Cleanups with numbers in Method A Tables. Method B = Residential (Risk Based) Method C = 1) Commercial (Risk Based), 2) Industrial (Risk Based). Methods A or B cleanup levels are below Area Background Levels.

Contact: Mary Ellen McKain, Washington Department of Ecology, 206-407-7218

### Summary of West Virginia Cleanup Standards for Hydrocarbon Contaminated Groundwater

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8020	1ppb	any amount	5ppb	5ppb
	Toluene	EPA Method 8020	1ppb	any amount	1000 ppb	1000 ppb
	Ethylbenzene	EPA Method 8020	1ppb	any amount	700 ppb	700 ppb
	Xylenes	EPA Method 8020	1ppb	any amount	10,000 ppb	10,000 ppb
	TPH	EPA Method 8015	.5ppm	any amount		Site Specific
Diesel	Toluene	EPA Method 8020	1ppb	any amount	1000 ppb	1000 ppb
	Benzene	EPA Method 8020	1ppb	any amount	5ppb	5ppb
	Ethylbenzene	EPA Method 8020	1ppb	any amount	700 ppb	700 ppb
	Xylenes	EPA Method 8020	1ppb	any amount	10,000 ppb	10,000 ppb
	TPH	EPA Method 8015 Modified, GRO & DRO	.5ppm	any amount		Site Specific

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**Summary of West Virginia Cleanup Standards for Hydrocarbon Contaminated Soil**

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 8020		any amount	50ppb	Site Specific
	Toluene	EPA Method 8020		any amount	10ppm total BTEX	Site Specific
	Ethylbenzene	EPA Method 8020		any amount	10ppm total BTEX	Site Specific
	Xylenes	EPA Method 8020		any amount	10ppm total BTEX	Site Specific
	TPH	EPA Method 8015 Modified*			50ppm	Site Specific
Diesel	Benzene	EPA Method 8020		any amount	50ppb	Site Specific
	Toluene	EPA Method 8020		any amount	10ppm total BTEX	Site Specific
	Ethylbenzene	EPA Method 8020		any amount	10ppm total BTEX	Site Specific
	Xylenes	EPA Method 8020		any amount	10ppm total BTEX	Site Specific
	TPH	EPA Method 8015 Modified*			100ppm	Site Specific

\* Report GRO and DRO separately

Contact: Mike Sutphan, West Virginia Department of Natural Resources 304-558-6371

**Summary of Wisconsin Cleanup Standards for Hydrocarbon Contaminated Groundwater**

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	GRO, VOC <sup>3</sup>	DNR WI Modified GRO Method EPA Method 5030/ 8021	**	any amount	None	Site Specific
	PVOC <sup>4</sup>	*	**	any amount		Compound Specific
	Benzene	EPA Method 8021 or 5030/8020	**	any amount	5ppb	Site Specific
	Toluene	*	**	any amount	343 <sup>6</sup>	.5
	Xylenes	*	**	any amount	620 <sup>6</sup>	68.8 124
	Ethylbenzene	*	**	any amount	1360 <sup>6</sup>	140
	MTBE <sup>3</sup>	EPA Method 8021	**	any amount	60ppb	12
	Trimethylbenzene(s)					
	Lead <sup>3</sup>	EPA Method 3020/ 7421	**	any amount	15ppb <sup>6</sup>	1.5
	Diesel	GRO, VOC <sup>3</sup> , PVOC <sup>4</sup>	Same as above for Gasoline		None	None
PAH <sup>5</sup>		EPA Method 8310 (HDLC)	**	any amount	See Below	See Below
BTEX & MTBE		Same as above for Gasoline				
Waste Oil	PCBs <sup>5</sup>	EPA Method 3510/ 8080, or 3520/ 8080	**	any amount	.03 <sup>6</sup>	.003 <sup>6</sup>
	DRO, VOC <sup>3</sup> , PVOC	Same as above for Gasoline		None	None	
	Lead <sup>3</sup>	Same as above				
PAHs	CD <sup>3</sup>	EPA Method 3020/ 7131	**	any amount	5ppb <sup>6</sup>	.5ppb <sup>6</sup>
	Benzo (A) Pyrene Naphthalene	EPA Method 8310 (HDLC) EPA Method 8310 (HDLC)	** **	any amount any amount	.003ppb 40ppb	.0003ppb 8ppb

\* EPA Method 3030/ 8021 or 5030/ 8020 \*\* Test Specific: 1. Wisconsin Admin. Code NR140 Enforcement Standard (active remedy required); 2. Wisconsin Admin. Code NR140 Preventative Action Level (cleanup goal); 3. Sample at least once; 4. Petroleum Volatile Organic Compounds defined in analytical guidance; 5. Site Specific; 6. See analytical guidance; 7. Proposed new level, scheduled for early 1995.

**Summary of Wisconsin Criteria\* for Hydrocarbon Contaminated Soil**

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	GRO	WI DNR Modified GRO Method	**	any amount	10 ppm <sup>4</sup>	Site Specific
	PVOC <sup>1</sup> VOC <sup>3</sup>	EPA Method 8260 or 5030/8020 or 5030/8021	**	any amount	Any Amount <sup>5</sup>	***
	PB <sup>2</sup>	EPA Method 3050/ 7420 or 3050/7421 or 3050/6010	**	any amount	Any Amount <sup>5</sup>	Site Specific
Diesel	DRO	WI DNR Modified DRO Method	**	any amount	10 ppm <sup>4</sup>	Site Specific
	PVOC	EPA Method 8260 or 5030/8020 or 5030/8021	**	any amount	Any Amount <sup>5</sup>	***

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Waste Oil	PAH <sup>3</sup>	EPA Method 8310HDLC 3540/8270 or 3550/8270	**	any amount	Any Amount <sup>5</sup>	Site Specific
	PAH <sup>3</sup>	EPA Method 8310HDLC 3540/8270 or 3550/8270	**	any amount	Any Amount <sup>5</sup>	Site Specific
	VOC <sup>2,3</sup>	EPA Method 5030/8021 or 8260	**	any amount	Any Amount <sup>5</sup>	Site Specific
	PVOC	EPA Method 5030/8020 or 5030/8021 or 8260	**	any amount	Any Amount <sup>5</sup>	***
	PCB	EPA Method 3540/8080 or 3550/ 8080	**	any amount	Any Amount <sup>5</sup>	Site Specific

\* The soil cleanup standards given currently have the status of guidance and are expected to be adapted in code before the end of 1994. \*\* Test Specific. \*\*\*Benzene-5.5, Toluene-1500, Ethylbenzene-2900, Xylene-1100, 1,2, dichloroethane-4.9.  
Notes: (1) Petroleum Volatile Organic Compounds-defined in Analytical Guidance. (2) Sample at least once. (3) See Analytical Guidance. (4) At tank removal. (5) Site specific-may require investigation, may require cleanup.

Contact: Greg Parker, Wisconsin Department of Natural Resources 608-267-7560

Summary of Wyoming Cleanup Standards for Hydrocarbon Contaminated Groundwater						
Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Cleanup Level
Gasoline	Benzene	EPA Method 524.2	.5 µg/l	any amount	>5µg/l	5µg/l
	Ethylbenzene	EPA Method 524.2	.5 µg/l	any amount	>700µg/l	700µg/l
	Toluene	EPA Method 524.2	.5 µg/l	any amount	>1000µg/l	1000µg/l
	Xylenes	EPA Method 524.2	.5 µg/l	any amount	>10,000µg/l	10,000µg/l
Leaded Gas	Total Lead	EPA Method 239.2/6010	5 µg/l	any amount	>50µg/l	50µg/l
	TPH	Modified 8015	4 µg/l	any amount	>10mg/l	10mg/l
Waste Oil	BTEX same as Gasoline					
	TPH	Modified 8015	4 µg/l	any amount	>10mg/l	10mg/l
	Total Lead	EPA Method 239.2/6010	5 µg/l	any amount	>50µg/l	50µg/l
	Total Cadmium	EPA Method 213.2/6010	1 µg/l	any amount	>1µg/l	1µg/l
	Total Chromium	EPA Method 218.1/6010	50 µg/l	any amount	>100µg/l	100µg/l

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**Summary of Wyoming Clean-up Standards for Hydrocarbon Contaminated Soil**

Product	Parameter/ Constituent	Lab Test Protocol & Number	Detection Level	Notification Level	Action Level	Clean-up Level
Gasoline	Benzene	EPA Method 8020	.1mg/kg	any amount	*	*
	Ethylbenzene	EPA Method 8020	.1mg/kg	any amount	*	*
	Toluene	EPA Method 8020	.1mg/kg	any amount	*	*
	Xylenes	EPA Method 8020	.1mg/kg	any amount	*	*
Leaded Gas	Total Lead	EPA Method 289.2/6010	5mg/kg	any amount	*	*
	TPH	Modified 8015	4mg/kg	any amount	>30mg/l >100mg/l	30mg/l gw<50' 100mg/l gw>50'
Fuel Oils	BTEX same as Gasoline					
	TPH	Modified 8015	4 mg/kg	any amount	>100mg/kg	100mg/kg
Lubricating Oil	BTEX and TPH same as Fuel Oil					
Waste Oil	BTEX same as Gasoline					
	TPH	Modified 8015	4 mg/kg	any amount	>100mg/kg	100mg/kg
	Total Lead	EPA Method 239.9/ 6010	5 mg/kg	any amount	*	*
	Total Cadmium	EPA Method 213.1/ 6010	.5 mg/kg	any amount	*	*
	Total Chromium	EPA Method 218.1/ 6010	5 mg/kg	any amount	*	*

\* Site Specific. Note: Site Specific soil action/ cleanup levels for organic compounds/ elements are determined from an environmental fate/ transport-risk model contained in the WDEQ/ WQD technical guidance document, Procedures for Establishing Environmental Restoration Standards for Leaking Underground Storage Tank Remediation Actions.

Contact: LeRoy Feusber, Department of Environmental Quality 307-777-7096

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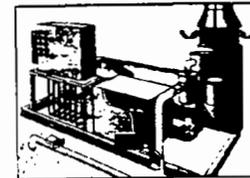
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## Soil leachability, from page 37

fine grained soils to adsorb significant quantities of petroleum contaminants leaked to the environment.

- The effectiveness of natural mechanisms for contaminant attenuation—biodegradation, dilution and dispersion—which are active at many leaking tank sites.
- Other site specific factors which may help limit the spread of contamination from the site—soil properties, hydrogeology, site capping, depth to groundwater—which may help protect water resources.

In addition, the short term remediation of contaminated soils to levels which were designed as water quality standards, often low ppb levels, may be neither technologically or economically feasible at many sites.

A better approach to the identification of cost-effective, site-specific soil cleanup levels to protect water resources may include the use of laboratory based contaminant leachability tests. The EPA's TCLP (Toxicity Characteristic Leaching Procedure) Method 1311 and the SPLP (Synthetic Precipitation Leaching Procedure) Method 1312, are tools which may be appropriate to evaluate contaminant leachability from soils. (See EPA SW846 for testing methods.) The TCLP is a waste classification procedure and has provisions which make it appropriate for the evaluation of wastes which contain volatile, semi-volatile and non-volatile contaminants. In many respects, the SPLP is similar to the TCLP, except the SPLP is designed to use simulated rain water as the solvent during the leachability test.

The EPA procedures are designed to measure the concentrations of contaminants in a leachate from a short term (less than 24 hours) lab test. There are some technical considerations that must be resolved before the results from laboratory leachability testing may be used to identify site-specific soil cleanup levels. Many of the technical issues involve appropriate sampling of the contaminated soil mass and integrating the results from the leachability tests with known, site-specific conditions, such as site hydrogeology and uses of groundwater resources. In some states, such as California, the corrective action regulations allow responsible parties at some contaminated underground storage tank sites to propose appropriate cleanup levels based on results of an impact assessment. (California Code of Regulations, Division 3, Chapter 16, Article 11.) In many cases, it may be appropriate for the responsible party to propose soil cleanup levels which are based on the results of leachability testing for the contaminants of concern. A technically sound proposal for establishing soil cleanup levels based on leachability testing merits serious consideration and possible acceptance by all parties—property owners, financial institutions and regulatory agencies involved in corrective action at petroleum contaminated sites. Appropriate and effective use of results from soil leachability testing could be helpful in establishing soil cleanup levels which are cost-effective and protective of long term groundwater quality. ■

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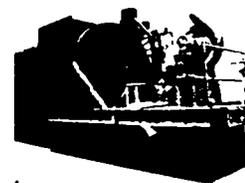
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# APPENDIX C

## EXAMPLE CALCULATIONS

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SAMPLE CALCULATIONS FOR EXCAVATION  
(Section 3)

A site has approximately 10,000 m<sup>3</sup> of soil contaminated with chloroform, 1,1,1-trichloroethane, and trichloroethylene in concentrations of 0.1, 10, and 1.0 ppm (μg/g), respectively. The distribution of the contamination within the soil is not accurately known. The soil's bulk density averages 1.5 g/cm<sup>3</sup>. Removal of all contaminants is expected to take 20 days of continual operation (1.728x10<sup>6</sup> sec).

First estimate the total emissions potential for the site using Equations 3-1 and 3-2 from page 3-12:

$$M_{\text{Chloro}} = (10,000 \text{ m}^3)(0.1 \text{ } \mu\text{g/g})(1.5 \text{ g/cm}^3)(1 \text{ g/} \mu\text{g cm}^3/\text{m}^3) = 1,500 \text{ g}$$

$$ER_{\text{Chloro}} = M/t_{\text{sv}} = 1,500 \text{ g} / 1.728 \times 10^6 \text{ sec} = 8.7 \times 10^{-4} \text{ g/sec};$$

$$ER_{\text{TCE}} = (10,000)(1.0)(1.5)(1) / (1.728 \times 10^6) = 8.7 \times 10^{-3} \text{ g/sec};$$

$$ER_{\text{TCA}} = (10,000)(10)(1.5)(1) / (1.728 \times 10^6) = 8.7 \times 10^{-2} \text{ g/sec}.$$

These represent the average long-term emission rate if 100% of the contamination were volatilized and stripped from the soil.

The calculations using the excavation model and the default values given in the report are shown below for chloroform. First, the excavation rate is calculated from the known information:  $Q = 10,000 \text{ m}^3 / 1.73 \times 10^6 \text{ sec} = 0.0058 \text{ m}^3/\text{sec}$ . Next, the concentration must be converted from ppmw to g/cm<sup>3</sup> using Equation 3-6:

$$C_s = (0.1 \text{ } \mu\text{g/g})(1.5 \text{ g/cm}^3)(10^{-6} \text{ g/} \mu\text{g}) = 1.5 \times 10^{-7} \text{ g/cm}^3$$

Now, the pore space and diffusion emissions can be calculated using Equations 3-3 and 3-4 from page 3-12:

$$ER_{\text{PS}} = (35)(100)(10^6)(0.44)(0.0058)(0.33) / (62,361)(298) = 0.16 \text{ g/sec}$$

$$ER_{\text{DIFF}} = (1.5 \times 10^{-7})(10,000)(290) / (0.44 / 0.613 * 0.15) + (3.14 * 60 / 0.0269 * 0.613)^{0.5} \\ = 0.4350 / 4.785 + (11,425)^{0.5} = 0.0039 \text{ g/sec}.$$

The value, ER<sub>PS</sub>, must be compared to the total mass of contamination present in the soil using Equation 3-7 on page 3-14:

$$ER_{\text{PS}} * t_{\text{sv}} = (0.16 \text{ g/sec})(1.728 \times 10^6 \text{ sec}) = 2.8 \times 10^5 \text{ g}$$

This value (2.8x10<sup>5</sup> g) is > 0.33 M (0.33 \* 1,500 = 500 g), so Equation 3-4 is giving a value that is far too conservative. Therefore, ER<sub>PS</sub> should be calculated using Equation 3-8:

EMISSIONS FROM EXCAVATION  
(Section 3)  
(Continued)

$$ER_{PS} = M * 0.33/t_{sv} = (1,500 \text{ g})(0.33) / (1.728 \times 10^6 \text{ sec}) = 2.9 \times 10^{-4} \text{ g/sec}$$

The total emission rate of chloroform is thus:

$$ER = ER_{PS} + ER_{DIFF} = 0.00029 + 0.0039 = 0.0042 \text{ g/sec}$$

This is somewhat greater than the  $8.7 \times 10^{-4}$  g/s rate found from Equation 3-1. Equation 3-1, however, predicts the average emission rate if all contamination in the soil were to volatilize. However, 100% of the VOCs will not volatilize and be stripped from the soil, so it is reasonable that the emission rate estimate exceeds the average emission potential.

More accurate estimates could be obtained using compound-specific and site-specific input values rather than the default values. For example, the vapor pressure of chloroform is 208 mm Hg versus the default value of 35 mm Hg, and the molecular weight of chloroform is 119.38 g/mol versus the default value of 100 g/mol.

SAMPLE CALCULATIONS FOR THERMAL DESORPTION  
(Section 4)

A site to be remediated contains soil with the following levels of contamination:

Benzene	1.0 $\mu\text{g/g}$
Toluene	24.0 $\mu\text{g/g}$
Xylene	110.0 $\mu\text{g/g}$
Ethyl Benzene	20.0 $\mu\text{g/g}$

The full-scale desorption unit has a capacity of 7.5 tons per hour, and the percent volatilized is 99.00 for the other compounds of interest (i.e., equals the default value for BTEX). A fume incinerator with a 98% control efficiency will be used. Note that 1  $\mu\text{g/g}$  = 1 mg/kg.

To find the emission rate using the equation on page 4-18, the first thing to do is to get the input values into the proper units. The mass treatment rate of 7.5 tons/hr = 6820 kg/hr. Thus:

$$E_{\text{Benz.}} = (1.0 \text{ mg/kg} / 1,000 \text{ mg/g})(6,820 \text{ kg/hr})(99.00/100)(1-98/100) = 0.135 \text{ g/hr}$$

$$= (0.135 \text{ g/hr}) / (3,600 \text{ sec/hr}) = 3.8 \times 10^{-5} \text{ g/sec};$$

$$E_{\text{Tol.}} = (24/1,000)(6,820)(99.00/100)(1-98/100) = 3.24 \text{ g/hr} = 9.0 \times 10^{-4} \text{ g/sec};$$

$$E_{\text{Xyl.}} = (110/1,000)(6,820)(99.00/100)(1-98/100) = 14.8 \text{ g/hr} = 4.1 \times 10^{-3} \text{ g/sec}; \text{ and}$$

$$E_{\text{Ethyl Benz.}} = (20/1,000)(6,820)(99.00/100)(1-98/100) = 2.70 \text{ g/hr} = 7.5 \times 10^{-4} \text{ g/sec}.$$

**SAMPLE CALCULATIONS FOR SOIL VAPOR EXTRACTION**  
(Section 5)

A contaminated site to be remediated contains soil contaminated to the following extent:

Benzene:	100 ppm	(100 $\mu\text{g/g}$ )
Toluene:	300 ppm	(300 $\mu\text{g/g}$ )
Carbon Tetrachloride:	50 ppb	(0.050 $\mu\text{g/g}$ )
Naphthalene:	800 ppb	(0.800 $\mu\text{g/g}$ )

The site is a 200 m<sup>2</sup> field behind a factory. The water table is 30 m below the surface at this location. The entire volume of soil down to the water table is assumed to be contaminated. A vendor has quoted an estimate of five months to complete the clean-up. No physical data on the type of soil is known.

The uncontrolled stack emission rates are calculated with the equation on page 5-12. Use of this equation requires knowledge of the vapor extraction rate; for this scenario, a medium-sized SVE system of 85 m<sup>3</sup>/min may be assumed. One further needs the concentration of the extracted vapors. The saturated vapor concentrations can be calculated using the equation on page 5-17 or can be obtained from the following reference: Eklund and Albert, 1993\*. The saturated vapor concentrations given in this reference are:

benzene	4.00 x 10 <sup>8</sup> $\mu\text{g/m}^3$
toluene	1.49 x 10 <sup>8</sup> $\mu\text{g/m}^3$
carbon tetrachloride	9.34 x 10 <sup>8</sup> $\mu\text{g/m}^3$
naphthalene	1.58 x 10 <sup>5</sup> $\mu\text{g/m}^3$

These values all assume that the soil is saturated with each contaminant. Given the low concentrations present in the soil, the extracted vapor will actually be well below saturation and the estimates will be quite conservative.

Putting the values given above into a mass balance equation for air emissions yields:

$$ER_{\text{benz}} = (4.00 \times 10^8 \mu\text{g/m}^3)(10^{-6} \text{ g}/\mu\text{g})(85 \text{ m}^3/\text{min}) / (60 \text{ sec}/\text{min}) = 570 \text{ g}/\text{sec}$$

$$ER_{\text{tolu}} = (1.49 \times 10^8)(10^{-6})(85) / (60) = 210 \text{ g}/\text{sec}$$

$$ER_{\text{CCl}_4} = (9.34 \times 10^8)(10^{-6})(85) / (60) = 1,300 \text{ g}/\text{sec}$$

$$ER_{\text{naph}} = (1.58 \times 10^5)(10^{-6})(85) / (60) = 0.22 \text{ g}/\text{sec}.$$

\* Eklund, B. and C. Albert. Models for Estimating Air Emission Rates from Superfund Remedial Actions. EPA-451/R-93-001 (NTIS PB93-186807). March 1993.

EMISSIONS FROM IN-SITU BIOTREATMENT SYSTEMS  
(Section 6)

Assume the same scenario as given above for soil vapor extraction: A contaminated site to be remediated contains soil contaminated to the following extent:

Benzene:	100 ppm	(100 $\mu\text{g/g}$ )
Toluene:	300 ppm	(300 $\mu\text{g/g}$ )
Carbon Tetrachloride:	50 ppb	(0.050 $\mu\text{g/g}$ )
Naphthalene:	800 ppb	(0.800 $\mu\text{g/g}$ )

The site is a 200 m<sup>2</sup> field behind a factory. The water table is 30 m below the surface at this location. The entire volume of soil down to the water table is assumed to be contaminated. A vendor has quoted an estimate of five months to complete the clean-up. No physical data on the type of soil is known. During a pilot-scale test of the suitability of bioventing, the off-gas was found to have a concentration of roughly 1x10<sup>4</sup>  $\mu\text{g/m}^3$  for benzene and toluene, and 1x10<sup>5</sup>  $\mu\text{g/m}^3$  for carbon tetrachloride. No naphthalene was detected (DL = 1x10<sup>-6</sup>  $\mu\text{g/m}^3$ ).

The extraction rate for the soil venting is calculated using the 2nd equation given on page 6-8. The volume of contaminated soil is 200 m<sup>2</sup> \* 30 m = 6,000 m<sup>3</sup>. The air filled porosity can be assumed to be 0.44 (see Table 3-4). Using these input values, the extraction rate can be calculated:

$$Q (\text{m}^3/\text{min}) = (1.0/1440 \text{ min})(6,000 \text{ m}^3)(0.44) = 1.83 \text{ m}^3/\text{min}$$

Using the available information, the emissions can be calculated as follows:

$$ER_{\text{benz}} = (1 \times 10^4 \mu\text{g/m}^3)(10^{-6} \text{ g}/\mu\text{g})(1.83 \text{ m}^3/\text{min}) / (60 \text{ sec}/\text{min}) = 3.05 \times 10^{-4} \text{ g}/\text{sec}$$

$$ER_{\text{tolu}} = (1 \times 10^4)(10^{-6})(1.83) / (60) = 3.05 \times 10^{-4} \text{ g}/\text{sec}$$

$$ER_{\text{CCl}_4} = (1 \times 10^5)(10^{-6})(1.83) / (60) = 3.05 \times 10^{-3} \text{ g}/\text{sec}$$

$$ER_{\text{naph}} = (1 \times 10^6)(10^{-6})(1.83) / (60) = < 1 \times 10^{-12} \text{ g}/\text{sec}.$$

EMISSIONS FROM EX-SITU BIOTREATMENT SYSTEMS  
(Section 7)

Consider a site with a contaminated lagoon. The lagoon holds 500,000 L with an area of 100 m<sup>2</sup>. The sludge beneath it is contaminated to a depth of about 3 m. The contaminants present in the sediments are benzene and chlorobenzene. The overlying water is considered to be uncontaminated. The concentrations are 10 µg/g benzene and 20 µg/g chlorobenzene in the sludge (µg/g = mg/kg). The bulk density of the sediments was measured and is 2.0 g/cm<sup>3</sup>. Therefore, the 300 m<sup>3</sup> of contaminated sludge would weigh 600,000 kg. A batch biotreatment system will be used with a treatment rate of 2,000 kg batches treated for one day (86,400 sec) each. The Henry's Law constants for both compounds are in the 10<sup>-3</sup> range, and V is assumed to be 20%.

Using the equation for batch treatment, the emission rates are estimated to be:

$$ER_{\text{BENZ}} = (10 \text{ mg/kg} / 1,000 \text{ mg/g})(2,000 \text{ kg})(20/100) / 86,400 \text{ sec} = 4.6 \times 10^{-5} \text{ g/sec; and}$$

$$ER_{\text{CHL}} = (20/1,000)(2,000)(20/100) / 86,400 = 9.3 \times 10^{-5} \text{ g/sec.}$$

**EMISSIONS FROM THERMAL DESTRUCTION**  
(Section 8)

Consider the following remediation scenario. The soil in a hypothetical site has been tested, and it contains:

PCBs	2%
1,2,4-Trichlorobenzene	2800 ppb

The contractor will use a rotary kiln incinerator with a feed rate of 6000 kg/hr. An ultimate analysis of the soil shows it to contain: 1.0% S, 0.5% Cl, 0.15% Ba, and 0.08% Pb. The device burns propane, which is assumed to not contribute measurably to the emissions of any of the above compounds. The exit gas flow rate is not known. A scrubber will be used to control emissions of acid gases, and the vendor indicates that control efficiencies of 95% for SO<sub>2</sub> and 99% for HCl can readily be achieved.

First, find the concentration of organic contaminants in the waste feed in the specified units of g/kg (note that 1% = 10,000 ppm, 1,000 ppb = 1 ppm, and ppm = μg/g):

$$C_{\text{PCB}} = (20,000 \mu\text{g/g})(10^{-6} \text{ g}/\mu\text{g})(1,000 \text{ g/kg}) = 20 \text{ g/kg};$$

$$C_{\text{TCB}} = (2.8)(10^{-6})(1,000) = 0.0025 \text{ g/kg}.$$

Next calculate the organic emissions using the 1st equation on page 8-13 and a DRE for PCBs of 99.9999%, and a DRE for TCB of 99.99%.

$$ER_{\text{PCB}} = (1 - 99.9999/100)(6,000 \text{ kg/hr})(20 \text{ g/kg}) = 0.12 \text{ g/hr}$$

$$= (0.12 \text{ g/hr}) / (3,600 \text{ sec/hr}) = 3.3 \times 10^{-5} \text{ g/s; and}$$

$$ER_{\text{TCB}} = (1 - 99.99/100)(6,000)(0.0025) = 0.0015 \text{ g/hr} = 4.2 \times 10^{-7} \text{ g/s}.$$

The uncontrolled metals emission rates are found using the second equation on page 8-13 (the controlled emissions may be significantly lower). First, find the concentration of contaminants in the waste feed in the specified units of g/kg (note that 1% = 10,000 ppm and ppm = μg/g):

$$C_{\text{Ba}} = (1,500 \mu\text{g/g})(10^{-6} \text{ g}/\mu\text{g})(1,000 \text{ g/kg}) = 1.5 \text{ g/kg; and}$$

$$C_{\text{Pb}} = (800)(10^{-6})(1,000) = 0.8 \text{ g/kg}.$$

The partitioning factor for both metals is 100% (from EPA, 1989); that is, the metals can be expected to be present in the gas-phase. The emission rates are then:

$$E_{\text{Ba}} = (1.5 \text{ g/kg})(6,000 \text{ kg/hr})(100/100) = 9,000 \text{ g/hr}$$

$$= (9,000 \text{ g/hr}) / (3,600 \text{ sec/hr}) = 2.5 \text{ g/sec; and}$$

$$E_{\text{Pb}} = (0.8)(6,000)(100/100) = 4,800 \text{ g/hr} = 1.3 \text{ g/sec}$$

EMISSIONS FROM THERMAL DESTRUCTION  
(Section 8)  
(Continued)

For acid gases, again the first step is to convert the concentration of the element in the waste to the proper units:

$$C_{Cl} = (5,000 \mu\text{g/g})(10^{-6} \text{ g}/\mu\text{g})(1,000 \text{ g/kg}) = 5.0 \text{ g/kg}; \text{ and}$$
$$C_S = (10,000)(10^{-6})(1,000) = 10 \text{ g/kg}.$$

Their stoichiometric ratios are 1.028 (g HCl / g Cl) for HCl and 1.998 (g SO<sub>2</sub> / g S) for SO<sub>2</sub>:

$$E_{HCl} = (5 \text{ g/kg})(1.028)(6,000 \text{ kg/hr})(1-99/100) = 308 \text{ g/hr}$$
$$= (308 \text{ g/hr}) / (3,600 \text{ sec/hr}) = 0.086 \text{ g/sec}; \text{ and}$$

$$E_{SO_2} = (10)(1.998)(6,000)(1-95/100) = 5,990 \text{ g/hr} = 1.7 \text{ g/sec}.$$

## **APPENDIX D**

### DERIVATION OF VOC EMISSION MODEL FOR EXCAVATION

APPENDIX D

MODEL DERIVATION

Derivation of a Screening Model for  
VOC Emissions From Soils Handling Activities

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# Screening Model for VOC Emissions from Soils Handling Activities

## APPENDIX A - MODEL DERIVATION

### A.1 INTRODUCTION

Background information about the modeling problem is presented in this appendix followed by a presentation of an emission model for estimating VOC emissions from the excavation of contaminated soil. A simplified version of the model is developed, then the models are evaluated.

#### **Objective**

Develop simple predictive model for estimating VOC emissions from soils handling activities, such as excavation.

#### **Intended Use**

The model will be used for assessing potential emissions during remediation of Superfund sites. At a minimum, the model should provide an emission factor to estimate emissions per unit time or unit operation. Ideally, it should also be appropriate for evaluating the effect of different remediation scenarios, e.g. starting waste concentrations, excavation rates, and control efficiencies.

#### **Requirements**

1. Model should be conservative, since the data may be used in some cases for health risk assessment.
2. Model should require as few input parameters as is feasible for ease of use.

#### **Assumptions**

1. During excavation, the surface area of soil in contact with the atmosphere is greatly increased. This results in up to one-third of the soil gas being released to the atmosphere. In dry soils containing very low levels of VOCs, most of the contaminants are present in the soil pore spaces, thus the percentage of the VOCs emitted is relatively high.
2. Once the soil has been dumped into place, the organic liquid to soil gas equilibrium is quickly re-established. The emissions can be estimated by a modification of the RTI landtreatment model.<sup>1</sup>

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<sup>1</sup>p. 5-14 and 5-15 of EPA-450/3-87-026, Review Draft, November 1989.

3. The freshly dumped soil is soon covered by relatively deep layers of subsequently excavated soil. These layers of soil result in longer-term emissions from the deeper layers being diffusion controlled, i.e., low. Therefore, the significant period for emissions is during excavation and the first six minutes or so afterwards. Subsequent (i.e.  $t > 6$  min) emissions from this material are assumed to be zero.
4. The total exposed surface area of contaminated soil is assumed to remain constant. New material is exposed at the same rate that previously exposed material is covered.
5. The emissions from the pit are approximately equivalent to the emissions from the pile of excavated soil. The emissions from the soil in the backhoe bucket are negligible.
6. Wet soils are assumed to have relatively low levels of VOC emissions, even if the soil VOC concentrations are high. Wet soils may have little air-filled porosity and therefore the rate of diffusion of VOCs through wet soils is relatively low.

#### **Possible Excavation Scenarios**

Two general scenarios are followed during excavations at waste sites.

1. Soil is excavated using a backhoe and placed into a short-term storage pile. The soil is later picked up from the pile and dumped directly into transport vehicles (e.g. trucks or railcars) that are subsequently covered to minimize further emissions. Overall, each  $m^3$  of soil is excavated and dumped two times.
2. Soil is excavated using a backhoe and placed into a temporary storage pile. The soil is moved from the pile using a front-end loader (and/or backhoe) to a staging area where a large storage pile is established. The pile is typically covered to minimize leaching and air emissions. The soil is eventually re-excavated and dumped into transport vehicles (e.g. trucks or railcars) that are subsequently covered to minimize further emissions. Alternatively, the soil may be re-excavated and fed to an on-site treatment system. Overall, each  $m^3$  of soil is excavated and dumped three times.

It is rarely feasible or efficient to dig soil and immediately transfer the soil directly to transport vehicles or treatment systems. The excavation scenario and the emission equations shown below are designed to predict the emissions from a single soil handling event. To predict the total emissions from excavation, the equations must be sequentially applied to each event where the soil is handled (i.e., two or three times in most cases). The values for certain input parameters to the equations, such as the concentration of the contaminant in the soil and the bulk density of the soil, will be

altered by the act of excavation and a separate (different) value will be required for these parameters when modeling each soil handling event of the overall excavation process.

### Details of Excavation Scenario

Soil is excavated for 50 min/hour<sup>2</sup>. Each scoop of soil contains 2 m<sup>3</sup> of material and has dimensions of 1m x 2m x 1m. The cycle time is 40 seconds<sup>3</sup>, so 75 scoops are moved per hour (= 150 m<sup>3</sup> of soil moved per hour). The excavation pit, after one hour of operation, has dimensions of 10m x 15m x 1m.

Each scoop of dumped soil is assumed to maintain its 1x2x1 dimensions, so that the pile of dumped soil is equivalent to a series of stacked blocks. After one hour, a pile 5m x 10m x 3m high is established. The total exposed surface area of the pile is 140 m<sup>2</sup> and the bottom of the pit has another 150 m<sup>2</sup> of exposed area (the sides of the excavation pit are assumed to be clean overburden). The exposed surface areas are assumed to remain constant during further hours of operation with any additional area being covered with some type of impermeable cover that acts as a barrier to further emissions.

## A.2 DERIVATION OF EMISSION MODELS

The models are based on adding the emissions resulting from the release of soil-gas (pore space gas) to the atmosphere when excavation soil is dumped onto a storage pile to the emissions resulting from diffusion from contaminated soil present in the excavation pit and in the storage pile. A discussion of the input parameters and typical input values are given in Sections A.4 and A.5. Limitations of the models are also given in those sections.

### Pore-Space Gas Model

The general form of the equation used to estimate the emission rate from the pore space gas for any given compound is the ideal gas law:

$$P V = nR T \quad (\text{Eq. A-1})$$

where:     P     =     Vapor pressure of compound i (mm Hg);  
              V     =     Volume (cm<sup>3</sup>);  
              n     =     Number of moles of gas;

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<sup>2</sup>Page 8-35 of the Excavation Handbook by H.K. Church (MCGraw-Hill, 1981) states that excavation equipment can be assumed to be in use for 30 to 50 minutes per hour.

<sup>3</sup>Page 12-38, op cit, gives a cycle time of 0.67 minutes for a 25 foot hoist distance and a 90° angle of swing return.

R = Gas constant; and  
 T = Temperature (°K).

The mass of contaminants present in the pore space of soil can be determined as follows. First substitute  $M_{PS}/MW$  for  $n$  and then solve for  $M_{PS}$ :

$$M_{PS} = \frac{P V MW}{R T} \quad (\text{Eq. A-2})$$

where:  $M_{PS}$  = Mass of pore space contaminants (g); and  
 $MW$  = Molecular weight of species  $i$  (g/g-mole).

Then substitute soil volume and air-filled porosity terms for  $V$  to account for the volume of air within a given volume of soil. Air-filled porosity is the fraction of the total soil volume that is air. A factor of  $10^6$  to convert from  $\text{cm}^3$  to  $\text{m}^3$  is also needed:

$$M_{PS} = \frac{P MW}{RT} (10^6)(E_a)(S_v) \quad (\text{Eq. A-3})$$

where:  $E_a$  = Air-filled porosity (dimensionless);  
 $10^6$  = Conversion factor ( $\text{cm}^3/\text{m}^3$ );  
 $S_v$  = Volume of soil moved ( $\text{m}^3$ ); and  
 $R$  = Gas constant, 62,361 (mm Hg ·  $\text{cm}^3/\text{g-mole } ^\circ\text{K}$ ).

To derive an emission rate, Equation A-3 must be modified to account for the rate at which soil is being moved and to account for the percentage of soil gas that is released or exchanged with the atmosphere:

$$ER_{PS} = \frac{P MW}{RT} (10^6)(E_a)(Q)(ExC) \quad (\text{Eq. A-4})$$

where:  $ER_{PS}$  = Average emission rate from the pore space gas (g/sec);  
 $ExC$  = Soil gas to atmosphere exchange constant (%/100); and  
 $Q$  = Excavation rate ( $\text{m}^3/\text{sec}$ ).

The excavation rate term,  $Q$ , is equal to  $S_v$  divided by the total time period in seconds over which the given volume of soil is being moved. Equation A-4 assumes that the instantaneous emission rate is equivalent throughout the excavation cycle, whereas the emissions from each scoop of soil are probably due primarily to two emission puffs: one when the backhoe bucket enters the soil and initially disturbs the soil and the second, larger puff, when the bucket dumps the soil onto the storage pile. Equation A-4 also assumes that the pore space is saturated with the contaminant vapor.

## Diffusion Model

The general form of the equation used to estimate the emission rate from the contaminated soil in the excavation pit and in the storage pile is the RTI landtreatment model:

$$EF = \frac{M_o}{l} \left[ \frac{1}{\left( \frac{E_a}{K_{eq} k_g} \right) + \left( \frac{\pi t}{D_e K_{eq}} \right)^{\frac{1}{2}}} \right] e^{-t/t_b} \quad (\text{Eq. A-5})$$

where:

- EF = Emission flux through the soil at some time t (g/cm<sup>2</sup>-sec);
- M<sub>o</sub> = Initial loading of contaminant in soil (g/cm<sup>2</sup>);
- l = Depth to which contaminant is mixed in soil (cm);
- K<sub>eq</sub> = Weight fraction of VOC in air space (dimensionless);
- k<sub>g</sub> = Gas-phase mass transfer coefficient (cm/sec);
- D<sub>e</sub> = Effective diffusivity (cm<sup>2</sup>/sec);
- t = Time since start of excavation of soil of interest (sec); and
- t<sub>b</sub> = Time constant for biological decay of contaminant i (sec).

Several modifications to the model were made to make it applicable to excavation. First, the biological exponential decay term (e<sup>-t/t<sub>b</sub></sup>) was set equal to one since the timeframes of interest are very short. Second, the initial loading term (M<sub>o</sub>) and the depth to which the waste is mixed term (l) were combined into a waste loading term, designated C. Third, a factor of 10,000 was added to convert the emission units from mass per cm<sup>2</sup> to mass per m<sup>2</sup>. Fourth, a term was added to account for the surface area of the emitting soil. The resulting equation is:

$$ER_{Diff} = \frac{(C)(10,000)}{\left( \frac{E_a}{K_{eq} k_g} \right) + \left( \frac{\pi t}{D_e K_{eq}} \right)^{\frac{1}{2}}} [SA] \quad (\text{Eq. A-6})$$

where:

- ER<sub>Diff</sub> = Instantaneous emission rate from diffusion through the soil (g/sec);
- C = Soil concentration of species of interest (g/cm<sup>3</sup>);
- 10,000 = Conversion factor (cm<sup>2</sup>/m<sup>2</sup>); and
- SA = Surface area of emission source (m<sup>2</sup>).

The surface area term, SA, includes the area of the exposed contaminated soil for both the excavation pit and the storage pile. It is assumed that the surface area of the emission source remains constant, i.e., excavation was already underway before the particular soil being modeled was handled and excavated soil is moved off-site or covered to reduce emissions at the same rate that new soil is being uncovered and excavated. To model the case where no contaminated soil is initially exposed, the surface area term in Equation A-6 can be divided by a factor of two to yield an average amount of exposed surface area.

### A.3 EMISSION MODELS

The overall emission rate equation is formed by adding Equations A-4 and A-6. Note that the timeframes of the two equations as shown are not equivalent. Equation A-4 describes the emissions over the course of excavating and dumping one scoop of soil (40 seconds in the assumed scenario), while Equation A-6 gives an instantaneous emission rate at some time t since the contaminated material was first exposed to the air. An average value for t is discussed in Section A.4 and the timeframe of the two models are reconciled so that they yield an average emission rate.

The general form of the emission models for estimating an "average" emission rate for the excavation of contaminated soil is given as Equation A-7 and a worst-case emission rate is given as Equation A-8. It is a simple matter to modify either of these equations to calculate an emission flux (i.e., rate per area) or total emissions for a given period of time.

#### Emission Rate

An emission rate in g/sec for excavation was derived in the previous section and is:

$$ER = \frac{P \text{ MW}}{RT} (10^6)(E_a)(Q)(ExC) + \frac{(C)(10,000)}{\left(\frac{E_a}{K_{cq}k_g}\right) + \left(\frac{\pi t}{D_e K_{cq}}\right)^{\frac{1}{2}}} (SA) \quad (\text{Eq. A-7})$$

#### Worst-Case Emission Rates

The worst-case (i.e., maximum) instantaneous emission rate,  $ER_{MAX}$ , for contaminated soil occurs when the exposed surface area is at a maximum and immediately after a bucket load of soil is dumped onto the storage pile. This emission rate can be approximated by considering the case where a pure chemical is exposed to the atmosphere. This emission rate can be determined from Equation A-6 (there is no need to consider pore space gas concentrations and diffusion since the pure chemical is already exposed to the atmosphere). Set the time term, t, equal to zero and replace the  $K_{cq}$  term with the equivalent expression:  $P \cdot MW \cdot E_a / R \cdot T \cdot C$ . Equation A-6 then reduces to:

$$ER_{MAX} = \frac{(k_g)(P)(MW)(SA)(10,000)}{RT} \quad (\text{Eq. A-8})$$

#### A.4 SIMPLIFIED EMISSION MODELS

The first half of Equation A-7 is simplified first, followed by simplification of the second half of Equation A-7.

##### Simplified Pore-Space Gas Model

The first half of Equation A-7 can be simplified as follows. Assume the following:

$$\begin{aligned} R &= 62,361; \\ MW &= 100; \\ T &= 298; \\ ExC^4 &= 0.33. \end{aligned}$$

Substituting these values into the first half of Equation A-7 yields an emission rate for pore space gas,  $ER_{PS}$ , of:

$$ER_{PS} = \frac{P MW}{RT} (10^6)(E_a)(Q)(ExC) = \frac{(P)(E_a)(Q)(100)(10^6)(0.33)}{(62,361)(298)} \quad (\text{Eq. A-9})$$

$$ER_{PS} = \left( \frac{5.4 \text{ g/m}^3}{\text{mm Hg}} \right) * P * E_a * Q * 0.33 \quad (\text{Eq. A-10})$$

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<sup>4</sup>Assume  $ExC = 0.33$  for dry, sandy soils and  $ExC = 0.10$  for wet soils or those with a high clay content.

Vapor pressures for most VOCs of interest are available in tabulated physical constants in Appendix B. These values are for 25°C, but P can be estimated at other temperatures<sup>5</sup>. According to SEAMs, the air-filled porosity ( $E_a$ ) can be assumed to be:

$E_a$	Soil Conditions
0.35	Wet, or compacted soil
0.55	Dry, uncompacted soil

$E_a$  can be assumed to be 0.05 for sludges, tarry wastes, and saturated soils. Alternatively,  $E_a$  can be calculated as follows:

$$E_a = 1 - \left[ \frac{\beta + (\beta)(M_{FRAC})}{\rho} \right] \quad (\text{Eq. A-11})$$

where:  $\beta$  = Bulk density of soil (g/cm<sup>3</sup>);  
 $M_{FRAC}$  = Moisture fraction in soil (Wt.% Moisture/100); and  
 $\rho$  = Particle density (g/cm<sup>3</sup>).

Default values are as follows. Bulk density ( $\beta$ ) usually is in the range of 1.0 to 2.0 and can be assumed to be about 1.5 for uncompacted soils prior to excavation. After excavation, the bulk density is lower and a value of 1.2 may be assumed. Particle density ( $\rho$ ) is typically about 2.65 ± 5% for soils. These default values yield an  $E_a$  for dry soil of 0.43 before excavation and 0.55 after excavation.

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<sup>5</sup>Vapor pressure can be roughly estimated at temperatures other than 25°C by the following equation:

$$P = P^{\circ} e^{\left( \frac{-21T_B}{1.987} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right)} \quad (\text{Eq. A-12})$$

where: P = Vapor pressure of compound i at temperature T (mmHg);  
 $P^{\circ}$  = Vapor pressure of compound i at temperature  $T_0$  (mmHg);  
 $T_B$  = Normal boiling point of compound i (°K);  
T = Temperature (°K);  
 $T_0$  = Reference Temperature (°K) - Usually 298°K;  
1.987 = Gas constant (cal/g-mol °K); and  
21 = Heat of vaporization constant (cal/g-mol °K).

Using the SEAMS value for  $E_a$  (0.55), Equation A-10 for dry soil then reduces down to:

$$ER_{PS} = P * Q * 0.98 \text{ g/mmHg-m}^3 \quad (\text{Eq. A-13})$$

Equation A-13 is the simple screening model. If desired, it can be further reduced. Using the excavation scenario described above, Q can be assumed to be  $150 \text{ m}^3/3600 \text{ sec}$ . Equation A-13 for dry soil then reduces down to:

$$ER_{PS} = (0.04 \text{ g/mm Hg}) * P \quad (\text{Eq. A-14})$$

### Simplified Landtreatment Model

The second half of Equation A-7 can be simplified as follows. The following equations<sup>6,7</sup> can be used to describe the terms  $K_{eq}$  and  $D_e$ , which appear in Equation A-7:

$$K_{eq} = \frac{P \text{ MW } E_a}{RT C} \quad (\text{Eq. A-15})$$

$$D_e = \frac{D_a (E_a)^{3.33}}{(E_T)^2} \quad (\text{Eq. A-16})$$

where:  $D_a$  = Diffusivity in air of species i ( $\text{cm}^2/\text{sec}$ ); and  
 $E_T$  = Total porosity (dimensionless).

---

<sup>6</sup>The equation shown for calculating  $K_{eq}$  assumes that the contaminant is an oily waste. For dilute aqueous wastes,  $K_{eq} = H/RT$ , where H = Henry's Law constant in  $\text{mm Hg-cm}^3/\text{g-mol}$ .

<sup>7</sup>Strictly speaking, the concentration term, C, in Equations A-15 and A-7 should be adjusted to account for the mass of contaminant lost with the pore-space gas. This adjustment has not been included in the model for the sake of simplicity.

$K_{eq}$  represents the relative saturation of the soil-gas with respect to a given compound and cannot realistically exceed 1. Calculated values of  $K_{eq}$  using Equation A-15 will exceed 1 if the soil-gas is below saturation with respect to that compound. If the output of Equation A-15 is  $K_{eq} > 1$ , then a value of  $K_{eq} = 1$  should be used in all equations having a  $K_{eq}$  term. Alternatively,  $K_{eq}$  could be determined by field measurements of the pore space concentration in the soil ratioed to the total concentration of the contaminant in the soil.

$E_T$  can be calculated by Equation A-11 if the moisture fraction is set to zero.

Assume the following:

$$\begin{aligned} R &= 62,361; \\ MW &= 100; \\ T &= 298; \\ D_a &= 0.1; \\ E_a &= 0.55; \\ E_T &= 0.625; \end{aligned}$$

Substitute these values into Equations A-15 and A-16 to yield:

$$K_{eq} = \frac{P}{C \ 332,200} \quad (\text{Eq. A-17})$$

$$D_e = 0.035 \quad (\text{Eq. A-18})$$

The second half of Equation A-7 can then be simplified by inserting Equations A-17 and A-18, and by assuming that  $E_a = 0.55$  and that  $k_g = 0.15$ . Equation A-7 then reduces to:

$$ER_{Diff} = \frac{(C)(10,000)}{\left(1.22 \times 10^6 \frac{C}{P}\right) + \left(2.98 \times 10^7 \frac{C t}{P}\right)^{\frac{1}{2}}} \quad (\text{SA}) \quad (\text{Eq. A-19})$$

Equation A-19 provides an instantaneous emission rate at time = t. It is assumed that emissions from freshly excavated soil are significant for a period of 360 seconds, after which the soil is covered by subsequent layers of excavated material. The emission rate versus time over this 360 second period for a given scoop of soil will generally exhibit an exponential decay. The exact shape of this decay curve will vary as

the input parameters such as vapor pressure and air-filled porosity vary. Therefore, it is necessary to determine at what time  $t$  the instantaneous emission rate approximates the average emission rate over the 360 second period. This can be done by calculating the instantaneous emission rates at  $t = 0$  second,  $t = 15$  seconds,  $t = 30$  seconds, and so on. The emission rate is calculated for every 15 second period up to  $t=360$  and the results plotted. The average emission rate is calculated by summing the instantaneous emission rates and dividing the sum by the number of data points (in this example, 24). The value for the average emission rate is then found on the plot of emission rate versus time, and the corresponding time found on the x-axis. This time  $t$  is then used in Equation A-19. For the typical case, the instantaneous rate at  $t = 60$  seconds is a good approximation of the overall emission rate for the first 360 seconds. Using this value Equation A-19 yields the simple screening equation:

$$ER_{\text{Diff}} = \frac{(C)(10,000)}{\left(1.22 \times 10^6 \frac{C}{P}\right) + \left(1.79 \times 10^9 \frac{C}{P}\right)^{\frac{1}{2}}} \quad (\text{SA}) \quad (\text{Eq. A-20})$$

Equation A-20 assumes that the emission flux arising from diffusion is equal for both the excavation pit and the excavated soil in the storage pile. Equation A-20 will overpredict emissions if  $K_{eq} > 1$ .  $P$  at temperatures other than 25°C can be estimated using Equation A-12. From the excavation scenario described earlier, SA can be assumed to be 290 m<sup>2</sup>.

Assuming a typical bulk density of undisturbed soil,  $C$  can be modified to a weight basis as follows:

$$C' = C * \frac{1 \text{ cm}^3}{1.5 \text{ g}} * 10^6 \mu\text{g/g} \quad (\text{Eq. A-21})$$

where:  $C'$  = Concentration of species in soil ( $\mu\text{g/g}$ ).

The overall emission rate is determined by adding Equations A-13 and A-20. This estimated value should be checked to see whether or not it exceeds the total mass of contaminants present in the soil that is moved, which is equal to the theoretical maximum emissions (not considering emissions from the un-excavated soil in the pit). To do this, the emission rate should be multiplied by 3,600 seconds to get the total emissions over a reasonably long period of time, one hour. The mass of contaminants present in the soil can be determined by:

$$C_{\text{TOT}} = C * S_v * 10^6 \text{ cm}^3/\text{m}^3 \quad (\text{Eq. A-22})$$

where:  $C_{\text{TOT}}$  = Total starting mass of contaminant in excavated soil (g).

Equations A-4 and A-13 are based on the assumption that the soil pore gas is saturated with the compound of interest. If this is not the case, then Equations A-4 or A-13 may overpredict the emission rate. The output from Equations A-4 or A-13 should be multiplied by the duration of excavation and compared to the total mass of

contaminants present in the soil. If Equations A-4 or A-13 gives a value that exceeds one-third of  $C_{TOT}$ , then they should be replaced with the following equation:

$$ER_{PS} = C_{TOT} * 0.33/t_{sv} \quad (\text{Eq. A-23})$$

where:  $t_{sv}$  = Time to excavate a given volume of soil (sec).

## A.5 MODEL EVALUATION

The emission model was evaluated to determine the sensitivity of the model to various input parameters. All the independent variables in Equation A-7 are listed in Table A-1. For each variable a typical value is given along with the range of values likely to be encountered at Superfund site excavations. The uncertainty associated with measuring each variable is also estimated in Table A-1. The range of physical properties was based on n-butane being the lightest VOC likely to be encountered at a site and naphthalene being the heaviest compound likely to be of concern. Typical physical property values were based on C6 to C8 compounds (e.g. benzene to xylene). The soil volume term was kept constant to show the variability in surface area for a given volume of soil. The gas-phase mass transfer coefficient ( $k_g$ ) was estimated using the correlations given with the RTI landtreatment model and the following input values:

Parameter	Units	Minimum Value	Maximum Value	Typical Value
Wind Speed	m/sec	1.0	4.47	2.0
Viscosity of air	g/cm-sec	1.81x10 <sup>-4</sup>		
Density of air	g/cm <sup>3</sup>	1.2x10 <sup>-3</sup>		
Diffusivity in air	cm <sup>2</sup> /sec	0.25	0.059	0.1
Diameter of excavation	m	24		

The minimum and maximum values for the independent input parameters from Table A-1 were combined to generate a best-case and worst-case set of emission scenarios. These are shown in Table A-2 along with the case using the typical input parameters. As seen in Table A-2, the three cases shown differ greatly in the estimated average emission rate.

To identify which parameters had the greatest effect on the overall emissions, a set of calculations were performed using the base or typical case as the starting point. The effect of each parameter was examined by substituting the minimum and maximum value for each into the base case conditions. The results of this first-order sensitivity analysis are shown in Table A-3. The two independent variables having the largest effect on the overall emission rate are the starting concentration of the contaminant in the soil and the vapor pressure of the contaminant. Note that temperature has a small effect, but that emissions are inversely proportional to temperature. This is, of course, contrary to the overall effect of temperature on emissions: emissions increase as temperature increases. This seeming anomaly is due to

**Table A-1.  
Input Parameters for Emission Equations**

Equation Parameter	Units	Typical Input Values			Typical Uncertainty (±%)	Comments
		Minimum	Maximum	Typical		
<b>Independent Variables</b>						
Concentration	ug/Kg (ppbw)	50	5,000,000	100,000	50	
Bulk Density	g/cm <sup>3</sup> (dry)	1.0	2.0	1.35	10	
Moisture	%	5.0	25	10	5	
Particle Density	g/cm <sup>3</sup>	2.55	2.8	2.65	5	
Temperature	K	273	313	298	2	
Da	cm <sup>2</sup> /sec	0.059	0.25	0.1	25	Varies w/temperature
P	mm Hg	0.053	1820	35	300	Varies w/temperature
MW	g/gmol	41	166	100	1	
R	mm Hg-cm <sup>3</sup> /gmol-K	62361	62361	62361	1	
pi	--	3.14	3.14	3.14	1	
kg	cm/sec	0.062	0.52	0.15	25	
t	sec	60	60	60	25	
Q	m <sup>3</sup> /sec	0.042	0.042	0.042	30	
Surface Area	m <sup>2</sup>	290	435	290	50	
Exchange Constant	%	1	50	33	200	
<b>Dependent Variables</b>						
C	g/cm <sup>3</sup>	5.00x10 <sup>8</sup>	0.010	1.35x10 <sup>-4</sup>		
Ea	vol/vol	0.588	0.107	0.440		
Et	vol/vol	0.608	0.286	0.491		
De	cm <sup>2</sup> /sec	0.0273	0.0018	0.0296		
Keq	g/g	1.50	0.166	0.613		
Keq	g/g (max)	1				Keq cannot exceed one

**Table A-2.  
Emission Scenarios**

Parameter	Units	Typical Input Values			Emission Scenarios		
		Minimum	Maximum	Typical	Best Case	Worst Case	Typical Case
Concentration	ug/Kg (ppbw)	50	5,000,000	100,000	50	5000000	1000
Bulk Density	g/cm <sup>3</sup> (dry)	1.0	2.0	1.35	2.0	1.0	1.35
Moisture	%	5.0	25	10	25	5.0	10
Particle Density	g/cm <sup>3</sup>	2.55	2.8	2.65	2.55	2.8	2.65
Temperature	K	273	313	298	273	313	298
C	g/cm <sup>3</sup>	5.00x10 <sup>-8</sup>	1.00x10 <sup>-2</sup>	1.35x10 <sup>-4</sup>	1.00x10 <sup>-7</sup>	5.00x10 <sup>-3</sup>	1.35x10 <sup>-4</sup>
Ea	vol/vol				0.020	0.625	0.440
Et	vol/vol				0.216	0.643	0.491
Da	cm <sup>2</sup> /sec	0.059	0.25	0.1	0.059	0.25	0.1
P	mm Hg	0.053	1820	35	0.053	1820	35
MW	g/gmol	41	166	100	166	41	100
R	mm Hg-cm <sup>3</sup> /gmol-K	62361	62361	62361	62361	62361	62361
pi	--	3.14	3.14	3.14	3.14	3.14	3.14
Kg	cm/sec	0.062	0.52	0.15	0.062	0.52	0.15
De	cm <sup>2</sup> /sec				3 x 10 <sup>-6</sup>	0.1265	0.0269
Keq	g/g				0.101	0.478	0.613
Keq	g/g (max)						
t	sec	60	60	60	60	60	60
Excavation Rate	m <sup>3</sup> /sec	0.042	0.042	0.042	0.042	0.042	0.042
Surface Area	m <sup>2</sup>	290	435	290	290	435	290
Exchange Constant	%	1	50	33	1	50	33
Emission Rate	g/sec				1.51 x 10 <sup>-5</sup>	422	4.65

Notes: 1. Use Keq(max) if Keq is >1.

**Table A-3.  
Results of Sensitivity Analysis**

Equation Parameter	Units	Typical Input Values			Change in Emission vs Base Case	
		Minimum	Maximum	Typical	Minimum Value (± %)	Maximum Value (± %)
<b>Independent Variables</b>						
Concentration	ug/Kg (ppbw)	50	5,000,000	100,000	-99.9	348
Bulk Density	g/cm3 (dry)	1.0	2.0	1.35	21.9	-66.4
Moisture	%	5.0	25	10	10.7	-29.1
Particle Density	g/cm3	2.55	2.8	2.65	-6.1	8.4
Temperature	K	273	313	298	5.8	-3.1
Da	cm2/sec	0.059	0.25	0.1	-16.9	41.0
P	mm Hg	0.053	1820	35	-98.5	38.0
MW	g/gmol	41	166	100	-42.7	38.0
R	mm Hg-cm3/gmol-K	62361	62361	62361	NA	NA
pi	--	3.14	3.14	3.14	NA	NA
kg	cm/sec	0.062	0.52	0.15	-4.3	2.4
t	sec	1	3600	60	1688	-65.4
Excavation Rate	m3/sec	0.042	0.042	0.042	NA	NA
Surface Area	m2	290	435	290	0.0	37.7
Exchange Constant	%	1	50	33	-23.8	12.6
<b>Dependent Variables</b>						
C	g/cm3	1.00x10 <sup>-7</sup>	5.00x10 <sup>-3</sup>	1.35x10 <sup>-4</sup>	-99.9	302
Ea	vol/vol	0.020	0.625	0.440	-98.8	89.0
Et	vol/vol	0.216	0.643	0.491	87.1	-17.3
De	cm2/sec	3.00x10 <sup>-6</sup>	0.1265	0.0269	-74.7	80.4
Keq	--	1.00x10 <sup>-4</sup>	1	0.613	-75.3	21.8

main effect of temperature being to increase the vapor pressure and diffusivity terms. If these terms are not corrected for temperature, then the model will become less accurate as the temperature deviation from 25°C increases.

Equation A-7 requires the input of the time after the start of excavation (t). It was assumed earlier that the emission rate at t=60 seconds was equal to the average emission rate over t=0 to t=360 seconds. It was further assumed that after 360 seconds, the excavated soil would be covered with additional layers of soil and the diffusion of further material (emissions) would be minimal. The effect of time (t) was examined by substituting a range of times into the base case conditions. The results of these trials are given in Table A-4 and depicted in Figure A-1 and A-2.

The effect of the initial soil concentration of the contaminant on the predicted emission rate was examined by using the same base case assumptions and varying the concentration from 1 ppbw to 10,000 ppmw. These results are shown in Table A-5 and are plotted in Figure A-3. As the concentration increases, the percentage of the total mass of material emitted decreases. Also, the relative contribution of pore-space gas to the total emissions also decreases. The effect of vapor pressure (and molecular weight) was examined by inserting the values for vapor pressure and molecular weight for several common organic species into the base case. All compounds were assumed to be present at 100 ppmw in the soil. These results are shown in Table A-6.

A final check of the models was made by comparing model predictions to field data (Eklund, et al. Field Measurement of VOC Emissions From Soils Handling Operations at Superfund Sites. EPA Contract No. 68-02-4392, Work Assignment 64. September 1990). Comparisons of both the detailed (Equation A-7) and simple models (Equations A-13 and A-20) to field data are shown in Table A-7. Total emissions for twenty minute sampling periods are shown for two different field sites. The detailed model using site-specific input data agrees with the field measurements within a factor of five in all but two cases. The simplified model shows equally good agreement.

The equations presented here are a first attempt to model emissions from soils handling operations. The equations are limited by a lack of laboratory or field data to define certain key relationships between the variables. For example, the excavation rate and the total exposed area are assumed in the equations to have a direct linear relationship with the emission rate. No data, however, exist to support this assumption. Similarly, the effects of temperature, scoop size, and surface area to volume ratio on emissions have not been investigated. Another limiting assumption is that 33% of the pore space gas is exchanged with the atmosphere. This value is arbitrary and was selected since it fit reasonably well with the very limited field data that are available.

Measurements of emission rates from dynamic processes such as excavation are very difficult to perform and are of limited accuracy. Limitations exist for dispersion models used in indirect approaches (e.g., transect) and in the sampling and analytical precision when attempting to determine emission rates using a mass balance approach. Emerging measurement technologies, such as remote optical sensing, may allow more detailed evaluation of the effect of these parameters in the future.

**Table A-4.****Effect of Time (t) on Emissions**

Time (sec)	Diffusion Emission Rate (mg/sec)	Total Emission Rate (mg/sec)
0	81.9	83.1
5	11.0	12.1
10	8.09	9.23
20	5.89	7.03
30	4.87	6.01
40	4.25	5.39
50	3.83	4.96
60	3.51	4.65
90	2.89	4.02
120	2.51	3.65
180	2.06	3.20
240	1.79	2.93
300	1.61	2.74
360	1.47	2.61
420	1.36	2.50
480	1.28	2.41
540	1.20	2.34
600	1.14	2.28
1200	0.81	1.95
1800	0.66	1.80
2400	0.58	1.71
3000	0.51	1.65
3600	0.47	1.61

Emission Rate vs. Time (0 to 360 sec)

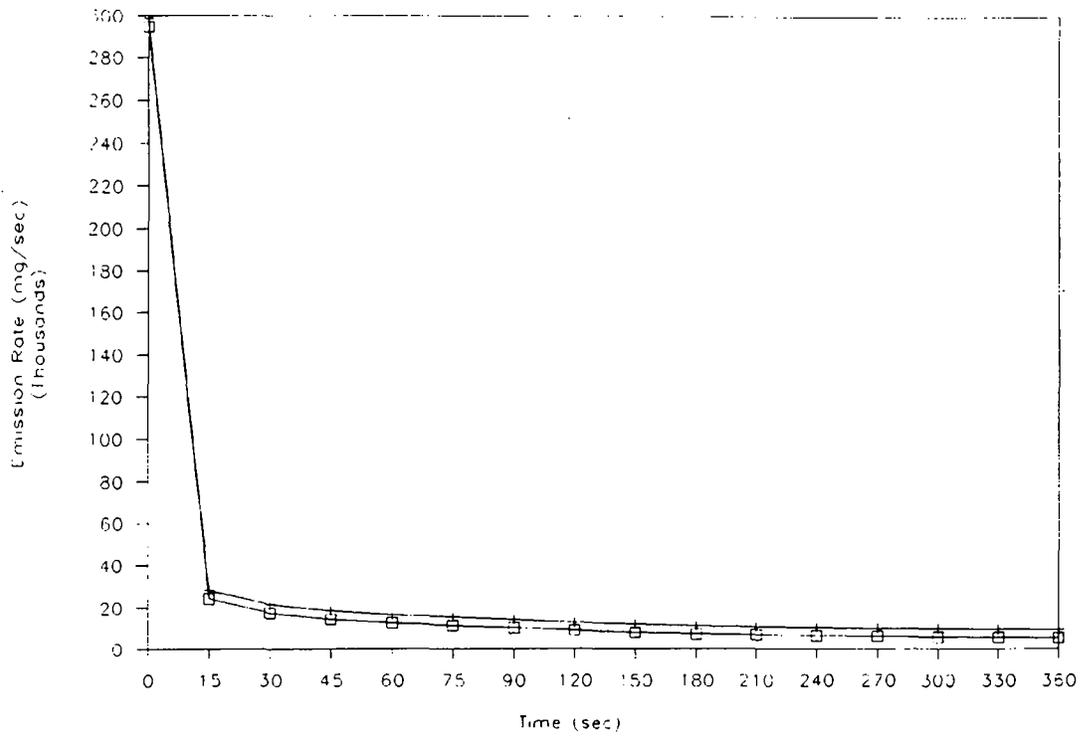


Figure A-1. Emission Rate vs. Time for Base Case Conditions for 0 to 360 seconds.

Emission Rate Vs. Time (0 to 60 min)

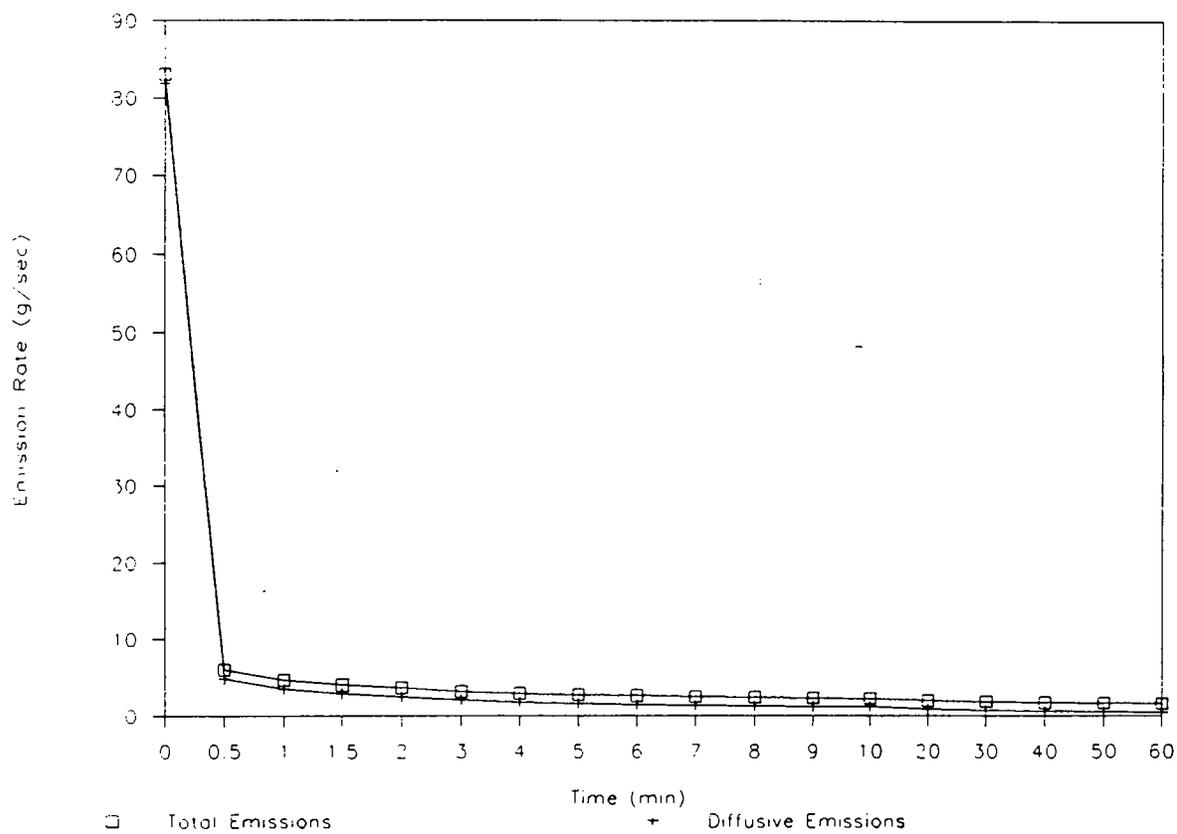


Figure A-2. Emission Rate vs. Time for Base Case Conditions for 0 to 60 Minutes.

Table A-5.

Effect of Conc. (C) on Emissions

Conc (ug/Kg)	Log Conc (ug/Kg)	Pore Gas Emission Rate (g/sec)	Diffusive Emission Rate (g/sec)	Total Emission Rate (g/sec)	Emissions* Vs. Total Mass (%)
1	1	$1.88 \times 10^{-5}$	$4.52 \times 10^{-5}$	$6.40 \times 10^{-5}$	114
10	2	$1.88 \times 10^{-4}$	$4.52 \times 10^{-4}$	$6.40 \times 10^{-4}$	114
100	3	$1.87 \times 10^{-3}$	$4.52 \times 10^{-3}$	$6.40 \times 10^{-3}$	114
1000	4	0.019	0.045	0.06	114
10000	5	0.188	1.14	1.33	236
100000	6	1.138	3.51	4.65	82.6
1000000	7	1.138	10.15	11.29	20.1
10000000	8	1.138	25.32	26.46	4.7

\* Includes only mass of contaminants in excavated soil

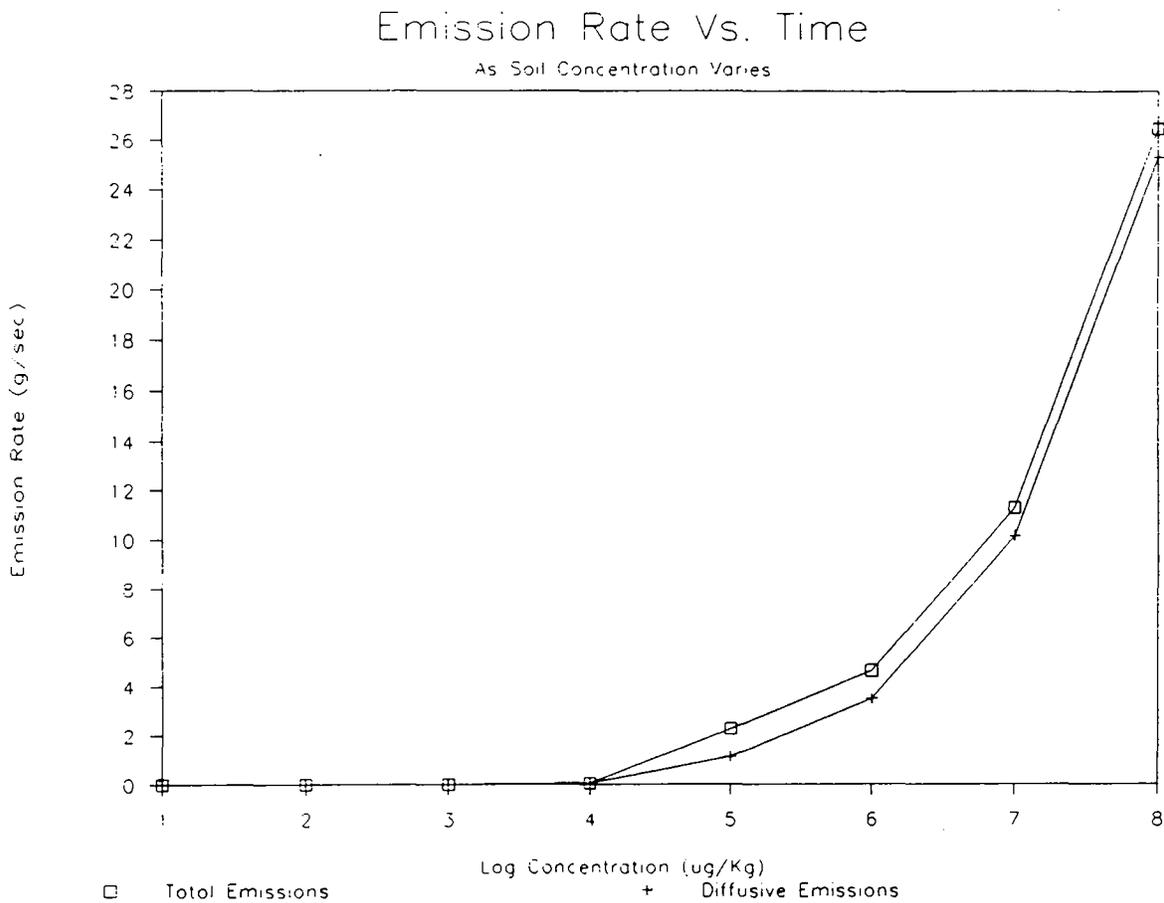


Figure A-3. Emission Rate vs. Time as Soil Concentration Increases.

Table A-6.

Effect of Molecular Weight (MW) + Vapor Pressure (P) on Emissions

Conc (ug/Kg)	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)	Diffusive Emission Rate (g/sec)	Total Emission Rate (g/sec)
<b>Alkanes</b>				
butane	58.12	1820	4.52	6.40 *
pentane	72.15	513	4.52	6.40 *
hexane	86.18	150	4.52	6.40 *
heptane	100.2	46	4.05	5.55
octane	114.23	17	2.57	3.21
nonane	128.26	4.3	1.30	1.48
<b>Aromatics</b>				
benzene	78.12	95.2	5.18	7.06
ethylbenzene	106.16	10	1.87	2.21
o-xylene	106.2	7.0	1.54	1.78

\* Pore space emissions equal the total mass of contaminant present divided by 3.

Table A-7

Comparison of Model Predictions to Field Data

Site	Run #	Compound	FIELD RESULTS		MODEL PREDICTIONS				PREDICTIONS FOR SIMPLE MODELS			
			Mass of Contam. Present (g)	Total Emissions (g)	Pore Space Emissions - EPS - (g)	Diffusive Emissions - Ei - (g)	Total Emissions (g)	Accuracy (%)	Pore Space Emissions -EPS- (g)	Diffusive Emissions - Ei - (g)	Total Emissions (g)	Accuracy (%)
A	1	Xylenes	855	24	49	182	231	863	7.4	62	69	189
	2	Xylenes <sup>a</sup>	12	37	4.0	20.3	24	-34	7.0	20	27	-27
	3	Xylenes <sup>a</sup>	140	82	47	203	249	204	83	203	285	248
A	1	Ethylbenzene	53	6.6	21	32	52	692	3.1	32	35	432
	2	Ethylbenzene <sup>a</sup>	1.2	8.4	0.4	4.2	4.6	-46	3.0	4.2	7.1	-15
	4	Ethylbenzene <sup>a</sup>	14	14	4.6	42	46	230	35	42	76	443
B	2	Xylenes <sup>a</sup>	0.13	7.2	4.3	20	24	236	5.8	2.0	7.8	8.3
	3	Xylenes <sup>a</sup>	2.7	2.2	0.9	9.2	10	357	5.8	9	15	581
	4	Xylenes <sup>a</sup>	3.7	2.3	1.2	11	12	421	5.8	11	17	621

Accuracy = (Model - Field)/Field x 100

<sup>a</sup> Pore space emissions equal total mass of contaminant present divided by 3.

**APPENDIX B**  
**PHYSICAL AND CHEMICAL CONSTANTS**  
**FOR SELECTED COMPOUNDS**

## APPENDIX B - PHYSICAL PROPERTY DATA

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) <sup>1</sup>	Diffusivity in Air (cm <sup>2</sup> /sec)
1	Acetaldehyde	75-07-0	C <sub>2</sub> H <sub>4</sub> O	44.00	760	0.1240
2	Acetic acid	64-19-7	C <sub>2</sub> H <sub>4</sub> O <sub>2</sub>	60.06	15.41	1.1300
3	Acetic anhydride	108-24-7	C <sub>4</sub> H <sub>6</sub> O <sub>3</sub>	102.09	5.266	0.2350
4	Acetone	67-64-1	C <sub>3</sub> H <sub>6</sub> O	58.08	266	0.1240
5	Acetonitrile	75-05-8	C <sub>2</sub> H <sub>3</sub> N	41.06	90	0.1280
6	Acrolein	107-02-8	C <sub>3</sub> H <sub>4</sub> O	56.1	244.2	0.1050
7	Acrylic acid	79-10-7	C <sub>3</sub> H <sub>4</sub> O <sub>2</sub>	72.1	5.2	0.0908
8	Acrylonitrile	107-13-1	C <sub>3</sub> H <sub>3</sub> N	53.06	114	0.1220
9	Allyl alcohol	107-18-6	C <sub>3</sub> H <sub>6</sub> O	58.08	23.3	0.1140
10	Allyl chloride	107-05-1	C <sub>3</sub> H <sub>5</sub> Cl	76.53	368	
11	Aniline	62-53-3	C <sub>6</sub> H <sub>7</sub> N	93.13	1	0.0700
12	Anthracene	120-12-7	C <sub>14</sub> H <sub>10</sub>	178.23	1.3E-06	
13	Benzaldehyde	100-52-7	C <sub>7</sub> H <sub>6</sub> O	106.12	1	
14	Benzene	71-43-2	C <sub>6</sub> H <sub>6</sub>	78.12	95.2	0.0932
15	Benzoic acid	65-85-0	C <sub>7</sub> H <sub>6</sub> O <sub>2</sub>	122.12	0.00704	
16	Benzyl alcohol	100-51-6	C <sub>7</sub> H <sub>8</sub> O	108.14	0.15	
17	Benzyl chloride	100-44-7	C <sub>6</sub> H <sub>5</sub> CH <sub>2</sub> Cl	126.6	1.21	0.0750
18	Bromoform	75-25-2	CHBr <sub>3</sub>	252.77	5.6	
19	1,3-Butadiene	106-99-0	C <sub>4</sub> H <sub>6</sub>	54.09	2100.00	0.2490
20	N-Butane	106-97-8	C <sub>4</sub> H <sub>10</sub>	58.12	1820	0.2490
21	2-Butanol	15892-23-6	C <sub>4</sub> H <sub>10</sub> O	74.12	10	
22	N-Butanol	71-36-3	C <sub>4</sub> H <sub>10</sub> O	74.12	6.5	
23	N-Butyl-Acetate	123-86-4	C <sub>6</sub> H <sub>12</sub> O <sub>2</sub>	116.16	15	
24	Tert-Butyl-Alcohol	75-65-0	C <sub>4</sub> H <sub>10</sub> O	74.12	0.17	
25	Carbon disulfide	75-15-0	CS <sub>2</sub>	76.13	366	0.1040
26	Carbon tetrachloride	56-23-5	CCL <sub>4</sub>	153.82	113	0.0632
27	Carbonyl sulfide	463-58-1	COS	60.1	--	
28	Catechol	120-80-9	C <sub>6</sub> H <sub>4</sub> (OH) <sub>2</sub>	110.1	--	
29	Chlorine	7782-50-5	Cl <sub>2</sub>	70.9	--	
30	Chlorobenzene	108-90-7	C <sub>6</sub> H <sub>5</sub> Cl	112.56	11.8	0.0730
31	Chlorodifluoromethane	75-45-6	CHClF <sub>2</sub>	86.47	--	
32	Chloroform	67-66-3	CHCl <sub>3</sub>	119.38	208	0.0888
33	Chloromethyl methyl ether	107-30-2	C <sub>2</sub> H <sub>5</sub> ClO	80.51	--	
34	Chloropentafluoroethane	76-15-3	C <sub>2</sub> ClF <sub>5</sub>	154.47	--	
35	Chloroprene	126-99-8	CH <sub>2</sub> CHCH <sub>2</sub> Cl	76.53	273	0.1040
36	M-Cresol	108-39-4	C <sub>7</sub> H <sub>8</sub> O	108.14	0.08	0.0740
37	O-Cresol	95-48-7	C <sub>7</sub> H <sub>8</sub> O	108.14	0.24	0.0740
38	P-Cresol	106-44-5	C <sub>7</sub> H <sub>8</sub> O	108.14	0.11	0.0740
39	Cyanogen	460-19-5	C <sub>2</sub> N <sub>2</sub>	52.04	3980	
40	Cyclohexane	110-82-7	C <sub>6</sub> H <sub>12</sub>	84.16	100	0.0839
41	Cyclohexanol	108-93-0	C <sub>6</sub> H <sub>12</sub> O	100.16	1.22	0.2140
42	Cyclohexanone	108-94-1	C <sub>6</sub> H <sub>10</sub> O	98.14	4.8	0.0784
43	Cyclohexene	110-83-8	C <sub>6</sub> H <sub>10</sub>	82.15	--	

## Appendix B. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) <sup>1</sup>	Diffusivity in Air (cm <sup>2</sup> /sec)
44	Cyclopentane	287-92-3	C <sub>5</sub> H <sub>10</sub>	70.13	317.44	
45	Diazomethane	334-88-3	CH <sub>2</sub> N <sub>2</sub>	42.04	—	
46	Dibutyl-O-Phthalate	84-74-2	C <sub>16</sub> H <sub>22</sub> O <sub>4</sub>	278.35	1.00E-05	0.0439
47	O-Dichlorobenzene	95-50-1	C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub>	147.00	1	0.0690
48	P-Dichlorobenzene	106-46-7	C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub>	147.00	1.2	0.0690
49	Dichloroethylether	111-44-4	C <sub>4</sub> H <sub>8</sub> Cl <sub>2</sub> O	143.02	1.4	
50	Dichlorodifluoromethane	75-71-8	CCL <sub>2</sub> F <sub>2</sub>	120.91	4870	
51	1,1-Dichloroethane	75-34-3	C <sub>2</sub> H <sub>4</sub> Cl <sub>2</sub>	98.96	234	0.0919
52	1,2-Dichloroethane	107-06-2	C <sub>2</sub> H <sub>4</sub> Cl <sub>2</sub>	98.96	80	0.0907
53	1,1-Dichloroethylene	75-35-4	C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub>	96.94	600	0.1040
54	cis-1,2-Dichloroethylene	156-59-2	C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub>	96.94	208	
55	trans-1,2-Dichloroethylene	156-60-5	C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub>	96.94	324	
56	Dichloromethane	75-09-2	CH <sub>2</sub> Cl <sub>2</sub>	84.93	362	
57	Dichloromonofluoromethane	75-43-4	CHCl <sub>2</sub> F	102.92	1360	
58	1,2-Dichloropropane	78-87-5	C <sub>3</sub> H <sub>6</sub> Cl <sub>2</sub>	112.99	42	
59	1,3-Dichloropropene	542-75-6	C <sub>3</sub> H <sub>4</sub> Cl <sub>2</sub>	110.98	43	
60	1,2-Dichloro-1,1,2,2-Tetrafluoroethane	76-14-2	C <sub>2</sub> Cl <sub>2</sub> F <sub>4</sub>	170.92	—	
61	Diethanolamine	111-42-2	C <sub>4</sub> H <sub>11</sub> NO <sub>2</sub>	105.14	—	
62	Diethyl amine	109-89-7	C <sub>4</sub> H <sub>11</sub> N	73.14	350@35C	
63	N,N-Dimethylaniline	121-69-7	C <sub>8</sub> H <sub>11</sub> N	121.18	—	
64	Diethyl ether	60-29-7	C <sub>4</sub> H <sub>10</sub> O	74.12	440@20C	0.0782
65	Dimethylamine	124-40-3	C <sub>2</sub> H <sub>7</sub> N	45.08	563 @ 0C	
66	Dimethyl formamide	68-12-2	C <sub>3</sub> H <sub>7</sub> NO	73.09	4.0	0.0939
67	1,1-Dimethyl hydrazine	57-14-7	C <sub>2</sub> H <sub>8</sub> N <sub>2</sub>	60.10	157	0.1060
68	2,4-Dinitrophenol	51-28-5	C <sub>6</sub> H <sub>4</sub> N <sub>2</sub> O <sub>5</sub>	184.11	53.8	
69	1,4-Dioxane	123-91-1	C <sub>4</sub> H <sub>8</sub> O <sub>2</sub>	88.11	37	0.2290
70	Diphenyl	92-52-4	C <sub>12</sub> H <sub>10</sub>	154.21	—	
71	Epichlorohydrin	106-89-8	C <sub>3</sub> H <sub>5</sub> ClO	92.53	17	0.0860
72	1,2-Epoxybutane	106-88-7	C <sub>4</sub> H <sub>8</sub> O	72.0	—	
73	Ethanol	64-17-5	C <sub>2</sub> H <sub>6</sub> O	46.07	50	0.1230
74	Ethyl acetate	141-78-6	C <sub>4</sub> H <sub>8</sub> O <sub>2</sub>	88.11	100	
75	Ethyl acrylate	140-88-5	C <sub>5</sub> H <sub>8</sub> O <sub>2</sub>	100.12	40	0.0770
76	Ethyl amine	75-04-7	C <sub>2</sub> H <sub>7</sub> N	45.08	1057	
77	Ethylbenzene	100-41-4	C <sub>8</sub> H <sub>10</sub>	106.16	10	0.0750
78	Ethyl Bromide	74-96-4	C <sub>2</sub> H <sub>5</sub> Br	108.97	—	
79	Ethyl carbamate	51-79-6	C <sub>3</sub> H <sub>7</sub> NO <sub>2</sub>	89.09	10	
80	Ethyl Chloride	75-00-3	C <sub>2</sub> H <sub>5</sub> Cl	64.51	1200	0.2710
81	Ethylenediamine	107-15-3	C <sub>2</sub> H <sub>8</sub> N <sub>2</sub>	60.10	10.7	
82	Ethylene dibromide	106-93-4	C <sub>2</sub> H <sub>4</sub> Br <sub>2</sub>	187.88	14	
83	Ethylene glycol	107-21-1	C <sub>2</sub> H <sub>6</sub> O <sub>2</sub>	62.07	0.13	0.1080
84	Ethylene imine	151-56-4	C <sub>2</sub> H <sub>5</sub> N	43.07	—	
85	Ethylene oxide	75-21-8	C <sub>2</sub> H <sub>4</sub> O	44.06	1250	0.1040

## Appendix B. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) <sup>1</sup>	Diffusivity in Air (cm <sup>2</sup> /sec)
86	Formaldehyde	50-00-0	CH <sub>2</sub> O	30.03	3500	0.1780
87	Formic acid	64-18-6	CH <sub>2</sub> O <sub>2</sub>	46.03	42	0.0790
88	Furan	110-00-9	C <sub>4</sub> H <sub>4</sub> O	68.08	596	0.1040
89	Glycerol	56-81-5	C <sub>3</sub> H <sub>8</sub> O <sub>3</sub>	92.09	1.60E-04	
90	N-Heptane	142-82-5	C <sub>7</sub> H <sub>16</sub>	100.2	46	
91	N-Hexane	110-54-3	C <sub>6</sub> H <sub>14</sub>	86.18	150.3	0.2000
92	Hydrazine	302-01-2	H <sub>4</sub> N <sub>2</sub>	32.05	14.4	
93	Hydrochloric acid	7647-01-0	HCl	36.46	32,450	
94	Hydrogen cyanide	74-90-8	CHN	27.03	--	
95	Hydrogen sulfide	7783-06-4	H <sub>2</sub> S	34.08	15,200	0.1760
96	Isobutanol	78-83-1	C <sub>4</sub> H <sub>10</sub> O	74.12	10	0.0860
97	Isobutyl acetate	110-19-0	C <sub>6</sub> H <sub>12</sub> O <sub>2</sub>	116.16	--	
98	Isopropyl alcohol	67-63-0	C <sub>3</sub> H <sub>8</sub> O	60.1	42.8	0.0980
99	Isopropyl amine	75-31-0	C <sub>3</sub> H <sub>9</sub> N	59.11	460	
100	Isopropylbenzene	98-82-8	C <sub>9</sub> H <sub>12</sub>	120.19	10.9@40C	
101	Methanol	67-56-1	CH <sub>4</sub> O	32.04	114	0.1500
102	Methyl acetate	79-20-9	C <sub>3</sub> H <sub>6</sub> O <sub>2</sub>	74.08	235	0.1040
103	Methyl acrylate	96-33-3	C <sub>4</sub> H <sub>7</sub> O <sub>2</sub>	86.09	--	
104	Methyl amine	74-89-5	CH <sub>5</sub> N	31.06	770@ -6C	
105	Methyl bromide	74-83-9	CH <sub>3</sub> BR	94.94	--	
106	Methyl-tert-butyl-ether	1634-04-4	C <sub>5</sub> H <sub>12</sub> O	88.15	245	0.0806
107	Methyl chloride	74-87-3	CH <sub>3</sub> CL	50.49	3830	0.1260
108	Methylcyclohexane	108-87-2	C <sub>7</sub> H <sub>14</sub>	98.19	43	
109	Methyl-ethyl-ketone	78-93-3	C <sub>4</sub> H <sub>8</sub> O	72.11	100	0.0808
110	Methyl formate	107-31-3	C <sub>2</sub> H <sub>4</sub> O <sub>2</sub>	60.05	500	
111	Methyl hydrazine	60-34-4	CH <sub>6</sub> N <sub>2</sub>	46.07	49.6	
112	Methyl iodide	74-88-4	CH <sub>3</sub> I	141.94	91	
113	Methyl-Isobutyl-Ketone	108-10-1	C <sub>6</sub> H <sub>12</sub> O	100.16	19.31	
114	Methyl isocyanate	624-83-9	C <sub>2</sub> H <sub>3</sub> NO	57.05	348	
115	Methyl-Isopropyl-Ketone	563-80-4	C <sub>5</sub> H <sub>10</sub> O	86.13	15.7	0.0750
116	Methyl mercaptan	74-93-1	CH <sub>4</sub> S	48.1	--	
117	Methyl methacrylate	80-62-6	C <sub>5</sub> H <sub>8</sub> O <sub>2</sub>	100.10	39	0.0770
118	Methyl-N-Propyl-Ketone	107-87-9	C <sub>5</sub> H <sub>10</sub> O	86.13	--	
119	Alpha-Methyl-Styrene	98-83-9	C <sub>9</sub> H <sub>10</sub>	118.18	0.076	0.2640
120	Monoethanolamine	141-43-5	C <sub>2</sub> H <sub>7</sub> NO	61.08	--	
121	Morpholine	110-91-8	C <sub>4</sub> H <sub>9</sub> NO	87.12	10.08	
122	Naphthalene	91-20-3	C <sub>10</sub> H <sub>8</sub>	128.19	0.023	0.0590
123	2-Nitropropane	79-46-9	C <sub>3</sub> H <sub>7</sub> NO <sub>2</sub>	89.09	12.9	
124	N-Nitrosodimethylamine	62-75-9	C <sub>2</sub> H <sub>6</sub> N <sub>2</sub> O	74.08	--	
125	N-Nitrosomorpholine	59-89-2	C <sub>4</sub> H <sub>8</sub> N <sub>2</sub> O	116.11	--	
126	N-Nonane	111-84-2	C <sub>9</sub> H <sub>20</sub>	128.26	4.28	
127	N-Octane	111-65-9	C <sub>8</sub> H <sub>18</sub>	114.23	17	

## Appendix B. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) <sup>1</sup>	Diffusivity in Air (cm <sup>2</sup> /sec)
128	N-Pentane	109-66-0	C <sub>5</sub> H <sub>12</sub>	72.15	513	
129	Phenanthrene	85-01-8	C <sub>14</sub> H <sub>10</sub>	178.23	2.00E-04	
130	Phenol	108-95-2	C <sub>6</sub> H <sub>6</sub> O	94.11	0.0341	0.0820
131	Phosgene	75-44-5	CCl <sub>2</sub> O	98.92	1.394	0.1080
132	Phosphine	7803-51-2	H <sub>3</sub> P	34.00	2.000	
133	Phthalic anhydride	85-44-9	C <sub>8</sub> H <sub>4</sub> O <sub>3</sub>	148.11	0.0015	0.0710
134	Propane	74-98-6	C <sub>3</sub> H <sub>8</sub>	44.1	760	
135	1,2-Propanediol	57-55-6	C <sub>3</sub> H <sub>8</sub> O <sub>2</sub>	76.11	0.3	
136	1-Propanol	71-23-8	C <sub>3</sub> H <sub>8</sub> O	60.1	20.85	
137	beta-Propiolactone	57-57-8	C <sub>3</sub> H <sub>4</sub> O <sub>2</sub>	72.06	3.4	
138	Propionaldehyde	123-38-7	C <sub>3</sub> H <sub>6</sub> O	58.08	300	
139	Propionic acid	79-09-4	C <sub>3</sub> H <sub>6</sub> O <sub>2</sub>	74.08	10	
140	N-Propyl-Acetate	109-60-4	C <sub>5</sub> H <sub>10</sub> O <sub>2</sub>	102.12	35	
141	Propylene oxide	75-56-9	C <sub>3</sub> H <sub>6</sub> O	58.08	524.5	0.1040
142	1,2-Propylenimine	75-55-8	C <sub>3</sub> H <sub>7</sub> N	54.1	112	
143	Pyridine	110-86-1	C <sub>5</sub> H <sub>5</sub> N	79.1	20	0.0910
144	Quinone	106-51-4	C <sub>6</sub> H <sub>4</sub> O <sub>2</sub>	108.09	--	
145	Styrene	100-42-5	C <sub>8</sub> H <sub>8</sub>	104.15	7.3	0.0710
146	1,1,1,2-Tetrachloro-2,2-Difluoroethane	76-11-9	C <sub>2</sub> Cl <sub>4</sub> F <sub>2</sub>	203.83	--	
147	1,1,2,2-Tetrachloroethane	79-34-5	C <sub>2</sub> H <sub>2</sub> Cl <sub>4</sub>	167.85	6.5	
148	Tetrachloroethylene	127-18-4	C <sub>2</sub> Cl <sub>4</sub>	165.83	19	0.0720
149	Tetrahydrofuran	109-99-9	C <sub>4</sub> H <sub>8</sub> O	72.11	72.1	0.0980
150	Toluene	108-88-3	C <sub>7</sub> H <sub>8</sub>	92.14	30	0.0870
151	P-Toluidine	106-49-0	C <sub>7</sub> H <sub>9</sub> N	107.16	0.3	
152	1,1,1-Trichloroethane	71-55-6	C <sub>2</sub> H <sub>3</sub> Cl <sub>3</sub>	133.41	123	0.0780
153	1,1,2-Trichloroethane	79-00-5	C <sub>2</sub> H <sub>3</sub> Cl <sub>3</sub>	133.41	25	0.0792
154	Trichloroethylene	79-01-6	C <sub>2</sub> HCl <sub>3</sub>	131.4	75	0.0790
155	Trichlorofluoromethane	75-69-4	CCl <sub>3</sub> F	137.37	667	
156	1,2,3-Trichloropropane	96-18-4	C <sub>3</sub> H <sub>5</sub> Cl <sub>3</sub>	147.43	3.1	
157	1,1,2-Trichloro-1,2,2-Trifluoroethane	76-13-1	C <sub>2</sub> Cl <sub>3</sub> F <sub>3</sub>	187.38	300	
158	Triethylamine	121-44-8	C <sub>6</sub> H <sub>15</sub> N	101.19	400	
159	Trifluorobromomethane	75-63-8	CF <sub>3</sub> Br	148.91	--	
160	1,2,3-Trimethylbenzene	526-73-8	C <sub>9</sub> H <sub>12</sub>	120.19	--	
161	1,2,4-Trimethylbenzene	95-63-6	C <sub>9</sub> H <sub>12</sub>	120.19	--	
162	1,3,5-Trimethylbenzene	108-67-8	C <sub>9</sub> H <sub>12</sub>	120.19	1.86	
163	Vinyl Acetate	108-05-4	C <sub>4</sub> H <sub>6</sub> O <sub>2</sub>	86.09	115	0.0850
164	Vinyl bromide	593-60-2	C <sub>2</sub> H <sub>3</sub> Br	107.0	895	
165	Vinyl-Chloride	75-01-4	C <sub>2</sub> H <sub>3</sub> Cl	62.5	2660	0.0900
166	M-Xylene	108-38-3	C <sub>8</sub> H <sub>10</sub>	106.2	8	0.0700
167	O-Xylene	95-47-6	C <sub>8</sub> H <sub>10</sub>	106.2	7	0.0870
168	P-Xylene	106-42-3	C <sub>8</sub> H <sub>10</sub>	106.2	9.5	

<sup>1</sup>All vapor pressures are at 25° C unless otherwise indicated.

## APPENDIX E - ARTICLE ON SOIL VAPOR EXTRACTION

(Source: Pedersen, T.A., and J.T. Curtis. Handbook on Soil Vapor Extraction Technology. EPA/540/2-91-003. February 1991.

### A PRACTICAL APPROACH TO THE DESIGN, OPERATION, AND MONITORING OF IN-SITU SOIL VENTING SYSTEMS

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#### INTRODUCTION

When operated properly, in-situ soil venting or vapor extraction can be one of the more cost-effective remediation processes for soils contaminated with gasoline, solvents, or other relatively volatile compounds. A "basic" system, such as that shown in Figure E-1, couples vapor extraction (recovery) wells with blowers or vacuum pumps to remove vapors from the vadose zone and thereby reduce residual levels of soil contaminants. More complex systems incorporate trenches, air injection wells, passive wells, and surface seals. Above-ground treatment systems condense, adsorb, or incinerate vapors; in some cases vapors are simply emitted to the atmosphere through diffuser stacks. In-situ soil venting is an especially attractive treatment option because the soil is treated in place, sophisticated equipment is not required, and the cost is typically lower than other options.

The basic phenomena governing the performance of soil venting systems are easily understood. By applying a vacuum and removing vapors from extraction wells, vapor flow through the unsaturated soil zone is induced. Contaminants volatilize from the soil matrix and are swept by the carrier gas flow (primarily air) to the extraction wells or trenches. Many complex processes occur on the microscale, however, the three main factors that control the performance of a venting operation are the chemical composition of the contaminant, vapor flowrates through the unsaturated zone, and the flowpath of carrier vapors relative to the location of the contaminants.

The components of soil venting systems are typically off-the-shelf items, and the installation of wells and trenches can be done by most reputable environmental firms. However, the design, operation, and monitoring of soil venting systems is not trivial. In fact, choosing whether or not

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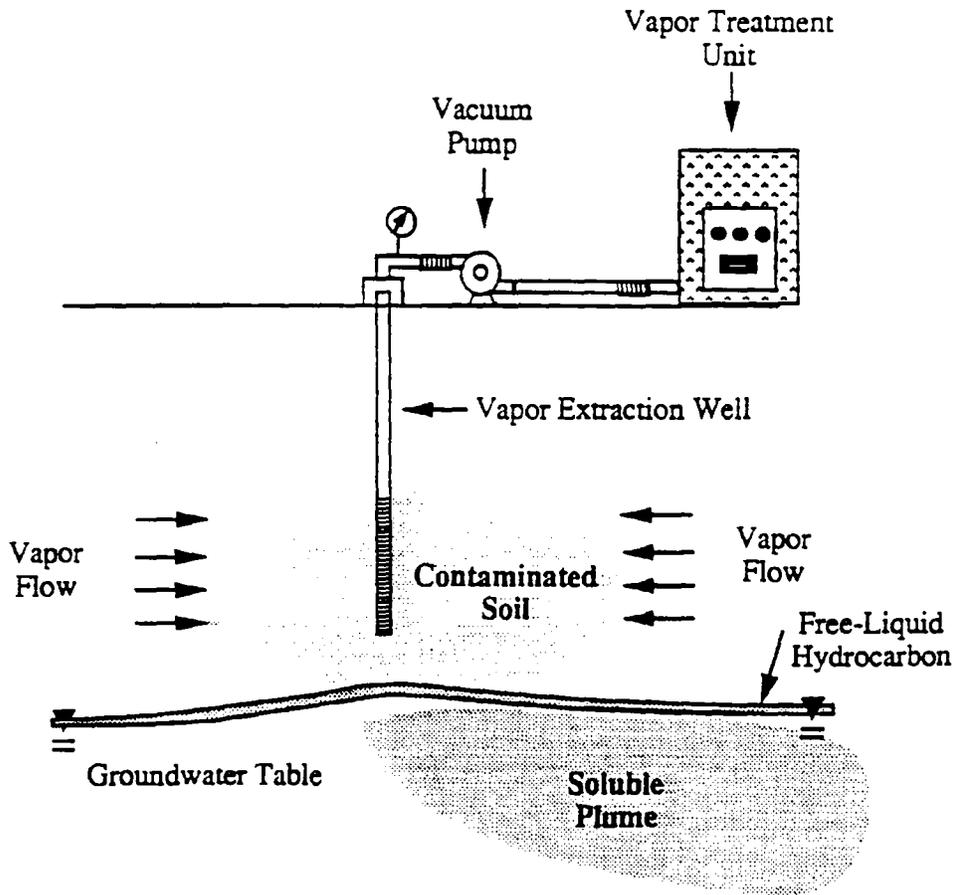


Figure E-1. "Basic" In-Situ Soil Venting System

venting should be applied at a given site is a difficult question in itself. If one decides to utilize venting, design questions involving the number of wells, well spacing, well location, well construction, and vapor treatment systems must then be answered. It is the current state-of-the-art that such questions are answered more by instinct than by rigorous logic. This is evidenced by the published soil venting "success stories" (see Hutzler et al.<sup>1</sup> for a good review), which rarely include insight into the design process.

In this paper we suggest a series of steps and questions that must be followed and answered in order to a) decide if venting is appropriate at a given site, and b) to design cost-effective in-situ soil venting systems. This series of steps and questions forms a "decision tree" process that could be easily incorporated in a PC-based expert system. In the development of this approach we will attempt to identify the limitations of in-situ soil venting, and subjects or behavior that are difficult to quantify and for which future study is needed.

#### THE "PRACTICAL APPROACH"

Figure E-2 presents a flowchart of the process discussed in this paper. Each step of the flowchart is discussed below in detail, and where appropriate, examples are given.

#### The Site Investigation

Whenever a soil contamination problem is detected or suspected, a site investigation is conducted to characterize and delineate the zone of soil and groundwater contamination. Often the sequence of steps after initial response and abatement is as follows:

(a) *background review*: Involves assembling historical records, plot plans, engineering drawings (showing utility lines), and interviewing site personnel. This information is used to help identify the contaminant, probable source of release, zone of contamination, and potentially impacted areas (neighbors, drinking water supplies, etc.).

(b) *preliminary site screening*: Preliminary screening tools such as soil-gas surveys and cone penetrometers are used to roughly define the zone of contamination and the site geology. Knowledge of site geology is essential to determine probable migration of contaminants through the unsaturated zone.

(c) *detailed site characterization*: Soil borings are drilled and monitoring wells are installed based on the results from steps (a) and (b).

(d) *contaminant characterization*: soil and groundwater samples are analyzed to determine contaminant concentrations and compositions.

Costs associated with site investigations can be relatively high depending on the complexity of the site and size of the spill or leak. For large spills and complex site geological/hydrogeological conditions, site

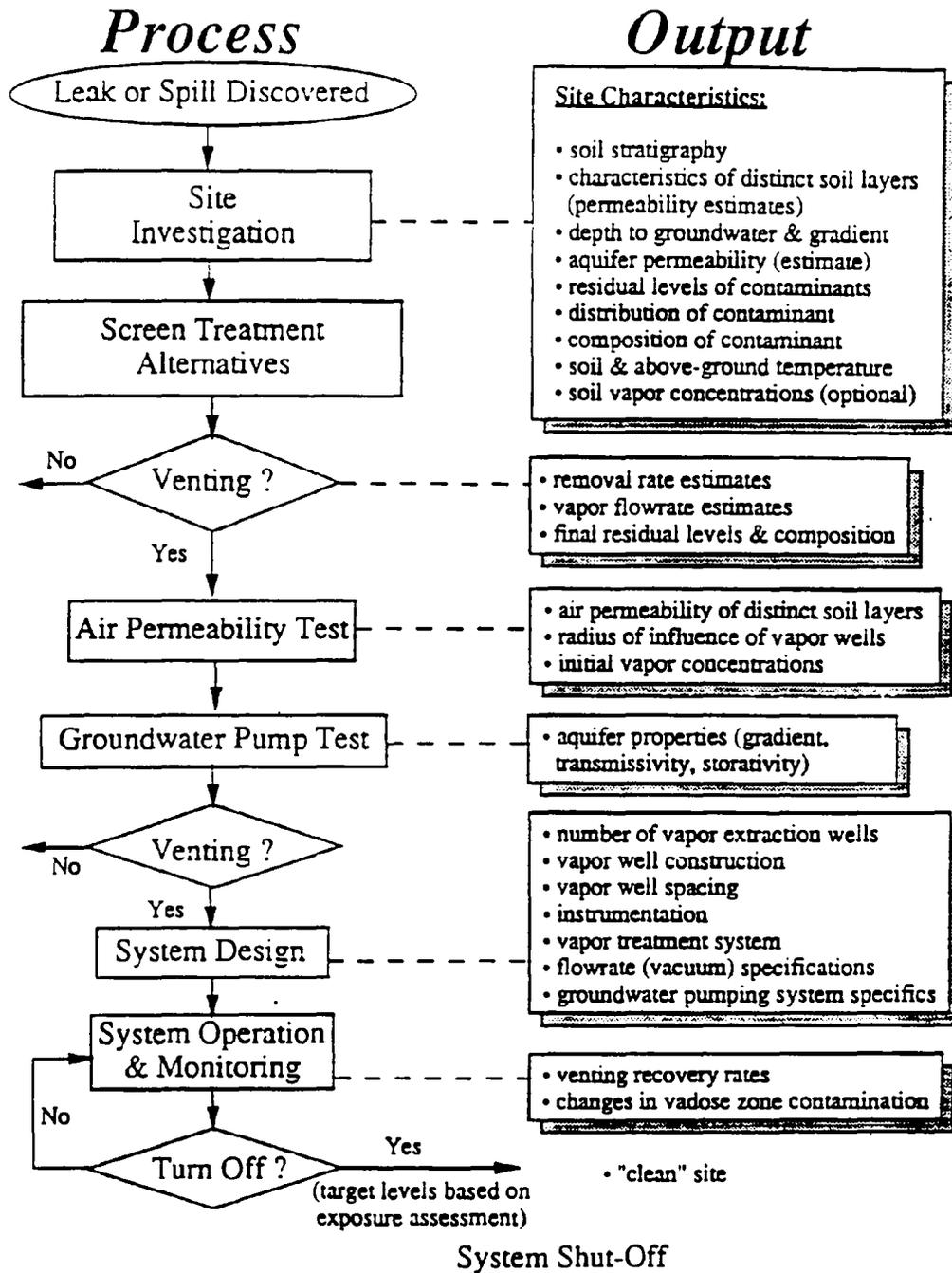


Figure E-2. In-Situ Soil Venting System Design Process.

investigation costs are often comparable to remediation costs. In addition, the choice and design of a remediation system is based on the data obtained during the site investigation. For these reasons it is important to insure that specific information is collected, and to validate the quality of the data.

If it is presumed that in-situ soil venting will be a candidate for treatment, then the following information needs to be obtained during the preliminary site investigation:

(a) *site geology* - this includes soil type and subsurface stratigraphy. While they are not essential, the moisture content, total organic carbon, and permeability of each distinct soil layer also provides useful information that can be used to choose and design a remediation system.

(b) *site hydrogeology* - the water table depth and gradient must be known, as well as estimates of the aquifer permeability.

(c) *contaminant composition, distribution and residual levels* - soil samples should be analyzed to determine which contaminants are present at what levels. Recommended analytical methods should be used to identify target compounds (i.e., benzene, toluene, or xylenes) and total hydrocarbons present. For soil analyses these methods are:

EPA 8240 - volatile organic chemicals  
EPA 8270 - semi-volatile organic chemicals  
EPA 418.1 - total petroleum hydrocarbons

The corresponding water analyses methods are:

EPA 624 - volatile organic chemicals  
EPA 625 - semi-volatile organic chemicals  
EPA 418.1 - total petroleum hydrocarbons

With the current high cost of chemical analyses it is important to intelligently select which analyses should be performed and which samples should be sent to a certified laboratory. Local regulations usually require that a minimum number of soil borings be performed, and target compounds must be analyzed for based on the suspected composition of the contamination. Costs can be minimized and more data obtained by utilizing field screening tools, such as hand-held vapor meters or portable field GC's. These instruments can be used to measure both residual soil contamination levels and headspace vapors above contaminated soils. At a minimum, soil samples corresponding to lithology changes or obvious changes in residual levels (based on visual observations or odor) should be analyzed.

For complex contamination mixtures, such as gasoline, diesel fuel, and solvent mixtures, it is not practical or necessary to identify and quantify each compound present. In such cases it is recommended that a "boiling point" distribution be measured for a representative sample of the residual

contamination. Boiling point distribution curves, such as shown in Figure E-3 for "fresh" and "weathered" gasoline samples, can be constructed from GC analyses of the soil residual contamination (or free-product) and knowledge of the GC elution behavior of a known series of compounds (such as straight-chain alkanes). Compounds generally elute from a GC packed column in the order of increasing boiling point, so a boiling point distribution curve is constructed by grouping all unknowns that elute between two known peaks (i.e. between n-hexane and n-heptane). Then they are assigned an average boiling point, molecular weight, and vapor pressure. Use of this data will be explained below.

(d) *temperature* - both above- and below-ground surface.

The cone penetrometer, which is essentially an instrumented steel rod that is driven into the soil, is becoming a popular tool for preliminary site screening investigations. By measuring the shear and normal forces on the leading end of the rod, soil structure, and hence permeability can be defined. Some cone penetrometers are also constructed to allow the collection of vapor or groundwater samples. This tool has several advantages over conventional soil boring techniques (as a preliminary site characterization tool): the subsurface soil structure can be defined better, no soil cuttings are generated, and more analyses can be performed per day.

Results from the preliminary site investigation should be summarized in contour plots, fence diagrams, and tables prior to analyses.

#### Deciding if Venting is Appropriate

As stated above, the three main factors governing the behavior of any in-situ soil venting operation are the vapor flow rate, contaminant vapor concentrations, and the vapor flowpath relative to the contaminant location. In an article by Johnson et al.<sup>2</sup> simple mathematical equations were presented to help quantify each of these factors. Below we illustrate how to utilize these "screening models" and the information collected during the preliminary site investigation to help determine if in-situ soil venting is appropriate at a given site. In making this decision we will answer the following questions:

- (1) *What contaminant vapor concentrations are likely to be obtained?*
- (2) *Under ideal vapor flow conditions (i.e. 100 - 1000 scfm vapor flowrates), is this concentration great enough to yield acceptable removal rates?*
- (3) *What range of vapor flowrates can realistically be achieved?*
- (4) *Will the contaminant concentrations and realistic vapor flowrates produce acceptable removal rates?*

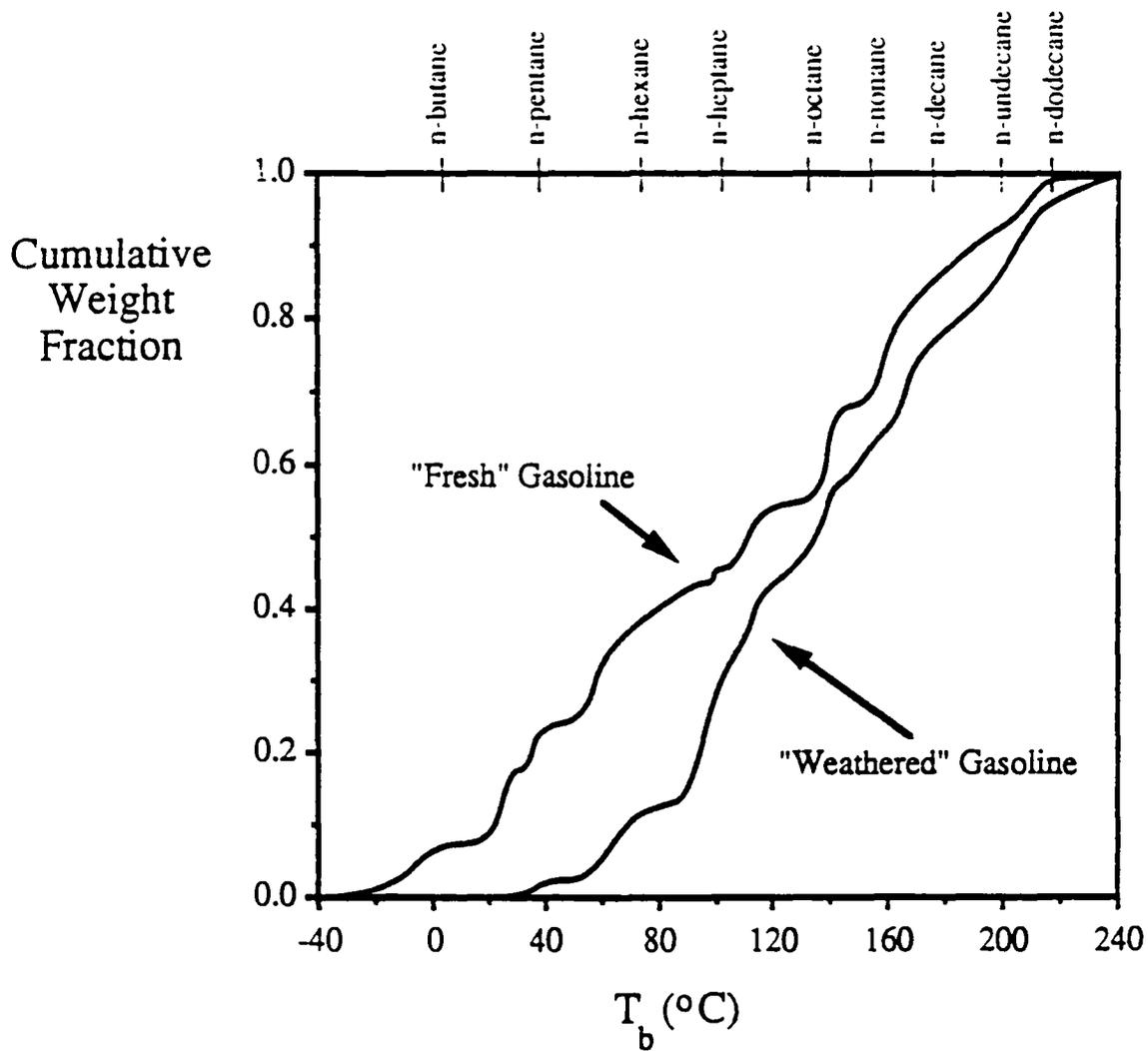


Figure E-3. Boiling Point Distribution Curves for Samples of "Fresh" and "Weathered" Gasolines.

(5) What are the vapor composition and concentration changes? What residual, if any, will be left in the soil?

(6) Are there likely to be any negative effects of soil venting?

Negative answers to questions (2), (3), or (4) will rule out in-situ soil venting as a practical treatment method.

(1) - What contaminant vapor concentrations are likely to be obtained?

Question (1) can be answered based on the results of soil vapor surveys, analyses of headspace vapors above contaminated soil samples, or equilibrium vapor models<sup>2</sup>. In some cases just knowing which compounds are present is sufficient to estimate if venting is feasible. In the absence of soil-vapor survey data, contaminant vapor concentrations can be estimated. The maximum vapor concentration of any compound (mixture) in extracted vapors is its equilibrium or "saturated" vapor concentration, which is easily calculated from knowledge of the compound's (mixture's) molecular weight, vapor pressure at the soil temperature, residual soil contaminant composition, and the ideal gas law:

$$C_{est} = \sum_i \frac{x_i P_i^v M_{v,i}}{RT} \quad (E-1)$$

where:

- $C_{est}$  - estimate of contaminant vapor concentration [mg/l]
- $x_i$  - mole fraction of component  $i$  in liquid-phase residual  
( $x_i = 1$  for single compound)
- $P_i^v$  - pure component vapor pressure at temperature  $T$  [atm]
- $M_{v,i}$  - molecular weight of component  $i$  [mg/mole]
- $R$  - gas constant = 0.0821 l-atm/mole-°K
- $T$  - absolute temperature of residual [°K]

Table E-1 presents data for some chemicals and mixtures often spilled in the environment. There are more sophisticated equations for predicting vapor concentrations in soil systems based on equilibrium partitioning arguments, but these require more detailed information (organic carbon content, soil moisture) than is normally available. If a site is chosen for remediation, the residual total hydrocarbons in soil typically exceed 500 mg/kg. In this residual concentration range the majority of hydrocarbons will be present as a separate or "free" phase, the contaminant vapor concentrations become independent of residual concentration (but still depend on composition), and Equation E-1 is applicable<sup>2</sup>. In any case, it should be noted that these are estimates only for vapor concentrations at the start of venting, which is when the removal rates are generally greatest. Contaminant concentrations in the extracted vapors will decline with time due to changes in composition, residual levels, or increased diffusional resistances. These topics are discussed below in more detail.

Table E-1. Selected Compounds and Their Chemical Properties.

Compound	M <sub>w</sub> (g/mole)	T <sub>b</sub> (1 atm) (°C)	P <sub>v</sub> <sup>o</sup> (20°C) (atm)	C <sub>sat</sub> (mg/l)
n-pentane	72.2	36	0.57	1700
n-hexane	86.2	69	0.16	560
trichloroethane	133.4	75	0.132	720
benzene	78.1	80	0.10	320
cyclohexane	84.2	81	0.10	340
trichloroethylene	131.5	87	0.026	140
n-heptane	100.2	98	0.046	190
toluene	92.1	111	0.029	110
tetrachloroethylene	166	121	0.018	130
n-octane	114.2	126	0.014	65
chlorobenzene	113	132	0.012	55
p-xylene	106.2	138	0.0086	37
ethylbenzene	106.2	138	0.0092	40
m-xylene	106.2	139	0.0080	35
o-xylene	106.2	144	0.0066	29
styrene	104.1	145	0.0066	28
n-nonane	128.3	151	0.0042	22.0
n-propylbenzene	120.2	159	0.0033	16
1,2,4 trimethylbenzene	120.2	169	0.0019	9.3
n-decane	142.3	173	0.0013	7.6
DBCP	263	196	0.0011	11
n-undecane	156.3	196	0.0006	3.8
n-dodecane	170.3	216	0.00015	1.1
napthalene	128.2	218	0.00014	0.73
tetraethyllead	323	dec. @200C	0.0002	2.6
gasoline <sup>1</sup>	95	-	0.34	1300
weathered gasoline <sup>2</sup>	111	-	0.049	220

<sup>1</sup> Corresponds to "fresh" gasoline defined in Table E-2 with boiling point distribution shown in Figure E-3.

<sup>2</sup> Corresponds to "weathered" gasoline defined in Table E-2 with boiling point distribution shown in Figure E-3.

(2) - Under ideal vapor flow conditions (i.e. 100 - 1000 scfm vapor flowrates), is this concentration great enough to yield acceptable removal rates?

Question (2) is answered by multiplying the concentration estimate  $C_{est}$ , by a range of reasonable flowrates, Q:

$$R_{est} = C_{est} Q \quad (E-2)$$

Here  $R_{est}$  denotes the estimated removal rate, and  $C_{est}$  and Q must be expressed in consistent units. For reference, documented venting operations at service station sites typically report vapor flowrates in the 10 - 100 scfm range<sup>1</sup>, although 100 - 1000 scfm flowrates are achievable for very sandy soils or large numbers of extraction wells. At this point in the decision process we are still neglecting that vapor concentrations decrease during venting due to compositional changes and mass transfer resistances. Figure E-4 presents calculated removal rates  $R_{est}$  [kg/d] for a range of  $C_{est}$  and Q values.  $C_{est}$  values are presented in [mg/l] and [ppm<sub>CH<sub>4</sub></sub>] units, where [ppm<sub>CH<sub>4</sub></sub>] represents methane-equivalent parts-per-million volume/volume (ppm<sub>v</sub>) units. The [ppm<sub>CH<sub>4</sub></sub>] units are used because field analytical tools that report [ppm<sub>v</sub>] values are often calibrated with methane. The [mg/l] and [ppm<sub>CH<sub>4</sub></sub>] units are related by:

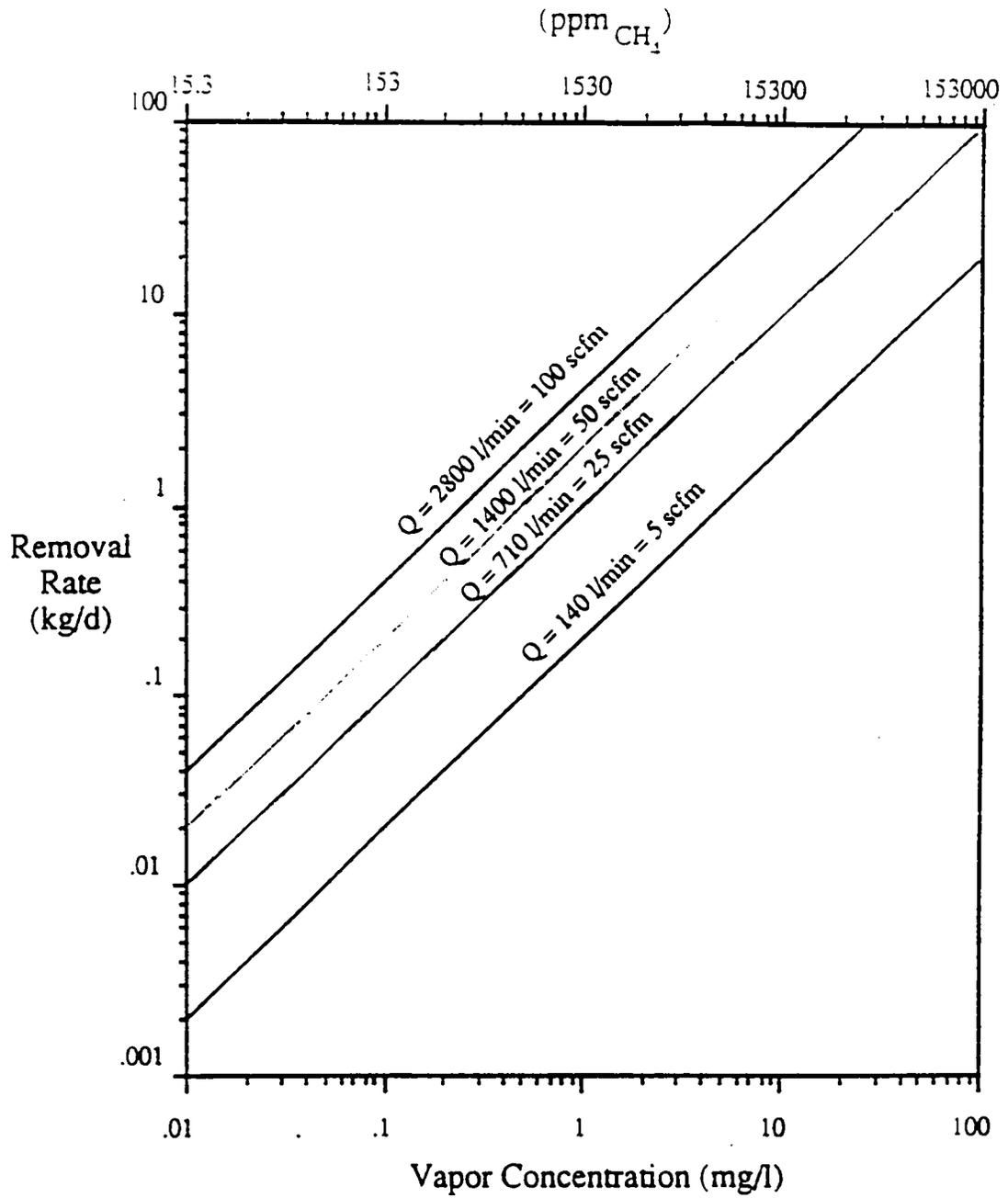
$$[\text{mg/l}] = \frac{[\text{ppm}_{\text{CH}_4}] * 16000\text{mg-CH}_4/\text{mole-CH}_4 * 10^{-6}}{(0.0821 \text{ l-atm/}^\circ\text{K-mole}) * (298\text{K})} \quad (E-3)$$

For field instruments calibrated with other compounds (i.e., butane, propane) [ppm<sub>v</sub>] values are converted to [mg/l] by replacing the molecular weight of CH<sub>4</sub> in Equation E-3 by the molecular weight [mg/mole] of the calibration compound.

Acceptable or desirable removal rates  $R_{acceptable}$ , can be determined by dividing the estimated spill mass  $M_{spill}$ , by the maximum acceptable clean-up time  $\tau$ :

$$R_{acceptable} = M_{spill}/\tau \quad (E-4)$$

For example, if 1500 kg (≈500 gal) of gasoline had been spilled at a service station and we wished to complete the clean-up within eight months, then  $R_{acceptable} = 6.3$  kg/d. Based on Figure E-4, therefore,  $C_{est}$  would have to average >1.5 mg/l (2400 ppm<sub>CH<sub>4</sub></sub>) for Q=2800 l/min (100 cfm) if venting is to be an acceptable option. Generally, removal rates <1 kg/d will be unacceptable for most spills, so soils contaminated with compounds (mixtures) having saturated vapor concentrations less than 0.3 mg/l (450 ppm<sub>CH<sub>4</sub></sub>) will not be good candidates for venting, unless vapor flowrates exceed 100 scfm. Judging from the compounds listed in Table E-1, this corresponds to compounds with



\* (ppm  $\text{CH}_4$ ) - concentration in methane-equivalent ppm (vol./vol.) units

Figure E-4. In-Situ Soil Venting Removal Rate Dependence on Vapor Extraction Rate and Vapor Concentration.

boiling points ( $T_b$ ) > 150°C, or pure component vapor pressures < 0.0001 atm evaluated at the subsurface temperature.

- What range of vapor flowrates can realistically be achieved?

Question (3) requires that we estimate realistic vapor flowrates for our site specific conditions. Equation E-5, which predicts the flowrate per unit thickness of well screen  $Q/H$  [ $\text{cm}^3/\text{s}$ ], can be used for this purpose:

$$\frac{Q}{H} = \frac{k}{\mu} P_v \frac{[1 - (P_{\text{atm}}/P_v)^2]}{\ln(R_v/R_I)} \quad (\text{E-5})$$

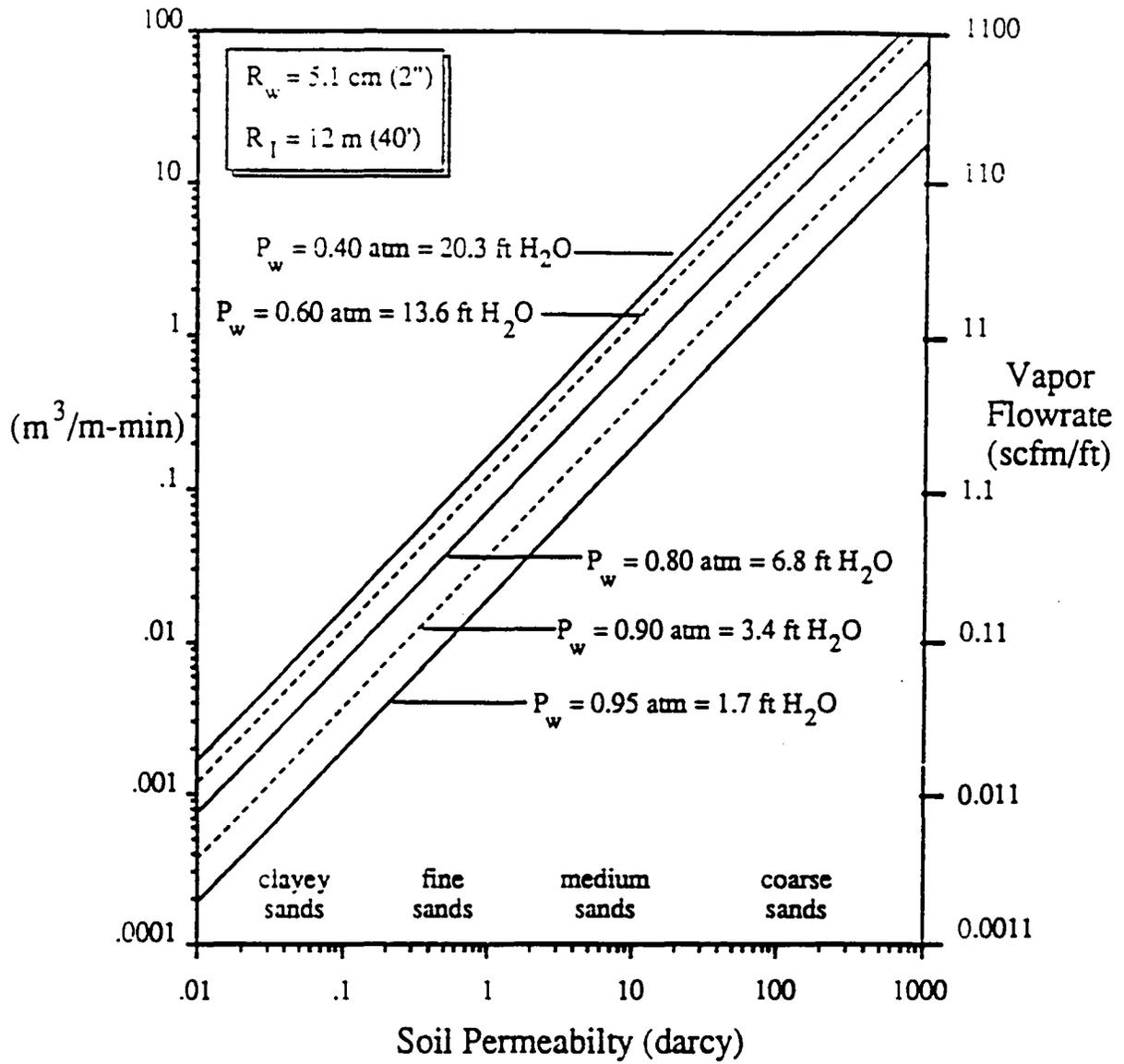
where:

- $k$  - soil permeability to air flow [ $\text{cm}^2$ ] or [darcy]
- $\mu$  - viscosity of air =  $1.8 \times 10^{-4}$  g/cm-s or 0.018 cp
- $P_v$  - absolute pressure at extraction well [g/cm-s<sup>2</sup>] or [atm]
- $P_{\text{atm}}$  - absolute ambient pressure  $\approx 1.01 \times 10^6$  g/cm-s<sup>2</sup> or 1 atm
- $R_v$  - radius of vapor extraction well [cm]
- $R_I$  - radius of influence of vapor extraction well [cm]

This equation is derived from the simplistic steady-state radial flow solution for compressible flow<sup>2</sup>, but should provide reasonable estimates for vapor flow rates. If we can measure or estimate  $k$ , then the only unknown parameter is the empirical "radius of influence"  $R_I$ . Values ranging from 9 m (30 ft) to 30 m (100 ft) are reported in the literature for a variety of soil conditions, but fortunately Equation E-5 is not very sensitive to large changes in  $R_I$ . For estimation purposes, therefore, a value of  $R_I = 12$  m (40 ft) can be used without a significant loss of accuracy. Typical vacuum well pressures range from 0.95 - 0.90 atm (20 - 40 in H<sub>2</sub>O vacuum). Figure E-5 presents predicted flowrates per unit well screen depth  $Q/H$ , expressed in "standard" volumetric units  $Q^*/H$  ( $= Q/H(P_v/P_{\text{atm}})$ ) for a 5.1 cm radius (4" diameter) extraction well, and a wide range of soil permeabilities and applied vacuums. Here  $H$  denotes the thickness of the screened interval, which is often chosen to be equal to the thickness of the zone of soil contamination (this minimizes removing and treating any excess "clean" air). For other conditions the  $Q^*/H$  values in Figure E-5 can be multiplied by the following factors:

- $R_v = 5.1$  cm (2")  $R_I = 7.6$  m (25') - multiply by  $Q^*/H$  by 1.09
- $R_v = 5.1$  cm (2")  $R_I = 23$  m (75') - multiply by  $Q^*/H$  by 0.90
- $R_v = 7.6$  cm (3")  $R_I = 12$  m (40') - multiply by  $Q^*/H$  by 1.08
- $R_v = 10$  cm (4")  $R_I = 12$  m (40') - multiply by  $Q^*/H$  by 1.15
- $R_v = 10$  cm (4")  $R_I = 7.6$  m (25') - multiply by  $Q^*/H$  by 1.27

As indicated by the multipliers given above, changing the radius of influence from 12 m (40 ft) to 23 m (75 ft) only decreases the predicted flowrate by 10%. The largest uncertainty in flowrate calculations will be due to the air permeability value  $k$ , which can vary by one to three orders of magnitude across a site and can realistically only be estimated from boring log data



[ft H<sub>2</sub>O] denote vacuums expressed as equivalent water column heights

Figure E-5. Predicted Steady-State Flowrates (per unit well screen depth) for a Range of Soil Permeabilities and Applied Vacuums ( $P_w$ ).

within an order of magnitude. It is prudent, therefore, to choose a range of  $k$  values during this phase of the decision process. For example, if boring logs indicate fine sandy soils are present, then flowrates should be calculated for  $k$  values in the range  $0.1 < k < 1.0$  darcy.

(4) - Will the contaminant concentrations and realistic vapor flowrates produce acceptable removal rates?

Again, estimated removal rates  $R_{est}$ , must be compared with an acceptable rate  $R_{acceptable}$ , as determined from Equation E-4. Maximum removal rates are achieved when the induced vapor flow travels only through the zone of soil contamination and no mass-transfer limitations are encountered. In other words, all vapor flows through contaminated soils and becomes saturated with contaminant vapors. For this "best" case the estimated removal rate is given by Equation E-2:

$$R_{est} = C_{est} Q \quad (E-2)$$

We are still neglecting changes in  $C_{est}$  with time due to composition changes. Other less optimal conditions are often encountered in practice and it is useful to be able to quantify how much lower the removal rate will be from the value predicted by Equation E-2. We will consider the three cases illustrated in Figure E-6a, b, and c.

In Figure E-6a, a fraction  $\phi$  of the vapor flows through uncontaminated soil. The fraction can be roughly estimated by assessing the location of the well relative the contaminant distribution. In Figure E-6a, for example, it appears that roughly 25% of the vapor flows through uncontaminated soil. The maximum removal rate for this case is then:

$$R_{est} = (1-\phi)Q C_{est} \quad (E-6)$$

In Figure E-6b, vapor flows parallel to, but not through, the zone of contamination, and the significant mass transfer resistance is vapor phase diffusion. This would be the case for a layer of liquid hydrocarbon resting on top of an impermeable strata or the water table. This problem was studied by Johnson et al.<sup>2</sup> for the case of a single component. Their solution is:

$$R_{est} = \eta Q C_{est}$$

$$\eta = \frac{1}{3H} (6D\mu/k)^{1/2} [\ln(R_1/R_v) / (P_{atm} - P_v)]^{1/2} [R_2^2 - R_1^2]^{1/2} \quad (E-7)$$

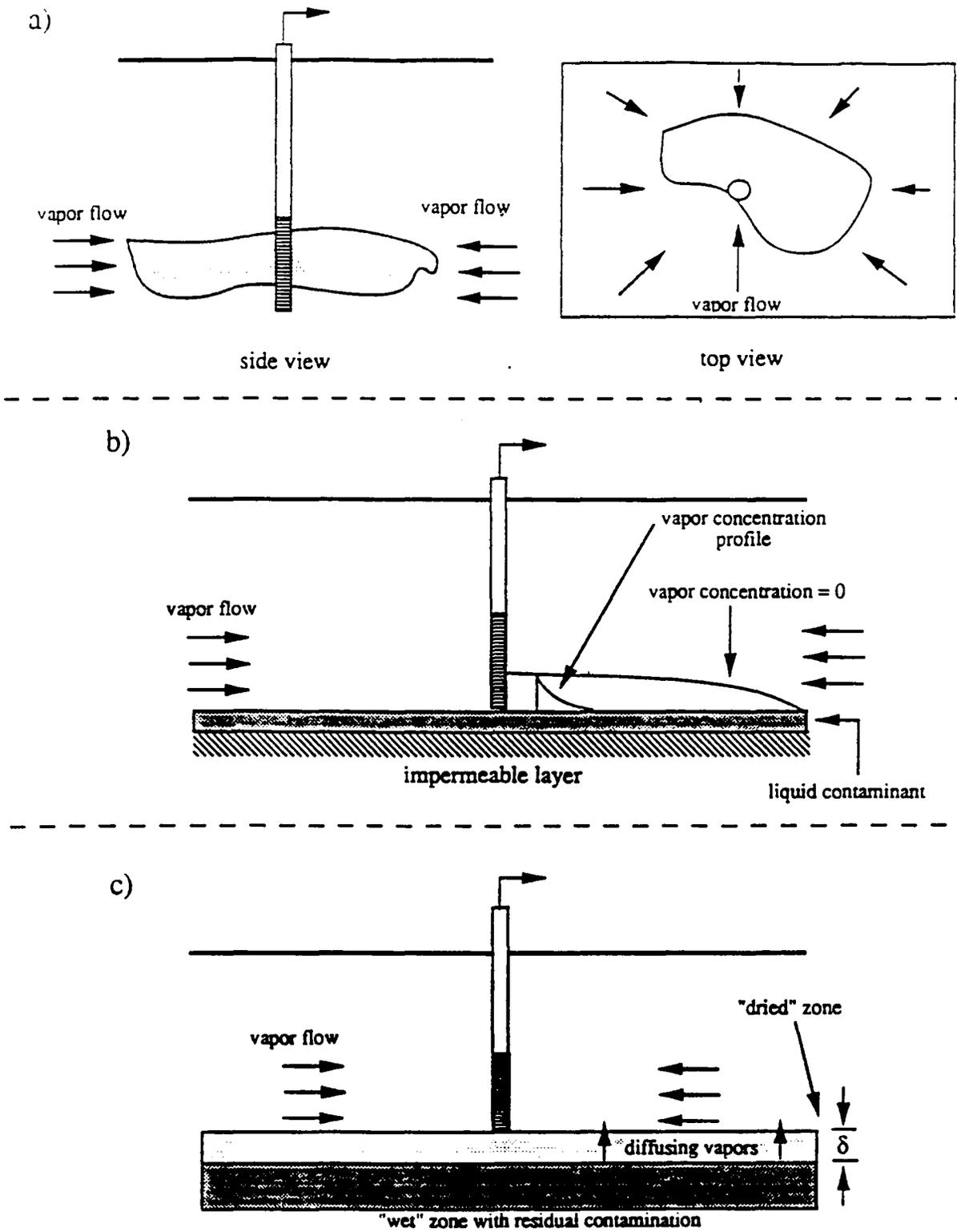


Figure E-6. Scenarios for Removal Rate Estimates.

where:

- $\eta$  - efficiency relative to maximum removal rate
- $D$  - effective soil vapor diffusion coefficient [ $\text{cm}^2/\text{s}$ ]
- $\mu$  - viscosity of air =  $1.8 \times 10^{-4}$  g/cm-s
- $k$  - soil permeability to vapor flow [ $\text{cm}^2$ ]
- $H$  - thickness of screened interval [cm]
- $R_I$  - radius of influence of venting well [cm]
- $R_w$  - venting well radius [cm]
- $P_{\text{atm}}$  - absolute ambient pressure =  $1.016 \times 10^6$  g/cm-s<sup>2</sup>
- $P_w$  - absolute pressure at the venting well [g/cm-s<sup>2</sup>]
- $R_1 < r < R_2$  - defines region in which contamination is present

Note that the efficiency  $\eta$  is inversely proportional to the screened interval thickness  $H$  because a larger interval will, in this geometry, pull in unsaturated air that has passed above the liquid-phase contamination.  $D$  is calculated by the Millington-Quirk<sup>3</sup> expression, which utilizes the molecular diffusion coefficient in air  $D^0$ , the vapor-filled soil porosity  $\epsilon_A$ , and the total soil porosity  $\epsilon_T$ :

(E-8)

$$D = D^0 \frac{\epsilon_A^{3.33}}{\epsilon_T^2}$$

where  $\epsilon_A$  and  $\epsilon_T$  are related by:

$$\epsilon_A = \epsilon_T - \rho_b \theta_M \quad (\text{E-9})$$

Here  $\rho_b$  and  $\theta_M$  are the soil bulk density [g/cm<sup>3</sup>] and soil moisture content [g-H<sub>2</sub>O/g-soil].

As an example, consider removing a layer of contamination bounded by sandy soil ( $k=1$  darcy). A 5.1-cm (2") radius extraction well is being operated at  $P_w=0.90$  atm ( $0.91 \times 10^6$  g/cm-s<sup>2</sup>), and the contamination extends from the region  $R_1 = R_w = 5.1$  cm to  $R_2 = 9$  m (30 ft). The well is screened over a 3m (10 ft) interval. Assuming that:

- $\rho_b$  - 1.6 g/cm<sup>3</sup>
- $\theta_M$  - 0.10
- $D^0$  - 0.087 cm<sup>2</sup>/s
- $\epsilon_T$  - 0.30
- $R_I$  - 12 m

then the venting efficiency relative to the maximum removal rate (Equation E-5), calculated from Equations E-7 through E-9 is:

$$\eta = 0.09 = 9\%$$

Figure E-6c depicts the situation in which vapor flows primarily past, rather than through the contaminated soil zone, such as might be the case for a contaminated clay lens surrounded by sandy soils. In this case vapor phase diffusion through the clay to the flowing vapor limits the removal rate. The maximum removal rate in this case occurs when the vapor flow is fast enough to maintain a very low vapor concentration at the permeable/impermeable soil interface. At any time  $t$  a contaminant-free or "dried out" zone of low permeability will exist with a thickness  $\delta$ . An estimate of the removal rate  $R_{est}$  from a contaminated zone extending from  $R_1$  to  $R_2$  is:

(E-10)

$$R_{est} = \pi \left( \frac{R_2^2}{2} - \frac{R_1^2}{2} \right) C_{est} D / \delta(t)$$

where  $D$  is the effective porous media vapor diffusion coefficient (as calculated above from Equations E-8 and E-9) and  $C_{est}$  is the estimated equilibrium vapor concentration (Equation E-1). With time  $\delta(t)$  will grow larger. In the case of a single component system the dry zone thickness can be calculated from the mass balance:

(E-11)

$$\rho_b C_s \frac{d\delta}{dt} = C_{est} D / \delta(\tau)$$

where  $C_s$  is the residual level of contamination in the low permeability zone [g-contamination/g-soil], and all other variables are defined above. The solution to Equations E-10 and E-11 yields the following equation that predicts the change in removal rate with time:

$$\delta(\tau) = \frac{[2C_{est}D\tau]^{1/2}}{\rho_b C_s}$$

$$R_{est} = \pi \left( \frac{R_2^2}{2} - \frac{R_1^2}{2} \right) \frac{[C_{est}DC_s\rho_b]^{1/2}}{2\tau}$$

(E-12)

As an example, consider the case where benzene ( $C_v = 3.19 \times 10^{-4}$  g/cm<sup>3</sup> @20°C) is being removed from a zone extending from  $R_1 = 5.1$  m to  $R_2 = 9$  m. The initial residual level is 10,000 ppm (0.01 g-benzene/g-soil),  $\rho_b = 1.6$  g/cm<sup>3</sup>,  $D^o = 0.087$  cm<sup>2</sup>/s, and  $\epsilon_T = \epsilon_A = 0.30$ . Figure E-7 presents the predicted removal rates and "dry" zone thickness  $d(t)$  as a function of time. Note that it would take approximately one year to clean a layer 1.5 m (5 ft) thick, for a compound as volatile as benzene. Equation E-12 predicts very high initial removal rates; in practice, however, the removal rate will be limited initially by the vapor-phase diffusion behavior described above for Figure E-6b.

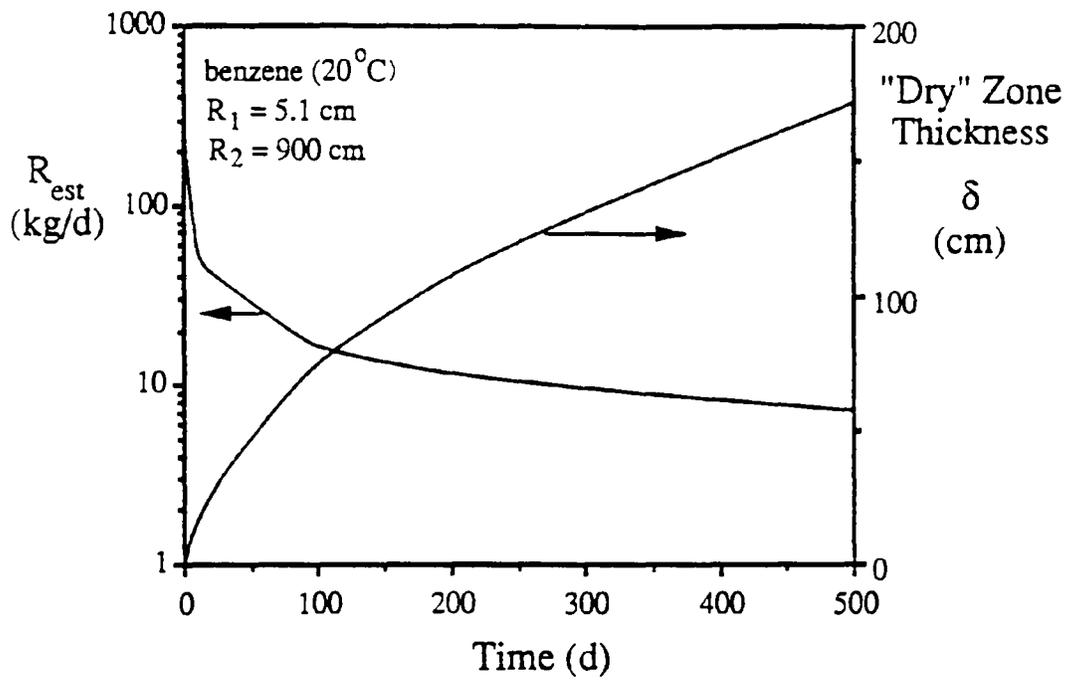


Figure E-7. Estimated Maximum Removal Rates for a Venting Operation Limited by Diffusion.

Mixture removal rates for the situations depicted in Figures E-6b and E-6c are difficult to estimate because changes in composition and liquid-phase diffusion affect the behavior. Presently there are no simple analytical solutions for these situations, but we can postulate that they should be less than the rates predicted above for pure components.

The use of equilibrium-based models to predict required removal rates is discussed below under the next question.

(5) - *What are the vapor composition and concentration changes? What residual, if any, will be left in the soil?*

As contaminants are removed during venting, the residual soil contamination level decreases and mixture compositions become richer in the less volatile compounds. Both of these processes result in decreased vapor concentrations, and hence, decreased removal rates with time. At low residual soil contamination levels (<500 ppm) Equation E-1 becomes less valid as sorption and dissolution phenomena begin to affect the soil residual - vapor equilibrium. In the limit of low residual contamination levels, contaminant equilibrium vapor concentrations are expected to become proportional to the residual soil contaminant concentrations. As venting continues and residual soil levels decrease, therefore, it becomes more difficult to remove the residual contamination. It is important to realize that, even with soil venting, there are practical limitations on the final soil contamination levels that can be achieved. Knowledge of these limits is necessary to realistically set clean-up criteria and design effective venting systems.

The maximum efficiency of a venting operation is limited by the equilibrium partitioning of contaminants between the soil matrix and vapor phases. The maximum removal rate is achieved when the vapor being removed from an extraction well is in equilibrium with the contaminated soil. Models for predicting this maximum removal rate have been presented by Marley and Hoag<sup>4</sup> and Johnson et al.<sup>2</sup> The former considered only compositions in a residual free-phase, while the latter also considered the effects of sorption and dissolution processes. A complete discussion of the development of these models is not appropriate here, but we will discuss use of the predictions.

The change in composition, vapor concentration, removal rate, and residual soil contamination level with time are functions of the initial residual composition, vapor extraction well flowrate, and initial soil contamination level. It is not necessary to generate predictions for every combination of variables, however, because with appropriate scaling all results will form a single curve for a given initial mixture composition. Figure E-8a presents the results computed with the model presented by Johnson et al.<sup>2</sup> for the "weathered" gasoline mixture whose composition is given by Table E-2. The important variable that determines residual soil levels, vapor concentrations, and removal rates is the ratio  $Q_t/M(t=0)$ , which represents the volume of air drawn through the contaminated zone per unit mass of contaminant. In Figure E-8, the scaled removal rate (or equivalently the

Table E-2. Composition of "Fresh" and "Weathered" Gasolines.

Compound Name	Mw (g)	Fresh Gasoline	Weathered Gasoline	Approximate Composition
propane	44.1	0.0001	0.0000	0
isobutane	58.1	0.0122	0.0000	0
n-butane	58.1	0.0629	0.0000	0
trans-2-butene	56.1	0.0007	0.0000	0
cis-2-butene	56.1	0.0000	0.0000	0
3-methyl-1-butene	70.1	0.0006	0.0000	0
isopentane	72.2	0.1049	0.0069	0.0177
1-pentene	70.1	0.0000	0.0005	0
2-methyl-1-butene	70.1	0.0000	0.0008	0
2-methyl-1,3-butadiene	68.1	0.0000	0.0000	0
n-pentane	72.2	0.0586	0.0095	0
trans-2-pentene	70.1	0.0000	0.0017	0
2-methyl-2-butene	70.1	0.0044	0.0021	0
3-methyl-1,2-butadiene	68.1	0.0000	0.0010	0
3,3-dimethyl-1-butene	84.2	0.0049	0.0000	0
cyclopentane	70.1	0.0000	0.0046	0.0738
3-methyl-1-pentene	84.2	0.0000	0.0000	0
2,3-dimethylbutane	86.2	0.0730	0.0044	0
2-methylpentane	86.2	0.0273	0.0207	0
3-methylpentane	86.2	0.0000	0.0186	0
n-hexane	86.2	0.0283	0.0207	0
methylcyclopentane	84.2	0.0083	0.0234	0
2,2-dimethylpentane	100.2	0.0076	0.0064	0
benzene	78.1	0.0076	0.0021	0
cyclohexane	84.2	0.0000	0.0137	0.1761
2,3-dimethylpentane	100.2	0.0390	0.0000	0
3-methylhexane	100.2	0.0000	0.0355	0
3-ethylpentane	100.2	0.0000	0.0000	0
n-heptane	100.2	0.0063	0.0447	0
2,2,4-trimethylpentane	114.2	0.0121	0.0503	0
methylcyclohexane	98.2	0.0000	0.0393	0
2,2-dimethylhexane	114.2	0.0055	0.0207	0
toluene	92.1	0.0550	0.0359	0.1926
2,3,4-trimethylpentane	114.2	0.0121	0.0000	0
3-methylheptane	114.2	0.0000	0.0343	0
2-methylheptane	114.2	0.0155	0.0324	0
n-octane	114.2	0.0013	0.0300	0

Table E-2 (continued). Composition of "Fresh" and "Weathered" Gasolines.

2,4,4-trimethylhexane	128.3	0.0087	0.0034	0
2,2-dimethylheptane	128.3	0.0000	0.0226	0
ethylbenzene	106.2	0.0000	0.0130	0
p-xylene	106.2	0.0957	0.0151	0
m-xylene	106.2	0.0000	0.0376	0.1641
3,3,4-trimethylhexane	128.3	0.0281	0.0056	0
o-xylene	106.2	0.0000	0.0274	0
2,2,4-trimethylheptane	142.3	0.0105	0.0012	0
n-nonane	128.3	0.0000	0.0382	0
3,3,5-trimethylheptane	142.3	0.0000	0.0000	0
n-propylbenzene	120.2	0.0841	0.0117	0.1455
2,3,4-trimethylheptane	142.3	0.0000	0.0000	0
1,3,5-trimethylbenzene	120.2	0.0411	0.0493	0
1,2,4-trimethylbenzene	120.2	0.0213	0.0705	0
n-decane	142.3	0.0000	0.0140	0
methylpropylbenzene	134.2	0.0351	0.0170	0
dimethylethylbenzene	134.2	0.0307	0.0289	0.0534
n-undecane	156.3	0.0000	0.0075	0
1,2,4,5-tetramethylbenzene	134.2	0.0133	0.0056	0
1,2,3,4-tetramethylbenzene	134.2	0.0129	0.0704	0.1411
1,2,4-trimethyl-5-ethylbenzene	148.2	0.0405	0.0651	0
n-dodecane	170.3	0.0230	0.0000	0
naphthalene	128.2	0.0045	0.0076	0
n-hexylbenzene	162.3	0.0000	0.0147	0.0357
methylnaphthalene	142.2	0.0023	0.0134	0
Total		1.0000	1.0000	1.0000

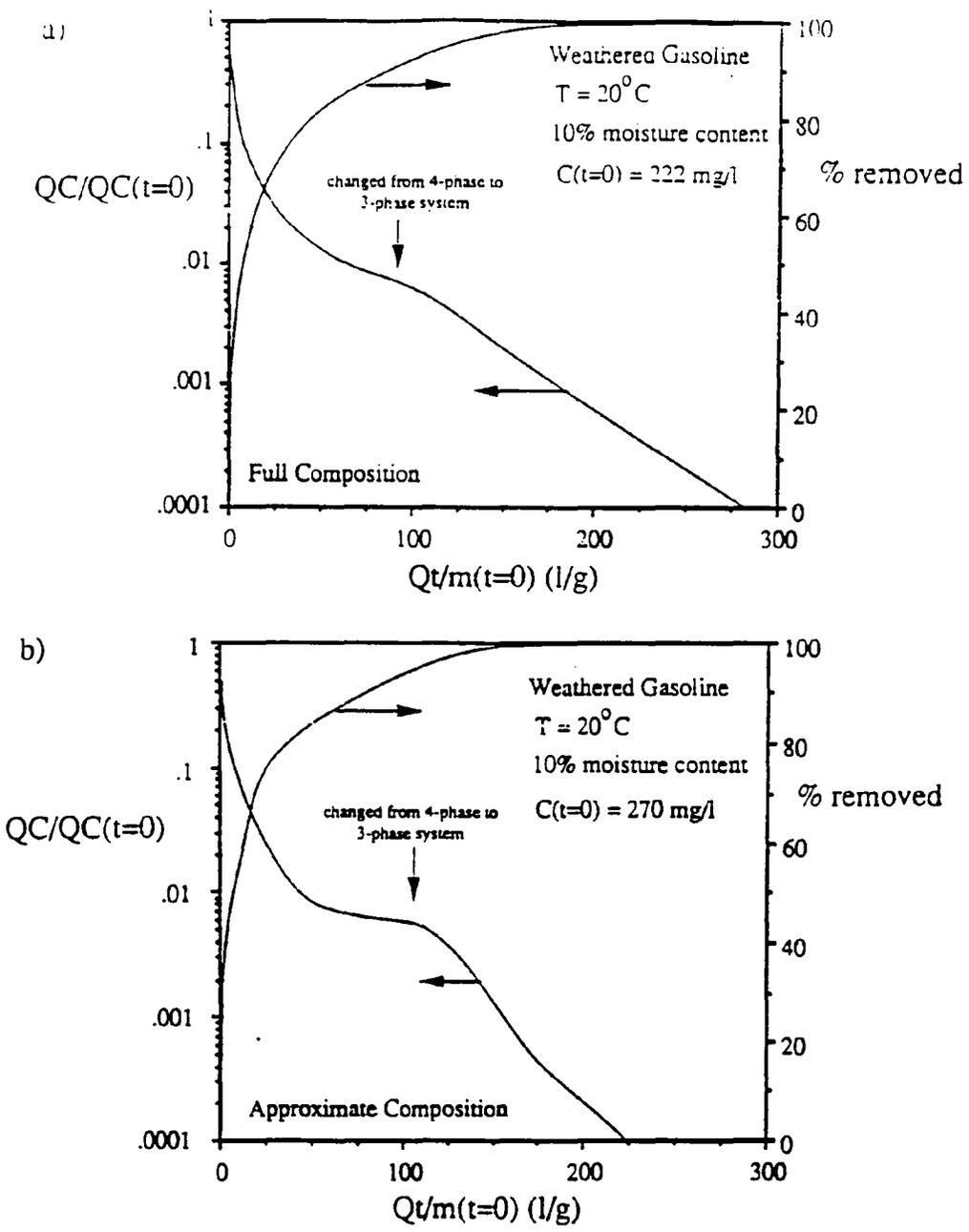


Figure E-8. Maximum Predicted Removal Rates for a Weathered Gasoline. a) full composition, b) approximate composition.

vapor concentration) decreases with time as the mixture becomes richer in the less volatile compounds.

While a detailed compositional analysis was available for this gasoline sample, an approximate composition based on a boiling point distribution curve predicts similar results. Figure E-8b presents the results for the approximate mixture composition also given in Table E-2.

Model predictions, such as those shown in Figure E-8 for the gasoline sample defined by Table E-2, can be used to estimate removal rates (if the vapor flowrate is specified), or alternatively the predictions can be used to estimate vapor flowrate requirements (if the desired removal rate is specified). For example, if we wanted to reduce the initial contamination level by 90%, then Figure E-8 predicts that  $\approx 100$  l-air/g-gasoline will be required. This is the minimum amount of vapor required, because it is based on an equilibrium-based model. The necessary minimum average vapor flowrate is then equal to the spill mass times the minimum required vapor flow/mass gasoline divided by the desired duration of venting. Use of this approach is illustrated in the service station site example provided at the end of this paper.

Figure E-8 also illustrates that there is a practical limit to the amount of residual contaminant that can be removed by venting alone. For example, it will take a minimum of 100 l-vapor/g-gasoline to remove 90% of the weathered gasoline defined in Table E-2, while it will take about 200 l-air/g-gasoline to remove the remaining 10%. In the case of gasoline, by the time 90% of the initial residual has been removed the residual consists of relatively insoluble and nonvolatile compounds. It is important to recognize this limitation of venting, and when setting realistic clean-up target levels, they should be based on the potential environmental impact of the residual rather than any specific total residual hydrocarbon levels.

(6) - *Are there likely to be any negative effects of soil venting?*

It is possible that venting will induce the migration of off-site contaminant vapors towards the extraction wells. This is likely to occur at a service station, which is often in close proximity to other service stations. If this occurs, one could spend a lot of time and money to unknowingly clean-up someone else's problem. The solution is to establish a "vapor barrier" at the perimeter of the contaminated zone. This can be accomplished by allowing vapor flow into any perimeter groundwater monitoring wells, which then act as passive air supply wells. In other cases it may be necessary to install passive air injection wells, or trenches, as illustrated in Figure E-9a.

As pointed out by Johnson et al.<sup>2</sup> the application of a vacuum to extraction wells can also cause a water table rise. In many cases contaminated soils lie just above the water table and they become water saturated, as illustrated in Figure E-9b. The maximum rise occurs at the vapor extraction well, where the water table rise will be equal to the vacuum

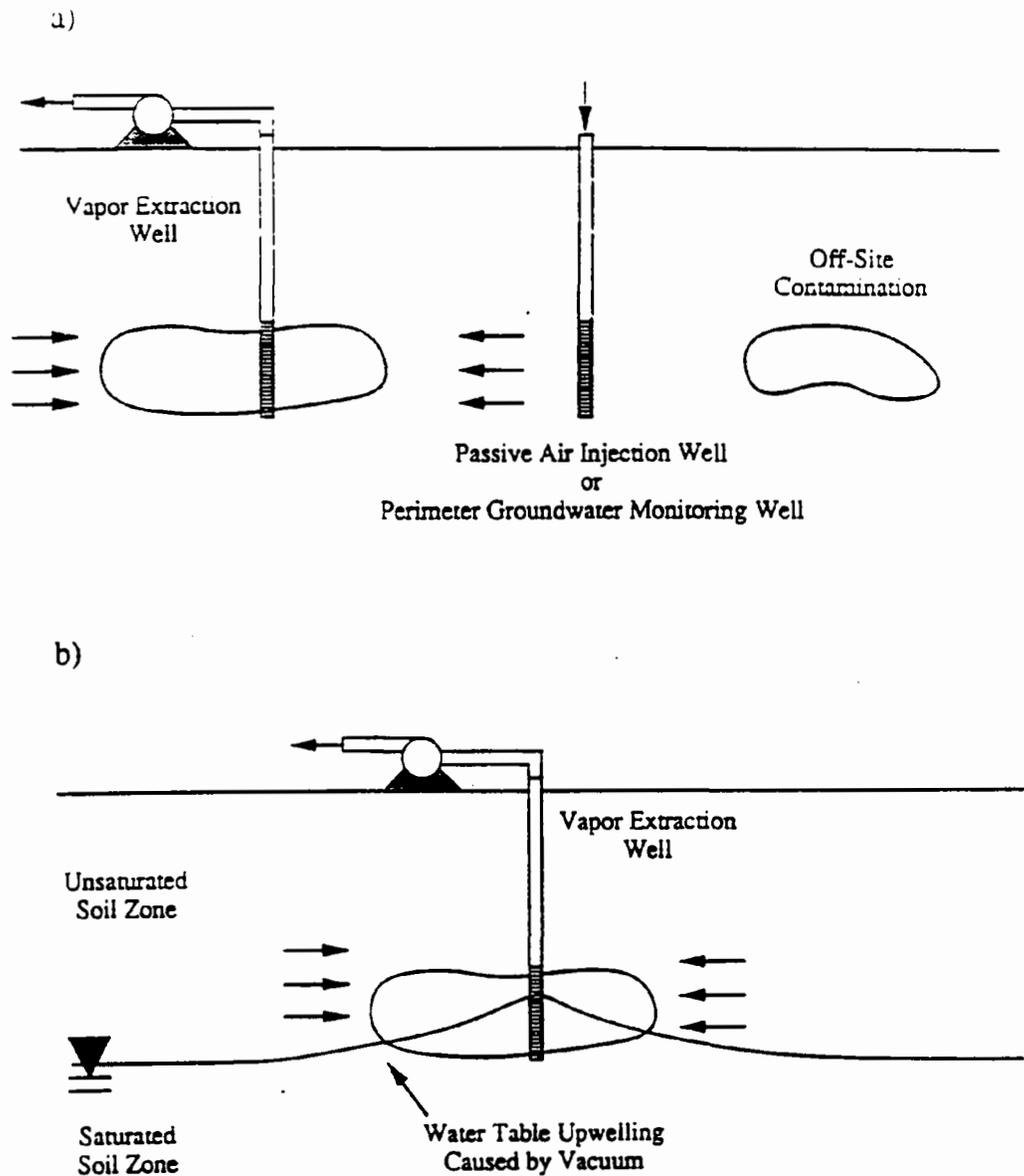


Figure E-9. a) Use of Passive Vapor Wells to Prevent Migration of Off-Site Contaminant Vapors. b) Water Table Rise Caused by the Applied Vacuum.

at the well expressed as an equivalent water column height (i.e., in or ft H<sub>2</sub>O). The solution to this problem is to install a dewatering system, with groundwater pumping wells located as close to vapor extraction wells as possible. The dewatering system must be designed to insure that contaminated soils remain exposed to vapor flow. Other considerations not directly related to venting system design, such as soluble plume migration control and free-liquid product yield, will also be factors in the design of groundwater pumping system.

Design Information

If venting is still a remediation option after answering the questions above, then more accurate information must be collected. Specifically, the soil permeability to vapor flow, vapor concentrations, and aquifer characteristics are required. These are obtained by two field experiments: air permeability and groundwater pump tests. These are described briefly below.

Air Permeability Tests

Figure E-10 depicts the set-up of an air permeability test. The object of this experiment is to remove vapors at a constant rate from an extraction well, while monitoring with time the transient subsurface pressure distribution at fixed points. Effluent vapor concentrations are also monitored. It is important that the test be conducted properly to obtain accurate design information. The extraction well should be screened through the soil zone that will be vented during the actual operation. In many cases existing groundwater monitoring wells are sufficient, if their screened sections extend above the water table. Subsurface pressure monitoring probes can be driven soil vapor sampling probes (for shallow <20 ft deep contamination problems) or more permanent installations.

Flowrate and transient pressure distribution data are used to estimate the soil permeability to vapor flow. The expected change in the subsurface pressure distribution with time P'(r,t) is predicted<sup>2</sup> by:

$$P' = \frac{Q}{4\pi m(k/\mu)} \int_0^{\infty} \frac{e^{-x}}{x} dx \quad (E-13)$$

$$\frac{r^2}{4kP_{Atm}t}$$

For (r<sup>2</sup> /4kP<sub>Atm</sub>t)<0.1 Equation E-13 can be approximated by:

$$P' = \frac{Q}{4\pi m(k/\mu)} [-0.5772 - \ln(\frac{r^2}{4kP_{Atm}t}) + \ln(t)] \quad (E-14)$$

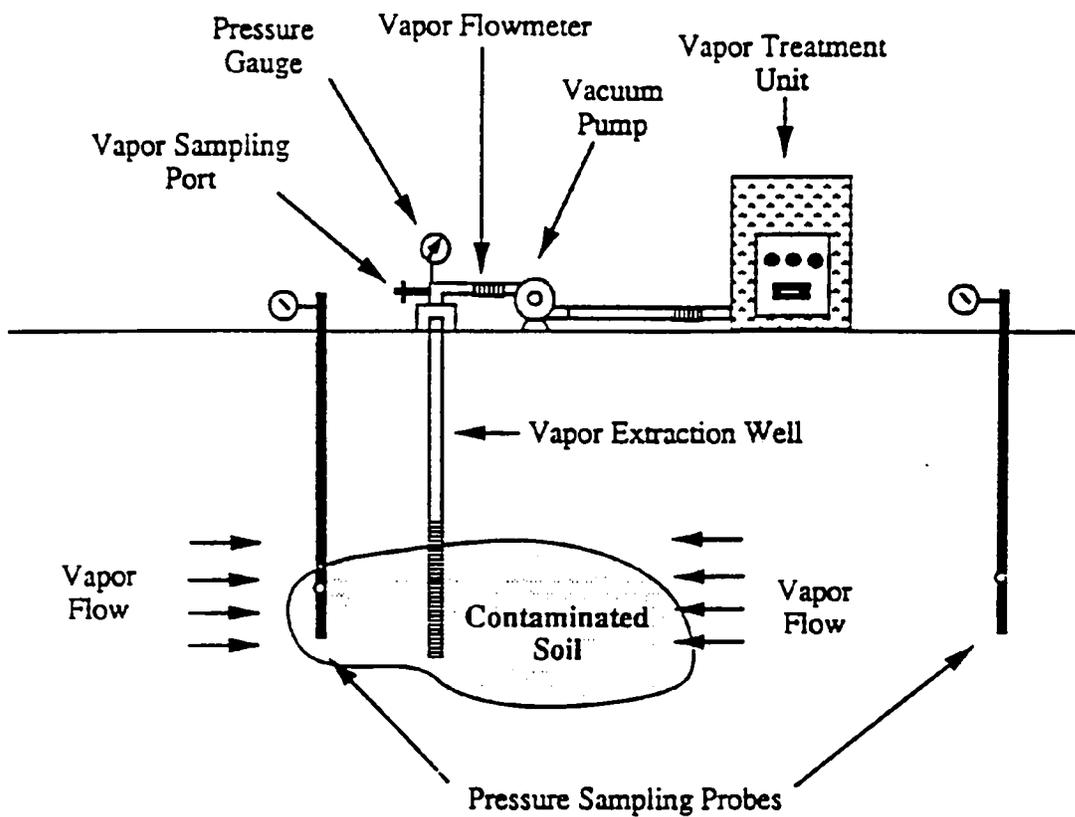


Figure E-10. Air Permeability Test System.

where:

- P' - "gauge" pressure measured at distance r and time t
- m - stratum thickness
- r - radial distance from vapor extraction well
- k - soil permeability to air flow
- $\mu$  - viscosity of air =  $1.8 \times 10^{-4}$  g/cm-s
- $\epsilon$  - air-filled soil void fraction
- t - time
- Q - volumetric vapor flowrate from extraction well
- $P_{Atm}$  - ambient atmospheric pressure = 1.0 atm =  $1.013 \times 10^6$  g/cm-s<sup>2</sup>

Equation E-14 predicts that a plot of P' -vs- ln(t) should be a straight line with slope A and y-intercept B equal to:

$$A = \frac{Q}{4\pi m(k/\mu)} \quad B = \frac{Q}{4\pi m(k/\mu)} \left[ -0.5772 - \ln\left(\frac{r^2\epsilon\mu}{4kP_{Atm}}\right) \right] \quad (E-15)$$

The permeability to vapor flow can then be calculated from the data by one of two methods. The first is applicable when Q and m are known. The calculated slope A is used:

$$k = \frac{Q\mu}{4A\pi m} \quad (E-16)$$

The second approach must be used whenever Q or m is not known. In this case the values A and B are both used:

$$k = \frac{r^2\epsilon\mu}{4P_{Atm}} \exp\left(\frac{B}{A} + 0.5772\right) \quad (E-17)$$

Equation E-13 can also be used to choose the locations of subsurface pressure monitoring points before conducting the air permeability test, given an estimation of k and the flowrate to be used.

Vapor samples should be taken at the beginning and end of the air permeability test, which should be conducted for a long enough time to extract at least one "pore volume"  $V_p$  of vapor from the contaminated soil zone. This insures that all vapors existing in the formation prior to venting are removed. The vapor concentration at the start of the test is representative of the equilibrium vapor concentration, while the concentration measured after one pore volume has been extracted gives an indication of realistic removal rates and the mixing or diffusional limitations discussed in association with Figure E-6. The time  $\tau_p$  for one pore volume to be removed is:

$$\tau_p = V_p/Q = \epsilon_A \pi R^2 H / Q \quad (E-18)$$

where  $R$ ,  $H$ ,  $\epsilon_A$ , and  $Q$  are the radius of the zone of contamination, vertical thickness of the zone of contamination, air-filled void fraction, and volumetric vapor flowrate from the extraction well. For example, consider the case where  $R=12$  m,  $H=3$  m,  $\epsilon_A=0.35$ , and  $Q=0.57$  m<sup>3</sup>/min (20 ft<sup>3</sup>/min). Then  $\tau_p=475$  m<sup>3</sup>/0.57 m<sup>3</sup>/min=833 min=14 h.

### Groundwater Pump Tests

To achieve efficient venting the hydrocarbon-contaminated soil has to be exposed to air flow, which in turn requires that the water table be lowered to counteract the water upwelling effect caused by the decreased vapor pressure in the vicinity of a venting well (Johnson et al.<sup>2</sup>) and to possibly expose contaminated soil below the water table. Thus the groundwater pumping system has to have a sufficient pumping rate and be operated for a long enough time period to obtain the required drawdowns. Since most venting systems are installed above phreatic aquifers, two aquifer parameters are needed for the design: average transmissivity  $T$  and effective porosity  $S$ . These parameters can be estimated using the results of the standard transient groundwater pump test with a constant pumping rate (Bear<sup>3</sup>). Using the estimated values the required pumping rate may be calculated as follows:

$$Q = 4\pi TS(r,t)/W(u) \quad (E-19)$$

where:  $W(u)$  is the well function<sup>3</sup> of  $u = Sr^2/4Tt$ , and  $s(r,t)$  is the required drawdown at distance  $r$  and pumping time equal to  $t$ .

### System Design

In this section we discuss the questions that must be answered in order to design an in-situ soil venting system. It is not our intention to provide a generic "recipe" for soil venting systems design; instead we suggest a structured thought process to guide in choosing the number of extraction wells, well spacing, construction, etc. Even in a structured thought process, intuition and experience play important roles. There is no substitute for a good fundamental understanding of vapor flow processes, transport phenomena, and groundwater flow.

#### *- Choosing the number of vapor extraction wells*

Three methods for choosing the number of vapor extraction wells are outlined below. The greatest number of wells from these three methods is then the value that should be used. The objective is to satisfy removal rate requirements and achieve vapor removal from the entire zone of contamination.

For the first estimate we neglect residual contaminant composition and vapor concentration changes with time. The acceptable removal rate  $R_{\text{acceptable}}$  is calculated from Equation E-4, while the estimated removal rate from a single well  $R_{\text{est}}$  is estimated from a choice of Equations E-2, E-6, E-7, or E-

12 depending on whether the specific site conditions are most like Figure E-6a, E-6b, or E-6c. The number of wells  $N_{well}$  required to achieve the acceptable removal rate is:

$$N_{well} = R_{acceptable}/R_{est} \quad (E-20)$$

Equations E-2, E-6, and E-7 require vapor flow estimates, which can be calculated from Equation E-5 using the measured soil permeability and chosen extraction well vacuum  $P_v$ . At this point one must determine what blowers and vacuum pumps are available because the characteristics of these units will limit the range of feasible  $(P_v, Q)$  values. For example, a blower that can pump 100 scfm at 2 in  $H_2O$  vacuum may only be able to pump 10 scfm at 100 in  $H_2O$  vacuum.

The second method, which accounts for composition changes with time, utilizes model predictions, such as those illustrated in Figure E-8. Recall that equilibrium-based models are used to calculate the minimum vapor flow to achieve a given degree of remediation. For example, if we wish to obtain a 90% reduction in residual gasoline levels, Figure E-8 indicates that  $\approx 100$  l-vapor/g-gasoline must pass through the contaminated soil zone. If our spill mass is 1500 kg ( $\approx 500$  gal), then a minimum of  $1.5 \times 10^8$  l-vapor must pass through the contaminated soil zone. If our target clean-up period is six months, this corresponds to a minimum average vapor flowrate of  $0.57 \text{ m}^3/\text{min}$  ( $\approx 20$  cfm). The minimum number of extraction wells is then equal to the required minimum average flowrate/flowrate per well.

The third method for determining the number of wells insures that we remove vapors and residual soil contamination from the entire zone of contamination  $N_{min}$ . This is simply equal to the ratio of the area of contamination  $A_{contamination}$ , to the area of influence of a single venting well  $\pi R_I^2$ :

$$N_{min} = \frac{A_{contamination}}{\pi R_I^2} \quad (E-21)$$

This requires an estimate of  $R_I$ , which defines the zone in which vapor flow is induced. In general,  $R_I$  depends on soil properties of the vented zone, properties of surrounding soil layers, the depth at which the well is screened, and the presence of any impermeable boundaries (water table, clay layers, surface seal, building basement, etc.). At this point it is useful to have some understanding of vapor flow patterns because, except for certain ideal cases<sup>6</sup>, one cannot accurately predict vapor flowpaths without numerically solving vapor flow equations. An estimate for  $R_I$  can be obtained by fitting radial pressure distribution data from the air permeability test to the steady-state radial pressure distribution equation<sup>2</sup>:

$$P(r) = P_v \left[ 1 + \left( 1 - \left( \frac{P_{Acem}}{P_v} \right)^2 \frac{\ln(r/R_w)}{\ln(R_w/R_I)} \right) \right]^{1/2} \quad (E-22)$$

where  $P(r)$ ,  $P_{Acem}$ ,  $P_v$ , and  $R_w$  are the absolute pressure measured at a distance  $r$  from the venting well, absolute ambient pressure, absolute pressure applied at the vapor extraction well, and extraction well radius, respectively. Given that these tests are usually conducted for less than a day, the results will generally underestimate  $R_I$ . If no site specific data is available, one can conservatively estimate  $R_I$  based on the published reports from in-situ soil venting operations. Reported  $R_I$  values for permeable soils (sandy soils) at depths greater than 20 ft below ground surface, or shallower soils beneath good surface seals, are usually 10 m - 40 m.<sup>1</sup> For less permeable soils (silts, clays), or more shallow zones  $R_I$  is usually less.

*- Choosing well location, spacing, passive wells, and surface seals*

To be able to successfully locate extraction wells, passive wells, and surface seals one must have a good understanding of vapor flow behavior. We would like to place wells so that we insure adequate vapor flow through the contaminated zone, while minimizing vapor flow through other zones.

If one well is sufficient, it will almost always be placed in the geometric center of the contaminated soil zone, unless it is expected that vapor flow channeling along a preferred direction will occur. In that case the well will be placed so as to maximize air flow through the contaminated zone.

When multiple wells are used it is important to consider the effect that each well has on the vapor flow to all other wells. For example, if three extraction wells are required at a given site, and they are installed in the triplate design shown in Figure E-11a, there would be a "stagnant" region in the middle of the wells where air flow would be very small in comparison to the flow induced outside the triplate pattern boundaries. This problem can be alleviated by the use of "passive wells" or "forced injection" wells as illustrated in Figure E-11b (it can also be minimized by changing the vapor flowrates from each well with time). A passive well is simply a well that is open to the atmosphere; in many cases groundwater monitoring wells are suitable. If a passive or forced injection well is to have any positive effect, it must be located within the extraction well's zone of influence. Forced injection wells are simply vapor wells into which air is pumped rather than removed. One must be very careful in choosing the locations of forced injection wells so that contaminant vapors are captured by the extraction wells, rather than forced off-site. To date there have not been any detailed reports of venting operations designed to study the advantages/disadvantages of using forced injection wells. Figure E-11c presents another possible extraction/injection well combination. As illustrated in Figure E-9, passive wells can also be used as vapor barriers to prevent on-site migration of off-site contamination problems.

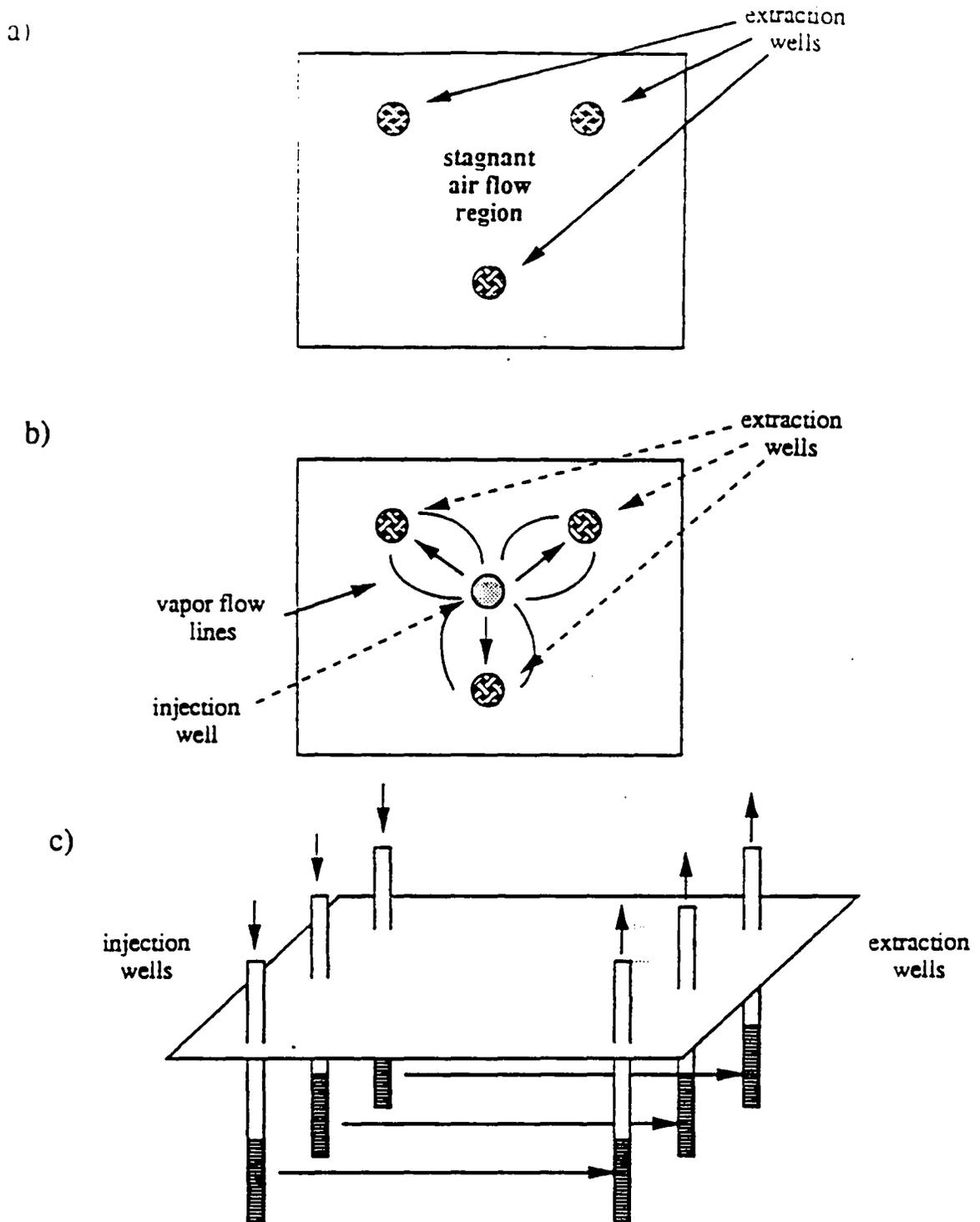


Figure E-11. Venting Well Configuration.

For shallow contamination problems (<4 m below ground surface) vapor extraction trenches combined with surface seals may be more effective than vertical wells. Trenches are usually limited to shallow soil zones because the difficulty of installation increases with depth.

Surface seals, such as polymer-based liners and asphalt, concrete, or clay caps, are sometimes used to control the vapor flow paths. Figure E-12 illustrates the effect that a surface seal will have on vapor flow patterns. For shallow treatment zones (<5 m) the surface seal will have a significant effect on the vapor flow paths, and seals can be added or removed to achieve the desired vapor flowpath. For wells screened below 8 m the influence of surface seals becomes less significant.

- *Well screening and construction*

Wells should be screened only through the zone of contamination, unless the permeability to vapor flow is so low that removal rates would be greater if flow were induced in an adjacent soil layer (see Figure E-6). Removal rate estimates for various mass-transfer limited scenarios can be calculated from Equations E-7 and E-12.

Based on Equation E-5, the flowrate is expected to increase by 15% when the extraction well diameter is increased from 10 cm (4 in) to 20 cm (8 in). This implies that well diameters should be as large as is practically possible.

A typical well as shown in Figure E-13a is constructed from slotted pipe (usually PVC). The slot size and number of slots per inch should be chosen to maximize the open area of the pipe. A filter packing, such as sand or gravel, is placed in the annulus between the borehole and pipe. Vapor extraction wells are similar to groundwater monitoring wells in construction but there is no need to filter vapors before they enter the well. The filter packing, therefore, should be as coarse as possible. Any dust carried by the vapor flow can be removed by an above-ground filter. Bentonite pellets and a cement grout are loaded above the filter packing. It is important that these be properly installed to prevent a vapor flow "short-circuit". Any groundwater monitoring wells installed near the extraction wells must also be installed with good seals.

- *Vapor treatment*

Currently there are four main treatment processes available. Each is discussed below.

- *vapor combustion units:* Vapors are incinerated and destruction efficiencies are typically >95%. A supplemental fuel, such as propane, is added before combustion unless extraction well vapor concentrations are on the order of a few percent by volume. This process becomes less economical as vapor concentrations decrease below  $\approx 10,000$  ppm<sub>v</sub>.

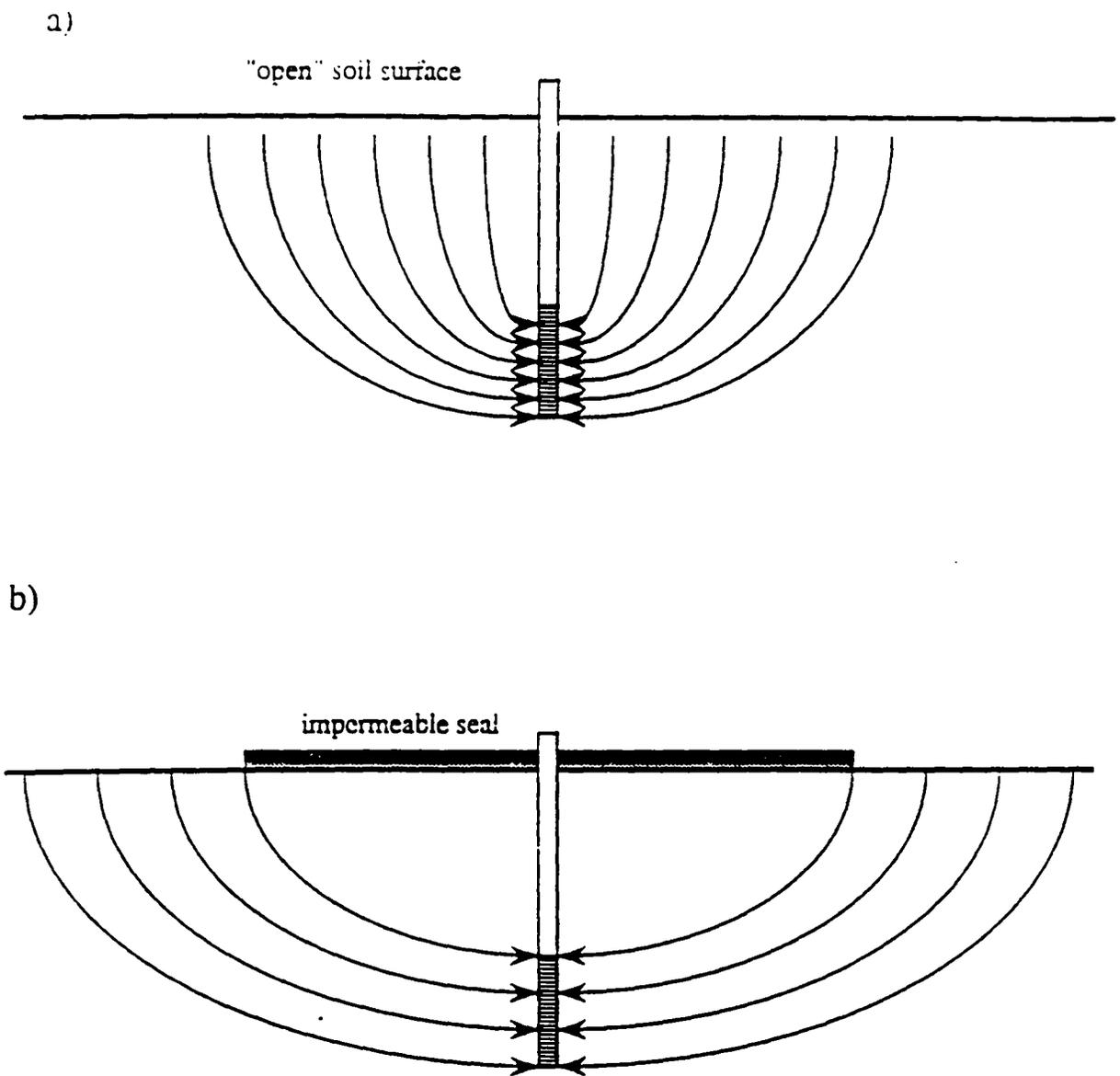


Figure E-12. Effect of Surface Seal on Vapor Flowpath.

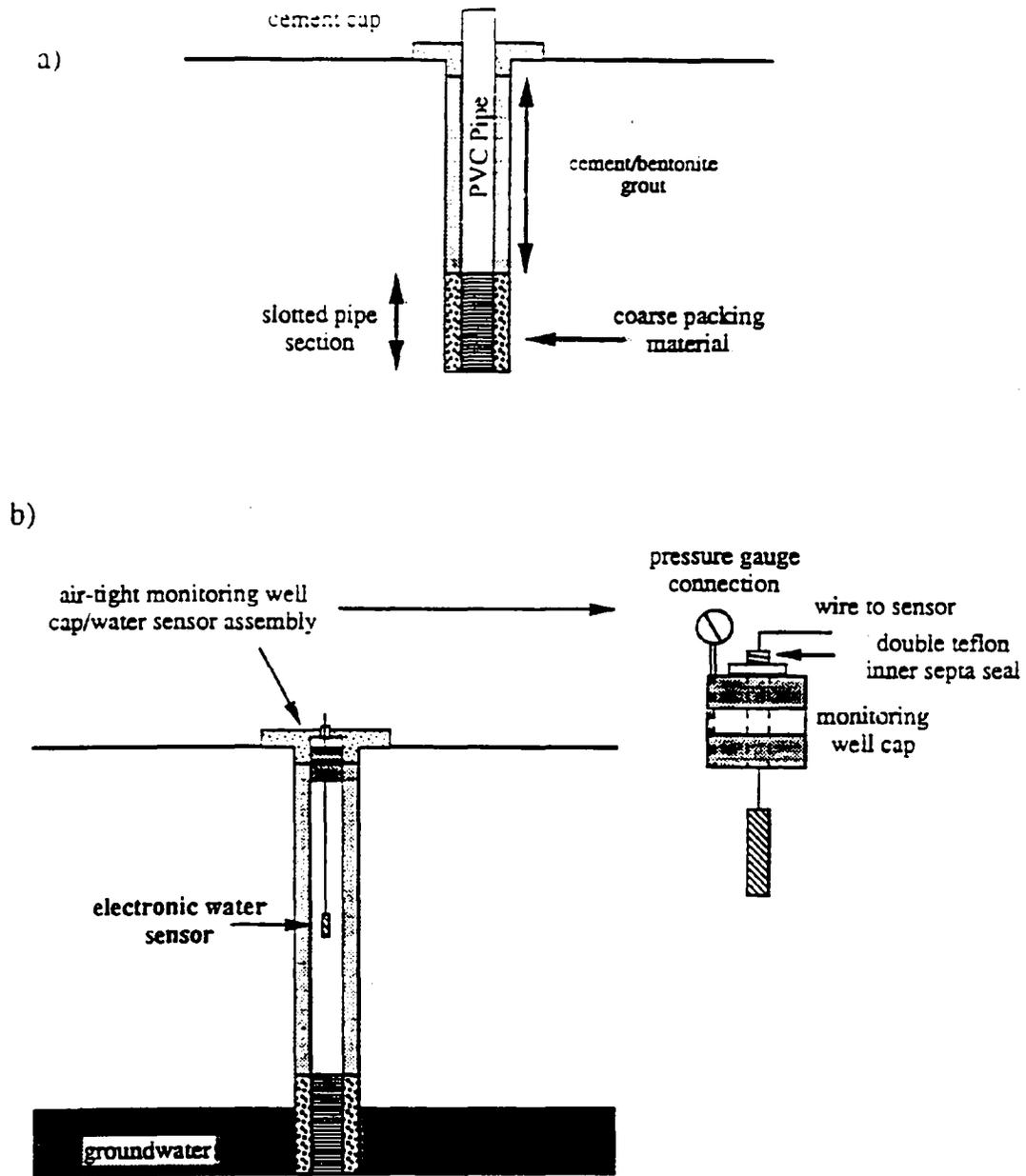


Figure E-13. a) Extraction Well Construction, and b) Air-Tight Groundwater Level Measuring System.

- *catalytic oxidation units*: Vapor streams are heated and then passed over a catalyst bed. Destruction efficiencies are typically >95%. These units are used for vapor concentrations <8000 ppm<sub>v</sub>. More concentrated vapors can cause catalyst bed temperature excursions and melt-down.

- *carbon beds*: Carbon can be used to treat almost any vapor streams, but is only economical for very low emission rates (<100 g/d)

- *diffuser stacks*: These do not treat vapors, but are the most economical solution for areas in which they are permitted. They must be carefully designed to minimize health risks and maximize safety.

- *Groundwater pumping system*

In cases where contaminated soils lie just above or below the water table, groundwater pumping systems will be required to insure that contaminated soils remain exposed. In designing a groundwater system it is important to be aware that upwelling (draw-up) of the groundwater table will occur when a vacuum is applied at the extraction well (see Figure E-9b). Because the upwelling will be greatest at the extraction wells, groundwater pumping wells should be located within or as close to the extraction wells as possible. Their surface seals must be airtight to prevent unwanted short-circuiting of airflow down the groundwater wells.

- *System integration*

System components (pumps, wells, vapor treating units, etc.) should be combined to allow maximum flexibility of operation. The review by Hutzler et al.<sup>1</sup> provides descriptions of many reported systems. Specific requirements are:

- separate valves, flowmeters, and pressure gauges for each extraction and injection well.

- air filter to remove particulates from vapors upstream of pump and flow meter.

- knock-out pot to remove any liquid from vapor stream upstream of pump and flow meter.

Monitoring

The performance of a soil venting system must be monitored in order to insure efficient operation, and to help determine when to shut-off the system. At a minimum the following should be measured:

- *date and time of measurement.*

- *vapor flow rates* from extraction wells and into injection wells: these can be measured by a variety of flowmeters including pitot tubes,

orifice plates, and rotameters. It is important to have calibrated these devices at the field operating pressures and temperatures.

- *pressure readings* at each extraction and injection well can be measured with manometers or magnahelic gauges.

- *vapor concentrations and compositions* from extraction wells: total hydrocarbon concentration can be measured by an on-line total hydrocarbon analyzer calibrated to a specific hydrocarbon. This information is combined with vapor flowrate data to calculate removal rates and the cumulative amount of contaminant removed. In addition, for mixtures the vapor composition should be periodically checked. It is impossible to assess if vapor concentration decreases with time are due to compositional changes or some other phenomena (mass transfer resistance, water table upwelling, pore blockage, etc.) without this information. Vapor samples can be collected in evacuated gas sampling cylinders, stored, and later analyzed.

- *temperature*: ambient and soil.

- *water table level* (for contaminated soils located near the water table): It is important to monitor the water table level to insure that contaminated soils remain exposed to vapor flow. Measuring the water table level during venting is not a trivial task because the monitoring well must remain sealed. Uncapping the well releases the vacuum and any effect that it has on the water table level. Figure E-13b illustrates a monitoring well cap (constructed by Applied Geosciences Inc., Tustin, CA) that allows one to measure simultaneously the water table level and vacuum in a monitoring well. It is constructed from a commercially available monitoring well cap and utilizes an electronic water level sensor.

Other valuable, but optional measurements are:

- *soil gas vapor concentrations and compositions*: these should be measured periodically at different radial distances from the extraction well. Figure E-14 shows the construction of a permanent monitoring installation that can be used for vapor sampling and subsurface temperature measurements. Another alternative for shallow contamination zones is the use of soil gas survey probes.

This data is valuable for two reasons: a) by comparing extraction well concentrations with soil gas concentrations it is possible to estimate the fraction of vapor that is flowing through the contaminated zone  $f = C_{\text{extraction well}} / C_{\text{soil gas}}$ , and b) it is possible to determine if the zone of contamination is shrinking towards the extraction well, as it should with time. Three measuring points are probably sufficient if one is located near the extraction well, one is placed near the original edge of the zone of contamination, and the third is placed somewhere in between.

These monitoring installations can also be useful for monitoring the subsurface vapors after venting has ceased.

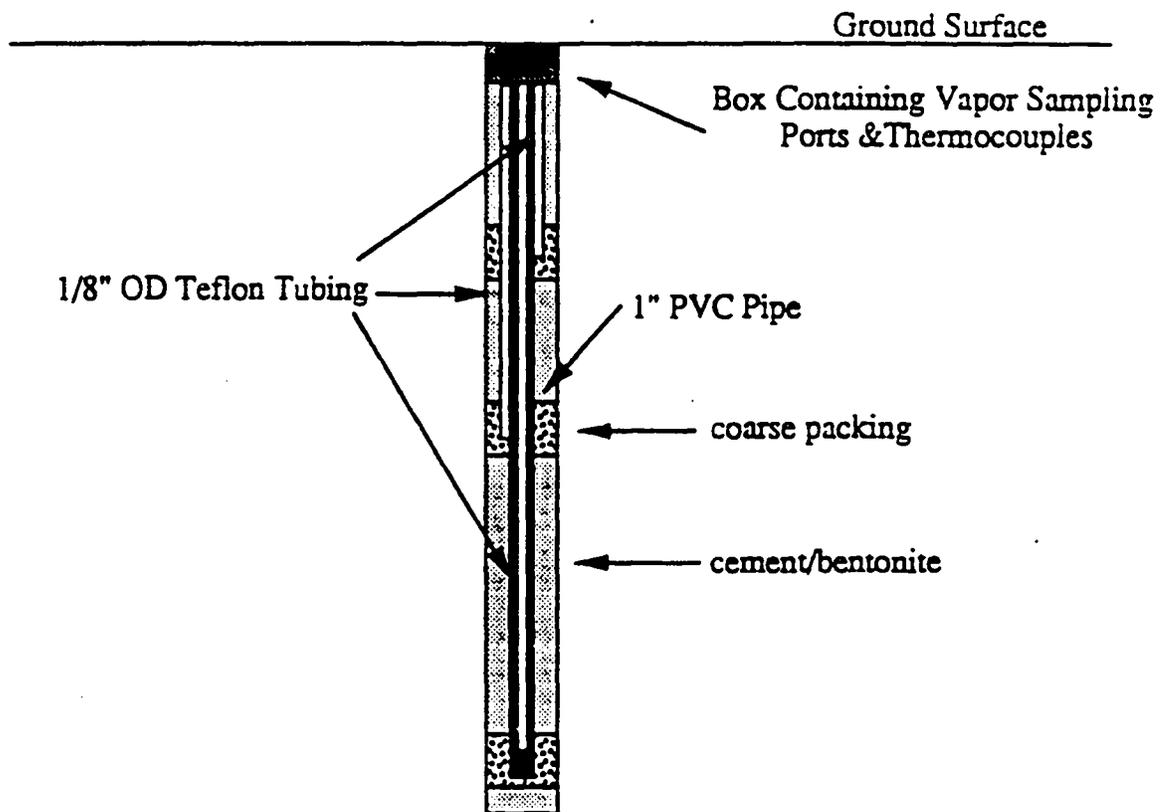


Figure E-14. Vadose Zone Monitoring Installation.

### When To Turn Off The System?

Target soil clean-up levels are often set on a site-by-site basis, and are based on the estimated potential impact that any residual may have on air quality, groundwater quality, or other health standards. They may also be related to safety considerations (explosive limits). Generally, confirmation soil borings, and sometimes soil vapor surveys, are required before closure is granted. Because these analyses are expensive and often disrupt the normal business of a site, it would be valuable to be able to determine when confirmation borings should be taken. If the monitoring is done as suggested above, then the following criteria can be used:

- *cumulative amount removed*: determined by integrating the measured removal rates (flowrate x concentration) with time. While this value indicates how much contaminant has been removed, it is usually not very useful for determining when to take confirmation borings unless the original spill mass is known very accurately. In most cases that information is not available and can not be calculated accurately from soil boring data.

- *extraction well vapor concentrations*: the vapor concentrations are good indications of how effectively the venting system is working, but decreases in vapor extraction well concentrations are not strong evidence that soil concentrations have decreased. Decreases may also be due to other phenomena such as water table level increases, increased mass transfer resistance due to drying, or leaks in the extraction system.

- *extraction well vapor composition*: when combined with vapor concentrations this data gives more insight into the effectiveness of the system. If the total vapor concentration decreases without a change in composition, it is probably due to one of the phenomena mentioned above, and is not an indication that the residual contamination has been significantly reduced. If a decrease in vapor concentration is accompanied by a shift in composition towards less volatile compounds, on the other hand, it is most likely due to a change in the residual contaminant concentration. For residual gasoline clean-up, for example, one might operate a venting system until benzene, toluene, and xylenes were not detected in the vapors. The remaining residual would then be composed of larger molecules, and it can be argued that these do not pose a health threat through volatilization or leaching pathways.

- *soil gas contaminant concentration and composition*: this data is the most useful because it yields information about the residual composition and extent of contamination. Vapor concentrations can not be used to determine the residual level, except for very low residual levels (<500 mg/kg).

### Other Factors

- *increased biodegradation*

It is often postulated that because the air supply to the vadose zone is

increased, the natural aerobic microbiological activity is increased during venting. While the argument is plausible and some laboratory data is available<sup>7</sup>, conclusive evidence supporting this theory has yet to be presented. This is due in part to the difficulty in making such a measurement. A mass balance approach is not likely to be useful because the initial spill mass is generally not known with sufficient accuracy. An indirect method would be to measure CO<sub>2</sub> levels in the extraction well vapors, but this in itself does not rule out the possibility that O<sub>2</sub> is converted to CO<sub>2</sub> before the vapors pass through the contaminated soil zone. The best approach is to measure the O<sub>2</sub>/CO<sub>2</sub> concentrations in the vapors at the edge of the contaminated zone, and in the vapor extraction wells. If the CO<sub>2</sub>/O<sub>2</sub> concentration ratio increases as the vapors pass through the contaminated soil, one can surmise that a transformation is occurring, although other possible mechanisms (inorganic reactions) must be considered. An increase in aerobic microbial populations would be additional supporting evidence.

- *in-situ heating/venting*

The main property of a compound that determines whether or not it can be removed by venting is its vapor pressure, which increases with increasing temperature. Compounds that are considered nonvolatile, therefore, can be removed by venting if the contaminated soil is heated to the proper temperature. In-situ heating/venting systems utilizing radio-frequency heating and conduction heating are currently under study<sup>8</sup>. An alternative is to reinject heated vapors from catalytic oxidation or combustion units into the contaminated soil zone.

- *air sparging*

Due to seasonal groundwater level fluctuations, contaminants sometimes become trapped below the water table. In some cases groundwater pumping can lower the water table enough to expose this zone, but in other cases this is not practical. One possible solution is to install air sparging wells and then inject air below the water table. Vapor extraction wells would then capture the vapors that bubbled up through the groundwater. To date, success of this approach has yet to be demonstrated. This could have a negative effect if foaming, formation plugging, or downward migration of the residual occurred.

## **Application of the Design Approach to a Service Station Remediation**

In the following we will demonstrate the use of the approach discussed above and outlined in Figure E-2 for the design operation, and monitoring of an in-situ venting operation at a service station.

### *Preliminary Site Investigation*

Prior to sampling it was estimated that 2000 gal of gasoline had leaked from a product line at this site. Several soil borings were drilled and the soil samples were analyzed for total petroleum hydrocarbons (TPH) and other specific compounds (benzene, toluene, xylenes) by a heated-headspace method utilizing a field GC-FID. Figure E-15 summarizes some of the results for one transect at this site. The following relevant information was collected:

- based on boring logs there are four distinct soil layers at this site between 0 - 18 m (0- 60 ft) below ground surface (BGS). Figure E-15 indicates the soil type and location of each of these layers.

- depth to groundwater was 15 m, with fine to medium sand aquifer soils

- the largest concentrations of hydrocarbons were detected in the sandy and silty clay layers adjacent to the water table. Some residual was detected below the water table. Based on the data presented in Figure E-15 it is estimated that - 4000 kg of hydrocarbons are present in the lower two soil zones.

- initially there was some free-liquid gasoline floating on the water table, and this was subsequently removed by pumping. A sample of this product was analyzed and its approximate composition (~20% of the compounds could not be identified) is listed in Table E-2 as the "weathered gasoline". The corresponding boiling point distribution curve for this mixture has been presented in Figure E-3.

- vadose zone monitoring installations similar to the one pictured in Figure E-14 were installed during the preliminary site investigation.

### *Deciding if Venting is Appropriate*

For the remainder of the analysis we will focus on the contaminated soils located just above the water table.

- *What contaminant vapor concentrations are likely to be obtained?*

Based on the composition given in Table E-2, and using Equation E-1, the predicted saturated TPH vapor concentration for this gasoline is:

$$C_{sat} = 220 \text{ mg/l}$$

Using the "approximate" composition listed in Table E-2 yields a value of 270 mg/l. The measured soil vapor concentration obtained from the vadose zone monitoring well was 240 mg/l. Due to composition changes with time, this will be the maximum concentration obtained during venting.

- *Under ideal flow conditions is this concentration great enough to yield acceptable removal rates?*

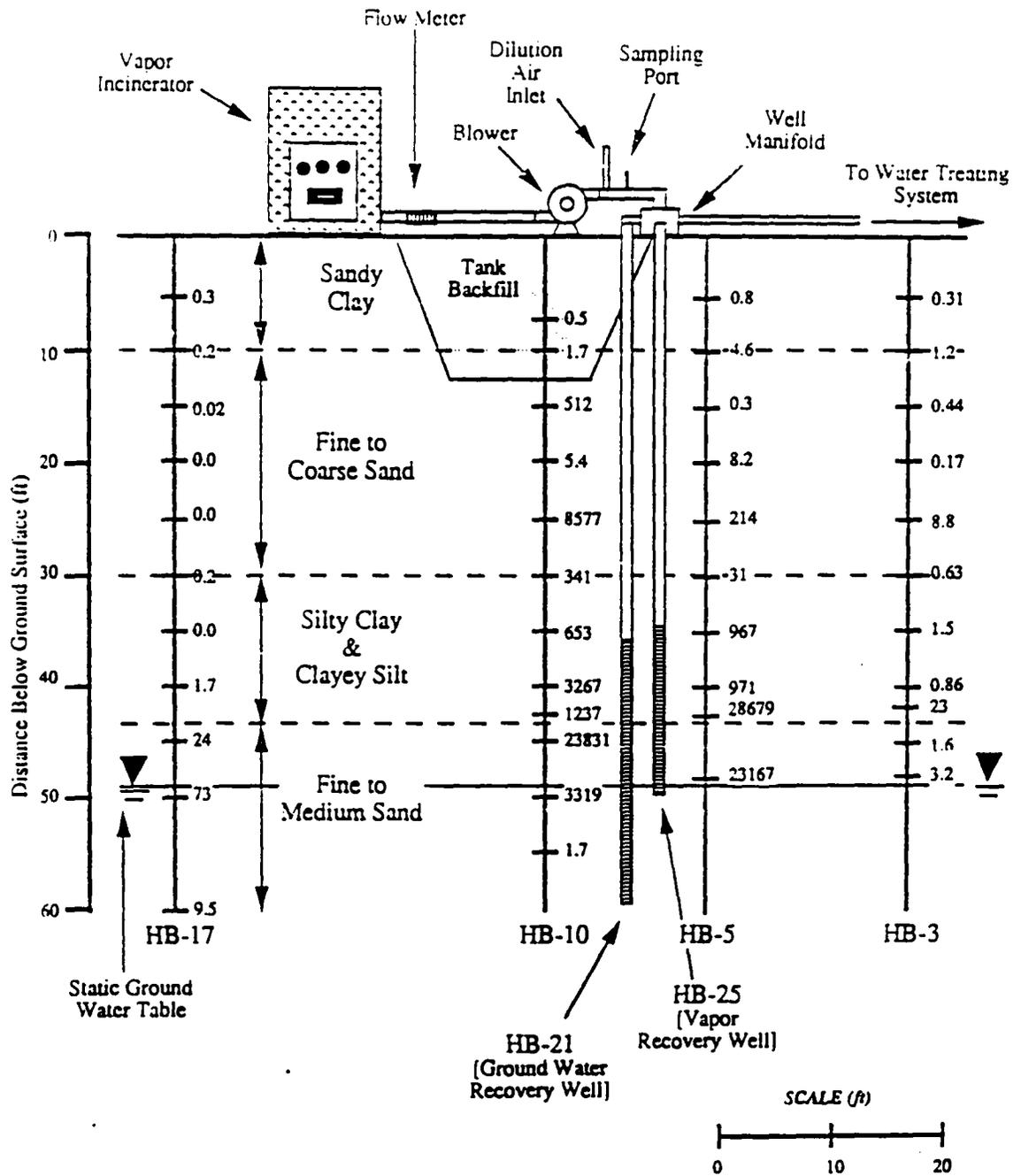


Figure E-15. Initial Total Hydrocarbon Distribution [mg/kg-soil] and Location of Lower Zone Vent Well.

Equation E-4 was used to calculate  $R_{\text{acceptable}}$ . Assuming  $M_{\text{spill}} = 4000$  kg and  $t = 180$  d, then:

$$R_{\text{acceptable}} = 22 \text{ kg/d}$$

Using Equation E-2,  $C_{\text{est}} = 240$  mg/l, and  $Q = 2800$  l/min (100 cfm):

$$R_{\text{est}} = 970 \text{ kg/d}$$

which is greater than  $R_{\text{acceptable}}$ .

- *What range of vapor flowrates can realistically be achieved?*

Based on boring logs the contaminated zone just above the water table is composed of fine to medium sands, which have an estimated permeability  $1 < k < 10$  darcy. Using Figure E-5, or Equation E-5, the predicted flowrates for an extraction well vacuum  $P_v = 0.90$  atm are:

$$\begin{aligned} 0.04 < Q < 0.4 \text{ m}^3/\text{m-min} \quad R_w = 5.1 \text{ cm}, R_r = 12 \text{ m} \\ 0.43 < Q < 4.3 \text{ ft}^3/\text{ft-min} \quad R_w = 2.0 \text{ in}, R_r = 40 \text{ ft} \end{aligned}$$

The thickness of this zone and probable screen thickness of an extraction well is about 2 m (6.6 ft). The total flowrate per well through this zone is estimated to be  $0.08 < Q < 0.8$  m<sup>3</sup>/min (2.8 cfm  $< Q < 28$  cfm).

- *Will the contaminant concentrations and estimated flowrates produce acceptable removal rates?*

Using  $C_{\text{est}} = 240$  mg/l, the maximum removal rates likely to be obtained are calculated from Equation E-2:

$$28 \text{ kg/d} < (R_{\text{est}})_{\text{max}} < 280 \text{ kg/d}$$

To be conservative, we will guess that only 50% of the vapor actually flows through contaminated soils, so our estimated removal rate per well will be half of these values. The estimated acceptable removal rate  $R_{\text{acceptable}} = 22$  kg/d falls within this range. Of course this calculation did not take into account the possibility of vapor concentration decreases during venting. We shall take this into account in the next subsection.

- *What residual, if any, will be left in the soil?*

A target clean-up level for most gasoline spill sites is  $< 1000$  mg/kg TPH residual. If our initial residual level is  $\sim 10,000$  ppm, then we need to remove at least 90% of the initial residual. According to the curves in Figure E-8, which represent the maximum removal rates for the gasoline analyzed at this site, approximately 100 l-vapor/g-residual will have to pass through the

contaminated zone to achieve this target. Based on our estimated initial residual of 4000 kg TPH,  $4 \times 10^8$  l-vapor are required. Over a six month period this corresponds to an average flowrate  $Q=1.5 \text{ m}^3/\text{min}$  (54 cfm). Recall that since this corresponds to the maximum removal rate, it is the minimum required flowrate.

- *Are there likely to be any negative effects of soil venting?*

Given that the contaminated soils are located just above and below the water table, water table upwelling during venting must be considered here.

#### Air Permeability Test

Figure E-16 presents data obtained from the air permeability test of this soil zone. In addition to vapor extraction tests, air injection tests were conducted. The data is analyzed in the same manner as discussed for vapor extraction tests. Accurate flowrate (Q) values were not measured, therefore, Equation E-17 was used to determine the permeability to vapor flow. The k values ranged from 2 to 280 darcys, with the median being ~8 darcys.

#### System Design

- *Number of vapor extraction wells:*

Based on the 8 darcys permeability, and assuming a 15 cm diameter (6 in) venting well, a 2 m screened section,  $P_v = 0.90 \text{ atm}$  (41 in  $\text{H}_2\text{O}$  vacuum) and  $R_f=12 \text{ m}$ , then Equation E-5 predicts:

$$Q = 0.7 \text{ m}^3/\text{min} = 25 \text{ cfm}$$

Based on the discussion above, a minimum average flowrate of  $1.5 \text{ m}^3/\text{min}$  is needed to reduce the residual to 1000 ppm in 6 months. The number of wells required is then  $1.5/0.7 = 2$ , assuming that 100% of the vapor flows through contaminated soils. It is not likely that this will occur, and a more conservative estimate of 50% vapor flowing through contaminated soils would require that twice as many wells (4) be installed.

A single vapor extraction well (HB-25) was installed in this soil layer with the knowledge that more wells were likely to be required. Its location and screened interval are shown in Figure E-15. Other wells were installed in the clay layer and upper sandy zone, but in this paper we will only discuss results from treatment of the lower contaminated zone. A groundwater pumping well was installed to maintain a 2 m drawdown below the static water level. Its location is also shown in Figure E-15.

#### System Monitoring

Three vadose monitoring wells similar in construction to the one pictured in Figure E-14 were installed so that the soil temperature, soil gas

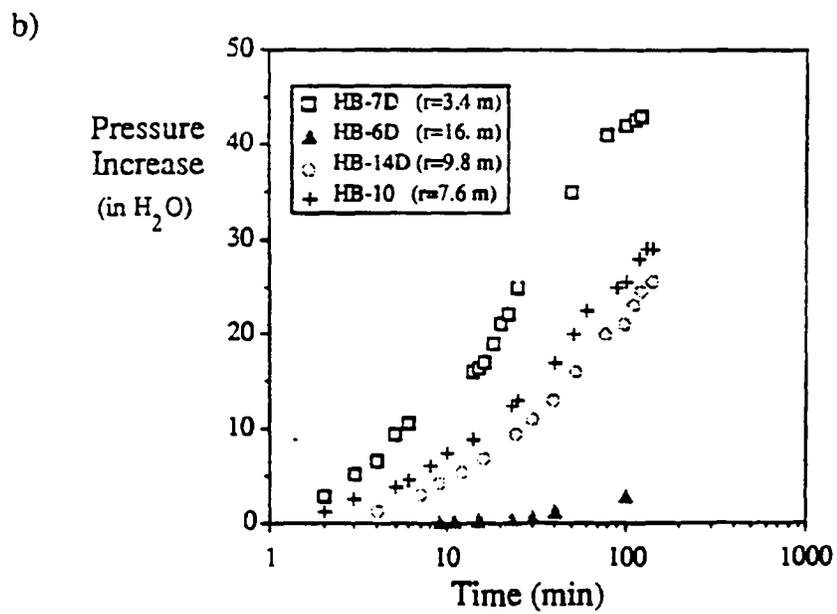
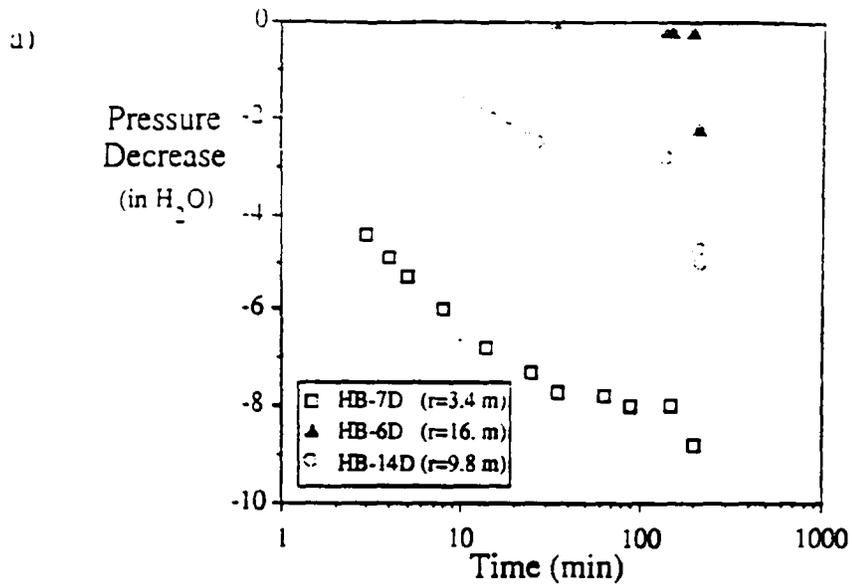


Figure E-16. Air Permeability Test Results: a) vapor extraction test, b) air injection test.

concentrations, and subsurface pressure distribution could be monitored at three depths. One sampling port is located in the zone adjacent to the aquifer. The vapor flowrate from HB-25 and vapor concentrations were measured frequently, and the vapor composition was determined by GC-FID analysis. In addition, the water level in the groundwater monitoring wells was measured with the system pictured in Figure E-13b. The results from the first four months of operation are discussed below.

In Figure E-17a the extraction well vacuum and corresponding vapor flowrate are presented. The vacuum was maintained at 0.95 atm (20 in H<sub>2</sub>O vacuum), and the flowrate was initially 12 scfm. It gradually decreased to about 6 scfm over 80 d. For comparison, Equation (5) predicts that Q=12 cfm for k=8 darcys. Increasing the applied vacuum to 0.70 atm (120 in H<sub>2</sub>O vacuum) had little effect on the flowrate. This could be explained by increased water table upwelling, which would act to decrease the vertical cross-section available for vapor flow. The scatter in the flowrate measurements is probably due to inconsistent operation of the groundwater pumping operation, which frequently failed to perform properly.

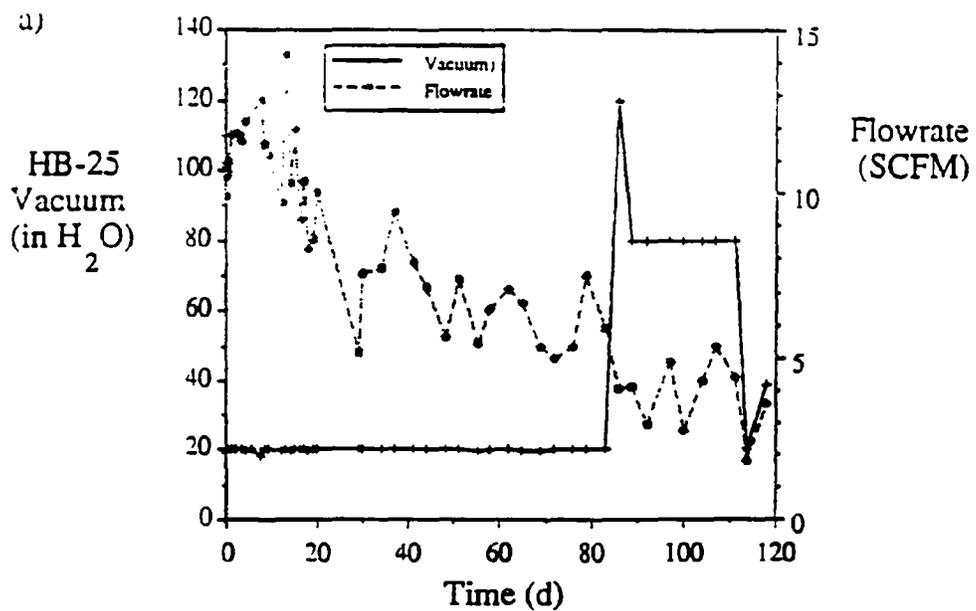
Figure E-17b presents the change in vapor concentration with time. Fifteen specific compounds were identified during the GC-FID vapor analyses; in this figure we present the total concentration of known and unknown compounds detected between five boiling point ranges:

- methane - isopentane (<28°C)
- isopentane - benzene (28 - 80°C)
- benzene - toluene (80 - 111°C)
- toluene - xylenes (111 - 144°C)
- >xylenes (>144°C)

There was a shift in composition towards less volatile compounds in the first 20 d, but after that period the composition remained relatively constant. Note that there is still a significant fraction of volatile compounds present. Within the first two days the vapor concentration decreased by 50%, which corresponds to the time period for the removal of the first pore volume of air. Comparing the subsequent vapor concentrations with the concentrations measured in the vadose zone monitoring wells indicates that only (80 mg/l)/(240 mg/l)\*100=33% of the vapors are flowing through contaminated soil.

Figure E-18a presents calculated removal rates (flowrate x concentration) and cumulative amount (1 gal = 3 kg) removed during the first four months. The decrease in removal rate with time is due to a combination of decreases in flowrate and hydrocarbon vapor concentrations. After the first four months approximately one-fourth of the estimated residual has been removed from this lower zone.

On day 80 the vacuum was increased from 20 - 120 in H<sub>2</sub>O vacuum and the subsequent increase in subsurface vacuum and water table upwelling was monitored. Figure E-18b presents the results. Note that the water table rise paralleled the vacuum increase, although the water table did not rise the same amount that the



[in H<sub>2</sub>O] denote vacuums expressed as equivalent water column heights

Figure E-17a. Soil Venting Results: Vacuum/Flowrate Data

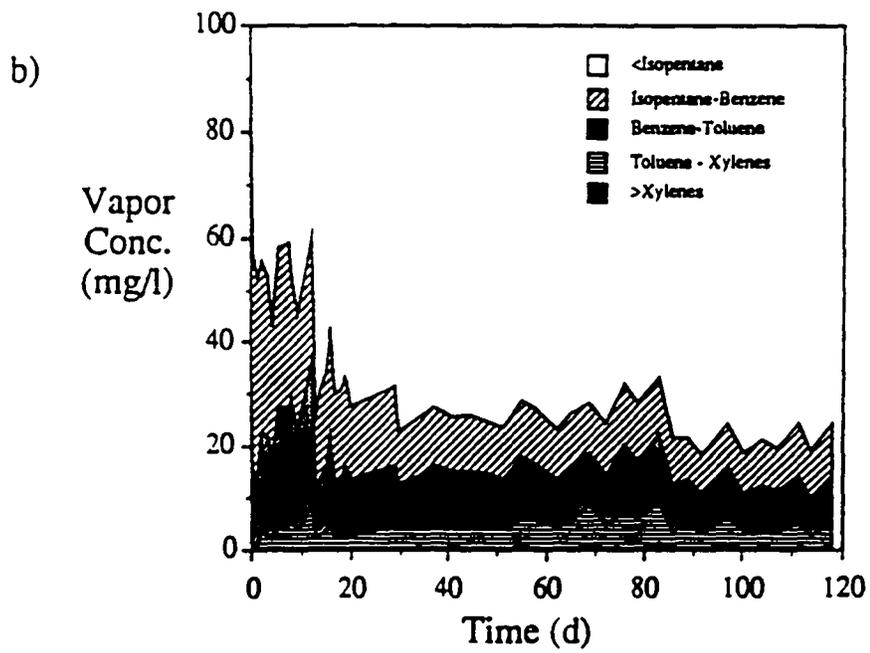
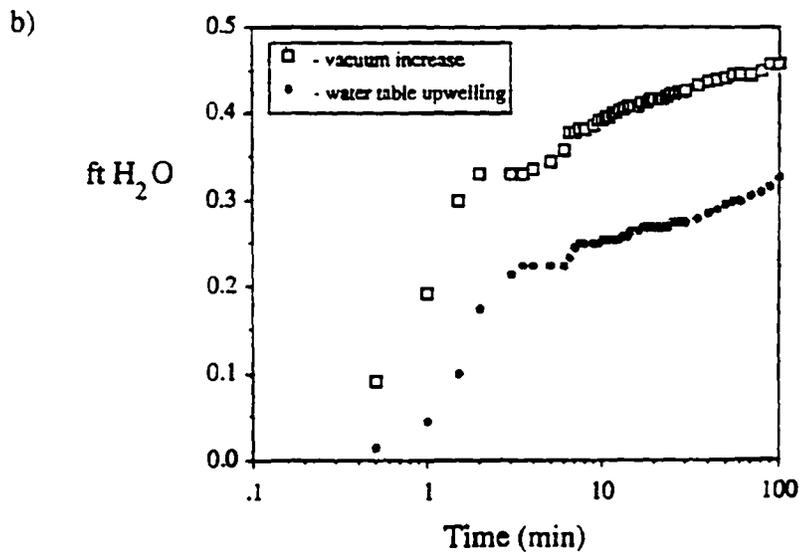
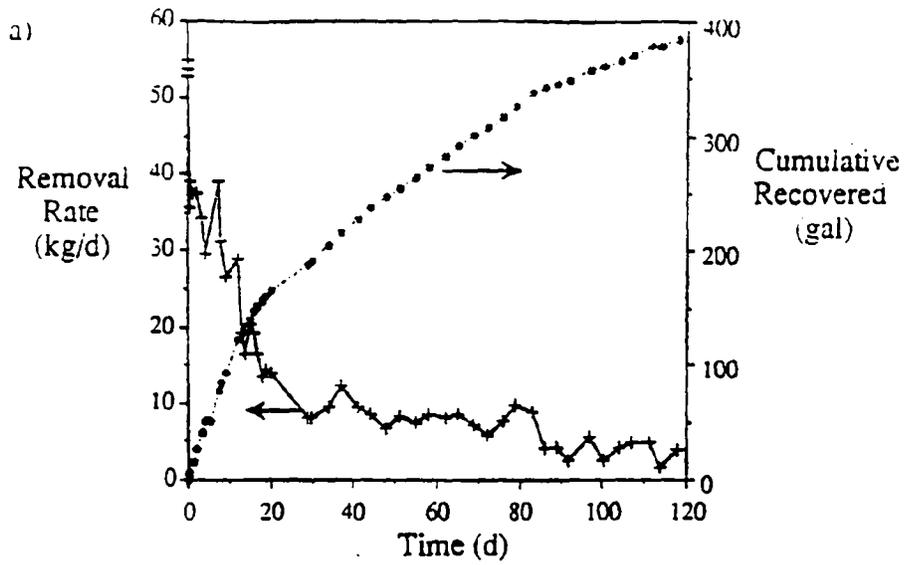


Figure E-17b. Soil Venting Results: Concentration/Composition Data



[ft H<sub>2</sub>O] denote vacuums expressed as equivalent water column heights

Figure E-18. Soil Venting Results: a) Removal Rate/Cumulative Recovered, b) Water Table Rise.

vacuum did.

Figure E-19 compares the reduced measured TPH vapor concentration  $C(t)/C(t=0)$  with model predictions.  $C(t=0)$  was taken to be the vapor concentration after one pore volume of air had passed through the contaminated zone ( $\approx 80$  mg/l),  $m(t=0)$  is equal to the estimated spill mass ( $\approx 4000$  kg), and  $V(t)$  is the total volume of air that has passed through the contaminated zone. This quantity is obtained by integrating the total vapor flowrate with time, then multiplying it by the fraction of vapors passing through the contaminated zone  $f$  ( $\approx 0.33$ ). As discussed, the quantity  $f$  was estimated by comparing soil gas concentrations from the vadose zone monitoring installations with vapor concentrations in the extraction well vapors. As can be seen, there is good quantitative agreement between the measured and predicted values.

Based on the data presented in Figures E-15 through E-19 and the model predictions in Figure E-8, it appears that more extraction wells ( $\approx 10$  more) are needed to remediate the site within a reasonable amount of time.

## CONCLUSIONS

A structured, technically based approach has been presented for the design, construction, and operation of venting systems. While we have attempted to explain the process in detail for those not familiar with venting operations or the underlying governing phenomena, the most effective and efficient systems can only be designed and operated by personnel with a good understanding of the fundamental processes involved. The service station spill example presented supports the validity and usefulness of this approach.

There are still many technical issues that need to be resolved in the future. In particular, we must be able to estimate removal rates for non-ideal situations, demonstrate that biodegradation is enhanced by venting, and investigate novel ideas for enhancing venting removal rates.

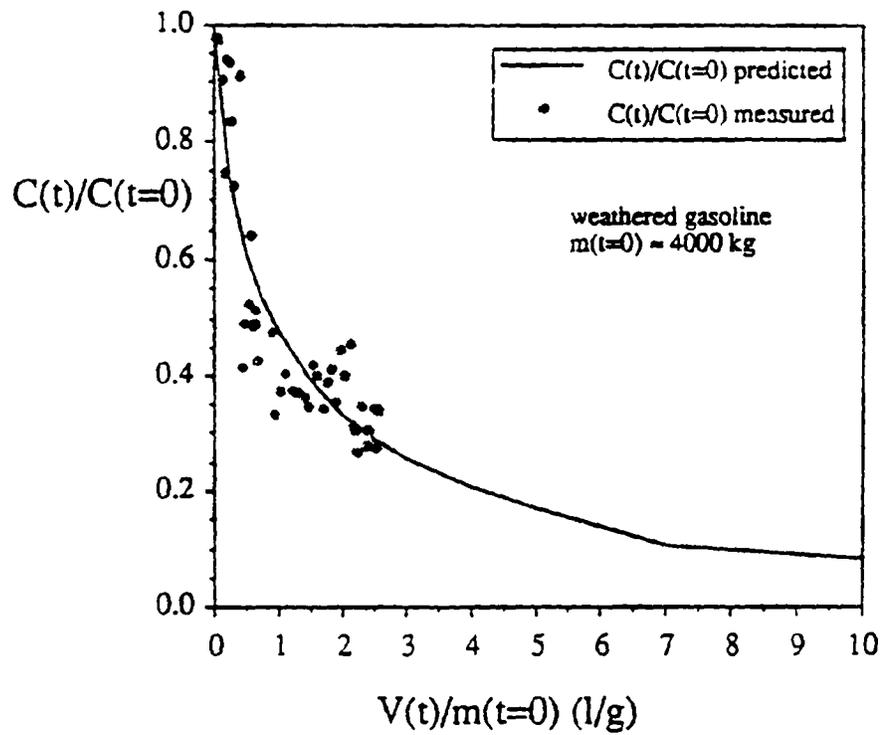


Figure E-19. Comparison of Model Predictions and Measured Response.

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## APPENDIX F

### ENGINEERING BULLETINS FOR TREATMENT PROCESSES

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Superfund

EPA/540/2-91/023

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## Engineering Bulletin

# Control of Air Emissions From Materials Handling During Remediation

### Purpose

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

### Abstract

This bulletin presents an overview discussion on the importance of and methods for controlling emissions into the air from materials handling processes at Superfund or other hazardous waste sites. It also describes several techniques used for dust and vapor suppression that have been applied at Superfund sites.

Air emission control techniques have been utilized for Superfund cleanups at the McColl site (CA) and at the LaSalle Electric site (IL). Foam suppression has been used at Rocky Mountain Arsenal (CO), Texaco Fillmore (CA), and at a petro-

leum refinery (CA) site. A number of temporary vapor suppression techniques have also been applied at other sites. Additionally, the experience gained in the mining industry and at hazardous waste treatment, storage, and disposal sites will yield applicable methods for Superfund sites.

This bulletin provides information on the applicability of air emission controls for materials handling at Superfund sites, limitations of the current systems, a description of the control methods that have found application to date, site requirements, a summary of the performance experience, the status of the existing techniques and identification of future development expectations, and sources of additional information.

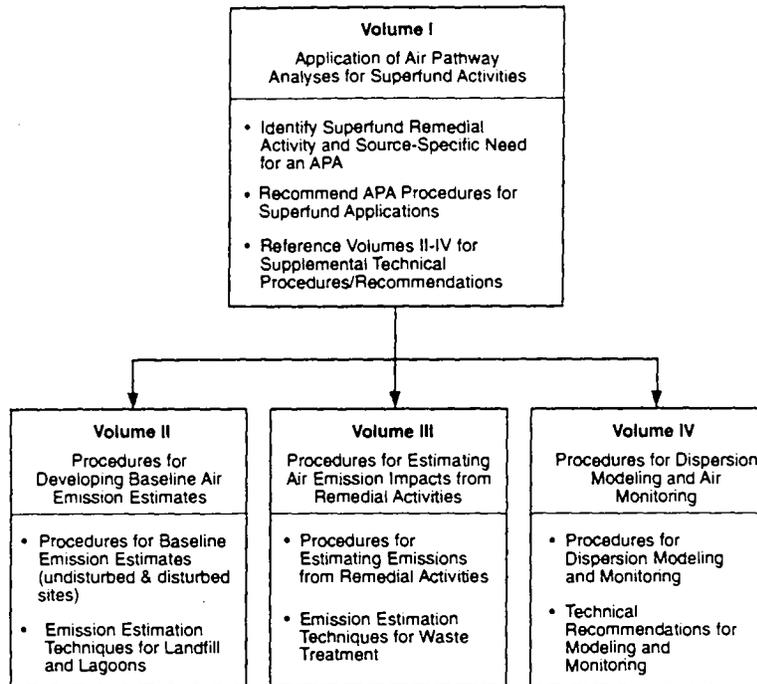
### Applicability of Materials Handling Controls

Estimation of the potential releases to the air and an analysis of the impacts to the air pathway are applicable to every activity in the Superfund process. Since nearly every Superfund site has a potential air emissions problem, the focus of this bulletin is to assist RPMs and OSCs in considering the appropriate methods for material handling at Superfund sites. To do that, the first step is to estimate the potential releases using the air pathway analysis (APA) process.

The amended National Contingency Plan expands upon the requirement to conduct and fully document a regimented process called an air pathway analysis (APA). The process is defined as a "systematic approach involving a combination of modeling and monitoring methods to assess actual or potential receptor exposure to air contaminants" [1 p. 1-1]\*. When considering removal or remedial responses (i.e., technologies), an APA detailing emission estimates is useful for determining the potential compliance with applicable or relevant and appropriate requirements (ARARs) during remedial action, particularly at a State or local level. Compliance with National Ambient Air Quality Standards during a remediation or the excavation and processing of the contaminated media must be addressed. With the passage of the Clean Air Act Amendments in November 1990 and the advent of numerous state air toxics programs, remediation of Superfund sites must address the

\* [reference number, page number]

**Figure 1**  
**Procedures for Conducting APA for Superfund**  
**Application—Overview [1, p.1-4]**



media transfer that excavation and materials handling (before and after treatment) will create, and the ARARs these regulations represent. Figure 1 [1, p. 1-4] indicates the applicability of the guidance study series documents on the air pathway analysis to remedial project managers/on-scene coordinators and to contractors and other technical staff.

The potential for short-term risk (i.e., during the remedial action) is a major criterion when selecting the best remedial alternative. The general classes of contaminants of concern are gaseous and particulate emissions. Particulate matter (PM) becomes airborne via wind erosion, mechanical disturbances (such as excavation and material processing), combustion, and desorption. Gaseous species are primarily volatilized contaminants (VCs), but natural processes such as biodegradation and photo-decomposition can result in releases once the site has been disturbed. Since volatilization is the primary mechanism for gaseous emissions, any volatile contaminant in the soil, a lagoon, a landfill, or even in open containers may be released to the air. The carcinogenic and noncarcinogenic hazards that gases and particulates present in the air pathway must be assessed.

When initially considering remediation technologies applicable to a site, the APA process can play an integral role in estimating the risk that excavation and materials processing pose to the receptors in the area. Any ex situ process that

requires such excavation and material sizing, screening, or other pretreatment processing will result in losses of particulate and volatile contaminants.

Similarly, emissions generated during the operation of the technology (i.e., losses from air pollution control equipment or fugitive losses from the treatment process itself) must be estimated in order to complete the air emissions source assessment prior to final selection of the remedial technology. The ambient concentrations of air contaminants may have to be monitored during the remediation process to ensure compliance with local air toxics regulations. All of these considerations should be assessed, a cost estimate prepared, and the results should become an integral input to the selection of alternative technologies according to the National Contingency Plan process. Of these criteria, overall protection of human health and the environment, ARAR compliance, implementability, cost, short-term effectiveness and State and community acceptance become paramount concerns for the air pathway impact.

Results of a recently published study [16] indicate significant VC losses during typical soil excavation, transport, and feed/preparation operations. The contribution of each remedial step to the VC emissions was examined. Table 1 presents the results for each step. Although different chemical constituents and concentrations were present in two different site zones, the contribution of each remedial step to the VC emissions during

**Table 1**  
**Remedial Step Fractional**  
**Contribution to VCs [16, p. 39]**

Remedial Activity	Overall Site
Excavation	0.0509
Bucket	0.0218
Truck Filling	0.0905
Transport	0.3051
Dumping	0.5016
Incinerator	0.0014
Exposed Soil	0.0287
Total	1.0000

**Table 2**  
**Common Control Technologies Available For**  
**Materials Handling [\*]**

Remedial Operation	Control Technology
Excavation	Water sprays of active areas Dust suppressants Surfactants Foam coverings Enclosures Aerodynamic considerations
Transportation	Watersprays of active areas Dust suppressants Surfactants Road carpets Road oiling Speed reduction Coverings for loads
Dumping	Water sprays of active areas Water spray curtains over bed during dumping Dust suppressants Surfactants
Storage (waste/residuals)	Windscreens Orientation of pile Slope of pile Foam covering and other coverings Dust suppressants Aerodynamic considerations Cover by structure with air displacement and control
Grading	Light water sprays Surfactants
Waste feed/preparation	Cover by structure with air displacement and control

\*Adapted from [1].

the excavation process remained constant. This contribution was dependent on the parameters of the soil and the remedial activity pattern. At this site, dumping and temporary storage at the incinerator accounted for 50 percent of the VC emissions; transport from the excavation zone was the second highest contributor of emissions. All activities were assumed to be uncontrolled. The use of tarps and/or foam suppressants could substantially reduce these emissions from transport and storage.

### Limitations

The control methods for dust and vapor suppression rarely remove 100 percent of the contaminants from the air. These releases have to be estimated, along with the cost estimate for application of the control method to properly assess the feasibility of implementing the remediation technology being considered. Site conditions determine the effectiveness of specific control methods.

Some methods have very limited periods of effectiveness, making multiple applications or specialized formulations necessary. The scheduling of media excavation and processing may be impacted, for example, in matching the length of effectiveness of a foam or spray suppression technique being used.

If gaseous emissions are expected to be high, or local fugitive limitations apply, costly areal containment methods may be required. If a very large site is to be excavated and the materials classified or preprocessed, portable versions will have to be designed for local air emission control. The use of such portable containment strategies will affect the overall schedule of the remediation and will mandate unique worker safety plans to ensure that the proper level of protective apparel and monitoring devices are used during the excavation process.

### Control Methods

A list of the most commonly used control technologies applicable to VCs and PMs released during soils handling is presented in Table 2 [1, p. 5-31].

Volatilization of contaminants from a hazardous waste site may be controlled by reducing soil vapor pore volume or using physical/chemical barriers [2, p. 116]. The rate of volatilization can be reduced by adding water to reduce the air-filled pore spaces or by reduction of the spaces themselves through compaction techniques. Compaction, however, would displace the volatiles occupying the free spaces (soil venting); water suppression might result in mobilizing the contaminant into a groundwater medium if not properly applied. Wastes amenable to this form of suppression include most volatile organic (e.g., benzene, gasoline, phenols) and inorganic (e.g., hydrogen sulfide, ammonia, radon, methyl mercury) compounds in soil. Contaminants with a high vapor phase mobility and low water phase partition potential are particularly amenable to this vapor control technique. However, the initial application of water will force VCs from the soil-free spaces.

Physical/chemical barriers have found broad utility in temporary vapor and particulate control from hazardous waste sites [3, p. 4-1 to 4-10]. Evaporation retardants such as foams may be applied, while simpler windscreens, synthetic covers, and water/surfactant sprays have been used during excavation and transportation operations. The most exotic system applied to a Superfund site included a special domed structure erected over the excavation area and equipped with carbon adsorption beds through which the internal vapors were drawn [4]. The domed structure was designed to limit emissions through the structure and was capable of being transported to the next excavation site when required. A similar structure may be necessary at the point of materials processing, prior to a proposed incinerator for the site. This facility might be fixed, provided a centralized location for the incinerator can be established.

Sound engineering practices include a multitude of methods for vapor and dust suppression; these techniques are shown in Table 3 [5, p. vi]. More than a dozen different techniques have been identified. Several of the methods in Table 3 can be used collectively to achieve fugitive emissions control. Application of foams during excavation operations and tarps for overnight storage can achieve a greater overall control efficiency at significantly lower cost than the use of an enclosure with carbon adsorption control. Good engineering practices employing the use of windscreens or other aerodynamic considerations may provide adequate control at some sites; other sites may require application of nearly every method in the list. Cost estimates of many control techniques for VCs are presented in Reference 6 [6, p. 68]. The cost estimates in Reference 6 are not specific to any particular Superfund site. Cost estimates vary significantly according to the site conditions, contaminant type, and ARARs to be met. Table 3 presents a relative cost index for illustrative purposes.

**Table 3**  
Relative PM/VC Suppression Technologies

Suppression technique	Relative Effectiveness			Relative Cost
	Low	Medium	High	
Minimize waste surface area	x	x	x	1
Aerodynamic considerations	x			1
• Windscreens	x			1
• Wind blocks	x			1
• Orientation of activities	x			1
Covers, mats, membranes, and fill materials	x	x		2-3
Water application	x	x		2-3
Water/additives	x	x		2-3
Inorganic control agents	x	x		2-3
Organic dust control		x		2-3
Foam suppressants		x	x	7-10
Enclosures			x	10

## Site Requirements

General site conditions that dictate the estimated magnitude of air emissions are provided in Table 4 [7, p. 16]. The requirements for implementation of the dust/vapor control techniques are a function of the estimated emissions once these site conditions have been assessed. Baseline estimation techniques are available for both undisturbed and disturbed sites, as well as mathematical modeling and actual direct measurement methods to verify estimates. Consideration of the particular weather conditions relative to the proposed remediation schedule is critical to efficient control of air emissions. Tables 3 and 4 should be considered concurrently when structuring an air emissions control strategy for the site and the remediation activities.

**Table 4**  
Important Parameters Affecting Baseline Air Emission Levels [7]

Parameter	Qualitative Effect <sup>a</sup>	
	Volatiles	Particulate Matter
<u>Site Conditions</u>		
Size of landfill or lagoon	Affects overall magnitude of emissions, but not per area.	Affects overall magnitude of emissions, but not per area.
Amount of exposed waste	High	High
Depth of cover on landfills	Medium	High
Presence of oil layer	High	High
Compaction of cover on landfills	Medium	Low
Aeration of lagoons	High	High
Ground cover	Medium	High
<u>Weather Conditions</u>		
Wind speed	Medium	High
Temperature	Medium	Low
Relative humidity	Low	Low
Barometric pressure	Medium	Low
Precipitation	High	High
Solar radiation	Low	Low
<u>Soil/Waste Characteristics</u>		
Physical properties of waste	High	High
Adsorption/absorption properties of soil	Medium	Low
Soil moisture content	High	High
Volatile fraction of waste	High	Low
Semivolatile/nonvolatile fraction of waste	Low	High
Organic content of soil and microbial activity	High	Low

<sup>a</sup>High, medium, and low in this table refer to the qualitative effect that the listed parameter typically has on baseline emissions.

**Table 5**  
**Summary of VOC Air Emissions Control Technologies For Landfills [\*]**

Control	Advantages	Disadvantages
Foams	<ul style="list-style-type: none"> <li>• Easy to Apply</li> <li>• Effective</li> <li>• Allow for Control of Working Faces</li> <li>• Can Reduce Decontamination</li> </ul>	<ul style="list-style-type: none"> <li>• Moderately Expensive</li> <li>• Requires Trained Operators</li> </ul>
Complete Enclosure/ Treatment System	<ul style="list-style-type: none"> <li>• May Provide the Highest Degree of Control For Some Applications</li> </ul>	<ul style="list-style-type: none"> <li>• High Cost</li> <li>• Air Scrubbing Required</li> <li>• High Potential Risk</li> <li>• Must Work Inside Enclosure</li> </ul>
Fill Material	<ul style="list-style-type: none"> <li>• Inexpensive</li> <li>• Equipment Usually Available</li> </ul>	<ul style="list-style-type: none"> <li>• Hard to Seal Air-Tight</li> <li>• No Control for Working Face</li> <li>• Creates More Contaminated Soil</li> </ul>
Synthetic Membrane	<ul style="list-style-type: none"> <li>• Simple Approach</li> </ul>	<ul style="list-style-type: none"> <li>• Worker Contact with Waste on Application</li> <li>• Hard to Seal Air-Tight</li> </ul>
Aerodynamic Modification	<ul style="list-style-type: none"> <li>• Simple</li> <li>• Lower Cost</li> <li>• Low Maintenance</li> </ul>	<ul style="list-style-type: none"> <li>• Variable Control</li> <li>• Requires Additional Controls</li> </ul>
Fugitive VC/PM Collection Systems	<ul style="list-style-type: none"> <li>• Can Be Used in Active Areas</li> </ul>	<ul style="list-style-type: none"> <li>• Limited Operational Data Exist</li> <li>• Effective Range Limited</li> <li>• Maintenance Required</li> </ul>
Minimum Surface Area, Shape	<ul style="list-style-type: none"> <li>• Inexpensive</li> <li>• Can Be Included in Plan</li> </ul>	<ul style="list-style-type: none"> <li>• Must Maintain</li> <li>• Cannot Always Dictate Shape</li> </ul>
Water	<ul style="list-style-type: none"> <li>• Easy to Apply</li> </ul>	<ul style="list-style-type: none"> <li>• A Potential Exists for Leaching to Groundwater</li> </ul>
Inorganic/Organic Control Agents	<ul style="list-style-type: none"> <li>• Similar to Foams</li> </ul>	<ul style="list-style-type: none"> <li>• Not as Effective as Foams For Working Areas</li> </ul>

\* Adapted from [14]

### Performance Experience

A study of fugitive dust control techniques conducted with test plots at an active cleanup area documented decreasing effectiveness of foam suppressants within 2 to 4 weeks of application. The effectiveness of water sprays on dump trucks and at the loading site was in the 40 to 60 percent range for the site and 60 to 70 percent range for the truck [8, p. 2]. Surfactants increased the effectiveness of the water sprays.

Foam suppressants have been thoroughly studied by at least two vendors: 3M and Rusmar Foam Technology [9][10]. Laboratory data for highly volatile organics, such as benzene and trichloroethylene contaminated sand, indicated more than 99 percent suppression effectiveness for several days. Complementary data indicated better barrier performance of foams over 10-mil polyethylene film in controlling volatilization [11, p.

7 & 8]. A burning landfill was coused and the vapors suppressed by more than 90 percent using foam at a site in Jersey City [12, p. 3]. Similarly, vapors from a petroleum waste site were compared using three different test agents: temporary foam, rigid urea-formaldehyde foam, and a stabilized foam. The temporary foam yielded an average 81 percent control for 20 minutes, rigid foam produced 73 percent control for about 2 hours, and the stabilized foam was 99 percent effective for 24 hours after application [13, p. 4-7].

The performance data reported are specific to the sites and contaminants controlled. There is no direct applicability of the performance data to general Superfund sites or conditions.

Table 5 presents a summary of VC air emissions control technologies for landfills [14, p. 38]. Many of the techniques used can control fugitive particulate emissions as well.

## Technology Status

The use of vapor and particulate control techniques has been directly applied to at least three Superfund sites: McColl (California), Purity Oil Site (California), and LaSalle Electric (Illinois). The McColl work is available as a Superfund Innovative Technology Evaluation demonstration of excavation techniques. Although the domed structure used controlled sulfur dioxide and VOC releases to the atmosphere, working conditions within the dome were difficult. High concentrations of dust and contaminants mandated use of a high level of personal protective apparel. Consequently, personnel were able to work within the dome for only short periods of time [15].

A variety of dust and vapor control techniques may be applied at Superfund sites. A systematic approach to estimate the quantities of air emissions to be controlled, the ambient impact, and the selection of the most appropriate control technique requires a thorough understanding of the site, wastes, emissions potential, and the most relevant combinations of control methods.

## EPA Contact

Technology-specific questions regarding air emissions may be directed to:

Mr. Michael Borst  
U.S. EPA, Releases Control Branch  
Risk Reduction Engineering Laboratory  
2890 Woodbridge Ave., Building 10 (MS-104)  
Edison, NJ 08837-3679  
Telephone FTS 340-6631 or (908) 321-6631

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## Engineering Bulletin

# Thermal Desorption Treatment

### Purpose

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

### Abstract

Thermal desorption is an ex situ means to physically separate volatile and some semivolatile contaminants from soil, sediments, sludges, and filter cakes. For wastes containing up to 10% organics or less, thermal desorption can be used alone for site remediation. It also may find applications in conjunction with other technologies or be appropriate to specific operable units at a site.

Site-specific treatability studies may be necessary to document the applicability and performance of a thermal desorption system. The EPA contact indicated at the end of this bulletin can assist in the definition of other contacts and sources of information necessary for such treatability studies.

Thermal desorption is applicable to organic wastes and generally is not used for treating metals and other inorganics. Depending on the specific thermal desorption vendor selected, the technology heats contaminated media between 200-1000°F, driving off water and volatile contaminants.

Offgases may be burned in an afterburner, condensed to reduce the volume to be disposed, or captured by carbon adsorption beds.

Commercial-scale units exist and are in operation. Thermal desorption has been selected at approximately fourteen Superfund sites [1]\* [2]. Three Superfund Innovative Technology Evaluation demonstrations are planned for the next year.

The final determination of the lowest cost alternative will be more site-specific than process equipment dominated. This bulletin provides information on the technology applicability, limitations, the types of residuals produced, the latest performance data, site requirements, the status of the technology, and sources for further information.

### Technology Applicability

Thermal desorption has been proven effective in treating contaminated soils, sludges, and various filter cakes. Chemical contaminants for which bench-scale through full-scale treatment data exist include primarily volatile organic compounds (VOCs), semivolatiles, and even higher boiling point compounds, such as polychlorinated biphenyls (PCBs) [3][4][5][6]. The technology is not effective in separating inorganics from the contaminated medium. Volatile metals, however, may be removed by higher temperature thermal desorption systems.

Some metals may be volatilized by the thermal desorption process as the contaminated medium is heated. The presence of chlorine in the waste can also significantly affect the volatilization of some metals, such as lead. Normally the temperature of the medium achieved by the process does not oxidize the metals present in the contaminated medium [7, p. 85].

The process is applicable for the separation of organics from refinery wastes, coal tar wastes, wood-treating wastes, creosote-contaminated soils, hydrocarbon-contaminated soils, mixed (radioactive and hazardous) wastes, synthetic rubber processing wastes, and paint wastes [8, p. 2][4][9].

Performance data presented in this bulletin should not be considered directly applicable to other Superfund sites. A number of variables, such as the specific mix and distribution

\* [reference number, page number]

**Table 1**  
**RCRA Codes for Wastes Treated**  
**by Thermal Desorption**

Wood Treating Wastes	K001
Dissolved Air Flotation (DAF) Float	K048
Slop Oil Emulsion Solids	K049
Heat Exchanger Bundles Cleaning Sludge	K050
American Petroleum Institute (API) Separator Sludge	K051
Tank Bottoms (leaded)	K052

**Table 2**  
**Effectiveness of Thermal Desorption on**  
**General Contaminant Groups for Soil,**  
**Sludge, Sediments, and Filter Cakes**

Contaminant Groups		Effectiveness			
		Soil	Sludge	Sedi-ments	Filter Cakes
Organic	Halogenated volatiles	■	▼	▼	■
	Halogenated semivolatiles	■	▼	▼	■
	Nonhalogenated volatiles	■	▼	▼	■
	Nonhalogenated semivolatiles	■	▼	▼	■
	PCBs	■	▼	▼	▼
	Pesticides	■	▼	▼	▼
	Dioxins/Furans	■	▼	▼	▼
	Organic cyanides	▼	▼	▼	▼
Inorganic	Organic corrosives	□	□	□	□
	Volatile metals	■	▼	▼	▼
	Nonvolatile metals	□	□	□	□
	Asbestos	□	□	□	□
	Radioactive materials	□	□	□	□
	Inorganic corrosives	□	□	□	□
Reactive	Inorganic cyanides	□	□	□	□
	Oxidizers	□	□	□	□
	Reducers	□	□	□	□

■ Demonstrated Effectiveness: Successful treatability test at some scale completed  
 ▼ Potential Effectiveness: Expert opinion that technology will work  
 □ No Expected Effectiveness: Expert opinion that technology will not work

of contaminants, affect system performance. A thorough characterization of the site and a well-designed and conducted treatability study are highly recommended.

Table 1 lists the codes for the specific Resource Conservation and Recovery Act (RCRA) wastes that have been treated by this technology [8, p. 2][4][9]. The indicated codes were derived from vendor data where the objective was to determine thermal desorption effectiveness for these specific industrial wastes. The effectiveness of thermal desorption on general contaminant groups for various matrices is shown in Table 2. Examples of constituents within contaminant groups are provided in "Technology Screening Guide For Treatment

of CERCLA Soils and Sludges" [7, p. 10]. This table is based on the current available information or professional judgment where no information was available. The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment efficiencies achieved will be acceptable at other sites. For the ratings used for this table, demonstrated effectiveness means that, at some scale, treatability was tested to show the technology was effective for that particular contaminant and medium. The ratings of potential effectiveness or no expected effectiveness are both based upon expert judgment. Where potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminant group in a particular medium. When the technology is not applicable or will probably not work for a particular combination of contaminant group and medium, a no expected effectiveness rating is given. Another source of general observations and average removal efficiencies for different treatability groups is contained in the Superfund Land Disposal Restrictions (LDR) Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions," (OSWER Directive 9347.3-06FS, September 1990) [10] and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions," (OSWER Directive 9347.3-06BFS, September 1990) [11].

### Limitations

The primary technical factor affecting thermal desorption performance is the maximum bed temperature achieved. Since the basis of the process is physical removal from the medium by volatilization, bed temperature directly determines which organics will be removed.

The contaminated medium must contain at least 20 percent solids to facilitate placement of the waste material into the desorption equipment [3, p. 9]. Some systems specify a minimum of 30 percent solids [12, p. 6].

As the medium is heated and passes through the kiln or desorber, energy is lost in heating moisture contained in the contaminated soil. A very high moisture content can result in low contaminant volatilization or a need to recycle the soil through the desorber. High moisture content, therefore, causes increased treatment costs.

Material handling of soils that are tightly aggregated or largely clay, or that contain rock fragments or particles greater than 1-1.5 inches can result in poor processing performance due to caking. Also, if a high fraction of fine silt or clay exists in the matrix, fugitive dusts will be generated [7, p. 83] and a greater dust loading will be placed on the downstream air pollution control equipment [12, p. 6].

The treated medium will typically contain less than 1 percent moisture. Dust can easily form in the transfer of the treated medium from the desorption unit, but can be mitigated by water sprays. Normally, clean water from air pollution control devices can be used for this purpose.

Although volatile organics are the primary target of the thermal desorption technology, the total organic loading is limited by some systems to up to 30 percent or less [13, p. 11-

30]. As in most systems that use a reactor or other equipment to process wastes, a medium exhibiting a very high pH (greater than 11) or very low pH (less than 5) may corrode the system components [7, p. 85].

There is evidence with some system configurations that polymers may foul and/or plug heat transfer surfaces [3, p. 9]. Laboratory/field tests of thermal desorption systems have documented the deposition of insoluble brown tars (presumably phenolic tars) on internal system components [14, p. 76].

High concentrations of inorganic constituents and/or metals will likely not be effectively treated by thermal desorption. The maximum bed temperature and the presence of chlorine can result in volatilization of some inorganic constituents in the waste, however.

### Technology Description

Thermal desorption is any of a number of processes that use either indirect or direct heat exchange to vaporize organic contaminants from soil or sludge. Air, combustion gas, or inert gas is used as the transfer medium for the vaporized components. Thermal desorption systems are physical separation processes and are not designed to provide high levels of organic destruction, although the higher temperatures of some systems will result in localized oxidation and/or pyrolysis. Thermal desorption is not incineration, since the destruction of organic contaminants is not the desired result. The bed temperatures achieved and residence times designed into thermal desorption systems will volatilize selected contaminants, but typically not oxidize or destroy them. System performance is typically measured by comparison of untreated soil/sludge contaminant levels with those of the processed soil/sludge. Soil/sludge is typically heated to 200 - 1000° F, based on the thermal desorption system selected.

Figure 1 is a general schematic of the thermal desorption process.

Waste material handling (1) requires excavation of the contaminated soil or sludge or delivery of filter cake to the system. Typically, large objects greater than 1.5 inches are screened from the medium and rejected. The medium is then delivered by gravity to the desorber inlet or conveyed by augers to a feed hopper [8, p. 1].

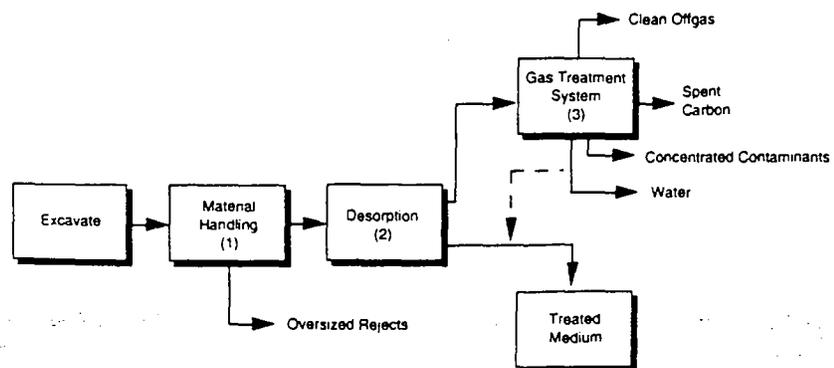
Significant system variation exists in the desorption step (2). The dryer can be an indirectly fired rotary asphalt kiln, a single (or set of) internally heated screw auger(s), or a series of externally heated distillation chambers. The latter process uses annular augers to move the medium from one volatilization zone to the next. Additionally, testing and demonstration data exist for a fluidized-bed desorption system [12].

The waste is intimately contacted with a heat transfer surface, and highly volatile components (including water) are driven off. An inert gas, such as nitrogen, may be injected in a countercurrent sweep stream to prevent contaminant combustion and to vaporize and remove the contaminants [8, p. 1][4]. Other systems simply direct the hot gas stream from the desorption unit [3, p. 5][5].

The actual bed temperature and residence time are the primary factors affecting performance in thermal desorption. These parameters are controlled in the desorption unit by using a series of increasing temperature zones [8, p. 1], multiple passes of the medium through the desorber where the operating temperature is sequentially increased, separate compartments where the heat transfer fluid temperature is higher, or sequential processing into higher temperature zones [15][16]. Heat transfer fluids used to date include hot combustion gases, hot oil, steam, and molten salts.

Offgas from desorption is typically processed (3) to remove particulates. Volatiles in the offgas may be burned in an afterburner, collected on activated carbon, or recovered in condensation equipment. The selection of the gas treatment system will depend on the concentrations of the contaminants, cleanup standards, and the economics of the offgas treatment system(s) employed.

Figure 1  
Schematic Diagram of Thermal Desorption



## Process Residuals

Operation of thermal desorption systems typically creates up to six process residual streams: treated medium, oversized medium rejects, condensed contaminants and water, particulate control system dust, clean offgas, and spent carbon (if used). Treated medium, debris, and oversized rejects may be suitable for return onsite.

Condensed water may be used as a dust suppressant for the treated medium. Scrubber purge water can be purified and returned to the site wastewater treatment facility (if available), disposed to the sewer [3, p. 8] [8, p. 2] [4, p. 2], or used for rehumidification and cooling of the hot, dusty media. Concentrated, condensed organic contaminants are containerized for further treatment or recovery.

Dust collected from particulate control devices may be combined with the treated medium or, depending on analyses for carryover contamination, recycled through the desorption unit.

Clean offgas is released to the atmosphere. If used, spent carbon may be recycled by the original supplier or other such processor.

## Site Requirements

Thermal desorption systems are transported typically on specifically adapted flatbed semitrailers. Since most systems consist of three components (desorber, particulate control, and gas treatment), space requirements on site are typically less than 50 feet by 150 feet, exclusive of materials handling and decontamination areas.

Standard 440V, three-phase electrical service is needed. Water must be available at the site. The quantity of water needed is vendor and site specific.

Treatment of contaminated soils or other waste materials require that a site safety plan be developed to provide for personnel protection and special handling measures. Storage should be provided to hold the process product streams until they have been tested to determine their acceptability for disposal or release. Depending upon the site, a method to store waste that has been prepared for treatment may be necessary. Storage capacity will depend on waste volume.

**Table 3**  
PCB Contaminated Soils  
Pilot X\*TRAX™ [4]

Matrix	Feed (ppm)	Product (ppm)	Removal (%)
Clay	5,000	24	99.3
Silty Clay	2,800	19	99.5
Clay	1,600	4.8	99.7
Sandy	1,480	8.7	99.1
Clay	630	17	97.3

Onsite analytical equipment capable of determining site-specific organic compounds for performance assessment make the operation more efficient and provide better information for process control.

## Performance Data

Several thermal desorption vendors report performance data for their respective systems ranging from laboratory treatability studies to full-scale operation at designated Superfund sites [17][9][18]. The quality of this information has not been determined. These data are included as a general guideline to the performance of thermal desorption equipment, and may not be directly transferrable to a specific Superfund site. Good site characterization and treatability studies are essential in further refining and screening the thermal desorption technology.

Chem Waste Management's (CWM's) X\*TRAX™ System has been tested at laboratory and pilot scale. Pilot tests were performed at CWM's Kettleman Hills facility in California. Twenty tons of PCB- and organic-contaminated soils were processed through the 5 TPD pilot system. Tables 3 and 4 present the results of PCB separation from soil and total hydrocarbon emissions from the system, respectively [4].

During a non-Superfund project for the Department of Defense, thermal desorption was used in a full-scale demonstration at the Tinker Air Force Base in Oklahoma. The success of this project led to the patenting of the process by Weston Services, Inc. Since then, Weston has applied its low-temperature thermal treatment (LT<sup>2</sup>) system to various contaminated soils at bench-scale through full-scale projects [19]. Table 5 presents a synopsis of system and performance data for a full-scale treatment of soil contaminated with No. 2 fuel oil and gasoline at a site in Illinois.

Canonie Environmental has extensive performance data for its Low Temperature Thermal Aeration (LTTA™) system at full-scale operation (15-20 cu. yds. per hour). The LTTA™ has been applied at the McKin (Maine), Ottati and Goss (New Hampshire) and Cannon Engineering Corp. (Massachusetts) Superfund sites. Additionally, the LTTA™ has been used at the privately-funded site in South Kearney (New Jersey). Table

**Table 4**  
Pilot X\*TRAX™  
TSCA Testing - Vent Emissions [4]

Total Hydrocarbons (ppm-V)		Removal (%)	VOC (lbs/day)	PCB* (mg/m <sup>3</sup> )
Before Carbon	After Carbon			
1,320	57	95.6	0.02	<0.00056
1,031	72	93.0	0.03	<0.00055
530	35	93.3	0.01	<0.00051
2,950	170	94.2	0.07	<0.00058
2,100	180	91.4	0.08	<0.00052

\*Note: OSHA permits 0.50 mg/m<sup>3</sup> PCB (1254) for 8-hr exposure.

6 presents a summary of Canonic LTTA<sup>SM</sup> data [5]. The Cannon Engineering (Mass) site, which was not included in Table 6, successfully treated a total of 11,330 tons of soil, containing approximately 1803 lbs. of VOC [20].

T.D.I. Services, Inc. has demonstrated its HT-5 Thermal Distillation Process at pilot- and full-scale for a variety of RCRA-listed and other wastes that were prepared to simulate American Petroleum Institute (API) refinery sludge [8]. The company has conducted pilot- and full-scale testing with the API

sludge to demonstrate the system's ability to meet Land Ban Disposal requirements for K048 through K052 wastes. Independent evaluation by Law Environmental confirms that the requirements were met, except for TCLP levels of nickel, which were blamed on a need to "wear-in" the HT-5 system [21, p. ii].

Remediation Technologies, Inc. (ReTec) has performed numerous tests on RCRA-listed petroleum refinery wastes. Table 7 presents results from treatment of refinery vacuum

**Table 5**  
Full-Scale Performance Results  
for the LT<sup>3</sup> System [19]

Contaminant	Soil Range (ppb)	Treated Range (ppb)	Range of Removal Efficiency
Benzene	1000	5.2	99.5
Toluene	24000	5.2	99.9
Xylene	110000	<1.0	>99.9
Ethyl benzene	20000	4.8	99.9
Napthalene	4900	<330	>99.3
<i>Carcinogenic</i>			
Priority PNAs	<6000	<330-590	<90.2-94.5
<i>Non-carcinogenic</i>			
Priority PNAs	890-6000	<330-450	<62.9-94.5

**Table 6**  
Summary Results of the LTTA<sup>SM</sup>  
Full-Scale Cleanup Tests [5]

Site	Processed	Contaminant	Soil (ppm)	Treated (ppm)
S. Kearney	16000 tons	VOCs PAHs	177.0 (avg.) 35.31 (avg.)	0.87 (avg.) 10.1 (avg.)
McKin	>9500 cu yds 2000 cu yds	VOCs PAHs	ND-3310	ND-0.04 <10
Ottati & Goss	4500 cu yds	VOCs	1500 (avg.)	<0.2 (avg.)

**Table 7**  
ReTec Treatment Results-Refinery  
Vacuum Filter Cake (A) [3]

Compound	Original Sample (ppm)	Treated Sample (ppm)	Removal Efficiency (%)
Napthalene	<0.1	<0.1	---
Acenaphthylene	<0.1	<0.1	---
Acenaphthene	<0.1	<0.1	---
Fluorene	10.49	<0.1	>98.9
Phenanthrene	46.50	<0.1	>99.3
Anthracene	9.80	<0.1	>96.6
Fluoranthrene	73.94	<0.1	>99.8
Pyrene	158.37	<0.1	>99.9
Benzo(b)anthracene	56.33	1.43	97.5
Chrysene	64.71	<0.1	>99.9
Benzo(b)fluoranthene	105.06	2.17	97.9
Benzo(k)fluoranthene	225.37	3.64	98.4
Benzo(a)pyrene	174.58	1.89	98.9
Dibenz(ab)anthracene	477.44	10.25	97.8
Benzo(ghi)perylene	163.53	5.09	96.6
Indeno(123-cd)pyrene	122.27	4.16	96.6

Treatment Temperature: 450°F

**Table 8**  
ReTec Treatment Results-Creosote  
Contaminated Clay [3]

Compound	Original Sample (ppm)	Treated Sample (ppm)	Removal Efficiency (%)
Napthalene	1321	<0.1	>99.9
Acenaphthylene	<0.1	<0.1	---
Acenaphthene	293	<0.1	>99.96
Fluorene	297	<0.1	>99.96
Phenanthrene	409	1.6	99.6
Anthracene	113	<0.1	>99.7
Fluoranthrene	553	1.5	99.7
Pyrene	495	2.0	99.6
Benzo(b)anthracene	59	<0.1	>99.99
Chrysene	46	<0.1	>99.8
Benzo(b)fluoranthene	14	2.5	82.3
Benzo(k)fluoranthene	14	<0.1	>99.8
Benzo(a)pyrene	15	<0.1	>99.9
Dibenz(ab)anthracene	<0.1	<0.1	---
Benzo(ghi)perylene	7	<0.1	>99.4
Indeno(123-cd)pyrene	3	<0.1	>99.3

Treatment Temperature: 500°F

**Table 9**  
**ReTec Treatment Results-Coal Tar**  
**Contaminated Soils [3]**

Compound	Original Sample (ppm)	Treated Sample (ppm)	Removal Efficiency (%)
Benzene	1.7	<0.1	>94
Toluene	2.3	<0.1	>95
Ethylbenzene	1.6	<0.1	>93
Xylenes	6.3	<0.3	>95
Naphthalene	367	<1.7	>99
Fluorene	114	<0.2	>99
Phenanthrene	223	18	91.9
Anthracene	112	7.0	93.8
Fluoranthrene	214	15	93.0
Pyrene	110	11	90.0
Benzo(b)anthracene	56	<1.4	>97
Chrysene	58	3.7	93.6
Benzo(b)fluoranthene	45	<1.4	>97
Benzo(k)fluoranthene	35	<2.1	>94
Benzo(a)pyrene	47	<0.9	>98
Benzo(ghi)perylene	24	<1.1	>95
Indeno(123-cd)pyrene	27	<6.2	>77

Treatment Temperature: 450°F

filter cake. Tests with creosote-contaminated clay and coal tar-contaminated soils showed significant removal efficiencies (Tables 8 and 9). All data were obtained through use of ReTec's 100 lb/h pilot scale unit processing actual industrial process wastes [3].

Recycling Sciences International, Inc. (formerly American Toxic Disposal, Inc.) has tested its Desorption and Vaporization Extraction System (DAVES), formerly called the Vaporization Extraction System (VES), at Waukegan Harbor, Illinois. The pilot-scale test demonstrated PCB removal from material containing up to 250 parts per million (ppm) to levels less than 2 ppm [12].

RCRA LDRs that require treatment of wastes to best demonstrated available technology (BDAT) levels prior to land disposal may sometimes be determined to be applicable or relevant and appropriate requirements for CERCLA response actions. Thermal desorption can produce a treated waste that meets treatment levels set by BDAT but may not reach these treatment levels in all cases. The ability to meet required treatment levels is dependent upon the specific waste constituents and the waste matrix. In cases where thermal desorption does not meet these levels, it still may, in certain situations, be selected for use at the site if a treatability variance establishing alternative treatment levels is obtained. Treatability variances are justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive

9347.3-06FS, September 1990) [10], and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.3-068FS, September 1990) [11]. Another approach could be to use other treatment techniques in series with thermal desorption to obtain desired treatment levels.

## Technology Status

Significant theoretical research is ongoing [22][23], as well as direct demonstration of thermal desorption through both treatability testing and full-scale cleanups.

A successful pilot-scale demonstration of Japanese soils "roasting" was conducted in 1980 for the recovery of mercury from highly contaminated (up to 15.6 percent) soils at a plant site in Tokyo. The high concentration of mercury made recovery and refinement to commercial grade (less than 99.99 percent purity) economically feasible [24].

In this country, thermal desorption technologies are the selected remedies for one or more operable units at fourteen Superfund sites. Table 10 lists each site's location, primary contaminants, and present status [1][2].

Most of the hardware components of thermal desorption are available off the shelf and represent no significant problem of availability. The engineering and configuration of the systems are similarly refined, such that once a system is designed full-scale, little or no prototyping or redesign is required.

On-line availability of the full-scale systems described in this bulletin is not documented. However, since the ex situ system can be operated in batch mode, it is expected that component failure can be identified and spare components fitted quickly for minimal downtime.

Several vendors have documented processing costs per ton of feed processed. The overall range varies from \$80 to \$350 per ton processed [6][4, p. 12][5][3, p. 9]. Caution is recommended in using costs out of context because the base year of the estimates vary. Costs also are highly variable due to the quantity of waste to be processed, term of the remediation contract, moisture content, organic constituency of the contaminated medium, and cleanup standards to be achieved. Similarly, cost estimates should include such items as preparation of Work Plans, permitting, excavation, processing itself, QA/QC verification of treatment performance, and reporting of data.

## EPA Contact

Technology-specific questions regarding thermal desorption may be directed to:

Michael Gruenfeld  
 U.S. Environmental Protection Agency  
 Risk Reduction Engineering Laboratory  
 Releases Control Branch  
 2890 Woodbridge Ave.  
 Bldg. 10 (MS-104)  
 Edison, NJ 08837  
 FTS 340-6625 or (908) 321-6625

**Table 10**  
**Superfund Sites Specifying Thermal Desorption as the Remedial Action**

<i>Site</i>	<i>Location</i>	<i>Primary Contaminants</i>	<i>Status</i>
Cannon Engineering (Bridgewater Site)	Bridgewater, MA (1)	VOCs (Benzene, TCE & Vinyl Chloride)	Project completed 10/90
McKin	McKin, ME (1)	VOCs (TCE, BTX)	Project completed 2/87
Ottati & Goss	New Hampshire (1)	VOCs (TCE; PCE; 1, 2-DCA, and Benzene)	Project completed 9/89
Wide Beach	Brandt, NY (2)	PCBs	In design • pilot study available 5/91
Metaltec/Aerosystems	Franklin Borough, NJ (2)	TCE and VOCs	In design • remedial design complete • remediation starting Fall '91
Caldwell Trucking	Fairfield, NJ (2)	VOCs (TCE, PCE, and TCA)	In design
Outboard Marine/ Waukegan Harbor	Waukegan Harbor, IL (5)	PCBs	In design • treatability studies complete
Reich Farms	Dover Township, NJ (02)	VOCs and Semivolatiles	Pre-design
Re-Solve	North Dartmouth, MA (1)	PCBs	In design • pilot study June/July '91
Waldick Aerospace Devices	New Jersey (2)	TCE and PCE	In design
Wamchem	Burton, SC (4)	BTX and SVOCs (Naphthalene)	In design • pilot study available 5/91
Fulton Terminals	Fulton, NY (2)	VOCs (Xylene, Styrene, TCE, Ethylbenzene, Toluene) and some PAHs	Pre-design
Stauffer Chemical	Cold Creek, AL (4)	VOCs and pesticides	Pre-design
Stauffer Chemical	Le Moyne, AL (4)	VOCs and pesticides	Pre-design

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Dr. Steve Lanier	Energy and Environmental Research Corp.
Ms. Evelyn Meagher-Hartzell	SAIC
Mr. James Rawe	SAIC
Ms. Tish Zimmerman	EPA-OERR

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## Engineering Bulletin

# In Situ Soil Vapor Extraction Treatment

### Purpose

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

### Abstract

Soil vapor extraction (SVE) is designed to physically remove volatile compounds, generally from the vadose or unsaturated zone. It is an in situ process employing vapor extraction wells alone or in combination with air injection wells. Vacuum blowers supply the motive force, inducing air flow through the soil matrix. The air strips the volatile compounds from the soil and carries them to the screened extraction well.

Air emissions from the systems are typically controlled by adsorption of the volatiles onto activated carbon, thermal destruction (incineration or catalytic oxidation), or condensation by refrigeration [1, p. 26].\*

SVE is a developed technology that has been used in commercial operations for several years. It was the selected remedy for the first Record of Decision (ROD) to be signed under the Superfund Amendments and Reauthorization Act of 1986 (the Verona Well Field Superfund Site in Battle Creek,

Michigan). SVE has been chosen as a component of the ROD at over 30 Superfund sites [2] [3] [4] [5] [6].

Site-specific treatability studies are the only means of documenting the applicability and performance of an SVE system. The EPA Contact indicated at the end of this bulletin can assist in the location of other contacts and sources of information necessary for such treatability studies.

The final determination of the lowest cost alternative will be more site-specific than process equipment dominated. This bulletin provides information on the technology applicability, the limitations of the technology, the technology description, the types of residuals produced, site requirements, the latest performance data, the status of the technology, and sources for further information.

### Technology Applicability

In situ SVE has been demonstrated effective for removing volatile organic compounds (VOCs) from the vadose zone. The effective removal of a chemical at a particular site does not, however, guarantee an acceptable removal level at all sites. The technology is very site-specific. It must be applied only after the site has been characterized. In general, the process works best in well drained soils with low organic carbon content. However, the technology has been shown to work in finer, wetter soils (e.g., clays), but at much slower removal rates [7, p. 5].

The extent to which VOCs are dispersed in the soil—vertically and horizontally—is an important consideration in deciding whether SVE is preferable to other methods. Soil excavation and treatment may be more cost effective when only a few hundred cubic yards of near-surface soils have been contaminated. If volume is in excess of 500 cubic yards, if the spill has penetrated more than 20 or 30 feet, or the contamination has spread through an area of several hundred square feet at a particular depth, then excavation costs begin to exceed those associated with an SVE system [8] [9] [10, p. 6].

The depth to groundwater is also important. Groundwater level in some cases may be lowered to increase the volume of the unsaturated zone. The water infiltration rate can be

\* [reference number, page number]

**Table 1**  
**Effectiveness of SVE on General**  
**Contaminant Groups For Soil**

Contaminant Groups		Effectiveness Soil
Organic	Halogenated volatiles	■
	Halogenated semivolatiles	▼
	Nonhalogenated volatiles	■
	Nonhalogenated semivolatiles	■
	PCBs	□
	Pesticides	□
	Dioxins/Furans	□
	Organic cyanides	□
Organic corrosives	□	
Inorganic	Volatile metals	□
	Nonvolatile metals	□
	Asbestos	□
	Radioactive materials	□
	Inorganic corrosives	□
	Inorganic cyanides	□
Reactive	Oxidizers	□
	Reducers	▼

■ Demonstrated Effectiveness: Successful treatability test at some scale completed  
 ▼ Potential Effectiveness: Expert opinion that technology will work  
 □ No Expected Effectiveness: Expert opinion that technology will not work

controlled by placing an impermeable cap over the site. Soil heterogeneities influence air movement as well as the location of chemicals. The presence of heterogeneities may make it more difficult to position extraction and inlet wells. There generally will be significant differences in the air permeability of the various soil strata which will affect the optimum design of the SVE facility. The location of the contaminant on a property and the type and extent of development in the vicinity of the contamination may favor the installation of an SVE system. For example, if the contamination exists beneath a building or beneath an extensive utility trench network, SVE should be considered.

SVE can be used alone or in combination with other technologies to treat a site. SVE, in combination with groundwater pumping and air stripping, is necessary when contamination has reached an aquifer. When the contamination has not penetrated into the zone of saturation (i.e., below the water table), it is not necessary to install a groundwater pumping system. A vacuum extraction well will cause the water table to rise and will saturate the soil in the area of the contamination. Pumping is then required to draw the water table down and allow efficient vapor venting [11, p.169].

SVE may be used at sites not requiring complete remediation. For example, a site may contain VOCs and nonvolatile contaminants. A treatment requiring excavation might be selected for the nonvolatile contaminants. If the site required excavation in an enclosure to protect a nearby populace from VOC emissions, it would be cost effective to extract the volatiles from the soil before excavation. This would obviate the need for the enclosure. In this case it would be necessary to vent the soil for only a fraction of the time required for complete remediation.

Performance data presented in this bulletin should not be considered directly applicable to other Superfund sites. A number of variables such as the specific mix and distribution of contaminants affect system performance. A thorough characterization of the site and a well-designed and conducted treatability study are highly recommended.

The effectiveness of SVE on general contaminant groups for soils is shown in Table 1. Examples of constituents within contaminant groups are provided in the "Technology Screening Guide For Treatment of CERCLA Soils and Sludges" [12]. This table is based on the current available information or professional judgment where no information was available. The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment efficiencies achieved will be acceptable at other sites. For the ratings used in this table, demonstrated effectiveness means that, at some scale, treatability tests showed that the technology was effective for that particular contaminant and matrix. The ratings of potential effectiveness, or no expected effectiveness are both based upon expert judgment. Where potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminant group in a particular matrix. When the technology is not applicable or will probably not work for a particular combination of contaminant group and matrix, a no-expected-effectiveness rating is given. Another source of general observations and average removal efficiencies for different treatability groups is contained in the Superfund Land Disposal Restrictions (LDR) Guide #6A, "Obtaining a Soil and Debris Treatability-Variance for Remedial Actions," (OSWER Directive 9347.3-06FS, July 1989) [13] and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions," (OSWER Directive 9347.3-07FS, December 1989) [14].

### Limitations

Soils exhibiting low air permeability are more difficult to treat with in situ SVE. Soils with a high organic carbon content have a high sorption capacity for VOCs and are more difficult to remediate successfully with SVE. Low soil temperature lowers a contaminant's vapor pressure, making volatilization more difficult [11].

Sites that contain a high degree of soil heterogeneity will likely offer variable flow and desorption performance, which will make remediation difficult. However, proper design of the vacuum extraction system may overcome the problems of heterogeneity [7, p. 19] [15].

It would be difficult to remove soil contaminants with low vapor pressures and/or high water solubilities from a site. The lower limit of vapor pressure for effective removal of a compound is 1 mm Hg abs. Compounds with high water solubilities, such as acetone, may be removed with relative ease from arid soils. However, with normal soils (i.e., moisture content ranging from 10 percent to 20 percent), the likelihood of successful remediation drops significantly because the moisture in the soil acts as a sink for the soluble acetone.

## Technology Description

Figure 1 is a general schematic of the in situ SVE process. After the contaminated area is defined, extraction wells (1) are installed. Extraction well placement is critical. Locations must be chosen to ensure adequate vapor flow through the contaminated zone while minimizing vapor flow through other zones [11, p. 170]. Wells are typically constructed of PVC pipe that is screened through the zone of contamination [11]. The screened pipe is placed in a permeable packing; the unscreened portion is sealed in a cement/bentonite grout to prevent a short-circuited air flow direct to the surface. Some SVE systems are installed with air injection wells. These wells may either passively take in atmospheric air or actively use forced air injection [9]. The system must be designed so that any air injected into the system does not result in the escape of VOCs to the atmosphere. Proper design of the system can also prevent offsite contamination from entering the area being extracted.

The physical dimensions of a particular site may modify SVE design. If the vadose zone depth is less than 10 feet and the area of the site is quite large, a horizontal piping system or trenches may be more economical than conventional wells.

An induced air flow draws contaminated vapors and entrained water from the extraction wells through headers—usually plastic piping—to a vapor-liquid separator (2). There, entrained water is separated and contained for subsequent treatment (4). The contaminant vapors are moved by a vacuum blower (3) to vapor treatment (5). The contaminant vapors are moved by a vacuum blower (3) to vapor treatment (5).

Vapors produced by the process are typically treated by carbon adsorption or thermal destruction. Other methods—such as condensation, biological degradation, and ultraviolet oxidation—have been applied, but only to a limited extent.

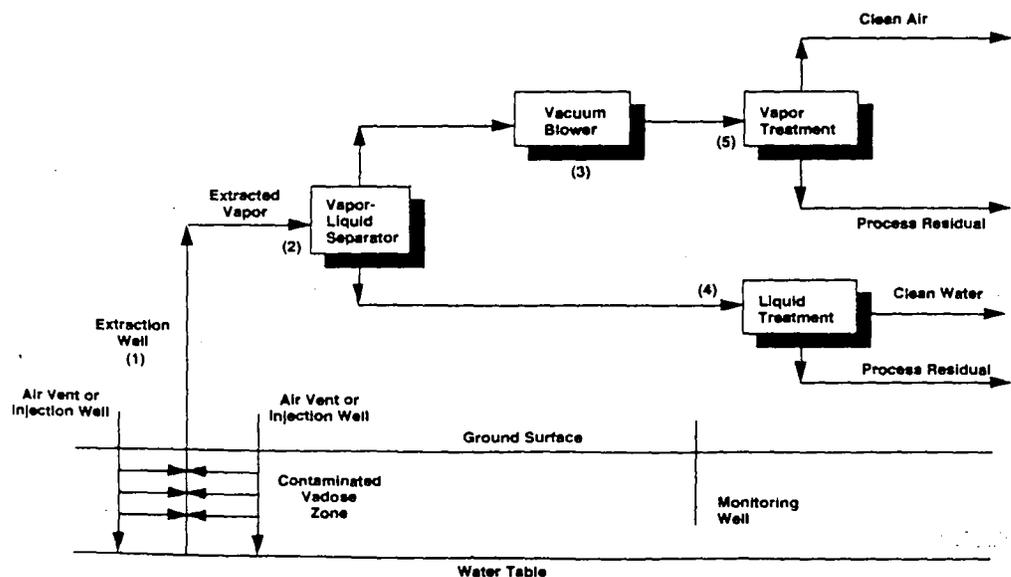
## Process Residuals

The waste streams generated by in situ SVE are vapor and liquid treatment residuals (e.g., spent granular activated carbon [GAC]), contaminated groundwater, and soil tailings from drilling the wells. Contaminated groundwater may be treated and discharged onsite [12, p. 86] or collected and treated off-site. Highly contaminated soil tailings from drilling must be collected and may be either cleaned onsite or sent to an offsite, permitted facility for treatment by another technology such as incineration.

## Site Requirements

SVE systems vary in size and complexity depending on the capacity of the system and the requirements for vapor and liquid treatment. They are typically transported by vehicles ranging from trucks to specifically adapted flatbed semitrailers; therefore, a proper staging area for these vehicles must be incorporated in the plans.

Figure 1  
Process Schematic of the In Situ Soil Vapor Extraction System



Adequate access roads must be provided to bring mobile drilling rigs onsite for construction of wells and to deliver equipment required for the process (e.g., vacuum blowers, vapor-liquid separator, emission control devices, GAC canisters).

A small commercial-size SVE system would require about 1,000 square feet of ground area for the equipment. This area does not include space for the monitoring wells which might cover 500 square feet. Space may be needed for a forklift truck to exchange skid-mounted GAC canisters when regeneration is required. Large systems with integrated vapor and liquid treatment systems will need additional area based on vendor-specific requirements.

Standard 440V, three-phase electrical service is needed. For many SVE applications, water may be required at the site. The quantity of water needed is vendor- and site-specific.

Contaminated soils or other waste materials are hazardous, and their handling requires that a site safety plan be developed to provide for personnel protection and special handling measures. Storage should be provided to hold the process product streams until they have been tested to determine their acceptability for disposal or release. Depending upon the site, a method to store soil tailings from drilling operations may be necessary. Storage capacity will depend on waste volume.

Onsite analytical equipment, including gas chromatographs and organic vapor analyzers capable of determining site-specific organic compounds for performance assessment, make the operation more efficient and provide better information for process control.

### Performance Data

SVE, as an in situ process (no excavation is involved), may require treatment of the soil to various cleanup levels mandated by federal and state site-specific criteria. The time required to meet a target cleanup level (or performance objective) may be estimated by using data obtained from bench-

scale and pilot-scale tests in a time-predicting mathematical model. Mathematical models can estimate cleanup time to reach a target level, residual contaminant levels after a given period of operation and can predict location of hot spots through diagrams of contaminant distribution [16].

Table 2 shows the performance of typical SVE applications. It lists the site location and size, the contaminants and quantity of contaminants removed, the duration of operation, and the maximum soil contaminant concentrations before treatment and after treatment. The data presented for specific contaminant removal effectiveness were obtained, for the most part, from publications developed by the respective SVE system vendors. The quality of this information has not been determined.

Midwest Water Resources, Inc. (MWRI) installed its VAPORTECH™ pumping unit at the Dayton, Ohio site of a spill of uncombusted paint solvents caused by a fire in a paint warehouse [19]. The major VOC compounds identified were acetone, methyl isobutyl ketone (MIBK), methyl ethyl ketone (MEK), benzene, ethylbenzene, toluene, naphtha, xylene, and other volatile aliphatic and alkyl benzene compounds. The site is underlain predominantly by valley-fill glacial outwash within the Great Miami River Valley, reaching a thickness of over 200 feet. The outwash is composed chiefly of coarse, clean sand and gravel, with numerous cobbles and small boulders. There are two outwash units at the site separated by a discontinuous till at depths of 65 to 75 feet. The upper outwash forms an unconfined aquifer with saturation at a depth of 45 to 50 feet below grade. The till below serves as an aquitard between the upper unconfined aquifer and the lower confined to semiconfined aquifer. Vacuum withdrawal extended to the depth of groundwater at about 40 to 45 feet. During the first 73 days of operation, the system yielded 3,720 pounds of volatiles and after 56 weeks of operation, had recovered over 8,000 pounds of VOCs from the site. Closure levels for the site were developed for groundwater VOC levels of ketones only. These soil action levels (acetone, 810 µg/l; MIBK, 260 µg/l, and MEK, 450 µg/l) were set so that waters recharging through contaminated soils would result in

Table 2.  
Summary of Performance Data for In Situ Soil Vapor Extraction

Site	Size	Contaminants	Quantity removed	Duration of operation	Soil concentrations (mg/kg)	
					max. before treatment	after treatment
Industrial - CA [17]	--	TCE	30 kg	440 days	0.53	0.06
Sheet Metal Plant - MI [18]	5,000 cu yds	PCE*	59 kg	35 days	5600	0.70
Prison Const. Site - MI [19]	165,000 cu yds	TCA	--	90 days	3.7	0.01
Sherwin-Williams Site - OH [19]	425,000 cu yds	Paint solvents	4,100 kg	6 mo	38	0.04
Upjohn - PR [20][21]	7,000,000 cu yds	CCl <sub>4</sub>	107,000 kg	3 yr	2200	<0.005
UST Belview - FL [7]	--	BTEX	9,700 kg	7 mo	97	<0.006
Verona Wellfield - MI [7][22]	35,000 cu yds	TCE, PCE, TCA	12,700 kg	Over 1 yr	1380	Ongoing
Petroleum Terminal - Owensboro, KY [19]	12,000 cu yds	Gasoline, diesel	--	6 mo	>5000	1.0 (target)
SITE Program - Groveland MA [7]	6,000 cu yds	TCE	590 kg	56 days	96.1	4.19

\*PCE = Perchloroethylene

groundwater VOC concentrations at or below regulatory standards. The site met all the closure criteria by June 1988.

A limited amount of performance data is available from Superfund sites. The EPA Superfund Innovative Technology Evaluation (SITE) Program's Groveland, Massachusetts, demonstration of the Terra Vac Corporation SVE process produced data that were subjected to quality assurance/quality control tests. These data appear in Table 2 [7, p. 29] and Table 3 [7, p. 31]. The site is contaminated by trichloroethylene (TCE), a degreasing compound which was used by a machine shop that is still in operation. The subsurface profile in the test area consists of medium sand and gravel just below the surface, underlain by finer and silty sands, a clay layer 3 to 7 feet in depth, and—below the clay layer—coarser sands with gravel. The clay layer or lens acts as a barrier against gross infiltration of VOCs into subsequent subsoil strata. Most of the subsurface contamination lay above the clay lens, with the highest concentrations adjacent to it. The SITE data represent the highest percentage of contaminant reduction from one of the four extraction wells installed for this demonstration test. The TCE concentration levels are weighted average soil concentrations obtained by averaging split spoon sample concentrations every 2 feet over the entire 24-foot extraction well depth. Table 3 shows the reduction of TCE in the soil strata near the same extraction well. The Groveland Superfund Site is in the process of being remediated using this technology [2].

The Upjohn facility in Barceloneta, Puerto Rico, is the first and, thus far, the only Superfund site to be remediated with SVE. The contaminant removed from this site was a mixture containing 65 percent carbon tetrachloride (CCl<sub>4</sub>) and 35 percent acetonitrile [20]. Nearly 18,000 gallons of CCl<sub>4</sub> were extracted during the remediation, including 8,000 gallons that were extracted during a pilot operation conducted from January 1983 to April 1984. The volume of soil treated at the Upjohn site amounted to 7,000,000 cubic yards. The responsible party originally argued that the site should be considered

clean when soil samples taken from four boreholes drilled in the area of high pretest contamination show nondetectable levels of CCl<sub>4</sub>. EPA did not accept this criterion but instead required a cleanup criteria of nondetectable levels of CCl<sub>4</sub> in all the exhaust stacks for 3 consecutive months [21]. This requirement was met by the technology and the site was considered remediated by EPA.

Approximately 92,000 pounds of contaminants have been recovered from the Tyson's Dump site (Region 3) between November 1988 and July 1990. The site consists of two unlined lagoons and surrounding areas formerly used to store chemical wastes. The initial Remedial Investigation identified no soil heterogeneities and indicated that the water table was 20 feet below the surface. The maximum concentration in the soil (total VOCs) was approximately 4 percent. The occurrence of dense nonaqueous-phase liquids (DNAPLs) was limited in areal extent. After over 18 months of operation, a number of difficulties have been encountered. Heterogeneities in soil grain size, water content, permeability, physical structure and compaction, and in contaminant concentrations have been identified. Soil contaminant concentrations of up to 20 percent and widespread distribution of DNAPLs have been found. A tar-like substance, which has caused plugging, has been found in most of the extraction wells. After 18 months of operation, wellhead concentrations of total VOCs have decreased by greater than 90 percent [23, p. 28].

As of December 31, 1990, approximately 45,000 pounds of VOCs had been removed from the Thomas Solvent Raymond Road Operable Unit at the Verona Well Field site (Region 5). A pilot-scale system was tested in the fall of 1987 and a full-scale operation began in March, 1988. The soil at the site consists of poorly-graded, fine-to-medium-grained loamy soils underlain by approximately 100 feet of sandstone. Groundwater is located 16 to 25 feet below the surface. Total VOC concentrations in the combined extraction well header have decreased from a high of 19,000 ug/l in 1987 to approximately 1,500 ug/l in 1990 [22].

**Table 3**  
Extraction Well 4: TCE Reduction In Soil Strata—EPA Site Demonstration (Groveland, MA) [7, p. 31]

Depth (ft)	Description of strata	Hydraulic Conductivity (cm/s)	Soil TCE concentration (mg/kg)	
			Pre-treatment	Post-treatment
0-2	Med. sand w/gravel	10 <sup>-4</sup>	2.94	ND
2-4	Lt. brown fine sand	10 <sup>-4</sup>	29.90	ND
4-6	Med. stiff lt. brown fine sand	10 <sup>-5</sup>	260.0	39.0
6-8	Soft dk. brown fine sand	10 <sup>-5</sup>	303.0	9.0
8-10	Med. stiff brown sand	10 <sup>-4</sup>	351.0	ND
10-12	V. stiff lt. brown med. sand	10 <sup>-4</sup>	195.0	ND
12-14	V. Stiff brown fine sand w/silt	10 <sup>-4</sup>	3.14	2.3
14-16	M. stiff gm-brn clay w/silt	10 <sup>-8</sup>	ND	ND
16-18	Soft wet clay	10 <sup>-8</sup>	ND	ND
18-20	Soft wet clay	10 <sup>-8</sup>	ND	ND
20-22	V. stiff brn med-coarse sand	10 <sup>-4</sup>	ND	ND
22-24	V. stiff brn med-coarse w/gravel	10 <sup>-3</sup>	6.17	ND

ND - Nondetectable level

An SVE pilot study has been completed at the Colorado Avenue Subsite of the Hastings (Nebraska) Groundwater Contamination site (Region 7). Trichloroethylene (TCE), 1,1,1-trichloroethane (TCA), and tetrachloroethylene (PCE) occur in two distinct unsaturated soil zones. The shallow zone, from the surface to a depth of 50 to 60 feet, consists of sandy and clayey silt. TCE concentrations as high as 3,600 ug/l were reported by EPA in this soil zone. The deeper zone consists of interbedded sands, silty sands, and gravelly sands extending from about 50 feet to 120 feet. During the first 630 hours of the pilot study (completed October 11, 1989), removal of approximately 1,488 pounds of VOCs from a deep zone extraction well and approximately 127 pounds of VOCs from a shallow zone extraction well were reported. The data suggest that SVE is a viable remedial technology for both soil zones [24].

As of November, 1989, the SVE system at the Fairchild Semi-conductor Corporation's former San Jose site (Region 9) has reportedly removed over 14,000 pounds of volatile contaminants. Total contaminant mass removal rates for the SVE system fell below 10 pounds per day on October 5, 1989 and fell below 6 pounds per day in December, 1989. At that time, a proposal to terminate operation of the SVE system was submitted to the Regional Water Quality Control Board for the San Francisco Bay Region [25, p.3].

Resource Conservation and Recovery Act (RCRA) LDRs that require treatment of wastes to best demonstrated available technology (BDAT) levels prior to land disposal may sometimes be determined to be applicable or relevant and appropriate requirements for CERCLA response actions. SVE can produce a treated waste that meets treatment levels set by BDAT but may not reach these treatment levels in all cases. The ability to meet required treatment levels is dependent upon the specific waste constituents and the waste matrix. In cases where SVE does not meet these levels, it still may, in certain situations, be selected for use at the site if a treatability variance establishing alternative treatment levels is obtained. EPA has made the treatability variance process available in order to ensure that LDRs do not unnecessarily restrict use of alternative and innovative treatment technologies. Treatability variances are justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.3-06FS, July 1989) [13], and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.3-07FS, December 1989) [14]. Another approach could be to use other treatment techniques in series with SVE to obtain desired treatment levels.

### Technology Status

During 1989, at least 17 RODs specified SVE as part of the remedial action [5]. Since 1982, SVE has been selected as the remedial action, either alone or in conjunction with other treatment technologies, in more than 30 RODs for Superfund sites [2] [3] [4] [5] [6]. Table 4 presents the location, primary

contaminants, and status for these sites [3] [4] [5]. The technology also has been used to clean up numerous underground gasoline storage tank spills.

A number of variations of the SVE system have been investigated at Superfund sites. At the Tinkhams Garage Site in New Hampshire (Region 1), a pilot study indicated that SVE, when used in conjunction with ground water pumping (dual extraction), was capable of treating soils to the 1 ppm clean-up goal [26, 3-7] [27]. Soil dewatering studies have been conducted to determine the feasibility of lowering the water table to permit the use of SVE at the Bendix, PA Site (Region 3) [28]. Plans are underway to remediate a stockpile of 700 cubic yards of excavated soil at the Sodeyco Site in Mt. Holly, NC using SVE [29].

With the exception of the Barceloneta site, no Superfund site has yet been cleaned up to the performance objective of the technology. The performance objective is a site-specific contaminant concentration, usually in soil. This objective may be calculated with mathematical models with which EPA evaluates delisting petitions for wastes contaminated with VOCs [30]. It also may be possible to use a TCLP test on the treated soil with a corresponding drinking water standard contaminant level on the leachate.

Most of the hardware components of SVE are available off the shelf and represent no significant problems of availability. The configuration, layout, operation, and design of the extraction and monitoring wells and process components are site specific. Modifications may also be required as dictated by actual operating conditions.

On-line availability of the full-scale systems described in this bulletin is not documented. System components are highly reliable and are capable of continuous operation for the duration of the cleanup. The system can be shut down, if necessary, so that component failure can be identified and replacements made quickly for minimal downtime.

Based on available data, SVE treatment estimates are typically \$50/ton for treatment of soil. Costs range from as low as \$10/ton to as much as \$150/ton [7]. Capital costs for SVE consist of extraction and monitoring well construction; vacuum blowers (positive displacement or centrifugal); vapor and liquid treatment systems piping, valves, and fittings (usually plastic); and instrumentation [31]. Operations and maintenance costs include labor, power, maintenance, and monitoring activities. Offgas and collected groundwater treatment are the largest cost items in this list; the cost of a cleanup can double if both are treated with activated carbon. Electric power costs vary by location (i.e., local utility rates and site conditions). They may be as low as 1 percent or as high as 2 percent of the total project cost.

Caution is recommended in using these costs out of context, because the base year of the estimates vary. Costs also are highly variable due to site variations as well as soil and contaminant characteristics that impact the SVE process. As contaminant concentrations are reduced, the cost effectiveness of an SVE system may decrease with time.

**Table 4**  
**Superfund Sites Specifying SVE as a Remedial Action**

<i>Site</i>	<i>Location (Region)</i>	<i>Primary Contaminants</i>	<i>Status</i>
Groveland Wells 1 & 2	Groveland, MA (1)	TCE	SITE demonstration complete [2][7] Full-scale Remediation in design
Kellogg-Deering Well Field	Norwalk, CT (1)	PCE, TCE, and BTX	Pre-design [3] [5] [6]
South Municipal Water Supply Well	Peterborough, NH (1)	PCE, TCE, Toluene	Pre-design completion expected in the fall of 1991 [3] [5][6]
Tinkham Garage	Londonderry, NH (1)	PCE, TCE	Pre-design pilot study completed [26] [27]
Wells G & H	Woburn, MA (1)	PCE, TCE	In design [3] [5]
FAA Technical Center	Atlantic County, NJ (2)	BTX, PAHs, Phenols	In design [3] [5]
UpJohn Manufacturing Co.	Barceloneta, PR (2)	CCl <sub>4</sub>	Project completed in 1988 [20] [21]
Allied Signal Aerospace-Bendix Flight System Div.	South Montrose, PA (3)	TCE	Pre-design tests and dewatering study completed [28]
Henderson Road	Upper Merion Township, PA (3)	PCE, TCE, Toluene, Benzene	Pre-design [3] [4]
Tyson's Dump	Upper Merion Township, PA (3)	PCE, TCE, Toluene, Benzene, Trichloropropane	In operation (since 11/88) [23]
Stauffer Chemical	Cold Creek, AL (4)	CCL <sub>4</sub> , pesticides	Pre-design [5] [6]
Stauffer Chemical	Lemoynne, AL (4)	CCL <sub>4</sub> , pesticides	Pre-design [5] [6]
Sodyeco	Mt. Holly, NC (4)	TCE, PAHs	Design approved [29]
Kysor Industrial	Cadillac, MI (5)	PCE, TCE, Toluene, Xylene	In design; pilot studies in progress [3] [5] [6]
Long Prairie	Long Prairie, MN (5)	PCE, TCE, DCE, Vinyl chloride	SVE construction expected in the Fall of 1991 [3] [6]
MIDCO 1	Gary, IN (5)	BTX, TCE, Phenol, Dichloromethane, 2-Butanone, Chlorobenzene	In Design [3] [5] [6]
Miami County Incinerator	Troy, OH (5)	PCE; TCE; Toluene	Pre-design [3] [5] [6]
Pristine	Cincinnati, OH (5)	Benzene; Chloroform; TCE; 1,2-DCA; 1,2-DCE	Pre-design [3] [6]
Seymour Recycling	Seymour, IN (5)	TCE; Toluene; Chloromethane; cis-1, 2-DCE; 1,1,1-DCA; Chloroform	Pre-design investigation completed [32]
Verona Well Field	Battle Creek, MI (5)	PCE, TCA	Operational since 3/81 [22]
Wausau Groundwater Contamination	Wausau, WI (5)	PCE, TCE	Pre-design [3] [5] [6]
South Valley/General Electric	Albuquerque, NM (6)	Chlorinated solvents	Pilot studies scheduled for Summer of 1991 [4] [6]
Hastings Groundwater Contamination	Hastings, NE (7)	CCL <sub>4</sub> , Chloroform	Pilot studies completed for Colorado Ave. & Far-Marco subsites [24]
Sand Creek Industrial	Commerce City, CO (8)	PCE, TCE, pesticides	Pilot study completed [33]
Fairchild Semiconductor	San Jose, CA (9)	PCE, TCA, DCE, DCA, Vinyl chlorides, Phenols, and Freon	Operational since 1988, Currently conducting resaturation studies [25]
Fairchild Semiconductor/MTV-1	Mountain View, CA (9)	PCE, TCA, DCE, DCA, Vinyl chlorides, Phenols, and Freon	Pre-design [3] [5]
Fairchild Semiconductor/MTV-2	Mountain View, CA (9)	PCE, TCA, DCE, DCA, Vinyl chlorides, Phenols, and Freon	Pre-design [3] [5]
Intel Corporation	Mountain View, CA (9)	PCE, TCA, DCE, DCA, Vinyl chlorides, Phenols, and Freon	Pre-design [3] [5]
Raytheon Corporation	Mountain View, CA (9)	PCE, TCA, DCE, DCA, Vinyl chlorides, Phenols, and Freon	Pre-design [3] [5]
Motorola 52nd Street	Phoenix, AZ (9)	TCA, TCE, CCL <sub>4</sub> , Ethylbenzene	Pre-design [3] [4] [6]
Phoenix-Goodyear Airport Area (also Litchfield Airport Area)	Goodyear, AZ (9)	TCE, DCE, MEK	North Unit - In design [34] South Unit - pilot study completed

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## Engineering Bulletin

# Slurry Biodegradation

### Purpose

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

### Abstract

In a slurry biodegradation system, an aqueous slurry is created by combining soil or sludge with water. This slurry is then biodegraded aerobically using a self-contained reactor or in a lined lagoon. Thus, slurry biodegradation can be compared to an activated sludge process or an aerated lagoon, depending on the case.

Slurry biodegradation is one of the biodegradation methods for treating high concentrations (up to 250,000 mg/kg) of soluble organic contaminants in soils and sludges. There are two main objectives for using this technology: to destroy the organic contaminant and, equally important, to reduce the volume of contaminated material. Slurry biodegradation is not effective in treating inorganics, including heavy metals. This technology is in developmental stages but appears to be a promising technology for cost-effective treatment of hazardous waste.

Slurry biodegradation can be the sole treatment technology in a complete cleanup system, or it can be used in conjunction with other biological, chemical, and physical treatment. This technology was selected as a component of the remedy for polychlorinated biphenyl (PCB)-contaminated oils at the General Motors Superfund site at Massena, New York, [11, p. 2]\* but has not been a preferred alternative in any record of decision [6, p. 6]. It may be demonstrated in the Superfund Innovative Technology Evaluation (SITE) program. Commercial-scale units are in operation. Vendors should be contacted to determine the availability of a unit for a particular site. This bulletin provides information on the technology applicability, the types of residuals produced, the latest performance data, site requirements, the status of the technology, and sources for further information.

### Technology Applicability

Biodegradation is a process that is considered to have enormous potential to reduce hazardous contaminants in a cost-effective manner. Biodegradation is not a feasible treatment method for all sites. Each vendor's process may be capable of treating only some contaminants. Treatability tests to determine the biodegradability of the contaminants and the solids/liquid separation that occurs at the end of the process are very important.

Slurry biodegradation has been shown to be effective in treating highly contaminated soils and sludges that have contaminant concentrations ranging from 2,500 mg/kg to 250,000 mg/kg. It has the potential to treat a wide range of organic contaminants such as pesticides, fuels, creosote, pentachlorophenol (PCP), PCBs, and some halogenated volatile organics. It is expected to treat coal tars, refinery wastes, hydrocarbons, wood-preserving wastes, and organic and chlorinated organic sludges. The presence of heavy metals and chlorides may inhibit the microbial metabolism and require pretreatment. Listed Resource Conservation and Recovery Act (RCRA) wastes it has treated are shown in Table 1 [10, p. 106].

\*[Reference number, page number]

Table 1  
RCRA-Listed Hazardous Wastes

Wood Treating Wastes	K001
Dissolved Air Flootation (DAF) Float	K048
Slop Oil Emulsion Solids	K049
American Petroleum Institute (API) Separator Sludge	K051

The effectiveness of this slurry biodegradation on general contaminant groups for various matrices is shown in Table 2 [12, p. 13]. Examples of constituents within contaminant groups are provided in Reference 12, "Technology Screening Guide for Treatment of CERCLA Soils and Sludges." This table is based on current available information or professional judgment when no information was available. The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment efficiency achieved will be acceptable at other sites. For the ratings used for this table, demonstrated biodegradability means that, at some scale, treatability was tested to show that, for that particular contaminant and matrix, the technology was effective. The ratings of potential biodegradability and no expected biodegradability are based upon expert judgment. Where potential biodegradability is indicated, the technology is believed capable of successfully treating the contaminant group. When the technology is not applicable or will probably not work for a particular contaminant group, a no-expected-biodegradability rating is given. Another source of general observations and average removal efficiencies for different treatability groups is contained in the Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions," (OSWER Directive 9347.3-06FS [10]), and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions," (OSWER Directive 9347.3-07FS [9]).

### Limitations

The various characteristics limiting the process feasibility, the possible reasons for these, and actions to minimize impacts of these limitations are listed in Table 3 [11, p. 2]. Some of these actions could be a part of the pretreatment process. The variation of these characteristics in a particular hardware design, operation, and/or configuration for a specific site will largely determine the viability of the technology and cost-effectiveness of the process as a whole.

Table 2  
Degradability Using Slurry Biodegradation  
Treatment on General Contaminant Groups for  
Soils, Sediments, and Sludges

Contaminant Groups		Biodegradability All Matrices
Organic	Halogenated volatiles	▼
	Halogenated semivolatiles	■
	Nonhalogenated volatiles	▼
	Nonhalogenated semivolatiles	■
	PCBs	▼
	Pesticides	■
	Dioxins/Furans	□
	Organic cyanides	▼
	Organic corrosives	□
	Inorganic	Volatile metals
Nonvolatile metals		□
Asbestos		□
Radioactive materials		□
Inorganic corrosives		□
Inorganic cyanides		▼
Reactive	Oxidizers	□
	Reducers	□

■ Demonstrated Effectiveness: Successful treatability test at some scale completed  
▼ Potential Effectiveness: Expert opinion that technology will work  
□ No Expected Effectiveness: Expert opinion that technology will not work

### Technology Description

Figure 1 is a schematic of a slurry biodegradation process.

Waste preparation (1) includes excavation and/or moving the waste material to the process where it is normally screened to remove debris and large objects. Particle size reduction, water addition, and pH and temperature adjustment are other important waste preparation steps that may be required to achieve the optimum inlet feed characteristics for maximum contaminant reduction. The desired inlet feed characteristics [6, p. 14] are:

Organics: .025-25% by weight    Temperature: 15-35°C  
Solids: 10-40% by weight    pH: 4.5-8.8  
Water: 60-90% by weight  
Solids particle size: Less than 1/4"

After appropriate pretreatment, the wastes are suspended in a slurry form and mixed in a tank (2) to maximize the mass transfer rates and contact between contaminants and microorganisms capable of degrading those contaminants. Aerobic treatment in batch mode has been the most common mode of operation. This process can be performed in contained reactors (3) or in lined lagoons [7, p. 9]. In the latter case, synthetic liners have to be placed in existing unlined lagoons, complicating the operation and maintenance of the system. In this case, excavation of a new lagoon or above-ground tank reactors should be considered. Aeration is provided by floating or submerged aerators or by compressors and spargers. Mixing is provided by aeration alone or by aeration and mechanical mixing. Nutrients and neutralizing agents are supplied to relieve any chemical limitations to microbial activity. Other materials, such as surfactants, dispersants, and compounds supporting growth and inducing degradation of contaminant compounds, can be used to improve the materials' handling characteristics or increase substrate availability for degradation [8, p. 5]. Microorganisms may be added initially to seed the bioreactor or added continuously to maintain the correct concentration of biomass. The residence time in the bioreactor varies with the soil or sludge matrix; physical/chemical nature of the contaminant, including concentration; and the biodegradability of the contaminants. Once biodegradation of the contaminants is completed, the treated slurry is sent to a separation/dewatering system (4). A clarifier for gravity separation, or any standard dewatering equipment, can be used to separate the solid phase and the aqueous phase of the slurry.

### Process Residuals

There are three main waste streams generated in the slurry biodegradation system: the treated solids (sludge or soil), the process water, and possible air emissions. The solids are dewatered and may be further treated if they still contain organic contaminants. If the solids are contaminated with inorganics and/or heavy metals, they can be stabilized before disposal. The process water can be treated in an onsite treatment system prior to discharge, or some of it (as high as 90 percent by weight of solids) is usually recycled to the front end of the system for slurrifying. Air emissions are possible during operation of the system (e.g., benzene, toluene, xylene [BTX] compounds); hence, depending on the waste characteristics, air pollution control, such as activated carbon, may be necessary [4, p. 29].

### Site Requirements

Slurry biodegradation tank reactors are generally transported by trailer. Therefore, adequate access roads are required to get the unit to the site. Commercial units require a setup area of 0.5-1 acre per million gallons of reactor volume.

Standard 440V three-phase electrical service is required. Compressed air must be available. Water needs at the site can be high if the waste matrix must be made into slurry form. Contaminated soils or other waste materials are hazardous and their handling requires that a site safety plan be developed to provide for personnel protection and special handling measures.

Climate can influence site requirements by necessitating covers over tanks to protect against heavy rainfall or cold for long residence times.

Large quantities of wastewater that results from dewatering the slurred soil or that is released from a sludge may need to be stored prior to discharge to allow time for analytical tests to verify that the standard for the site has been met. A place to discharge this wastewater must be available.

Onsite analytical equipment for conducting dissolved oxygen, ammonia, phosphorus, pH, and microbial activity are needed for process control. High-performance liquid chromatographic and/or gas chromatographic equipment is desirable for monitoring organic biodegradation.

### Performance Data

Performance results on slurry biodegradation systems are provided based on the information supplied by various vendors. The quality assurance for these results has not been evaluated. In most of the performances, the cleanup criteria were based on the requirements of the client; therefore, the data do not necessarily reflect the maximum degree of treatment possible.

Remediation Technologies, Inc.'s (ReTeC) full-scale slurry biodegradation system (using a lined lagoon) was used to treat wood preserving sludges (K0001) at a site in Sweetwater, Tennessee, and met the closure criteria for treatment of these sludges. The system achieved greater than 99 percent removal efficiency and over 99 percent reduction in volume attained for PCP and polynuclear aromatic hydrocarbons (PAHs) (Table 4 and Table 5).

Figure 1  
Slurry Biodegradation Process

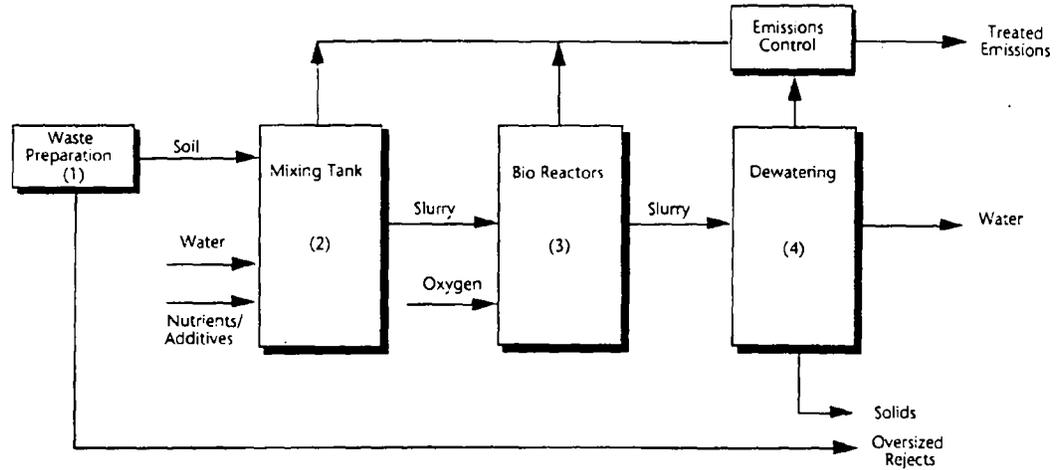


Table 3  
Characteristics Limiting the Slurry Biodegradation Process

CHARACTERISTICS LIMITING THE PROCESS FEASIBILITY	REASONS FOR POTENTIAL IMPACT	ACTIONS TO MINIMIZE IMPACTS
Variable waste composition	Inconsistent biodegradation caused by variation in biological activity	Dilution of waste stream. Increase mixing
Nonuniform particle size	Minimize the contact with microorganisms	Physical separation
Water solubility	Contaminants with low solubility are harder to biodegrade	Addition of surfactants or other emulsifiers
Biodegradability	Low rate of destruction inhibits process	Addition of microbial culture capable of degrading particularly difficult compounds or longer residence time
Temperature outside 15-35°C range	Less microbial activity outside this range	Temperature monitoring and adjustments
Nutrient deficiency	Lack of adequate nutrients for biological activity	Nutrient monitoring; adjustment of the carbon/nitrogen/phosphorus ratio
Oxygen deficiency	Lack of oxygen is rate limiting	Oxygen monitoring and adjustments
Insufficient Mixing	Inadequate microbes/solids/organics contact	Optimize mixing characteristics
pH outside 4.5 - 8.8 range	Inhibition of biological activity	Sludge pH monitoring. Addition of acidic or alkaline compounds
Microbial population	Insufficient population results in low biodegradation rates	Culture test, addition of culture strains
Water and air emissions discharges	Potential environmental and/or health impacts	Post-treatment processes (e.g., air scrubbing, carbon filtration)
Presence of elevated, dissolved levels of: <ul style="list-style-type: none"> <li>• Heavy metals</li> <li>• Highly chlorinated organics</li> <li>• Some pesticides, herbicides</li> <li>• Inorganic salts</li> </ul>	Can be highly toxic to microorganisms	Pretreatment processes to reduce the concentration of toxic compounds in the constituents in the reactor to nontoxic range

**Table 4**  
**Results Showing Reduction in Concentration for Wood Preserving Wastes**

Compounds	Initial Concentration		Final Concentration		Percent Removal	
	Solids (mg/kg)	Slurry (mg/kg)	Solids (mg/kg)	Slurry (mg/kg)	Solids (mg/kg)	Slurry (mg/kg)
Phenol	14.6	1.4	0.7	<0.1	95.2*	92.8
Pentachlorophenol	687	64	12.3	0.8	98.2	92.8
Naphthalene	3,670	343	23	1.6	99.3*	99.5*
Phenanthrene & Anthracene	30,700	2,870	200	13.7	99.3	99.5
Fluoranthene	5,470	511	67	4.6	98.8	99.1
Carbazole	1,490	139	4.9	0.3	99.7	99.8

\*May be due to combined effect of Volatilization and Biodegradation. [Source: ReTec, 50,000 gal. reactor]

**Table 5**  
**Results Showing Reduction in Volume For Wood Preserving Wastes**

Compounds	Before Treatment (Total pounds)	After Treatment (Total pounds)	Percent Volume Reduction
Phenol	368	41.4	88.8*
Pentachlorophenol	141,650	193.0	99.9
Naphthalene	179,830	36.6	99.9*
Phenanthrene & Anthracene	2,018,060	303.1	99.9
Fluoranthene	190,440	341.7	99.8
Carbazole	114,260	93.7	99.9

\*May be due to combined effect of Volatilization and Biodegradation. [Source: ReTec, 50,000 gal. reactor]

Data for one of these pilot-scale field demonstrations, which treated 72,000 gallons of oil refinery sludges, are shown in Figure 2 [8, p. 24]. In this study, the degradation of PAHs was relatively rapid and varied depending on the nature of the waste and loading rate. The losses of carcinogenic PAHs (principally the 5- and 6-ring PAHs) ranged from 30 to 80 percent over 2 months while virtually all of the noncarcinogenic PAHs were degraded. The total PAH reduction ranged from 70 to 95 percent with a reactor residence time of 60 days.

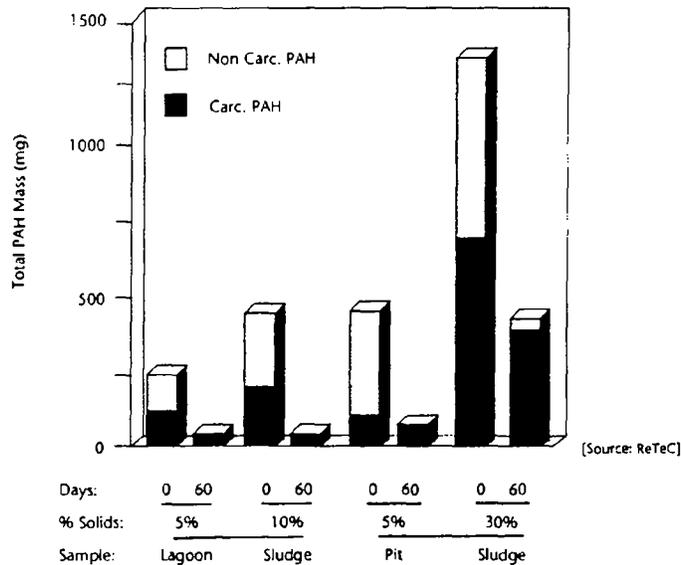
ECOVA's full-scale, mobile slurry biodegradation unit was used to treat more than 750 cubic yards of soil contaminated with 2,4-Dichlorophenoxy acetic acid (2,4-D) and 4-chloro-2-methyl-phenoxyacetic acid (MCPA) and other pesticides such as alachlor, trifluralin, and carbofuran. To reduce 2,4-D and MCPA levels from 800 ppm in soil and 400 ppm in slurry to less than 20 ppm for both in 13 days, 26,000-gallon bioreactors capable of handling approximately 60 cubic yards of soil were used. The residuals of the process were further treated through land application [3, p. 4]. Field application of the slurry bio-

degradation system designed by ECOVA to treat PCP-contaminated wastes has resulted in a 99-percent decrease in PCP concentrations (both in solid and aqueous phase) over a period of 24 days [3, p. 5].

Performance data for Environmental Remediation, Inc. (ERI) is available for the treatment of American Petroleum Institute (API) separator sludge and wood-processing wastes. Two lagoons containing an olefin sludge from an API separator were treated. In one lagoon, containing, 4,000 cubic yards of sludge, a degradation time of 21 days was required to achieve 68 percent volume reduction and 62 percent mass oil and grease reduction at an operating temperature of 18°C. In the second lagoon, containing 2,590 cubic yards of sludge, a treatment time of 61 days was required to achieve 61 percent sludge reduction and 87.3 percent mass oil and grease reduction at an operating temperature of 14°C [1, p. 367].

At another site, the total wood-preserving constituents were reduced to less than 50 ppm. Each batch process was

Figure 2  
Pilot Scale Results on Oil Refinery Sludges



carried out with a residence time of 28 days in 24-foot-diameter, 20-foot-height tank reactors handling 40 cubic yards per batch [6]. The mean concentrations of K001 constituents before treatment and the corresponding concentrations after treatment, for both settled solids and supernatant, are provided in Table 6 [2, p. 11]. The supernatant was discharged to a local, publicly owned wastewater treatment works.

RCRA Land Disposal Restrictions (LDRs) that require treatment of wastes to best demonstrated available technology (BDAT) levels prior to land disposal may sometimes be determined to be applicable or relevant and appropriate requirements (ARARs) for CERCLA response actions. Slurry biodegradation can produce a treated waste that meets treatment levels set by BDAT, but may not reach these treatment levels in all cases. The ability to meet required treatment levels is dependent upon the specific waste constituents and the waste matrix. In cases where slurry biodegradation does not meet these levels, it still may, in certain situations, be selected for use at the site if a treatability variance establishing alternative treatment levels is obtained. EPA has made the treatability variance process available in order to ensure that LDRs do not unnecessarily restrict the use of alternative and innovative treatment technologies. Treatability variances may be justified for handling complex soil and debris matrices. The

following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions," (OSWER Directive 9347.3-06FS) [10] and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.3-07FS) [9]. Another approach could be to use other treatment techniques in series with slurry biodegradation to obtain desired treatment levels.

### Technology Status

Biotrol, Inc. has a pilot-scale slurry bioreactor that consists of a feed storage tank, a reactor tank, and a dewatering system for the treated slurry. It was designed to treat the fine-particle slurry from its soil-washing system. Biotrol's process was included in the SITE program demonstration of its soil-washing system at the MacGillis and Gibbs wood-preserving site in New Brighton, Minnesota, during September and October of 1989. Performance data from the SITE demonstration are not currently available; the Demonstration and Applications Analysis Report is scheduled to be published in late 1990.

**Table 6**  
**Results of Wood Preserving Waste Treatment**

Wood Preserving Waste Constituents	Before treatment	After Treatment	
	In Soil (mg/kg)	In Settled Soil (mg/kg)	In Supernatant (mg/L)
2-Chlorophenol	1.89	<0.01	<0.01
Phenol	3.91	<0.01	<0.01
2,4-Dimethylphenol	7.73	<0.01	<0.01
2,4,6-Trichlorophenol	6.99	<0.01	<0.01
p-Chloro-m-cresol	118.62	<0.01	<0.01
Tetrachlorophenol	11.07	<0.02	<0.02
2,4-Dinitrophenol	4.77	<0.03	<0.03
Pentachlorophenol	420.59	3.1	<0.01
Naphthalene	1078.55	<0.01	0.04
Acenaphthylene	998.80	1.4	1.60
Phenanthrene + Anthracene	6832.07	3.8	3.00
Fluoranthene	1543.06	4.9	16.00
Chrysene + Benz(a)anthracene	519.32	1.4	8.20
Benzo(b)fluoranthene	519.32	<0.03	4.50
Benzo(a)pyrene	82.96	0.1	2.50
Indeno(1,2,3-cd)pyrene + Dibenz(a,h)anthracene	84.88	0.5	1.70
Carbazole	135.40	<0.05	1.70

[Source: Environmental Solutions, Inc.]

ECOVA Corporation has a full-scale mobile slurry biodegradation system. This system was demonstrated in the field on soils contaminated with pesticides and PCP. ECOVA has developed an innovative treatment approach that utilizes contaminated ground water on site as the make up water to prepare the slurry for the bioreactor.

ERI has developed a full-scale slurry biodegradation system. ERI's slurry biodegradation system was used to reduce sludge volumes and oil and grease content in two wastewater treatment lagoons at a major refinery outside of Houston, Texas, and to treat 3,000 cubic yards of wood-preserving waste (creosote-K001) over a total cleanup time of 18 months.

Environmental Solutions, Inc. reportedly has a full-scale slurry biodegradation system, with a treatment capacity of up to 100,000 cubic yards, that has been used to treat petroleum and hydrocarbon sludges.

Groundwater Technology, Inc. reportedly has a full-scale slurry biodegradation system, which employs flotation, reactor, and clarifier/sedimentation tanks in series, that has been used to treat soils contaminated with heavy oils, PAHs, and light organics.

ReTeC's full-scale slurry biodegradation system was used in two major projects: Valdosta, Georgia, and Sweetwater, Tennessee. Both projects involved closure of RCRA-regulated surface impoundments containing soils and sludges

contaminated with creosote constituents and PCP. Each project used in-ground, lined slurry-phase bioreactor cells operating at 100 cubic yards per week. Residues were chemically stabilized and further treated by tillage. For final closure, the impoundment areas and slurry-phase cells were capped with clay and a heavy-duty asphalt paving [5]. ReTeC has also performed several pilot-scale field demonstrations with their system on oil refinery sludges (RCRA K048-51).

One vendor estimates the cost of full-scale operation to be \$80 to \$150 per cubic yard of soil or sludge, depending on the initial concentration and treatment volume. The cost to use slurry biodegradation will vary depending upon the need for additional pre- and post-treatment and the addition of air emission control equipment.

### EPA Contact

Technology-specific questions regarding slurry biodegradation may be directed to:

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## Engineering Bulletin

# Rotating Biological Contactors

### Purpose

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

### Abstract

Rotating biological contactors (RBCs) employ aerobic fixed-film treatment to degrade either organic and/or nitrogenous (ammonia-nitrogen) constituents present in aqueous waste streams. Treatment is achieved as the waste passes by the media, enabling fixed-film systems to acclimate biomass capable of degrading organic waste [1, p. 91]\*. Fixed-film RBC reactors provide a surface to which soil organisms can adhere; many indigenous soil organisms are effective degraders of hazardous wastes.

An RBC consists of a series of corrugated plastic discs mounted on a horizontal shaft. As the discs rotate through the aqueous waste stream, a microbial slime layer forms on the surface of the discs. The microorganisms in this slime layer degrade the waste's organic and nitrogenous constituents. Approximately 40 percent of the RBC's surface area is immersed in the waste stream as the RBC rotates through the liquid. The remainder of the surface area is exposed to the atmosphere, which provides oxygen to the attached microorganisms and facilitates oxidation of the organic and nitrogenous contaminants [2, p. 6]. In gen-

eral, the large microbial population growing on the discs provides a high degree of waste treatment in a relatively short time. Although RBC systems are capable of performing organic removal and nitrification concurrently, they may be designed to primarily provide either organic removal or nitrification singly [3, p. 1-2].

RBCs were first developed in Europe in the 1950s [1, p. 6]. Commercial applications in the United States did not occur until the late 1960s. Since then, RBCs have been used in the United States to treat municipal and industrial wastewaters. Because biological treatment converts organics to innocuous products such as CO<sub>2</sub>, investigators have begun to evaluate whether biological treatment systems like RBCs can effectively treat liquid waste streams from Superfund sites. Treatability studies have been performed at at least three Superfund sites to evaluate the effectiveness of this technology at removing organic and nitrogenous constituents from hazardous waste leachate. A full-scale RBC treatment system is presently operating in at least one Superfund site in the United States.

### Technology Applicability

Research demonstrates that RBCs can potentially treat aqueous organic waste streams from some Superfund sites. During the treatability studies for the Stringfellow, New Lyme, and Moyer Superfund sites, RBC systems efficiently removed the major organic and nitrogenous constituents in the leachates. Because waste stream composition varies from site to site, treatability testing to determine the degree of contaminant removal is an essential element of the remedial action plan. Although recent Superfund applications have been limited to the treatment of landfill leachates, this technology may be applied to groundwater treatment [4].

In general, biological systems can degrade only the soluble fraction of the organic contamination. Thus the applicability of RBC treatment is ultimately dependent upon the solubility of the contaminant. RBCs are generally applicable to influents containing organic concentrations of up to 1 percent organics, or between 40 and 10,000 mg/l of SBOD. (Note: Soluble biochemical oxygen demand, or SBOD, measures the soluble fraction of the biodegradable organic content in terms of oxygen demand.) RBCs can be designed to reduce influent biochemical oxygen demand (BOD) concentrations below 5 mg/l SBOD and ammo-

\*[reference number, page number]

**Table 1**  
**Effectiveness of RBCs on General Contaminant**  
**Groups for Liquid Waste Streams**

	Contaminant Groups	Effectiveness
Organic	Halogenated volatiles	■
	Halogenated semivolatiles	■
	Nonhalogenated volatiles	■
	Nonhalogenated semivolatiles	■
	PCBs	▼
	Pesticides	▼
	Dioxins/Furans	□
	Organic cyanides	▼
Inorganic	Organic corrosives	▼
	Volatile metals	□
	Nonvolatile metals	□
	Asbestos	□
	Radioactive materials	□
	Inorganic corrosives	□
Reactive	Inorganic cyanides	▼
	Oxidizers	□
	Reducers	□

■ Demonstrated Effectiveness: Successful treatability test at some scale completed.  
 ▼ Potential Effectiveness: Expert opinion that technology will work.  
 □ No Expected Effectiveness: Expert opinion that technology will not work.

nia-nitrogen (NH<sub>3</sub>-N) levels below 1.0 mg/l [5, p. 2] [6, p. 60]. RBCs are effective for treating solvents, halogenated organics, acetone, alcohols, phenols, phthalates, cyanides, ammonia, and petroleum products [7, p. 6] [8, p. 69]. RBCs have fully nitrified leachates containing ammonia-nitrogen concentrations up to 700 mg/l [6, p. 61].

The effectiveness of RBC treatment systems on general contaminant groups is shown in Table 1. Examples of constituents within contaminant groups are provided in "Technology Screening Guide for Treatment of CERCLA Soils and Sludges" [9]. Table 1 is based on the current available information or professional judgment where no information was available. The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment efficiencies achieved will be acceptable at other sites. For the ratings used for this table, demonstrated effectiveness means that, at some scale, treatability was tested to show the technology was effective for that particular contaminant group. The ratings of potential effectiveness or no expected effectiveness are based upon expert judgment. Where potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminant group in a particular medium. When the technology is not applicable or will probably not work for a particular combination of contaminant group and medium, a no expected effectiveness rating is given.

## Limitations

Although RBCs have proven effective in treating waste streams containing ammonia-nitrogen and organics, they are not effective at removing most inorganics or non-biodegradable organics. Wastes containing high concentrations of heavy metals and certain pesticides, herbicides, or highly chlorinated organics can resist RBC treatment by inhibiting microbial activity. Waste streams containing toxic concentrations of these compounds may require pretreatment to remove these materials prior to RBC treatment [10, p. 3].

RBCs are susceptible to excessive biomass growth, particularly when organic loadings are elevated. If the biomass fails to slough off and a blanket of biomass forms which is thicker than 90 to 125 mils, the resulting weight may damage the shaft and discs. When necessary, excess biofilm may be reduced by either adjusting the operational characteristics of the RBC unit (e.g., the rotational speed or direction) or by employing air or water to shear off the excess biomass [11, p. 2].

In general, care must be taken to ensure that organic pre-lutants do not volatilize into the atmosphere. To control their release, gaseous emissions may require offgas treatment [12, p. 31].

All biological systems, including RBCs, are sensitive to temperature changes and experience drops in biological activity at temperatures lower than 55°F. Covers should be employed to protect the units from colder climates and extraordinary weather conditions. Covers should also be used to protect the plastic discs from degradation by ultraviolet light, to inhibit algal growth, and to control the release of volatiles [13]. In general, organic degradation is optimum at a pH between 6 and 8.5. Nitrification requires the pH be greater than 6 [6, p. 61].

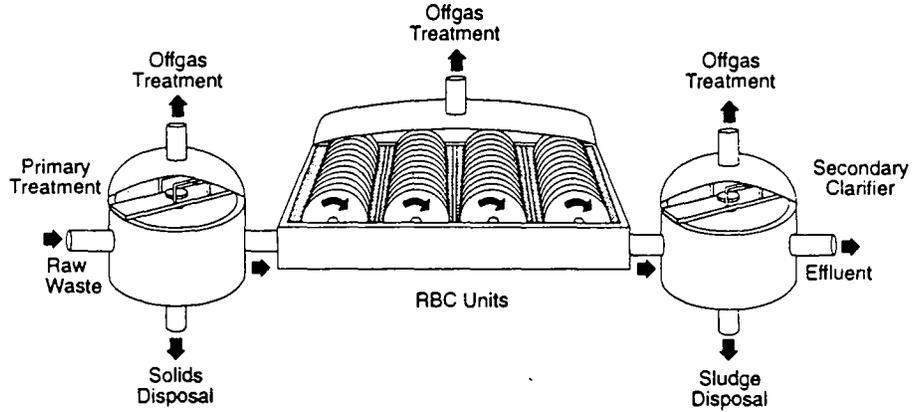
Additionally, nutrient and oxygen deficiencies can reduce microbial activity, causing significant decreases in biodegradation rates [14, p. 39]. Extremes in pH can limit the diversity of the microbial population and may suppress specific microbes capable of degrading the contaminants of interest. Fortunately, these variables can be controlled by modifying the system design.

## Technology Description

A typical RBC unit consists of 12-foot-diameter plastic discs mounted along a 25-foot horizontal shaft. The total disc surface area is normally 100,000 square feet for a standard unit and 150,000 square feet for a high density unit. Figure 1 is a diagram of a typical RBC system.

As the RBC slowly rotates through the groundwater or leachate at 1.5 rpm, a microbial slime forms on the discs. These microorganisms degrade the organic and nitrogenous contaminants present in the waste stream. During rotation, approximately 40 percent of the discs' surface area is in contact with the aqueous waste while the remaining surface area is exposed to the atmosphere. The rotation of the media through the atmosphere causes the oxygenation of the attached organisms. When

Figure 1  
Typical RBC Plant Schematic (12)



operated properly, the shearing motion of the discs through the aqueous waste causes excess biomass to shear off at a steady rate. Suspended biological solids are carried through the successive stages before entering the secondary clarifier [2, p. 13.101].

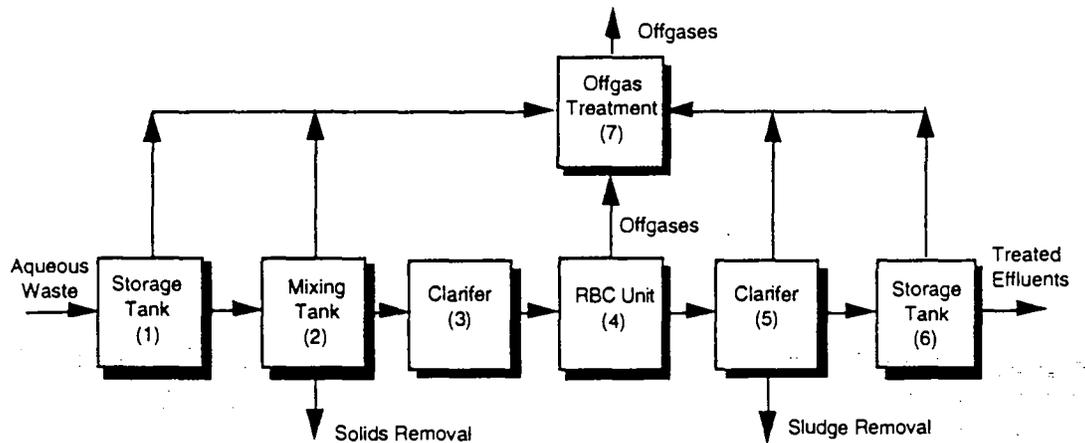
Primary treatment (e.g., clarifiers or screens), to remove materials that could settle in the RBC tank or plug the discs, is often essential for good operation. Influent containing high concentrations of floatables (e.g., grease, etc.) will require treatment using either a primary clarifier or an alternate removal system [11, p. 2].

The RBC treatment process may involve a variety of steps, as indicated by the block diagram in Figure 2. Typically, aqueous waste is transferred from a storage or equalization tank (1) to a mixing tank (2) where chemicals may be added for metals precipitation, nutrient adjustment, and pH control. The waste

stream then enters a clarifier (3) where the solids are separated from the liquid. The effluent from the clarifier enters the RBC (4) where the organics and/or ammonia are converted to innocuous products. The treated waste is then pumped into a second clarifier (5) for removal of the biological solids. After secondary clarification the effluent enters a storage tank (6) where, depending upon the contamination remaining in the effluent, the waste may be stored pending additional treatment or discharged to a sewer system or surface stream. Throughout this treatment process the offgases from the various stages should be collected for treatment (7). The actual treatment train will, of course, depend upon the nature of the waste and will be selected after the treatability study is conducted.

Staging, which employs a number of RBCs in series, enhances the biochemical kinetics and establishes selective biological cultures acclimated to successively decreasing organic load-

Figure 2  
Block Diagram of the RBC Treatment Process



ings. As the waste stream passes from stage to stage, progressively increasing levels of treatment occur [2, p. 13.105].

In addition to maximizing the system's efficiency, staging can improve the system's ability to handle shock loads by absorbing the impact of a shock load in the initial stages, thereby enabling subsequent stages to operate until the affected stages recover [15, p. 10.200].

Factors effecting the removal efficiency of RBC systems include the type and concentration of organics present, hydraulic residence time, rotational speed, media surface area exposed and submerged, and pre- and post-treatment activities. Design parameters for RBC treatment systems include the organic and hydraulic load rates, design of the disc train(s), rotational velocity, tank volume, media area submerged and exposed, retention time, primary treatment and secondary clarifier capacity, and sludge production [8, p. 69].

### Process Residuals

During primary clarification, debris, grit, grease, metals, and suspended solids (SS) are separated from the raw influent. The solids and sludges resulting from primary clarification may contain metallic and organic contaminants and may require additional treatment. Primary clarification residuals must be disposed of in an appropriate manner (e.g., land disposal, incineration, solidification, etc.).

Following RBC treatment, the effluent undergoes secondary clarification to separate the suspended biomass solids from the treated effluent. Refractory organics may contaminate both the clarified effluent and residuals. Additional treatment of the solids, sludges, and clarified effluent may be required. Clarified secondary effluents which meet the treatment standards are generally discharged to a surface stream, while residual solids and sludges must be disposed of in an appropriate manner, as outlined above for primary clarification residuals [2, p. 13.120].

Volatile organic compound (VOC)-bearing gases are often liberated as a byproduct of RBC treatment. Care must be taken to ensure that offgases do not contaminate the work space or the atmosphere. Various techniques may be employed to control these emissions, including collecting the gases for treatment [13].

### Site Requirements

RBCs vary in size depending upon the surface area needed to treat the hazardous waste stream. A single full size unit with a walkway for access on either side of the unit takes up approximately 550 square feet [16]. The total area required for an RBC system is site-specific and depends on the number, size, and configuration of RBC units installed.

Contaminated groundwater, leachates, or waste materials are often hazardous. Handling and treatment of these materials requires that a site safety plan be developed to provide for personnel protection and special handling measures. Storage should

be provided to hold the process product streams until they have been tested to determine their acceptability for disposal, reuse, or release. Depending on the site, a method to store waste that has been prepared for treatment may be necessary. Storage capacity will depend on waste volume.

Onsite analytical equipment capable of determining site-specific organic compounds for performance assessment make the operation more efficient and provide better information for process control.

### Performance Data

Limited information is available on the effectiveness of RBCs in treating waste from Superfund sites. Most of the data came from studies done on leachate from the New Lyme, Ohio; Stringfellow, California; and Moyer, Pennsylvania Superfund sites. The results of these studies are summarized below.

In order to compensate for the lack of Superfund performance data, non-Superfund applications are also discussed. The majority of the performance data for non-Superfund applications were obtained from industrial RBC operations. Theoretically this information has a high degree of application to Superfund leachate and groundwater treatment.

The quality of the information present in this section has not been determined. The data are included as a general guidance, and may not be directly transferrable to a specific Superfund site. Good characterization and treatability studies are essential in further refining and screening of RBC technology.

#### *New Lyme Treatability Study*

The EPA performed a remedy selection study on the leachate from the New Lyme Superfund site located in New Lyme Township, Ashtabula County, Ohio, to help determine the applicability of an RBC to treat hazardous waste from a Superfund site. Samples of leachate collected from various seeps surrounding the landfill showed that the leachate was highly concentrated. Results indicated that the leachate contained up to 2,000 mg/l dissolved organic carbon (DOC), 2,700 mg/l SBOD, and 5,200 mg/l soluble chemical oxygen demand (SCOD) [17, p. 12]. (Note: SCOD measures the soluble fraction of the organics amenable to chemical oxidation, as well as certain inorganics such as sulfides, sulfites, ferrous iron, chlorides, and nitrites.)

Leachate from the New Lyme site was transported from New Lyme to a demonstration-scale RBC located at the EPA's Testing and Evaluation Facility in Cincinnati, Ohio. After an adequate biomass was developed on the RBC discs using a primary effluent supplied by Mill Creek Treatment Facility (a local industrial wastewater treatment facility), the units were gradually acclimated to an influent consisting of 100 percent leachate. Results indicated that within 20 hours the RBC removed 97 percent of the gross organics, as represented by DOC, from the leachate (see Figure 3 and Table 2) [18, p. 7]. Priority pollutants were either converted and/or stripped from the leachate during treatment. After normal clarification, the effluent from the RBC was

eligible for disposal into the sewer system leading to the Mill Creek facility.

### Stringfellow Treatability Study

A remedy selection study using an RBC was conducted on leachate from the Stringfellow Superfund site located in Glen Avon, California. After the leachate from this site received lime treatment to remove metal contamination, the leachate was transported to the EPA's Testing and Evaluation Facility in Cincinnati for testing similar to the New Lyme study. The objective of this study was to determine whether the leachate from Stringfellow could be treated economically with an RBC system.

The leachate from this site was generated at a daily rate of 2,500 gallons. Compared to the New Lyme leachate, it contained moderate concentrations of gross organics with DOC values of 300 mg/l, SBOD values of 420 mg/l, and SCOD values of 800 mg/l [4, p. 44].

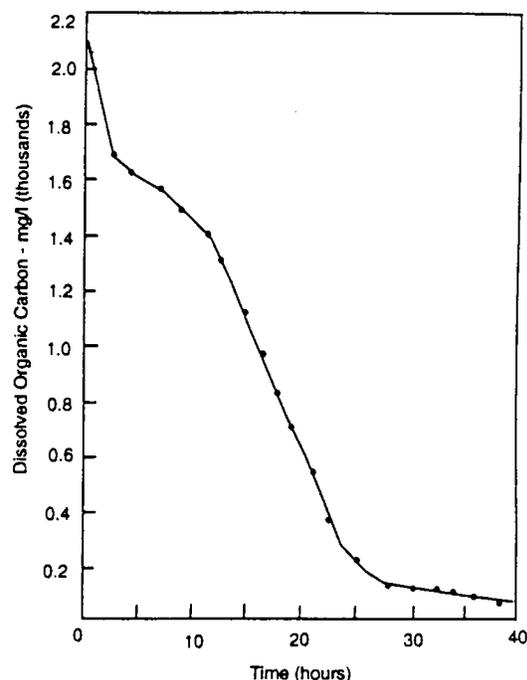
Results indicated that greater than 99 percent of SBOD was removed, 65 percent of DOC was removed, and 54 percent SCOD was removed within four days using the RBC laboratory-scale treatment system [4, p. 44]. Table 3 presents pertinent information on the treatment of 100 percent leachate. Since the DOC and SCOD conversion rates were low, a significant fraction of the refractory organics remained following treatment. Activated carbon was used to reduce the DOC to limits acceptable to the Mill Creek Treatment Facility.

**Table 2**  
Removal of Pollutants from New Lyme Leachate (17, p. 17)  
Experiment 5

	Influent (mg/l)	Effluent (mg/l)
SBOD	2700	4
BOD <sub>T</sub>	3000	6.6
DOC	2000	17
TOC	2100	19
SCOD	5200	33
NO <sub>3</sub> -N	<1	60
SS	1400	6600
VSS	240	2600
<u>Volatile PP</u>		
Benzene	0.28	<0.002
Toluene	4.9	<0.002
<u>Additional Volatiles</u>		
Cis 1,2-Dichloroethene	0.94	ND
Xylenes	2.8	ND
Acetone	140	ND
Methyl Ethyl Ketone	470	ND
Total Organic Halides	-	1.2
Total Toxic Organics	<0.250	<0.010

BOD<sub>T</sub> = Total Biochemical Oxygen Demand  
NO<sub>3</sub>-N = Nitrogen as Nitrate  
VSS = Volatile Suspended Solids

**Figure 3**  
Disappearance of DOC with Time (17, p. 14)  
Experiment 5\*



\* The influent for Experiment 5 consisted of 100 percent leachate and the biomass on the RBCs was acclimated. Nutrient addition was also employed (at a ratio of 160/5/2 for C/N/P).

### Moyer Treatability Study

During a recent remedy selection study, three treatability-scale RBCs were used to degrade a low-BOD (26 mg/l), high ammonia (154 mg/l) leachate from the Moyer Landfill Superfund site in Lower Providence Township near Philadelphia, Pennsylvania [19, p. 971]. The leachate has low organic strength (e.g., 26 mg/l BOD, 358 mg/l COD, and 68 mg/l TOC) which is typical of an older landfill and it also contains mainly non-biodegradable organic compounds [19, p. 972]. (Note: Total organic carbon, or TOC, is a measure of all organic carbon expressed as carbon.) The abundance of ammonia found in the leachate prompted investigators to attempt ammonia oxidation with an RBC system. Relatively low substrate loading rates were employed during the study (0.2, 0.4, and 0.6 gpd/square foot of disc surface area per stage). Ammonia oxidation was essentially complete (98 percent) and a maximum of 80 percent of the BOD and 38 percent of the COD in the leachate was oxidized [19, p. 980]. Runs performed using lower loading rates experienced the largest removals. A limited denitrification study was also performed using an anoxic RBC to treat an RBC effluent generated during the aerobic segment of the treatability investigation. This study demonstrated the feasibility of using denitrification to treat

the nitrate produced by aerobic ammonia oxidation [19, p. 980].

### Non-Superfund Applications

The Homestake Mine in Lead, South Dakota has operated an RBC wastewater treatment plant since 1984. Forty-eight RBCs treat up to 5.5 million gallons per day (MGD) (21,000 m<sup>3</sup>) of discharge water per day. The system was designed to degrade thiocyanate, free cyanide, and metal-complexed cyanides, to reduce heavy metal concentrations, and to remove ammonia, which is a byproduct of cyanide degradation [20, p. 2]. Eight parallel treatment trains, utilizing five RBCs in series, were employed to degrade and nitrify the metallurgical process waters (see Table 4 for a characterization of the influent). The first two RBCs in each train were used to degrade the cyanides and remove heavy toxic metals and particulate solids through biological adsorption. The last three RBCs employed nitrification to convert the ammonia to nitrate. Table 5 provides an average performance breakdown for the system. During its operation, overall performance improved significantly, as demonstrated by an 86 percent increase in the systems ability to reduce total effluent cyanide concentrations (e.g., from 0.45 to 0.06 mg/l). Concurrently, the cost per kg to treat cyanide dropped from \$11.79 to \$3.10, while the cost per m<sup>3</sup> to treat effluent decreased by 50 percent [21, p. 9]. In general, the system has responded well to any upsets or disturbances. Diesel fuels, lubricants, degreasers, biocides, dispersants, and flocculants have been periodically found in the influent wastewater but normally only create minor upsets in the performance of the plant. During the life of the system, the number of upsets and the biomass's ability to recuperate have both improved [21, p. 6].

A significant difference between the Homestake system and the other RBC systems described within this report is that instead of removing the metals contaminating the wastewater in the pretreatment stage, metal reduction is accomplished through bioadsorption during the treatment phase. Bioadsorption of metals by biological cells is not unlike the use of activated carbon, however the number and complexity of binding sites on the cell wall are enormous in comparison [20, p. 2].

In a study by Israel's Institute of Technology, a laboratory-scale RBC was used to treat an oil refinery wastewater. The wastewater had been pretreated using oil-water separation and dissolved air flotation. As summarized in Table 6, 91 percent of the hydrocarbon and 97 percent of the phenol were removed, as well as 96 percent of the ammonia-nitrogen [22, p. 4]. By gradually increasing the concentration of phenols present in the influent (e.g., over a 5 day period) from 5 mg/l to 30 mg/l, the system demonstrated that it was capable of quickly adapting to influent changes and higher phenolic loads [22, p. 6]. During this period, the RBC was able to maintain effluent COD concentrations at levels comparable to previous loadings. The system's resiliency was further demonstrated by its ability to recover from a major disturbance (e.g., such that effluent COD removal was interrupted) within 4 days [22, p. 7].

### Technology Status

RBCs have been used commercially in the United States since

**Table 3**  
Treatment of 100% Stringfellow Leachate (4, p. 44)

	Leachate (mg/l)	RBC Effluent (mg/l)	Use APC plus Effluent (mg/l)
SBOD	420	<3.0	0.9
BOD	440		22
DOC	300	110	20
TOC	310		22
SCOD	800	360	79
COD	840		95
SS	43		23
VSS	31		14
NH <sub>3</sub> -N	3.4		6.3
NO <sub>3</sub> -N	44		34

APC = Activated Powered Carbon  
COD = Chemical Oxygen Demand

**Table 4**  
Homestake Mine Wastewater Matrix \*

	Decant Water (mg/l)	Mine Water (mg/l)	Influent Blend (mg/l)
Thiocyanate	110-350	1-33	35-110
Total Cyanide	5.5-65.0	0.30-2.50	0.50-11.50
WAD Cyanide	3.10-38.75	0.50-1.10	0.50-7.15
Copper	0.5-3.1	0.10-2.65	0.15-2.95
Ammonia-N	5-10	5.00-19.00	6-12
Phosphorus-P	0.10-0.20	0.10-0.15	0.10-0.15
Alkalinity	50-200	150-250	125-225
pH	7-9	7-9	7.5-8.5
Hardness	400-500	650-1400	500-850
Temperature°C	1.0-27.2	24-33	5-25

WAD = Weak Acid Dissociable  
\*Adapted from reference [20, p. 8]

**Table 5**  
Influent, Effluent and Permit Concentrations at the  
Homestake Mines (20, p. 8)

	Influent (mg/l)	Effluent (mg/l)	Permit (mg/l)
Thiocyanate	62.0	<0.5	-
Total Cyanides	4.1	0.06	1.00
WAD Cyanide	2.3	<0.02	0.10
Total Copper	0.56	0.07	0.13
Total Suspended Solids	-	6.0	10.0
Ammonia-Nitrogen	5.60*	<0.50	1.0-3.9

\*Ammonia peaks at 25 mg/l within the plant as a cyanide degradation byproduct

**Table 6**  
**Refinery Wastewater Quality Before and After**  
**RBC Treatment (22, p. 4)**

Constituent		Influent (mg/l)	Effluent (mg/l)
COD	Total	715	197
	Soluble	685	186
BOD	Total	140	8
	Soluble	128	6
Phenols		7.5	0.22
Suspended Solids			
	Total	32	7
	Volatile	29	6
NH <sub>3</sub> -N		12.8	0.48

the late 1960s to treat municipal and industrial wastes. In the past decade, studies have been performed to evaluate the effectiveness of RBCs in treating leachate from hazardous waste sites.

Treatability studies have been performed on leachate from the Stringfellow, New Lyme, and Moyer Superfund sites. Results of these studies indicate that RBCs are effective in removing organic and nitrogenous constituents from hazardous waste leachate. Additional research is needed to define the effectiveness of an RBC in treating leachates and contaminated groundwater and to determine the degree of organic stripping that occurs during the treatment process. RBCs are being used to treat leachate from the New Lyme Superfund site.

RBCs require a minimal amount of equipment, manpower, and space to operate. Staging of RBCs will vary from site to site depending on the waste stream. The cost to install a single RBC unit with a protective cover and a surface area of 100,000 to 150,000 square feet ranges from \$80,000 to \$85,000 [16] [23].

During the Stringfellow treatability study researchers determined that by augmenting the existing carbon treatment system with RBCs, reductions in carbon costs would pay for the RBC plant within 3.3 years [4, p. 44]. The RBC plant model used to formulate this estimate was a scaled-up version of the pilot unit used during the treatability study.

### EPA Contact

Technology-specific questions regarding rotating biological contactors may be directed to:

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# Guide for Conducting Treatability Studies Under CERCLA: Biodegradation Remedy Selection

Office of Emergency and Remedial Response  
Hazardous Site Control Division OS-220

QUICK REFERENCE FACT SHEET

Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 mandates EPA to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment that "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants is a principal element." Treatability studies provide data to support remedy selection and implementation. They should be performed as soon as it becomes evident that the available information is insufficient to ensure the quality of the decision. Conducting treatability studies early in the remedial investigation/feasibility study (RI/FS) process should reduce uncertainties associated with selecting the remedy and should provide a sound basis for the Record of Decision (ROD). Regional planning should factor in the time and resources required for these studies.

This fact sheet provides a summary of information to facilitate the planning and execution of biodegradation remedy selection treatability studies in support of the RI/FS and the remedial design/remedial action (RD/RA) processes. It is intended to provide Remedial Project Managers (RPMs), On Scene Coordinators (OSCs), Potentially Responsible Parties (PRPs), and other interested persons with enough information to determine whether biodegradation treatability studies may be considered in the remedy selection phase of the RI/FS for the CERCLA site of interest. This fact sheet follows the organization of the "Guide for Conducting Treatability Studies Under CERCLA: Biodegradation Remedy Selection," EPA/540/R-93/514A, 1993. Detailed information on designing and implementing remedy selection treatability studies for biodegradation is provided in the guidance document.

## INTRODUCTION

There are three levels or tiers of treatability studies: remedy screening, remedy selection, and RD/RA testing. Treatability studies conducted during the RI/FS phase (remedy screening and remedy selection) indicate whether the technology can meet the cleanup goals for the site, whereas treatability studies conducted during the RD/RA phase establish design and operating parameters for optimization of technology performance. Although the purpose and scope of these studies differ, they complement one another, since information obtained in support of remedy selection may also be used to support RD/RA.

Remedy screening studies are designed to provide a quick and relatively inexpensive indication of whether biological degradation is a potentially viable remedial technology. The remedy screening evaluation should provide a preliminary indication that reductions in contaminant concentrations are due to biodegradation and not abiotic processes such as photodecomposition or volatilization.

Remedy selection studies should simulate conditions during bioremediation, allowing researchers to determine the technology's performance on a waste-specific basis. Bench-scale testing is typically used for remedy selection testing; however, it may fall short of providing enough information for remedy selection. Pilot-scale testing also may be appropriate for some sites. Bench-scale studies can, in some cases, provide enough information for full-scale design.

RD/RA testing should provide accurate cost and performance data, confirming that biodegradation rates and cleanup levels determined during remedy selection can be achieved for the site.

This fact sheet and its parent document, the "Guide for Conducting Treatability Studies Under CERCLA: Biodegradation Remedy Selection," EPA/540/R-93/514A primarily focus on the remedy selection tier. These documents also briefly discuss remedy screening and RD/RA testing.

## TECHNOLOGY DESCRIPTION AND PRELIMINARY SCREENING

### Technology Description

Bioremediation generally refers to the breakdown of organic compounds (contaminants) by microorganisms. Bioremediation treatment technologies can be divided into two categories, in situ and ex situ, based upon the location of the contaminated medium during treatment.

#### • In Situ

In situ biological technologies treat contaminants in place, eliminating the need for soil excavation and limiting volatile releases into the atmosphere. As a result, many of the risks and costs associated with materials handling are reduced or eliminated.

In situ bioremediation usually involves enhancing natural biodegradation processes by adding nutrients, oxygen (if the process is aerobic), and in some cases, microorganisms to stimulate the biodegradation of contaminants. The technology has primarily been used for the treatment of saturated soils. In situ bioremediation is often used in conjunction with a groundwater-pumping and soil-flushing system to circulate nutrients and oxygen through a contaminated aquifer and associated soils.

Bioventing is an in situ biological technology predominantly used to treat reasonably permeable, unsaturated soils. Aeration systems, similar to those employed during soil vapor extraction, are used during bioventing to supply oxygen to the soil. An air pump, one or more air injection or vacuum extraction probes, and emissions monitoring at the ground surface are commonly used during bioventing. In order to minimize contaminant volatilization, low air pressures and air flow rates are typically utilized. Some systems, however, utilize higher air flow rates, thereby combining bioventing with soil vapor extraction.

- **Ex Situ**

Ex situ biological treatment technologies involve removal of the contaminated media followed by onsite or offsite treatment. Although media handling increases the costs of ex situ treatment, ex situ approaches generally allow greater control of process variables (e.g., pH, nutrient concentrations, temperature, aeration).

Solid-phase bioremediation (sometimes referred to as land treatment or land farming) is a process that treats soils in above-ground treatment systems using conventional soil management practices to enhance microbial degradation of contaminants. Solid-phase bioremediation at CERCLA sites usually involves placing excavated soil in an above-ground soil treatment area. If required, nutrients and microorganisms are added to the soil, which is tilled at regular intervals to improve aeration and contact between the microorganisms and the contaminants.

In slurry-phase bioremediation, excavated contaminated soil is typically placed in an onsite, stirred-tank reactor where the soil is combined with water to form a slurry. The solids content of the slurry depends on the type of soil, the type of mixing and aeration equipment available, and the rates of contaminant removal that need to be achieved. The water used in the process can be contaminated surfacewater or groundwater, thus facilitating the simultaneous treatment of contaminated soil and water. As with solid-phase bioremediation, nutrients and microorganisms may be added to the reactor to facilitate biodegradation.

Soil heap bioremediation involves piling contaminated soil in heaps several meters high. Aeration is usually provided by pulling a vacuum through the heap. Simple irrigation techniques are generally used to maintain moisture content, pH, and nutrient concentrations within ranges conducive to the biodegradation of contaminants. The system can be designed to control the release of VOCs by enclosing the soil pile and passing the exhaust from the vacuum through activated carbon or biofilters.

Composting involves the storage of biodegradable waste with a bulking agent (e.g., chopped hay or wood chips). The structurally-firm bulking agent is usually biodegradable. Adequate aeration; optimum temperature, moisture, and nutrient concentrations; and the presence of an appropriate microbial population are necessary to enhance the decomposi-

tion of organic compounds. The three basic types of composting systems are open windrow (where the piles are torn down and rebuilt for aeration), static windrow (where air is forced into the piles), and in-vessel (where tumbling, stirring, or forced aeration are used).

Biofilters can be used to treat organic vapors in a manner analogous to the biological treatment of wastewaters. By providing bacteria with a surface on which to grow and optimal oxygen, temperature, nutrients, moisture, and pH conditions, biofilters can significantly reduce vapor phase organic contaminants. The primary components of biofilters are: an air blower, an air distribution system, a moisturizing system, filter media, and a drainage system. Removal efficiencies in the range of 95 to 99 percent have been reported for light aliphatic compounds, while lower removal efficiencies are common for chlorinated aliphatic and aromatic compounds.

## Technology Status

As of October 1992, approximately 149 CERCLA, Resource Conservation and Recovery Act (RCRA), and underground storage tank (UST) sites, and other government regulated sites have been identified by EPA Regions and States as either considering (e.g., performing treatability studies), planning, operating full-scale, or having used biological treatment systems. Approximately 62 percent of the sites are CERCLA sites, 14 percent are RCRA sites, and 10 percent are UST sites. The remaining 14 percent represent Toxic Substance Control Act (TSCA), and other Federal and State efforts.

## Prescreening Characteristics

Before a treatability study is conducted, a literature search should be performed to confirm whether the compounds of interest are known to be amenable to biological treatment. Evidence of biodegradation under dissimilar conditions, as well as data relating to compounds of similar structure, should be considered. If preliminary research indicates that bioremediation is an unlikely candidate, further research may be warranted. Before discarding biological remediation as an option, expert recommendations regarding the technology's potential should be obtained. The "Guide for Conducting Treatability Studies Under CERCLA: Biodegradation Remedy Selection", EPA/540/R-93/514A, lists references and electronic databases that can be useful when conducting the literature search phase of a bioremediation project. The guide also provides contacts for technical assistance when determining the need or scope of a remedy selection treatability study. One important resource for OSCs and RPMs is the Technical Support Project (TSP) coordinated by EPA's Technology Innovation Office (703-308-8846). The TSP is operated by EPA laboratories and offers technical assistance ranging from review of contractor work plans to assistance in the performance of treatability studies.

The potential biodegradability of the contaminants of concern is an important characteristic to be examined prior to initiating treatability studies. Examples of classes of compounds that are readily amenable to bioremediation are: petroleum hydrocarbons such as gasoline and diesel; wood treating wastes such as creosote and pentachlorophenol; solvents such as acetone, ketones, and alcohols; and aromatic compounds such as benzene, toluene, xylenes, and phenols. Several documents and review articles that present detailed information on the biodegradability of compounds are listed in the reference section of the complete guidance document. However, discretion should be exercised when using these reference materials, as microorganisms that can

biodegrade compounds that have traditionally been considered nonbiodegradable are continually being isolated through ongoing research and development efforts.

Site and soil characteristics that impact bioremediation are listed in Table 1. The potential effects of these factors upon candidate bioremediation technologies should also be considered.

There is no steadfast rule that specifies when to proceed with remedy screening, when to eliminate biodegradation as a treatment technology, or when to proceed to remedy selection testing based on a preliminary screening analysis. An analysis of the existing literature coupled with the site characterization may provide the information required to make a decision. However, when in doubt, treatability studies are recommended.

### Technology Limitations

Many factors impact the feasibility of biodegradation. These factors should be addressed prior to the selection of

**Table 1. Site and Soil Characteristics Identified as Important in Biological Treatment**

	In situ	Ex situ
Soil type	X	X
Extent of contamination	X	X
Soil profile properties		
Boundary characteristics	X	
Depth of contamination	X	
Texture*	X	
Structure	X	X
Bulk density*	X	
Clay content	X	
Type of clay	X	X
Cation exchange	X	X
Organic matter content*	X	X
pH*	X	X
Redox potential*	X	X
Hydraulic properties and conditions		
Soil water characteristic curve	X	
Field capacity/permanent wilting point	X	X
Water holding capacity*	X	X
Permeability* (under saturated and a range of unsaturated conditions)	X	
Infiltration rates*	X	
Depth to impermeable layer or bedrock	X	
Depth to groundwater, including seasonal variations*	X	
Flooding frequency	X	
Runoff potential*	X	
Geological and hydrogeological factors		
Subsurface geological features	X	
Groundwater flow patterns and characteristics	X	
Meteorological and climatological data		
Wind velocity and direction		X
Temperature	X	X
Precipitation	X	X
Water budget	X	

\* Factors that may be managed to enhance soil treatment.

biodegradation and prior to the investment of time and funds in further testing. Some of these factors that may limit the use of bioremediation technologies include the amount, location, extent, and variability of the contamination. The physical form in which the contaminants are distributed, as well as heterogeneities within the media to be treated, may limit the applicability of biodegradation.

Soil characteristics, such as nonuniform particle size distribution, soil type, moisture content, hydraulic conductivity, and permeability, can also significantly affect biodegradation. Significant quantities of organic matter (humus, peat, non-regulated anthropomorphic compounds, etc.) also may cause high oxygen uptake rates, resulting in depleted oxygen supplies during in situ application. Contaminant volatility is particularly important, especially in stirred or aerated reactors where the contaminants can volatilize before being degraded.

The presence of either an indigenous or introduced microbial population capable of degrading the contaminants of concern is usually essential to the success of biological processes. Each contaminant has a range of concentrations at which the potential for biodegradation is maximized. Below this range microbial activity may not occur without the addition of a co-substrate. Above this range, microbial activity may be inhibited and, once toxic concentrations are reached, eventually arrested. During inhibition, contaminant degradation generally occurs at a reduced rate. In contrast, at toxic concentrations contaminant degradation does not occur. The concentrations at which microbial growth is either supported, inhibited, or arrested vary with the contaminant, media, and microbial species.

Although preliminary data may be obtained that seem to indicate that the technology is capable of reducing contamination levels to acceptable limits, the rate of contaminant removal from soil during bioremediation exhibits asymptotic characteristics. The initial rate of removal, after a potential lag period, is rapid. With time, the rate decreases to a near-zero value, and the contaminant concentration in the soil approaches a fixed concentration that is typically nonzero (the asymptote). Since the asymptote is difficult to predict and is sometimes greater than the cleanup criteria, treatability testing must be continued until either the removal goals are met or the asymptote is reached.

### THE USE OF TREATABILITY STUDIES IN REMEDY EVALUATION

Treatability studies should be performed in a systematic fashion to ensure that the data generated can support the remedy evaluation and implementation process. A well-designed treatability study can significantly reduce the overall uncertainty associated with the decision, but cannot guarantee that the chosen alternative will be completely successful. Care must be exercised to ensure that the treatability study is representative of the treatment (e.g., the sample is representative of waste to be treated) as it will be employed to minimize uncertainty in the decision.

### Treatability Testing Process

Treatability studies for a particular site will often entail multiple tiers of testing. By balancing the time and cost necessary to perform the testing with the risks inherent in the decision, the level of treatability testing required can be determined. Criteria for measuring the success of each level of treatability study are listed in Table 2.

Remedy screening is the first level of testing. It is used to determine whether biodegradation is possible with the site-specific waste material. These studies are generally low cost (e.g., \$10,000 to \$50,000) and usually require 1 week to several months to complete. Additional time must be allowed for project planning, chemical analyses, interpretation of test data, and report writing. Only limited quality control is required. These studies yield data indicating a technology's potential to meet performance goals.

Remedy selection testing is the second level of testing. To the maximum extent practical, remedy selection tests should simulate site conditions during treatment, allowing researchers to identify the technology's performance on a waste-specific basis for an operable unit. These studies are generally of moderate cost (e.g., \$50,000 to \$300,000) and may require several weeks to two years to complete. They yield data that verify that the technology is likely to meet expected cleanup goals and can provide information in support of the detailed analysis of the alternative.

RD/RA testing is the third level of testing. By operating a field unit under conditions similar to those expected during full-scale remediation, the study can provide data required for final full-scale design and accurate cost and time estimates. Unit operating parameters can be optimized and the ability to

achieve cleanup levels can be confirmed. These studies are of moderate to high cost (e.g., \$100,000 to \$500,000) and may require several months or more to complete. They are performed during the remedy implementation phase of a site cleanup. Figure 1 shows the relationship of the three levels of treatability study to each other and to the RI/FS process.

### Applicability of Treatability Tests

Before conducting treatability studies, the objectives of each tier of testing must be established. Biodegradation treatability study objectives are based upon the specific needs of the RI/FS. There are nine evaluation criteria specified in the document, "Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA" (EPA/540/6-89/004). A detailed analysis of different remedial alternatives using the nine CERCLA criteria is essential. Treatability studies provide data for up to seven of these criteria.

These seven criteria are:

- Overall protection of human health and the environment
- Compliance with applicable or relevant and appropriate requirements (ARARs)

Table 2. Biodegradation Criteria for Each Treatability Study Tier

Criteria	Remedy screening	Remedy selection	Remedy design
Biodegradation of most-resistant contaminants of concern	>20% net removal compared to removal in inhibited control	Meets cleanup standards under test conditions	Meets cleanup standards under site conditions
Initial contaminant concentration	Optimal for technology	Maximum concentration expected during remediation	Actual range of concentrations expected during remediation
Environmental conditions	Optimal for technology (include site conditions if possible)	Simulate expected site treatment conditions	Actual site treatment conditions for the specific technology
Extent of biodegradation	Estimate*	Quantify	Quantify
Biodegradation rate	Crude estimate*	Defensible estimate	Quantify
Estimate time to reach cleanup standards	NA	Estimate	Refined estimate
Mass balance	Crude*	Closure or defensible explanation	Closure or defensible explanation
Toxic byproducts	Detect*	Test for if appropriate*	Test for if appropriate
Process control and reliability	NA	Assess potential	Demonstrate
Microbial activity	Crude measure*	Verify/quantify*	Quantify/monitor*
Process optimization	NA	Estimate*	Refined estimate
Cost estimate for full-scale	NA	Rough, -30%, +50%	Detailed/refined
Bid specifications	NA	NA	Nearly complete
Experimental scale	Usually bench-scale	Either bench- or pilot-scale	Usually pilot- or full-scale

\* Not required, although sometimes possible to address significantly.

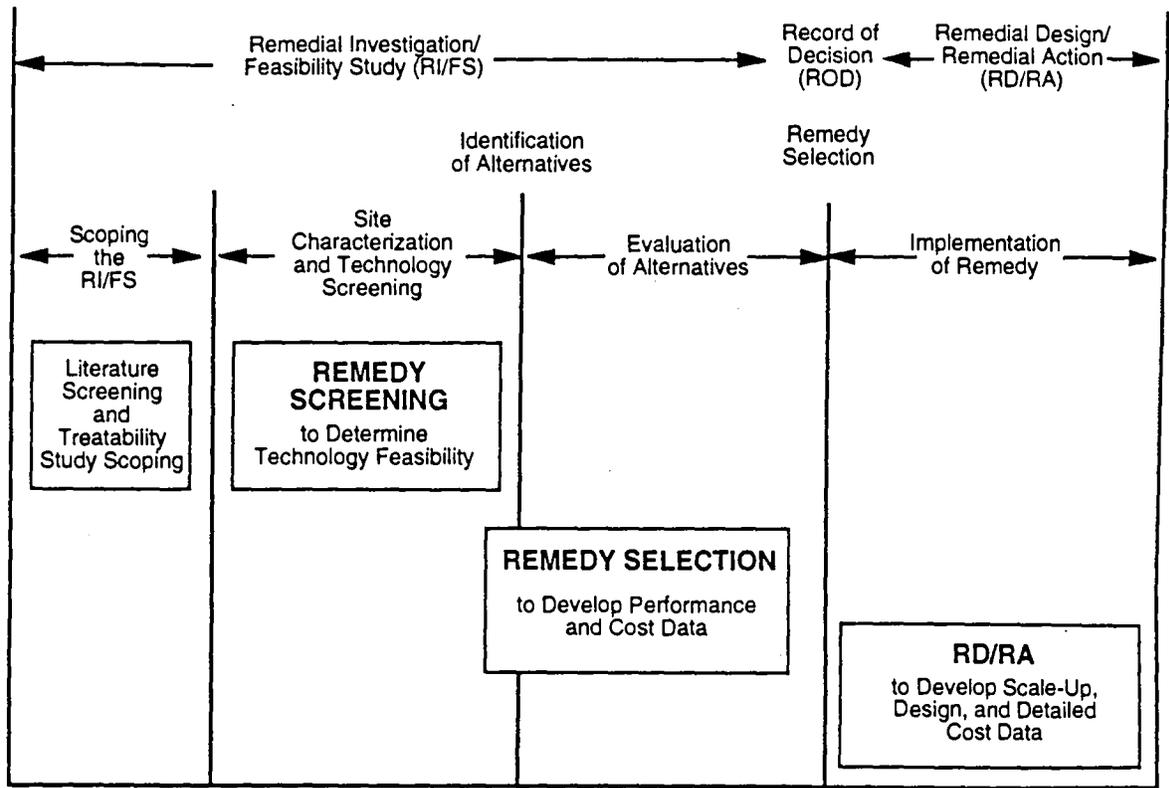


Figure 1. The Role of Treatability Studies in the RI/FS and RD/RA Process.

- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume through treatment
- Short-term effectiveness
- Implementability
- Cost

The two remaining CERCLA criteria, State and community acceptance, are based in part on the preferences and concerns of the State and community regarding alternative technologies. An available remediation technology may be eliminated from consideration if the state or community objects to its use. Table 3 shows how the study goals of a remedy selection treatability test address RI/FS criteria and the experimental parameters measured to assess the achievement of those goals.

#### REMEDY SELECTION TREATABILITY STUDY WORK PLAN

Carefully planned treatability studies are necessary to ensure that the data generated are useful for evaluating the validity or performance of a technology. The Work Plan, prepared by the contractor when the Work Assignment is in place, sets forth the contractor's proposed technical approach for completing the tasks outlined in the Work Assignment. It also assigns responsibilities and establishes the project schedule and costs. The Work Plan must be approved by the RPM

before initiating subsequent tasks. A suggested organization of the Work Plan is provided in the "Guide for Conducting Treatability Studies Under CERCLA: Biodegradation Remedy Selection", EPA/540/R-93/514a.

#### Test Goals

Remedy selection treatability goals must consider the existing site contaminant levels and cleanup goals for soils, sludges, and water at the site. The ideal technology performance goals for remedy selection treatability tests are the cleanup criteria for the site. Example remedy selection goals are listed in Table 3. In previous years, cleanup goals often reflected background site conditions. Attaining background cleanup levels through treatment has proved impractical in many situations. The present trend is toward the development of site-specific cleanup target levels that are risk-based rather than background-based.

#### Experimental Design

Careful planning during treatability study design is required to ensure adequate treatability study data are obtained. Among other requirements, the experimental design must identify the critical parameters and determine the required number of replicate tests. Treatability studies can be designed to simulate aerobic conditions, or may be planned to assess biodegradation under anaerobic conditions. Ultimately, remedy selection studies should strive to simulate the conditions encountered during full-scale applications of the technology under study.

**Table 3. Ability of Remedy Selection Treatability Studies to Address RI/FS Criteria**

Study goals	Experimental parameters	RI/FS criteria*
Compare performance, cost, etc., of different treatment systems at a specific site	Dependent on type of treatment systems compared	<ul style="list-style-type: none"> <li>● Overall protection of human health and the environment</li> <li>● Compliance with ARARs</li> <li>● Long-term effectiveness and permanence</li> <li>● Reduction of toxicity, mobility, and volume through treatment</li> <li>● Short-term effectiveness</li> <li>● Implementability</li> <li>● Cost</li> </ul>
Measure the initial and final contaminant concentrations, and calculate the percentage of contaminant removal from the soil, sludge, or water through biodegradation	Contaminant concentration	<ul style="list-style-type: none"> <li>● Overall protection of human health and the environment</li> <li>● Compliance with ARARs</li> <li>● Long-term effectiveness and permanence</li> <li>● Reduction of toxicity, mobility, and volume through treatment</li> </ul>
Estimate the type and concentration of residual contaminants and/or byproducts left in the soil after treatment	Contaminant/byproduct concentration	<ul style="list-style-type: none"> <li>● Overall protection of human health and the environment</li> <li>● Compliance with ARARs</li> <li>● Long-term effectiveness and permanence</li> </ul>
Develop estimates for reductions in contaminant toxicity, volume, or mobility	Contaminant concentration, toxicity testing	<ul style="list-style-type: none"> <li>● Reduction of toxicity, mobility, and volume through treatment</li> </ul>
Identify contaminant fate and the relative removals due to biological and nonbiological removal mechanisms	Contaminant concentrations present in solid, liquid, and gaseous phases taken from test and control reactors, oxygen uptake/CO <sub>2</sub> evolution	<ul style="list-style-type: none"> <li>● Overall protection of human health and the environment</li> <li>● Long-term effectiveness and permanence</li> <li>● Reduction of toxicity, mobility, and volume through treatment</li> <li>● Short-term effectiveness</li> </ul>
Produce design information required for next level of testing	Temperature, pH, moisture, nutrient concentrations and delivery, concentration and delivery of electron donors and acceptors, microbial composition, soil characteristics, test duration, nonbiological removal processes	<ul style="list-style-type: none"> <li>● Implementability</li> <li>● Cost</li> </ul>
Develop preliminary cost and time estimates for full-scale remediation	Treatability study cost (i.e., material and energy inputs, residuals quality and production, O&M costs, where appropriate), test duration, time required to meet performance goals	<ul style="list-style-type: none"> <li>● Short-term effectiveness</li> <li>● Implementability</li> <li>● Cost</li> </ul>
Evaluate need for pretreatment and requirements for long-term operation, maintenance, and monitoring	Soil characteristics, contaminant concentration/toxicity	<ul style="list-style-type: none"> <li>● Compliance with ARARs</li> <li>● Long-term effectiveness and permanence</li> <li>● Short-term effectiveness</li> <li>● Implementability</li> <li>● Cost</li> </ul>
Evaluate need for additional steps within treatment train	Soil characteristics, contaminant concentration, nonbiological removal processes, residual quality (relative to further treatment and/or disposal requirements)	<ul style="list-style-type: none"> <li>● Overall protection of human health and the environment</li> <li>● Long-term effectiveness and permanence</li> <li>● Implementability</li> <li>● Cost</li> </ul>
Assess ability of bioremediation to meet site-specific cleanup levels	Contaminant concentration	<ul style="list-style-type: none"> <li>● Overall protection of human health and the environment</li> <li>● Compliance with ARARs</li> <li>● Long-term effectiveness and permanence</li> <li>● Reduction of toxicity, mobility, and volume through treatment</li> </ul>
Determine optimal conditions for biodegradation and evaluate steps needed to stimulate biodegradation	Temperature, pH, nutrient concentrations and delivery, concentration and delivery of electron donors and acceptors, microbial composition, soil characteristics, test duration, contaminant concentration	<ul style="list-style-type: none"> <li>● Short-term effectiveness</li> <li>● Implementability</li> <li>● Cost</li> </ul>

\* Depending on specific components of the remedy selection treatability study, additional criteria may be applicable.

A number of factors influence the basic design of biological studies. These factors have a profound impact on both the treatability study operation and utility. Important factors to be considered when designing a biological treatability study include the following:

- Overall test objectives (as dictated by site remediation objectives)
- Specific removal goals or desired cleanup levels (as set for a specific site)
- Soil characteristics (soils with higher permeability are more amenable to in situ biodegradation)
- pH (most microbial degraders thrive when the pH is between 6.5 and 8.5)
- Temperature (optimum range is usually between 15°C and 30°C for aerobic processes and 25°C to 35°C for anaerobic processes)
- Moisture (optimum range is usually between 40 and 80 percent of field capacity)
- Nutrients (concentrations should be maintained at a reasonably moderate but steady-state concentration determined experimentally)
- Electron acceptors (usually oxygen derived from air, pure oxygen, ozone, or hydrogen peroxide for aerobic studies and nitrates for anaerobic tests)
- Microorganisms (the use of introduced versus indigenous populations)
- Duration of test (sufficient to determine ability of treatment to meet removal goals)
- Inhibitory compounds and their control (dilution of media may be required)
- Impact of nonbiological removal processes (extent of volatilization, sorption, photodecomposition, leaching, as experienced by inhibited controls)

- Toxicity testing (to evaluate the risk reduction experienced during treatment)
- Bioavailability (contaminants that biodegrade easily will be utilized earliest)

In situ remedy selection treatability studies are either field plot or soil column designs. Soil column studies may also be performed ex situ, usually within a laboratory setting. Three additional ex situ experimental designs are soil pans, soil slurries, and contained soil treatment systems. Table 4 presents information on remedy selection treatability study experimental designs, including their applicability, scale, typical size, and duration.

The test system used during remedy selection testing can consist of a single large reactor or multiple small reactors. Studies which employ large reactors include field studies, large flask studies, and soil pan studies. Multiple reactors consisting of serum bottles, small slurry reactors, and small soil reactors may be set up in place of a single large system. When a single reactor is used, small samples may be removed at various times and compared to samples from control reactors. When using large reactors, care should be taken to ensure that the availability of supplements (i.e., oxygen and moisture) are adequate, allowing for consistent degradation rates within the reactor. Additionally, sampling must be sized so that it does not affect the operation of the overall unit. Remedy selection treatability tests should include controls to measure the impact of nonbiological processes, such as volatilization, sorption, chemical degradation, migration, and photodecomposition. Inhibited controls can be established by adding formaldehyde, mercuric chloride (during non-EPA studies), sulfuric acid (added to lower the pH to 2 or below), or sodium azide to retard microbial activity. Contaminant concentrations are measured in both the test reactors and the control reactors at the beginning of the study ( $T_0$ ), at intermediate times, and at the end of the study. The mean contaminant concentrations in both the control and test reactors at the end of the test can be compared to their initial concentrations to see if a statistically significant change in concentration has occurred. The decrease in the control reactors may be attributed

Table 4. Remedy Selection Treatability Study Characteristics

Type of study	Applicability	Scale	Size	Duration
Field plots	In situ bioremediation	Field-scale	1 to 1,111 yd <sup>2</sup> plot of land*	2 months to 2 years
Soil columns	In situ bioremediation	Lab- and field-scale	0.01 - 3,200 ft <sup>3</sup> of soil, sand, sediment, or stone	1 week to 6 months
Soil pans	Solid-phase treatment	Lab-scale	2 to 100 lbs of soil	1 to 6 months
Slurry-phase reactors	Slurry-phase and solid-phase (occasionally) treatment	Field-scale	Greater than 20 gallons of slurried media	2 to 3 months
		Lab-scale	1 fluid oz to 20 gallons	1 to 8 weeks
Contained soil systems	Composting, soil heap bioremediation, and solid-phase treatment	Lab- and field-scale	7 ft <sup>3</sup> to 3,900 <sup>2</sup> yds of soil	10 days to 10 months

\* Field plot sizes are given as areas rather than volumes because treatment depths are frequently undefined.

to abiotic mechanisms, while the decrease in the test reactors would be a result of abiotic and biotic processes. The difference in mean contaminant concentrations between the test reactors and the inhibited control reactors will show whether there is a statistically significant reduction in contaminant concentration due to microbial activity. Care should be taken to assess the effects that the different sterilizing agents can have on the chemical behavior of the soil-contaminant system.

Complete sterilization of soils can be difficult to accomplish. Incomplete mixing of sterilization agents with soils can result in pockets of surviving microbes in soil pores. In some cases, microbial populations can transform and detoxify sterilizing agents. Additional sterilizing agents can be provided during the test to maintain reduced biological activity. The effectiveness of sterilizing agents can be measured by techniques such as microbial enumeration, respirometry, and enzyme analysis. Unless these or similar techniques show very low microbial activity, it may not be possible to distinguish between removal of contaminants by abiotic and biological processes in the control reactors. However, complete sterilization of the control is not necessary provided biological activity is inhibited to the extent that a statistically significant difference between the test and control means can be determined.

When designing a treatability study, the types of equipment required for the test must be considered. Standard laboratory equipment such as mixing flasks and sample collection bottles should be available for all treatability studies. A wide variety of equipment is employed during biodegradation treatability testing to contain the media under study or isolate it from the environment. During soil column studies, a metal, plastic, or glass cylinder may be used onsite or offsite as part of a laboratory study. Field plots, on the other hand, may require that in-ground barriers, such as sheets of steel driven into the ground, or above-ground barriers such as berms be used to separate testing plots from one another or from soil located outside of the testing area. Slurry reactors, which range in size from 1 fluid ounce vials to 70,000-gallon lagoons, typically utilize 0.1- to 130-gallon vessels. In contrast, contained soil treatment systems will generally require a bermed, watertight area in which the soil can be placed. The vessels required for contained soil treatability studies also vary considerably, since they may be designed to simulate composting, soil heaping, or other solid-phase biotreatment technologies. Depending on the type and scale of the system, a leachate collection system and other accessories may also be required.

## SAMPLING AND ANALYSIS PLAN

The Sampling and Analysis Plan (SAP) consists of two parts: the Field Sampling Plan (FSP) and the Quality Assurance Project Plan (QAPP). A SAP is required for all field activities conducted during the RI/FS. The purpose of the SAP is to ensure that samples obtained for characterization and testing are representative and that the quality of the analytical data generated is satisfactory. The SAP addresses field sampling, waste characterization, and sampling and analysis of the treated wastes and residuals from the testing apparatus or treatment unit. The SAP is usually prepared after Work Plan approval.

## TREATABILITY DATA INTERPRETATION

When conducting treatability studies, the test results and goals for each tier must be properly evaluated to assess the

treatment potential of bioremediation. The remedy screening tier establishes the general applicability of the technology. The remedy selection testing tier demonstrates the applicability of the technology to a specific site. The RD/RA tier provides information in support of the evaluation criteria.

Interpretation of remedy selection test results should allow the RPM or OSC to determine whether the bioremediation technology used is capable of meeting cleanup standards under simulated (or actual) site conditions. The experimental design of the study should have been constructed to produce quantitative and statistically defensible estimates of the extent and rate of biodegradation. Ideally, a statistical evaluation of the difference between biodegradation rates when parameters such as nutrient addition, loading rate, and microbial composition are varied, should also be designed. Example 1 describes a remedy selection treatability test and the interpretation of the test results.

## Estimation of Costs

Complete and accurate cost estimates are required in order to fully recommend technologies for site remediation. Consequently, when making preliminary cost estimates for full-scale bioremediation, achievable cleanup levels, degradation rates, concentration and application frequencies of various degradation enhancing supplements (e.g., nutrients, lime, water, etc.), contaminant migration controls, and monitoring requirements must be considered. The impact these parameters have on labor, analytical, material and energy costs, as well as the unit's design and possible pre- and post-treatment requirements, also must be considered.

Generally, large-scale field tests can be designed to simulate full-scale performance and costs more accurately than laboratory studies. However, estimating full-scale cost from treatability study data can be difficult. Given the variability and interaction of factors such as soil temperature, pH, moisture, heterogenous contaminant concentrations, and optimal nutrient concentrations, empirical results may not always depict the range of reasonable bioremediation results. One approach to examining the variability and interaction of these factors is simulation modeling. Simulation models (e.g., Monte Carlo models) attempt to quantify the probability that a certain set of events or values will occur based upon available empirical data. Using probabilistic simulation methods can produce time and cost estimates for a particular confidence level and a specific level of certainty (e.g., the ability to state with 90 percent certainty that the cost of the project will be within  $\pm 40$  percent of the estimate).

## TECHNICAL ASSISTANCE

Information from existing literature and consultation with experts are important factors in determining the need for and ensuring the usefulness of treatability studies. A reference list of sources on treatability studies is provided in the "Guide for Conducting Treatability Studies Under CERCLA" (EPA/540/R-92/071a).

It is recommended that a Technical Advisory Committee (TAC) be used. This committee includes experts who provide technical support from the scoping phase of the treatability study through data evaluation. Members of the TAC may include representatives from EPA (Regions or ORD), other Federal agencies, States, and consulting firms.

The Office of Solid Waste and Emergency Response and Office of Research and Development operate the TSP which provides assistance in the planning, performance, and review

### Example 1

A remedy selection treatability study was performed to evaluate a slurry-phase technology's ability to remediate an impoundment contaminated with petroleum refinery sludges. Surfactants and nutrients were added. Reactor performance was monitored by measuring the oxygen uptake rate and oil and grease (O&G) removal. Based on extensive experience with O&G biodegradation, toxicity testing was not performed.

The average initial O&G concentration in the sediment was 41,000 ppm, the maximum concentration expected in the full-scale (70,000 gallon), slurry bioreactor. A cleanup goal of 20,000 ppm O&G was targeted during the study. After 4 weeks, the average O&G concentration in the inhibited control was reduced to 39,000 ppm, a reduction of nearly 5 percent. The average O&G concentration in the biologically active system was reduced to 14,000 ppm, a 66 percent reduction in the same time period. The leveling out of O&G concentrations at the end of the experiment indicates that the maximum extent of biodegradation achievable under the test conditions had been reached.

Sample	O&G				
	T <sub>0</sub>	T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>4</sub>
<i>Bioreactor</i>					
Replicate 1	39,000	32,000	21,000	13,000	14,000
Replicate 2	41,000	34,000	24,000	15,000	16,000
Replicate 3	43,000	39,000	24,000	17,000	12,000
Mean Value	41,000	35,000	23,000	15,000	14,000
<i>Inhibited Control</i>					
Replicate 1	39,000	36,000	37,000	37,000	42,000
Replicate 2	41,000	39,000	40,000	41,000	36,000
Replicate 3	43,000	42,000	40,000	39,000	39,000
Mean Value	41,000	39,000	39,000	39,000	39,000

The average contaminant concentration in the slurry-phase bioreactor at each time-point is compared to the average contaminant concentration in the inhibited control at the same time-point to measure the biodegradation at that time-point. The inhibited control accounts for contaminant losses due to volatilization, adsorption to soil particles, and chemical reactions. Some contaminant loss in the control due to biodegradation may occur since total sterilization is difficult to accomplish. However, an O&G analysis of the extract generated from the slurry-phase reactor indicated that abiotic losses were due mainly to adsorption. Since a statistically significant difference between the test and control means exists, O&G reductions in the test bioreactor were attributed to biodegradation.

of treatability studies. For further information on treatability study support or the TSP, please contact:

**Groundwater Fate and Transport Technical Support Center**  
Robert S. Kerr Environmental Research Laboratory, (RSKERL)  
Ada, OK 74820  
Contact: Don Draper  
(405) 332-8800

**Engineering Technical Support Center (ETSC)**  
Risk Reduction Engineering Laboratory (RREL)  
Cincinnati, OH 45268  
Contact: Ben Blaney or Joan Colson  
(513) 569-7406 or (513) 569-7501

#### FOR FURTHER INFORMATION

Sources of information on treatability studies and bioremediation are listed in the "Guide for Conducting Treatability Studies Under CERCLA" (EPA/540/R-92/071a) and the "Guide for Conducting Treatability Studies Under CERCLA: Biodeg-

radation Remedy Selection" (EPA/540/R-93/541A). Additionally, the Office of Emergency and Remedial Response's Hazardous Site Control Division (OERR/HSCD) Regional Coordinator for each Region should be contacted for information and assistance.

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# Engineering Bulletin Mobile/Transportable Incineration Treatment

## Purpose

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

## Abstract

Incineration treats organic contaminants in solids and liquids by subjecting them to temperatures typically greater than 1000°F in the presence of oxygen, which causes the volatilization, combustion, and destruction of these compounds. This bulletin describes mobile/transportable incineration systems that can be moved to and subsequently removed from Superfund and other hazardous waste sites. It does not address other thermal processes that operate at lower temperatures or those that operate at very high temperatures, such as a plasma arc. It is applicable to a wide range of organic wastes and is generally not used in treating inorganics and metals. Mobile/transportable incinerators exhibit essentially the same environmental performance as their stationary counterparts. To date, 49 of the 95 records of decision (RODs) designating thermal remedies at Superfund sites have selected onsite incineration as an integral part of a preferred treatment alternative. There are 22

commercial-scale units in operation [5]\*. This bulletin provides information on the technology applicability, the types of residuals resulting from the use of the technology, the latest performance data, site requirements, the status of the technology, and where to go for further information.

## Technology Applicability

Mobile/transportable incineration has been shown to be effective in treating soils, sediments, sludges, and liquids containing primarily organic contaminants such as halogenated and nonhalogenated volatiles and semivolatiles, polychlorinated biphenyls (PCBs), pesticides, dioxins/furans, organic cyanides, and organic corrosives. The process is applicable for the thermal treatment of a wide range of specific Resource Conservation and Recovery Act (RCRA) wastes and other hazardous waste matrices that include pesticides and herbicides, spent halogenated and nonhalogenated solvents, chlorinated phenol and chlorinated benzene manufacturing wastes, wood preservation and wastewater sludge, organic chemicals production residues, pesticides production residues, explosives manufacturing wastes, petroleum refining wastes, coke industry wastes, and organic chemicals residues [1] [2] [4] [6 through 11] [13].

Information on the physical and chemical characteristics of the waste matrix is necessary to assess the matrix's impact on waste preparation, handling, and feeding; incinerator type, performance, size, and cost; air pollution control (APC) type and size; and residue handling. Key physical parameters include waste matrix physical characteristics (type of matrix, physical form, handling properties, and particle size), moisture content, and heating value. Key chemical parameters include the type and concentration of organic compounds including PCBs and dioxins, inorganics (metals), halogens, sulfur, and phosphorous.

The effectiveness of mobile/transportable incineration on general contaminant groups for various matrices is shown in Table 1 [7, p. 9]. Examples of constituents within contaminant groups are provided in Reference 7, "Technology Screening Guide for Treatment of CERCLA Soils and Sludges." This table

\* [reference number, page number]

**Table 1**  
**Effectiveness of Incineration on General Contaminant Groups for Soil, Sediment, Sludge, and Liquid**

Contaminant Groups		Soil/ Sediment	Sludge	Liquid
Organic	Halogenated volatiles	■	■	■
	Halogenated semivolatiles	■	■	■
	Nonhalogenated volatiles	■	■	■
	Nonhalogenated semivolatiles	■	■	■
	PCBs	■	■	■
	Pesticides (halogenated)	▼	■	■
	Dioxins/Furans	■	■	■
	Organic cyanides	▼	▼	▼
	Organic corrosives	▼	▼	▼
Inorganic	Volatile metals	□	□	□
	Nonvolatile metals	□	□	□
	Asbestos	□	□	□
	Radioactive materials	□	□	□
	Inorganic corrosives	□	□	□
	Inorganic cyanides	▼	▼	▼
Reactive	Oxidizers	▼	▼	▼
	Reducers	▼	▼	▼
■ Demonstrated Effectiveness: Successful treatability test at some scale completed				
▼ Potential Effectiveness: Expert opinion that technology will work				
□ No Expected Effectiveness: Expert opinion that technology will not work				

is based on current available information or professional judgment when no information was available. The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment efficiency achieved will be acceptable at other sites. For the ratings used for this table, demonstrated effectiveness means that, at some scale, treatability was tested to show that the technology was effective for a particular contaminant and matrix. The ratings of potential effectiveness or no expected effectiveness are based upon expert judgment. Where potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminant group in a particular matrix. When the technology is not applicable or will probably not work for a particular combination of contaminant group and matrix, a no-expected-effectiveness rating is given. Other sources of general observations and average removal efficiencies for different treatability groups are the Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions," (OSWER Directive 9347.3-06FS [13], and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions," (OSWER Directive 9347.3-07FS [14].

## Limitations

Toxic metals such as arsenic, lead, mercury, cadmium, and chromium are not destroyed by combustion. As a result, some will be present in the ash while others are volatilized and released into the flue gas [1, pp. 3-6].

Alkali metals, such as sodium and potassium, can cause severe refractory attack and form a sticky, low-melting-point submicron particulate, which causes APC problems. A low feed stream concentration of sodium and potassium may be achieved through feed stock blending [1, pp. 3-11].

When PCBs and dioxins are present, higher temperatures and longer residence times may be required to destroy them to levels necessary to meet regulatory criteria [7, p. 34].

Moisture/water content of waste materials can create the need to co-incinerate these materials with higher BTU streams, or to use auxiliary fuels.

The heating value (BTU content) of the feed material affects feed capacity and fuel usage of the incinerator. In general, as the heating value of the feed increases, the feed capacity and fuel usage of the incinerator will decrease. Solid materials with high calorific values also may cause transient behaviors that further limit feed capacity [9, p. 4].

The matrix characteristics of the waste affect the pretreatment required and the capacity of the incinerator and can cause APC problems. Organic liquid wastes can be pumped to and then atomized in the incinerator combustion chamber. Aqueous liquids may be suitable for incineration if they contain a substantial amount of organic matter. However, because of the large energy demand for evaporation when treating large volumes of aqueous liquids, pretreatment to dewater the waste may be cost effective [1, pp. 3-14]. Also, if the organic content is low, other methods of treatment may be more economical. For the infrared incinerator, only solid and solid-like materials within a specific size and moisture content range can be processed because of the unique conveyor belt feed system within the unit.

Sandy soil is relatively easy to feed and generally requires no special handling procedures. Clay, which may be in large clumps, may require size reduction. Rocky soils usually require screening to remove oversize stones and boulders. The solids can then be fed by gravity, screw feeder, or ram-type feeder into the incinerator. Some types of solid waste may also require crushing, grinding, and/or shredding prior to incineration [1, pp. 3-17].

The form and structure of the waste feed can cause periodic jams in the feed and ash handling systems. Wooden pallets, metal drum closure rings, drum shards, plastics, trash, clothing, and mud can cause blockages if poorly prepared. Muddy soils can stick to waste processing equipment and plug the feed system [9, p. 8].

The particle size distribution of the ash generated from the waste can affect the amount of particulate carry-over from the combustion chamber to the rest of the system [9, p. 16].

Incineration of halogens, such as fluorine and chlorine, generates acid gases that can affect the capacity, the water removal and replacement rates that control total dissolved solids in the process water system, and the particulate emissions [9, p. 12]. The solutions used to neutralize these acid gases add to the cost of operating this technology.

Organic phosphorous compounds form phosphorous pentoxide, which attacks refractory material, causes slagging problems and APC problems. Slagging can be controlled by feed blending or operating at lower temperatures [1, pp. 3-10].

### Technology Description

Figure 1 is a schematic of the mobile/transportable incineration process.

Waste preparation (1) includes excavation and/or moving the waste to the site. Depending on the requirements of the

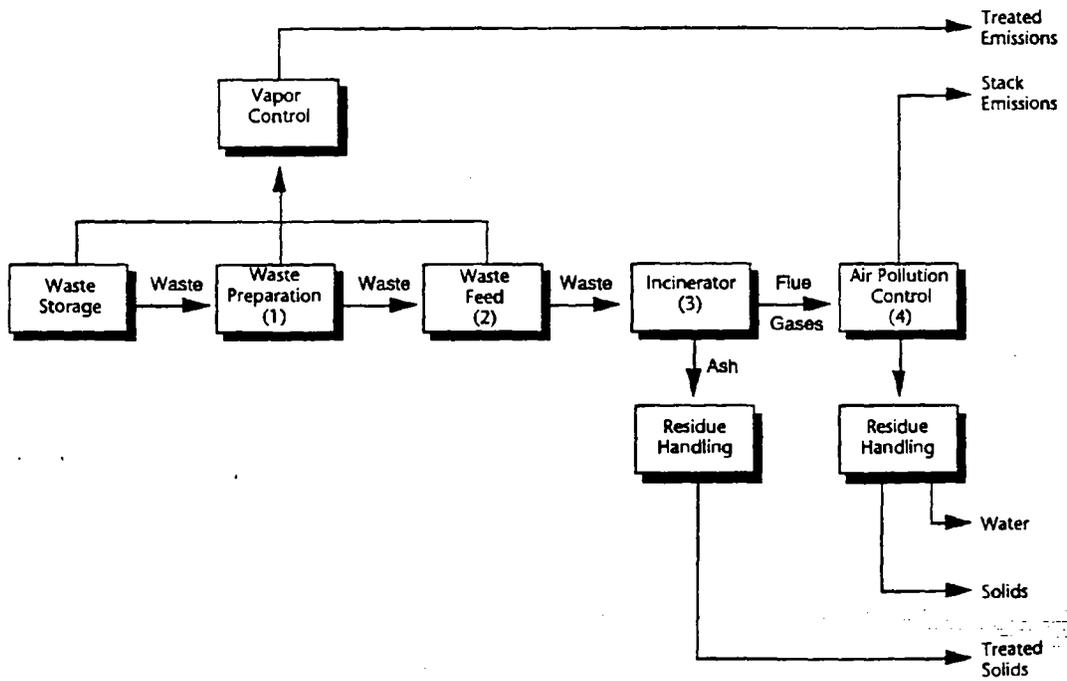
incinerator type for soils and solids, various equipment is used to obtain the necessary feed size. Blending is sometimes required to achieve a uniform feed size and moisture content or to dilute troublesome components [1, pp. 3-19].

The waste feed mechanism (2), which varies with the type of the incinerator, introduces the waste into the combustion system. The feed mechanism sets the requirements for waste preparation and is a potential source of problems in the actual operation of incinerators if not carefully designed [1, pp. 3-19].

Different incinerator designs (3) use different mechanisms to obtain the temperature at which the furnace is operated, the time during which the combustible material is subject to that temperature, and the turbulence required to ensure that all the combustible material is exposed to oxygen to ensure complete combustion. Three common types of incineration systems for treating contaminated soils are rotary kiln, circulating fluidized bed, and infrared.

The rotary kiln is a slightly inclined cylinder that rotates on its horizontal axis. Waste is fed into the high end of the rotary kiln and passes through the combustion chamber by gravity. A secondary combustion chamber (afterburner) further destroys unburned organics in the flue gases [7, p. 40].

Figure 1  
Mobile/Transportable Incineration Process



Circulating fluidized bed incinerators use high air velocity to circulate and suspend the fuel/waste particles in a combustor loop. Flue gas is separated from heavier particles in a solids separation cyclone. Circulating fluidized beds do not require an afterburner [7, p. 35].

Infrared processing systems use electrical resistance heating elements or indirect fuel-fired radiant U-tubes to generate thermal radiation [1, pp. 4-5]. Waste is fed into the combustion chamber by a conveyor belt and exposed to the radiant heat. Exhaust gases pass through a secondary combustion chamber.

Offgases from the incinerator are treated by the APC equipment to remove particulates and capture and neutralize acids (4). Rotary kilns and infrared processing systems may require both external particulate control and acid gas scrubbing systems. Circulating fluidized beds do not require scrubbing systems because limestone can be added directly into the combustor loop but may require a system to remove particulates [1, pp. 4-11] [2, p. 32]. APC equipment that can be used include venturi scrubbers, wet electrostatic precipitators, baghouses, and packed scrubbers.

## Process Residuals

Three major waste streams are generated by this technology: solids from the incinerator and APC system, water from the APC system, and emissions from the incinerator.

Ash and treated soil/solids from the incinerator combustion chamber may be contaminated with heavy metals. APC system solids, such as fly ash, may contain high concentrations of volatile metals. If these residues fail required leachate toxicity tests, they can be treated by a process such as stabilization/solidification and disposed of onsite or in an approved landfill [7, p. 126].

Liquid waste from the APC system may contain caustic, high chlorides, volatile metals, trace organics, metal particulates, and inorganic particulates. Treatment may require neutralization, chemical precipitation, reverse osmosis, settling, evaporation, filtration, or carbon adsorption before discharge [7, p. 127].

The flue gases from the incinerator are treated by APC systems such as electrostatic precipitators or venturi scrubbers before discharge through a stack.

## Site Requirements

The site should be accessible by truck or rail and a graded/gravel area is required for setup of the system. Concrete pads may be required for some equipment (e.g., rotary kiln). For a typical 5 tons per hour commercial-scale unit, 2 to 5 acres are required for the overall system site including ancillary support [10, p. 25].

Standard 440V three-phase electrical service is needed. A continuous water supply must be available at the site. Auxiliary fuel for feed BTU improvement may be required.

Contaminated soils or other waste materials are hazardous and their handling requires that a site safety plan be developed to provide for personnel protection and special handling measures.

Various ancillary equipment may be required, such as liquid/sludge transfer and feed pumps, ash collection and solids handling equipment, personnel and maintenance facilities, and process-generated waste treatment equipment. In addition, a feed-materials staging area, a decontamination trailer, an ash handling area, water treatment facilities, and a parking area may be required [10, p. 24].

Proximity to a residential neighborhood will affect plant noise requirements and may result in more stringent emissions limitations on the incineration system.

Storage area and/or tanks for fuel, wastewater, and blending of waste feed materials may be needed.

No specific onsite analytical capabilities are necessary on a routine basis; however, depending on the site characteristics or a specific Federal, State, or local requirement, some analytical capability may be required.

## Performance Data

More than any other technology, incineration is subject to a series of technology-specific regulations, including the following Federal requirements: the Clean Air Act 40 CFR 52.21 for air emissions; Toxic Substances Control Act (TSCA) 40 CFR 761.40 for PCB treatment and disposal; National Environmental Policy Act 40 CFR 6; RCRA 40 CFR 261/262/264/270 for hazardous waste generation, treatment performance, storage, and disposal standards; National Pollutant Discharge Elimination System 33 U.S.C. 1251 for discharge to surface waters; and the Noise Control Act P.L. 92-574. RCRA incineration standards have been proposed that address metal emissions and products of incomplete combustion. In addition, State requirements must be met if they are more stringent than the Federal requirements [1, p. 6-1].

All incineration operations conducted at CERCLA sites on hazardous waste must comply with substantive and defined Federal and State applicable or relevant and appropriate requirements (ARARs) at the site. A substantial body of trial burn results and other quality assured data exists to verify that incinerator operations remove and destroy organic contaminants from a variety of waste matrices to the parts per billion or even the parts per trillion level, while meeting stringent stack emission and water discharge requirements. The demonstrated treatment systems that will be discussed in the technology status section, therefore, can meet all the performance standards defined by the applicable Federal and State regulations on waste treatment, air emissions, discharge of process waters, and residue ash disposal [1, p. A-1] [4, p. 4] [10, p. 9].

RCRA Land Disposal Restrictions (LDRs) that require treatment of wastes to best demonstrated available technology (BDAT) levels prior to land disposal may sometimes be determined to be ARARs for CERCLA response actions. The solid

residuals from the incinerator may not meet required treatment levels in all cases. In cases where residues do not meet BDAT levels, mobile incineration still may be selected, in certain situations, for use at the site if a treatability variance establishing alternative treatment levels is obtained. EPA has made the treatability variance process available in order to ensure that LDRs do not unnecessarily restrict the use of alternative and innovative treatment technologies. Treatability variances may be justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions," (OSWER Directive 9347.3-06FS) [13] and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions," (OSWER Directive 9347.3-07FS) [14].

### Technology Status

To date, 49 of the 95 RODs designating thermal remedies at Superfund sites have selected onsite incineration as an integral part of a preferred treatment alternative.

Table 2 lists the site experience of the various mobile, transportable incinerator systems. It includes information on the incinerator type/size, the site size, location, and contaminant source or waste type treated [5] [3, p. 80] [8, p. 74].

The cost of incineration includes fixed and operational costs. Fixed costs include site preparation, permitting, and mobilization/demobilization. Operational costs such as labor, utilities, and fuel are dependent on the type of waste treated and the size of the site. Figure 2 gives an estimate of the total cost for incinerator systems based on site size [12, pp. 1-3]. Superfund sites contaminated with only volatile organic compounds can have even lower costs for thermal treatment than the costs shown in Figure 2.

### EPA Contact

Technology-specific questions regarding mobile/transportable incineration may be directed to Donald A. Oberacker, U.S. EPA Risk Reduction Engineering Laboratory, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, telephone: FTS 684-7510 or (513) 569-7510.

Table 2.  
Technology Status

Treatment System/ Vendor	Thermal Capacity (MM BTU/Hr)	Experience		
		Site, Location	Waste Volume (tons)	Contaminant Source or Waste Type
Rotary Kiln EnSCO	35	Sydney Mines, Valrico, FL <sup>a</sup> Lenz Oil NPL Site, Lemont, IL <sup>a</sup> Naval Construction Battalion Center (NCBC), Gulfport, MS Union Carbide, Seadrift, TX <sup>a</sup> Smithville, Canada <sup>a</sup>	10,000 26,000 22,000  N/A 7,000	Waste oil Hydrocarbon - sludge/solid/liquid Dioxin/soil  Chemical manufacturing PCB transformer leaks
	100	Bridgeport Rental, Bridgeport, NJ <sup>a*</sup>	100,000	Used oil recycling
Rotary Kiln IT	56	Comhusker Army Ammunition Plant (CAAP), Grand Island, NE <sup>a</sup>	45,000	Munitions plant redwater pits
		Louisiana Army Ammunition Plant (LAAP), Shreveport, LA <sup>a*</sup>	100,000	Munitions plant redwater lagoon
		Motco, Texas City, TX <sup>a*</sup>	80,000	Styrene tar disposal pits
Rotary Kiln Vesta	8	Fairway Six Site, Aberdeen, NC	50	Pesticide dump
	12	Fort A.P. Hill, Bowling Green, VA Nyanza/Nyacol Site, Ashland, MA <sup>a</sup> Southern Crop Services Site Delray Beach, FL American Crossarm & Conduit Site Chehalis, WA <sup>a</sup> Rocky Boy, Havre, MT <sup>a</sup>	200 1,000 1,500  900 1,800	Army base Dye manufacturing Crop dusting operation  Wood treatment Wood treatment

NA - Not available \* Contracted, others completed <sup>a</sup> Superfund Site

[Source: References 3, 5, 8]

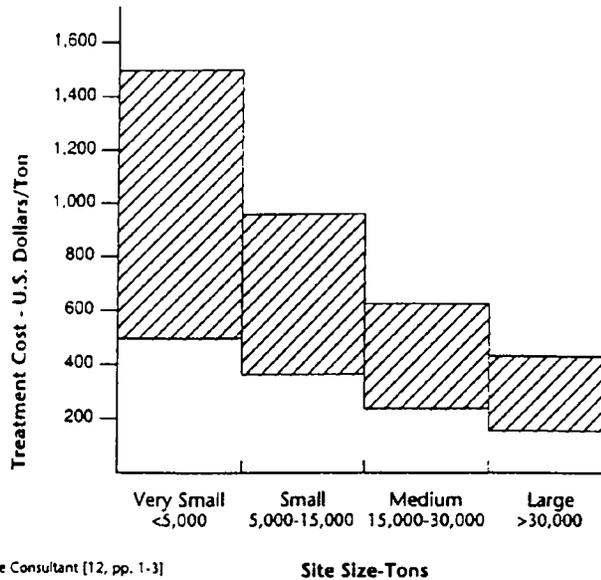
**Table 2  
Technology Status (Continued)**

Treatment System/ Vendor	Thermal Capacity (MM BTU/Hr)	Experience		
		Site, Location	Waste Volume (tons)	Contaminant Source or Waste Type
Rotary Kiln <i>Weston</i>	35	Lauder Salvage, Beardstown, IL Paxton Ave., Chicago, IL*	8,500 16,000	Metal scrap salvage Waste lagoon
Rotary Kiln <i>AET</i>	20	Valdez, AK	NA	Crude oil spill
Rotary Kiln <i>Boliden</i>	40	Oak Creek, WI	50,000	Dye manufacturing
Rotary Kiln <i>Harmon</i>	82	Prentis Creosote & Forest Products Prentis, MS Bog Creek, Howell Township, NJ <sup>a</sup>	9,200 22,500	Creosote/soil Organics
Rotary Kiln <i>Bell</i>	30	Bell Lumber&Pole, New Brighton, MN <sup>a</sup>	21,000	Wood treatment
Rotary Kiln <i>Kimmins</i>	100	Lasalle, IL <sup>a*</sup>	69,000	PCB capacitor manufacturing
Rotary Kiln <i>USEPA</i>	10	Denney Farm, MO	6,250	Dioxin Soils
Rotary Kiln <i>Vertac</i>	35	Vertac, Jacksonville, AR <sup>a*</sup>	6,500	Chemical manufacturing
Shirco Infrared <i>Haztech</i>	30	Peak Oil, Tampa, FL <sup>a</sup> Lasalle, IL <sup>a</sup>	7,000 30,000	Used oil recycling, PCBs/Lead Transformer reconditioning
Shirco Infrared <i>GDC Engr.</i>	NA	Rubicon, Geismar, LA*	52,000	Chemical manufacturing
Shirco Infrared <i>OH Materials</i>	30	Florida Steel, Indiantown, FL <sup>a</sup> Twin City AAP, New Brighton, MN Goosebay, Canada	18,000 2,000 4,000	Steel mill used oils Munitions plant PCBs
	12	Gas Station Site, Cocoa, FL	1,000	Petroleum tank leak
Shirco Infrared <i>U.S. Waste</i>	10	Private Site, San Bernadino, CA	5,400	Hydrocarbons
Circulating Bed Combustor <i>Ogden</i>	10	Arco Swanson River Field Kenai, AK* Stockton, CA*	80,000 16,000	Oil pipeline compressor oil Underground tank oil leak

NA - Not available    \* Contracted, others completed    <sup>a</sup>Superfund Site

[Source: References 3, 5, 8]

Figure 2  
Effect of Site Size on Incineration Costs



Source: The Hazardous Waste Consultant [12, pp. 1-3]

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## Engineering Bulletin

# Soil Washing Treatment

### Purpose

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

### Abstract

Soil washing is a water-based process for mechanically scrubbing soils ex-situ to remove undesirable contaminants. The process removes contaminants from soils in one of two ways: by dissolving or suspending them in the wash solution (which is later treated by conventional wastewater treatment methods) or by concentrating them into a smaller volume of soil through simple particle size separation techniques (similar to those used in sand and gravel operations). Soil washing systems incorporating both removal techniques offer the greatest promise for application to soils contaminated with a wide variety of heavy metal and organic contaminants.

The concept of reducing soil contamination through the use of particle size separation is based on the finding that most organic and inorganic contaminants tend to bind, either chemically or physically, to clay and silt soil particles. The silt and clay, in turn, are attached to sand and gravel particles by physical processes, primarily compaction and adhesion. Washing processes that separate the fine (small) clay and silt particles from the coarser sand and gravel soil particles effectively

separate and concentrate the contaminants into a smaller volume of soil that can be further treated or disposed. The clean, larger fraction can be returned to the site for continued use. This set of assumptions forms the basis for the volume-reduction concept upon which most soil washing technology applications are being developed.

At the present time, soil washing is used extensively in Europe and has had limited use in the United States. During 1986-1989, the technology was one of the selected source control remedies at eight Superfund sites.

The final determination of the lowest cost alternative will be more site-specific than process equipment dominated. Vendors should be contacted to determine the availability of a unit for a particular site. This bulletin provides information on the technology applicability, the types of residuals resulting from the use of the technology, the latest performance data, site requirements, the status of the technology, and where to go for further information.

### Technology Applicability

Soil washing can be used either as a stand-alone technology or in combination with other treatment technologies. In some cases, the process can deliver the performance needed to reduce contaminant concentrations to acceptable levels and, thus, serve as a stand-alone technology. In other cases, soil washing is most successful when combined with other technologies. It can be cost-effective as a pre-processing step in reducing the quantity of material to be processed by another technology such as incineration; it also can be used effectively to transform the soil feedstock into a more homogeneous condition to augment operations in the subsequent treatment system. In general, soil washing is effective on coarse sand and gravel contaminated with a wide range of organic, inorganic, and reactive contaminants. Soils containing a large amount of clay and silt typically do not respond well to soil washing, especially if it is applied as a stand-alone technology.

A wide variety of chemical contaminants can be removed from soils through soil washing applications. Removal efficiencies depend on the type of contaminant as well as the type of soil. Volatile organic contaminants often are easily removed from soil by washing; experience shows that volatiles can be removed with 90-99 percent efficiency or more. Semivolatile organics

may be removed to a lesser extent (40-90 percent) by selection of the proper surfactant. Metals and pesticides, which are more insoluble in water, often require acids or chelating agents for successful soil washing. The process can be applicable for the treatment of soils contaminated with specific listed Resource Conservation and Recovery Act (RCRA) wastes and other hazardous wastes including wood-preserving chemicals (pentachlorophenol, creosote), organic solvents, electroplating residues (cyanides, heavy metals), paint sludges (heavy metals), organic chemicals production residues, pesticides and pesticides production residues, and petroleum/oil residues [1, p. 659][2, p. 15][4][7 through 13]\*.

The effectiveness of soil washing for general contaminant groups and soil types is shown in Table 1 [1, p. 659][3, p. 13][15, p.1]. Examples of constituents within contaminant groups are provided in Reference 3, "Technology Screening Guide For Treatment of CERCLA Soils and Sludges." This table is based on currently available information or professional judgment where definitive information is currently inadequate or unavailable. The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment efficiency achieved will be acceptable at other sites. For the ratings used in this table, good to excellent applicability means the probability is high that soil

**Table 1**  
Applicability of Soil Washing on General Contaminant Groups for Various Soils

Contaminant Groups		Matrix	
		Sandy/ Gravelly Soils	Silty/Clay Soils
Organic	Halogenated volatiles	■	▼
	Halogenated semivolatiles	▼	▼
	Nonhalogenated volatiles	■	▼
	Nonhalogenated semivolatiles	▼	▼
	PCBs	▼	▼
	Pesticides (halogenated)	▼	▼
	Dioxins/Furans	▼	▼
	Organic cyanides	▼	▼
Organic corrosives	▼	▼	
Inorganic	Volatile metals	■	▼
	Nonvolatile metals	■	▼
	Asbestos	□	□
	Radioactive materials	▼	▼
	Inorganic corrosives	▼	▼
Inorganic cyanides	▼	▼	
Reactive	Oxidizers	▼	▼
	Reducers	▼	▼

■ Good to Excellent Applicability: High probability that technology will be successful  
 ▼ Moderate to Marginal Applicability: Exercise care in choosing technology  
 □ Not Applicable: Expert opinion that technology will not work

\* [reference number, page number]

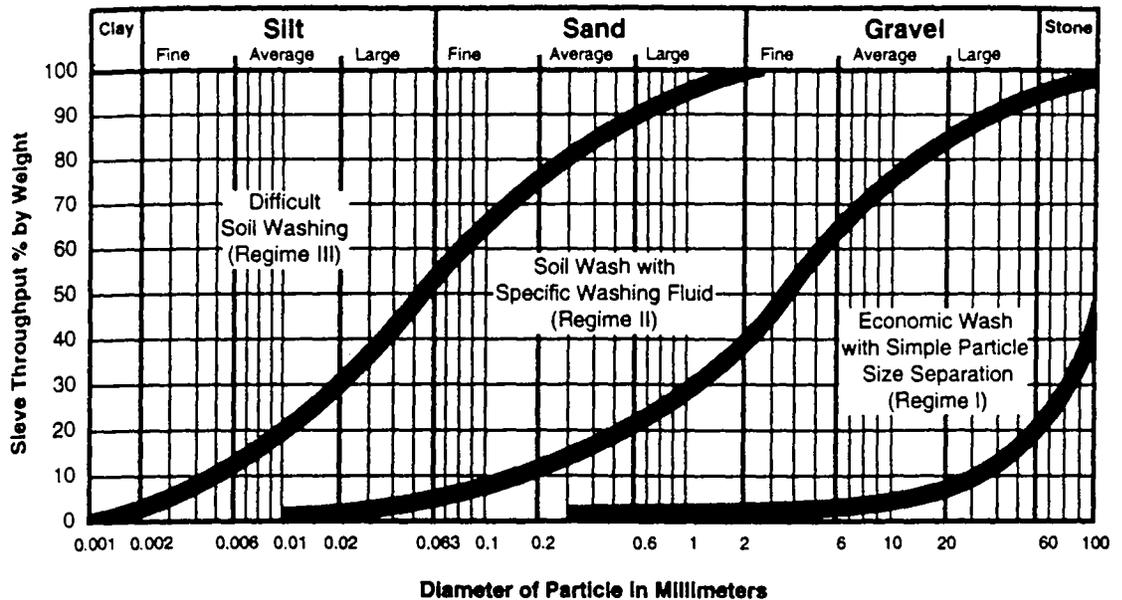
washing will be effective for that particular contaminant and matrix. Moderate to marginal applicability indicates situations where care needs to be exercised in choosing the soil washing technology. When not applicable is shown, the technology will probably not work for that particular combination of contaminant group and matrix. Other sources of general observations and average removal efficiencies for different treatability groups are the Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.3-06FS), [16] and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.3-07FS) [17].

Information on cleanup objectives as well as the physical and chemical characteristics of the site soil and its contaminants is necessary to determine the potential performance of this technology and the requirements for waste preparation and pretreatment. Treatability tests are also required at the laboratory screening, bench-scale and/or pilot-scale level(s) to determine

**Table 2**  
Waste Soil Characterization Parameters

Parameter	Purpose and Comment
<b>Key Physical</b>	
Particle size distribution:	
>2 mm	Overize pretreatment requirements
0.25-2 mm	Effective soil washing
0.063-0.25 mm	Limited soil washing
<0.063 mm	Clay and silt fraction—difficult soil washing
<b>Other Physical</b>	
Type, physical form, handling properties	Affects pretreatment and transfer requirements
Moisture content	Affects pretreatment and transfer requirements
<b>Key Chemical</b>	
Organics Concentration Volatility Partition coefficient	Determine contaminants and assess separation and washing efficiency, hydrophobic interaction, washing fluid compatibility, changes in washing fluid with changes in contaminants. May require preblending for consistent feed. Use the jar test protocol to determine contaminant partitioning.
Metals	Concentration and species of constituents (specific jar test) will determine washing fluid compatibility, mobility of metals, posttreatment.
Humic acid	Organic content will affect adsorption characteristics of contaminants on soil. Important in marine/wetland sites.
<b>Other Chemical</b>	
pH, buffering capacity	May affect pretreatment requirements, compatibility with equipment materials of construction, wash fluid compatibility.

Figure 1  
Soil Washing Applicable Particle Size Range



the feasibility of the specific soil washing process being considered and to understand waste preparation and pretreatment steps needed at a particular site. If bench-test results are promising, pilot-scale demonstrations should normally be conducted before final commitment to full-scale implementation. Treatability study procedures are explained in the EPA's forthcoming document entitled "Superfund Treatability Study Protocol: Bench-Scale Level of Soils Washing for Contaminated Soils" [14].

Table 2 contains physical and chemical soil characterization parameters that must be established before a treatability test is conducted on a specific soil washing process. The parameters are defined as either "key" or "other" and should be evaluated on a site-specific basis. Key parameters represent soil characteristics that have a direct impact on the soil washing process. Other parameters should also be determined, but they can be adjusted prior to the soil washing step based on specific process requirements. The table contains comments relating to the purpose of the specific parameter to be characterized and its impact on the process [6, p. 90][14, p. 35].

Particle size distribution is the key physical parameter for determining the feasibility of using a soil washing process. Although particle size distribution should not become the sole reason for choosing or eliminating soil washing as a candidate technology for remediation, it can provide an initial means of screening for the potential use of soil washing. Figure 1 presents a simplistic particle size distribution range of curves that illustrate a general screening definition for soil washing technology.

In its simplest application, soil washing is a particle size separation process that can be used to segregate the fine fractions from the coarse fractions. In Regime I of Figure 1, where coarse soils are found, the matrix is very amenable to soil washing using simple particle size separation.

Most contaminated soils will have a distribution that falls within Regime II of Figure 1. The types of contaminants found in the matrix will govern the composition of the washing fluid and the overall efficiency of the soil washing process.

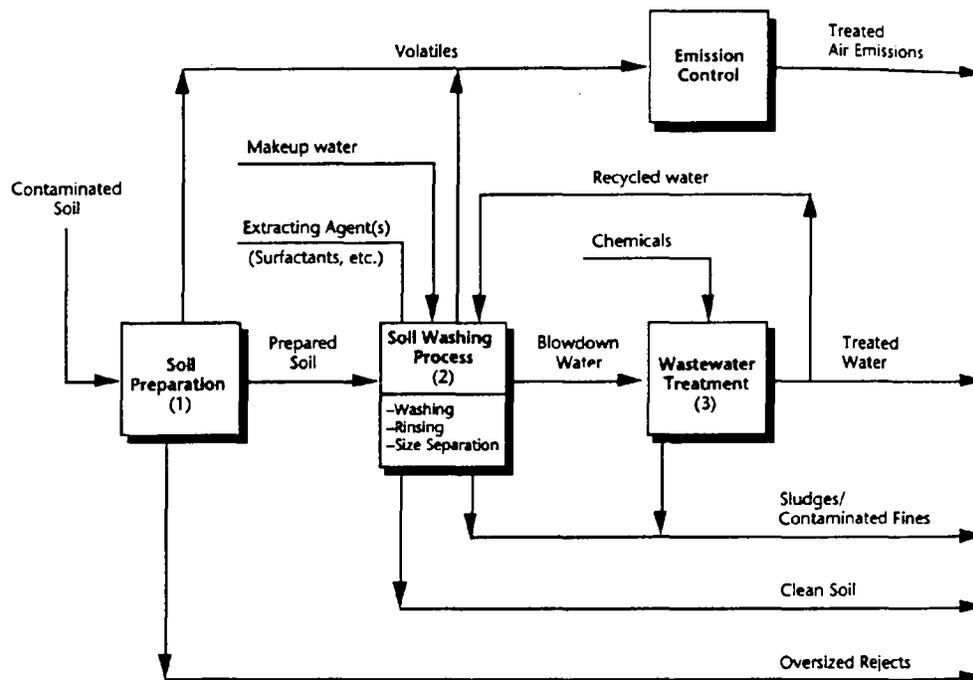
In Regime III of Figure 1, soils consisting largely of finer sand, silt, and clay fractions, and those with high humic content, tend to contain strongly adsorbed organics that generally do not respond favorably to systems that work by only dissolving or suspending contaminants in the wash solution. However, they may respond to soil washing systems that also incorporate a particle size separation step whereby contaminants can be concentrated into a smaller volume.

### Limitations

Contaminants in soils containing a high percentage of silt- and clay-sized particles typically are strongly adsorbed and difficult to remove. In such cases, soil washing generally should not be considered as a stand-alone technology.

Hydrophobic contaminants generally require surfactants or organic solvents for their removal from soil. Complex mixtures of contaminants in the soil (such as a mixture of metals, nonvolatile organics, and semivolatile organics) and

Figure 2  
Aqueous Soil Washing Process



frequent changes in the contaminant composition in the soil matrix make it difficult to formulate a single suitable washing fluid that will consistently and reliably remove all of the different types of contaminants from the soil particles. Sequential washing steps may be needed. Frequent changes in the wash formulation and/or the soil/wash fluid ratio may be required [3, p. 76][14, p. 7].

While washwater additives such as surfactants and chelants may enhance some contaminant removal efficiencies in the soil washing portion of the process, they also tend to interfere with the downstream wastewater treatment segments of the process. The presence of these additives in the washed soil and in the wastewater treatment sludge may cause some difficulty in their disposal [14, p. 7][15, p. 1]. Costs associated with handling the additives and managing them as part of the residuals/wastewater streams must be carefully weighed against the incremental improvements in soil washing performance that they may provide.

### Technology Description

Figure 2 is a general schematic of the soil washing process [1, p. 657][3, p. 72][15, p. 1].

Soil preparation (1) includes the excavation and/or moving of contaminated soil to the process where it is normally screened to remove debris and large objects. Depending upon the technology and whether the process is semibatch or continuous, the soil may be made pumpable by the addition of water.

A number of unit processes occur in the soil washing process (2). Soil is mixed with washwater and possibly extraction agent(s) to remove contaminants from soil and transfer them to the extraction fluid. The soil and washwater are then separated, and the soil is rinsed with clean water. Clean soil is then removed from the process as product. Suspended soil particles are recovered directly from the spent washwater, as sludge, by gravity means, or they may be removed by flocculation with a selected polymer or chemical, and then separated by gravity. These solids will most likely be a smaller quantity but carry higher levels of contamination than the original soil and, therefore, should be targeted for either further treatment or secure disposal. Residual solids from recycle water cleanup may require post-treatment to ensure safe disposal or release. Water used in the soil washing process is treated by conventional wastewater treatment processes to enable it to be recycled for further use.

Wastewater treatment (3) processes the blowdown or discharge water to meet regulatory requirements for heavy metal content, organics, total suspended solids, and other parameters. Whenever possible, treated water should be recycled to the soil washing process. Residual solids, such as spent ion exchange resin and carbon, and sludges from biological treatment may require post-treatment to ensure safe disposal or release.

Vapor treatment may be needed to control air emissions from excavation, feed preparation, and extraction; these emissions are collected and treated, normally by carbon adsorption or incineration, before being released to the atmosphere.

### Process Residuals

There are four main waste streams generated during soil washing: contaminated solids from the soil washing unit, wastewater, wastewater treatment sludges and residuals, and air emissions.

Contaminated clay fines and sludges resulting from the process may require further treatment using acceptable treatment technologies (such as incineration, low temperature desorption, solidification and stabilization, biological treatment, and chemical treatment) in order to permit disposal in an environmentally safe manner [16]. Blowdown water may need treatment to meet appropriate discharge standards prior to release to a local, publicly owned wastewater treatment works or receiving stream. To the maximum extent practical, this water should be recovered and reused in the washing process. The wastewater treatment process sludges and residual solids, such as spent carbon and spent ion exchange resin, must be appropriately treated before disposal. Any air emissions from the waste preparation area or the washing unit should be collected and treated, as appropriate to meet applicable regulatory standards.

### Site Requirements

Access roads are required for transport of vehicles to and from the site. Typically, mobile soil washing process systems are located onsite and may occupy up to 4 acres for a 20 ton/hour unit; the exact area will depend on the vendor system selected, the amount of soil storage space, and/or the number of tanks or ponds needed for washwater preparation and wastewater treatment.

Typical utilities required are water, electricity, steam, and compressed air. An estimate of the net (consumed) quantity of local water required for soil washing, assuming water cleanup and recirculation, is 130,000-800,000 gallons per 1,000 cubic yards (2,500,000 lbs.) of soil (approximately 0.05-0.3 gallons per pound).

Because contaminated soils are usually considered hazardous, their handling requires that a site safety plan be developed to provide for personnel protection and special handling measures during soil washing operations.

Moisture content of soil must be controlled for consistent handling and treatment; this can be accomplished, in part, by covering excavation, storage, and treatment areas.

Fire hazard and explosion considerations should be minimal, since the soil washing fluid is predominantly water. Generally, soil washing does not require storing explosive, highly reactive materials.

Climatic conditions such as annual or seasonal precipitation cause surface runoff and water infiltration. Berms, dikes, or other runoff control methods may be required. Cold weather freezing must also be considered for aqueous systems and soil excavation operations.

Proximity to a residential neighborhood will affect plant noise requirements and emissions permitted in order to minimize their impact on the population and meet existing rules and regulations.

If all or part of the processed soil is to be redeposited at the site, storage areas must be provided until analytical data are obtained that verifies that treatment standards have been achieved. Onsite analytical capability could expedite the storage/final disposition process. However, soil washing might be applied to many different contaminant groups. Therefore, the analytes that would have to be determined are site specific, and the analytical equipment that must be available will vary from site to site.

### Performance Data

The performances of soil washing processes currently shown to be effective in specific applications are listed in Table 3 [1][2][4][7 through 13]. Also listed are the range of particle size treated, contaminants successfully extracted, byproduct wastes generated, extraction agents used, major extraction equipment for each system, and general process comments.

The data presented for specific contaminant removal effectiveness were obtained from publications developed by the respective soil washing system vendors. The quality of this information has not been determined.

RCRA Land Disposal Restrictions (LDRs) that require treatment of wastes to best demonstrated available technology (BDAT) levels prior to land disposal may sometimes be determined to be applicable or relevant and appropriate requirements (ARARs) for CERCLA response actions. The soil washing technology can produce a treated waste that meets treatment levels set by BDAT, but may not reach these treatment levels in all cases. The ability to meet required treatment levels is dependent upon the specific waste constituents and the waste matrix. In cases where soil washing does not meet these levels, it still may, in certain situations, be selected for use at the site if a treatability variance establishing alternative treatment levels is obtained. EPA has made the treatability variance process available in order to ensure that LDRs do not unnecessarily restrict the use of alternative and innovative treatment technologies. Treatability variances may be justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil

and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.3-06FS) [16], and Superfund LDR Guide #68, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.3-07FS) [17]. Another approach could be to use other treatment techniques in series with soil washing to obtain desired treatment levels.

### Technology Status

During 1986-1989, soil washing technology was selected as one of the source control remedies at eight Superfund sites: Vineland Chemical, New Jersey; Koppers Oroville Plant, California; Cape Fear Wood Preserving, North Carolina; Ewan Property, New Jersey; Tinkam Garage, New Hampshire; United Scrap, Ohio; Koppers/Texarkana, Texas; and South Cavalcade, Texas [18].

A large number of vendors provide a soil washing technology. Table 3 shows the current status of the technology for 14 vendors. The front portion of the table indicates the scale of equipment available from the vendor and gives some indication of the vendor's experience by showing the year it began operation.

Processes evaluated or used for site cleanups by the EPA are identified separately by asterisks in the Proprietary Vendor Process/EPA column in Table 3.

The following soil washing processes that are under development have not been evaluated by the EPA or included

in Table 3. Environmental Group, Inc. of Webster, Texas, has a process that reportedly removes metals and oil from soil. Process efficiency is stated as greater than 99 percent for lead removal from soils cleaned in Concord, California; greater than 99 percent for copper, lead, and zinc at a site in Racine, Wisconsin; and 94 percent for PCB removal on a Morrison-Knudsen Company project. The process does not appear to separate soil into different size fractions. Detailed information on the process is not available. Consolidated Sludge Company of Cleveland, Ohio, has a soil washing system planned that incorporates their Mega-sludge Press at the end of the process for dewatering solids. The system has not yet been built.

Vendor-supplied treatment costs of the processes reviewed ranged from \$50 to \$205 per ton of feed soil. The upper end of the cost range includes costs for soil residue disposal.

### EPA Contact

Technology-specific questions regarding soil washing may be directed to:

Michael Gruenfeld  
U.S. EPA, Releases Control Branch  
Risk Reduction Engineering Laboratory  
Woodbridge Avenue, Building 10  
Edison, New Jersey 08837  
Telephone FTS 340-6625 or (201) 321-6625.

Table 3. Summary of Performance Data and Technology Status - Part I

Proprietary Vendor Process/EPA	Highest Scale of Operation	Year Operation Began	Range of Particle Size Treated	Contaminants Extracted From Soil	Extraction Agent(s)
<b>U.S. Processes</b>					
(1) SOIL CLEANING COMPANY OF AMERICA [5][15, p. 2]	Full scale 15 tons/hr	1988	Bulk soil	Oil and grease	Hot water with surfactant
(2)* BIOTROL SOIL TREATMENT SYSTEM (BSTS) [4, p. 6][12]	Pilot scale 500 lbs/hr	Fail, 1987	Above clay size and below 0.5 in. Some cleaning of fine particles in bio-reactor	Organics - pentachlorophenol, creosote, naphthalene, pyrene, fluorene, etc.	Proprietary conditioning chemicals
(3) EPA'S MOBILE COUNTER-CURRENT EXTRACTOR [9][5, p. 5]	Pilot scale 4.1 tons/hr	Modified with drum washer and shakedown-1982 Full Scale-1986	2-25 mm in drum washer <2 mm in four-stage extractor	Soluble organics (phenol, etc.) Heavy metals (Pb, etc.)	Various solvents, additives, surfactants, redox acids and bases Chelating agent (EDTA)
(4)* EPA'S FIRST GENERATION PILOT DRUM SCREEN WASHER [10, p. 8]	Pilot scale	1988	Overize (>2 mm) removed prior to treatment	Petroleum hydrocarbons	Biodegradable surfactant (aqueous slurry)
(5)* MTA REMEDIAL RESOURCES [11][15, p. 2]	Bench scale	N/A	Overize removed prior to treatment	Organics (oil) Heavy metals (inorganics) removed using counter-current decantation with leaching	Surfactants and alkaline chemicals added upstream of froth flotation cells. Acid for leaching.
<b>Non-U.S. Processes</b>					
(6) ECOTECHNIEK BV [2, p. 17]	Commercial 100 ton/hr max	1982	Sandy soil	Crude oil	None. Water-sand slurry heated to 90°C max. with steam.
(7) BODEMSANERING NEDERLAND BV (BSN) [2, p. 17]	Commercial 20 ton/hr	1982	>100 mm removed No more than 20% <63 µm Sludge <30 µm not cleaned	Oil from sandy soil	None. Uses high pressure water jet for soils washing.
(8) HARBAUER [2, p. 20][7, p. 5]	Commercial 15-20 tons/hr	Lab - 1985 Commercial - 1986 With fines removal - 1987	15 µm - 5mm Pre-treatment: coarse screens, electromagnet blade washer	Mostly organics Limited heavy metals removal experience	Hydraulically produced oscillation/vibration Surfactants Acid/base
(9) HWZ BODEMSANERING BV [2, p. 17]	Commercial 20-25 tons/hr	1984	<10 mm and >63 µm	Cyanide, Chlorinated HC, some heavy metals, PNA	Sodium Hydroxide to adjust pH Surfactants
(10) HEIJMAN MILIEUTECHNIEK BV [2,p.17][7, p. 6]	Pilot scale 10-15 tons/hr	1985	<10 mm and no more than 30% <63 µm	Cyanide, heavy metals, mineral oil (water immiscible hydrocarbons)	Proprietary extraction agents. Hydrogen Peroxide (H <sub>2</sub> O <sub>2</sub> ) added to react with extracted CN to form CO <sub>2</sub> and NH <sub>3</sub>
(11) HEIDEMIJ FROTH FLOTATION [7, p. 8]	Full scale	N/A	<4 mm and no more than 20% <50 µm	Cyanide, heavy metals, chlorinated HCs, oil, toluene, benzene, pesticides, etc.	Proprietary Surfactants and other proprietary chemicals

\*Process evaluated or used for site cleanup by the EPA. N/A = Not available.

Table 3. Summary of Performance Data and Technology Status - Part I (continued)

Proprietary Vendor Process/EPA	Highest Scale of Operation	Year Operation Began	Range of Particle Size Treated	Contaminants Extracted From Soil	Extraction Agent(s)
<b>Non U.S. Processes (continued)</b>					
(12) EWH ALSEN - BREITENBURG Dekomat System [2, p. 20]	Pilot scale 8-10 cu. m/hr	N/A	<80 mm Clays treated offsite	Oil from sandy soil	Proprietary
(13) TBSG INDUSTRIEVEITETUNGEN Oil Crep I System [7, p. 7]	Pilot scale	1986	Sand <50 mm Particles <100 µm treated offsite	Hydrocarbon and oil	Proprietary combination of surfactants, solvents, and aromatic hydrocarbons
(14) KLOCKNER UMWELTECHNIK Jet-Modified BSN [2, p. 20]	Pilot scale	N/A	No more than 20% <63 µm	Aliphatics and aromatics with densities < water, volatile organics, some other hydrocarbons	None. Soil blasted with a water jet (at 5,075 psi)

Table 3. Summary of Performance Data and Technology Status - Part II

Proprietary Vendor Process/EPA	Byproduct Wastes Generated	Extraction Equipment	Efficiency of Contaminant Removal	Additional Process Comments
<b>U.S. Processes</b>				
(1) SOIL CLEANING OF AMERICA	Wet oil	Screw conveyors	Contaminant Oil and grease Removal Efficiency % 50-83 Residual ppm 250-600	Three screw conveyors operated in series, hot water with surfactant injected into each stage. Final soil rinse on a fourth screw conveyor.
(2)* BIOTROL SOIL TREATMENT SYSTEM (BSTS)	Oil and grease Sludge from biological treatment	Agitated conditioning tank Froth flotation Slurry bioreactor	For the case presented: 90-95% for Pentachlorophenol; to residuals <115 ppm. 85-95% for most other organics; to residuals <1 ppm.	Dewatered clays and organics to be treated offsite by incineration, solidification, etc. Washed soil was approx. 78% of feed. Therefore, significant volume reduction was achieved.
(3) EPA'S MOBILE COUNTER-CURRENT EXTRACTOR	Clay fraction Recovered organics (extractor skimmings) Spent carbon (oversize)	Drum screen Water knife Soil scrubber 4-Stage Counter-current chemical extractor	Contaminant Phenol AS <sub>2</sub> O <sub>3</sub> Removal Efficiency % 90 from in. soil 80 from or. soil 50-80 Residual ppm 1 96 0.5-1.3	Clay fraction treated elsewhere.
(4)* EPA'S FIRST GENERATION PILOT DRUM SCREEN WASHER (PDSW)	Sludge Flocculated fines	Drum screen washer	Soil Size Contam-Fraction mm Oil and grease 0.25-2 <0.25 Removal Effic. % 99 90 Residual ppm <5 2400	Process removal efficiency increases if extracting medium is heated. Install wet classifiers beneath the PDSW to remove waste water from treated soil. Auger classifiers are required to discharge particles effectively.
(5)* MTA REMEDIAL RESOURCES (MTARRI) Froth Flotation	Flocculation froth	Reagent blend tank Flotation cells Counter-current decantation	Contaminant Volatile organics Semivolatile organics Most fuel products Removal Efficiency % 98-99+ 98-99+ 98-99+ Residual ppm < 50 < 250 < 2200	Flotation cells linked by underflow weir gates. Induced air blown down a center shaft in each cell. Continuous flow operation. Froth contains 5-10 wt% of feed soil.

\*Process evaluated or used for site cleanup by the EPA. N/A = Not available.

Table 3. Summary of Performance Data and Technology Status - Part II (continued)

Proprietary Vendor Process/EPA	Byproduct Wastes Generated	Extraction Equipment	Efficiency of Contaminant Removal	Additional Process Comments
<b>Non U.S. Processes</b>				
(6) ECOTECHNIEK BV	Wet oil	Jacketed, agitated tank	About 90% 20,000 ppm residual oil	Effectiveness of process dependent on soil particle size and type of oil to be separated.
(7) BODEMSANERING NEDERLAND BV (BSN)	Oil/organics recovered from wastewater fines	Water jet	Selected results: Contaminant Removal Efficiency % Residual ppm Aromatics >81 >45 PNAs 95 15 Crude oil 97 2300	No comments
(8) HARBAUER OF AMERICA	Carbon which may contain contaminants	Conditioning tank  Low frequency vibration unit	Contaminant Removal Efficiency % Residual ppm Organic-Cl ND Tot. organics 96 159-201 Tot. phenol 86-94 7-22.5 PAH 86-90 91.4-97.5 PCB 84-88 0.5-1.3	Vibrating screw conveyor used.  Cleaned soil separated from extractant liquor in stages; coarse soil by sedimentation, medium fraction in hydroclone, fines (15-20 µm) by vacuum filter press.
(9) HWZ BODEMSANERING BV	Fines  Sludge containing iron cyanide  Large particles — carbon, wood, grass	Scrubber (for caustic addition)  Upflow classifier	Contaminant Removal Efficiency % Residual ppm CN 95 5-15 PNAs 98 15-20 Chlorin-HC 98 <1 Heavy metals 75 75-125	When the fines fraction (<63 µm) is greater than 20%, the process is not economical. HWZ has had some problems in extracting PNAs and oily material.
(10) HEIJMAN MILIEUTECHNIEK BV	Flocculated fines sludge  Oil (if any) and silt	Mix tank followed by soils fraction equipment — hydroclones, sieves, tilt plate separators	Contaminant Removal Efficiency % Residual ppm Cyanide 93-99 <15 Heavy metal cations approx. 70 <200	Process works best on sandy soils with a minimum of humus-like compounds. Because no sand or charcoal filters are employed by Heijmans, the system does not remove contaminants such as chlorinated hydrocarbons.
(11) HEIDEMIJ FROTH FLOTATION	Contaminated float	Conditioning tank  Froth flotation tanks	Contaminant Removal Efficiency % Residual ppm Cyanide >95 5 Heavy metals >90 avg >150 Chlorin-HC >99 0.5 Oil >99 20	Process has broad application for removing hazardous materials from soil. Most experience has been on a laboratory scale.
(12) EWH ALSEN - BREITENBURG Dekomat System	Recovered oil  Flocculated fines (sludge)	High-shear stirred tank	About 95% oil removed	Cleaned soil from high shear stirred tank is separated into fractions using vibrating screens, screw classifiers, hydroclones, and sedimentation tanks.
(13) TBSC INDUSTRIEVEITET-UNGEN Oil Crep I System	Oil phase containing Oil Crep I	Screw mixer followed by a rotating separation drum for oil recovery	>95% Removal of hydrocarbons has been achieved. Results are influenced by other contaminants present.	Oil Crep system was used successfully in Flensburg, FRG (in 1986) to remove PCBs, PAHs, and other hydrocarbons.
(14) KLOCKNER UMWELTECHNIK High Pressure Water Jet-Modified BSN	Oil/organics recovered from wastewater fines  Sludge	Water jet - circular nozzle arrangement	Selected results: Contaminant Removal Efficiency % Residual ppm HC 96.3 82.05 Chlorin-HC >75. <0.01 Aromatics 99.8 <0.02 PAHs 95.4 15.48 Phenol >99.8 <0.01	No comments

\*Process evaluated or used for site cleanup by the EPA. N/A = Not available.

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## Engineering Bulletin Solvent Extraction

### Purpose

Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) mandates the Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as a principal element." The Engineering Bulletins are a series of documents that summarize the latest information available on selected treatment and site remediation technologies and related issues. They provide summaries of and references for the latest information to help remedial project managers, on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site characteristics needed to evaluate a technology for potential applicability to their Superfund or other hazardous waste site. Those documents that describe individual treatment technologies focus on remedial investigation scoping needs. This bulletin replaces the one on solvent extraction issued in September 1990.

### Abstract

Solvent extraction does not destroy hazardous contaminants, but is a means of separating those contaminants from soils, sludges, and sediments, thereby reducing the volume of the hazardous material that must be treated. Generally it is used as one in a series of unit operations and can reduce the overall cost for managing a particular site. It is applicable to organic contaminants and is generally not used for treating inorganic compounds and metals [1, p.64].\* The technology generally uses an organic chemical as a solvent [2, p.30], and differs from soil washing, which generally uses water or water with wash improving additives. Commercial-scale units are in operation. There is no clear solvent extraction technology leader because of the solvent employed, type of equipment used, or mode of operation. The final determination of the lowest cost/best performance alternative will be more site specific than

process dominated. Vendors should be contacted to determine the availability of a unit for a particular site. This bulletin provides information on the technology applicability, the types of residuals produced, the latest performance data, site requirements, the status of the technology, and sources for further information.

### Technology Applicability

Solvent extraction has been shown to be effective in treating sediments, sludges, and soils containing primarily organic contaminants such as polychlorinated biphenyls (PCBs), volatile organic compounds (VOCs), halogenated solvents, and petroleum wastes. The technology is generally not used for extracting inorganics (i.e., acids, bases, salts, heavy metals). Inorganics usually do not have a detrimental effect on the extraction of the organic components, and sometimes metals that pass through the process experience a beneficial effect by changing to a less toxic or leachable form. The process has been shown to be applicable for the separation of the organic contaminants in paint wastes, synthetic rubber process wastes, coal tar wastes, drilling muds, wood treating wastes, separation sludges, pesticide/insecticide wastes, and petroleum refinery oily wastes [3].

Table 1 lists the codes for the specific Resources Conservation and Recovery Act (RCRA) wastes that have been treated by the technology [3][4, p.11]. The effectiveness of solvent extraction on general contaminant groups for various matrices is shown in Table 2 [5, p.1][1, p.10]. Examples of constituents within contaminant groups are provided in Reference 1 "Technology Screening Guide for Treatment of CERCLA Soils and Sludges." This table is based on the current available information or professional judgment where no information was available. The proven effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment efficiencies achieved will be acceptable at other sites. For the ratings used for this table, demonstrated effectiveness means that at some scale treatability was tested to show the technology was effective for that particular contaminant

\* [reference number, page number]

**Table 1**  
**RCRA Codes for Wastes Treated**  
**by Solvent Extraction**

Wood Treating Wastes	K001
Water Treatment Sludges	K044
Dissolved Air Flotation (DAF) Float	K048
Slop Oil Emulsion Solids	K049
Heat Exchanger Bundles Cleaning Sludge	K050
American Petroleum Institute (API) Separator Sludge	K051
Tank Bottoms (leaded)	K052
Ammonia Still Sludge	K060
Pharmaceutical Sludge	K084
Decanter Tar Sludge	K089
Distillation Residues	K101

and matrix. The ratings of potential effectiveness or no expected effectiveness are both based upon expert judgment. Where potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminated group in a particular matrix. When the technology is not applicable or will probably not work for a particular combination of contaminant group and matrix, a no expected effectiveness rating is given.

### Limitations

Organically bound metals can co-extract with the target organic pollutants and become a constituent of the concentrated organic waste stream. This is an unfavorable occurrence because the presence of metals can restrict both disposal and recycle options.

The presence of detergents and emulsifiers can unfavorably influence extraction performance and material throughput. Water soluble detergents found in some raw wastes (particularly municipal) will dissolve and retain organic pollutants in competition with the extraction solvent. This can impede a system's ability to achieve low concentration treatment levels. Detergents and emulsifiers can promote the evolution of foam, which hinders separation and settling characteristics and generally decreases materials throughput. Although methods exist to combat these problems, they will add to the process cost.

When treated solids leave the extraction subsystem, traces of extraction solvent are present [6, p.125]. The typical extraction solvents used in currently available systems either volatilize quickly from the treated solids or biodegrade easily. Ambient air monitoring can be employed to determine if the volatilizing solvents present a problem.

The types of organic pollutants that can be extracted successfully depend, in part, on the nature of the extraction solvent. Treatability tests should be conducted to determine which solvent or combination of solvents is best suited

**Table 2**  
**Effectiveness of Solvent Extraction on**  
**General Contaminant Groups for**  
**Soil, Sludges, and Sediments**

Contaminant Groups		Effectiveness		
		Soil	Sludge	Sediments
Organic	Halogenated volatiles	▼	▼	▼
	Halogenated semivolatiles	■	■	■
	Nonhalogenated volatiles	■	■	▼
	Nonhalogenated semivolatiles	■	■	■
	PCBs	■	■	■
	Pesticides	■	▼	▼
	Dioxins/Furans	▼	▼	▼
	Organic cyanides	▼	▼	▼
	Organic corrosives	▼	▼	▼
	Inorganic	Volatile metals	□	□
Nonvolatile metals		□	□	□
Asbestos		□	□	□
Radioactive materials		□	□	□
Inorganic corrosives		□	□	□
Inorganic cyanides		□	□	□
Reactive	Oxidizers	□	□	□
	Reducers	□	□	□
■ Demonstrated Effectiveness: Successful treatability test at some scale completed ▼ Potential Effectiveness: Expert opinion that technology will work □ No Expected Effectiveness: Expert opinion that technology will not work				

to the site-specific matrix and contaminants. In general, solvent extraction is least effective on very high molecular weight organics and very hydrophilic (having an affinity for water) substances.

Some commercially available extraction systems use solvents that are flammable, toxic, or both [7, p.2]. However, there are standard procedures used by chemical companies, service stations, etc. that can be used to greatly reduce the potential for accidents. The National Fire Protection Association (NFPA) Solvent Extraction Plants Standard (No. 36) has specific guidelines for the use of flammable solvents [8, p. 4-60].

### Technology Description

Some type of pretreatment is necessary. This may involve physical processing and, if needed, chemical conditioning after the contaminated medium has been removed from its original location. Soils and sediments can be removed by excavation or dredging. Liquids and pumpable sludges can be removed and transported using diaphragm or positive displacement pumps.

Any combination of material classifiers, shredders, and crushers can be used to reduce the size of particles being fed into a solvent extraction process. Size reduction of particles increases the exposed surface area, thereby increasing extraction efficiency. Caution must be applied to ensure that an overabundance of fines does not lead to problems with phase separation between the solvent and treated solids. The optimum particle size varies with the type of extraction equipment used.

Moisture content may affect the performance of a solvent extraction process depending on the specific system design. If the system is designed to treat pumpable sludges or slurries, it may be necessary to add water to solids or sediments to form a pumpable slurry. Other systems may require reduction of the moisture content in order to treat contaminated media effectively.

Chemical conditioning may be necessary for some wastes or solvent extraction systems. For example, pH adjustment may be necessary for some systems to ensure solvent stability or to protect process equipment from corrosion.

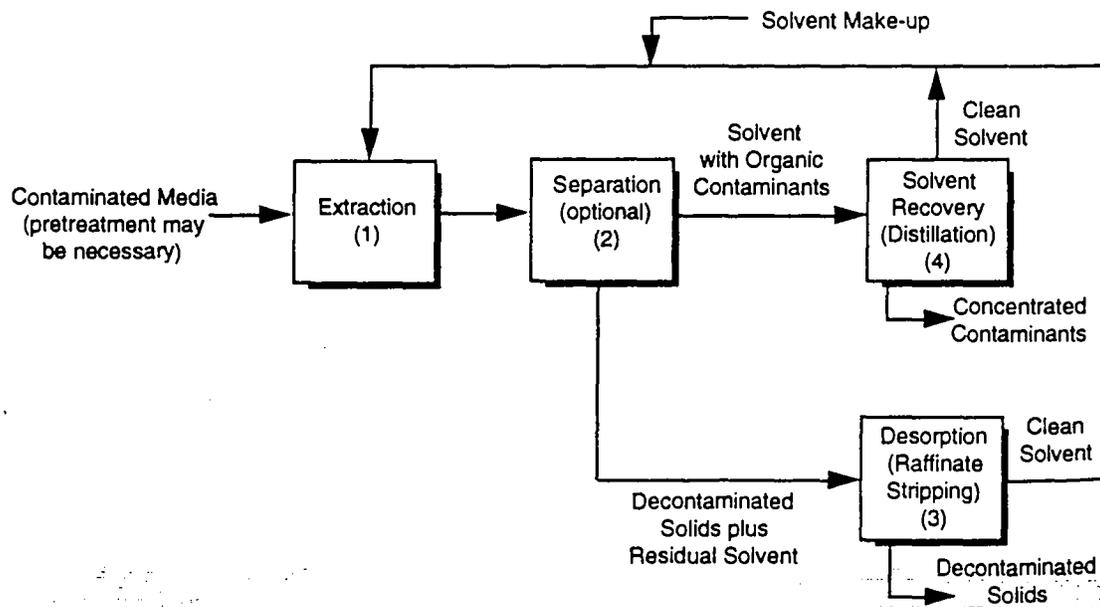
Depending on the nature of the solvent used, solvent extraction processes may be divided into three general types. These include processes using the following types of solvents: standard, liquefied gas (LG), and critical solution temperature (CST) solvents. Standard solvent processes use alkanes, alcohols, ketones, or similar liquid solvents at

or near ambient temperature and pressure. These types of solvents are used to treat contaminated solids in much the same way as they are commonly used by analytical laboratories to extract organic contaminants from environmental samples. LG processes use propane, butane, carbon dioxide, or other gases which have been pressurized at or near ambient temperature. Systems incorporating CST solvents utilize the unique solubility properties of those solvents. Contaminants are extracted at one temperature where the solvent and water are miscible and then the concentrated contaminants are separated from the decanted liquid fraction at another temperature where the solvent has minimal solubility in water. Triethylamine is an example of a CST solvent. Triethylamine is miscible in water at temperatures less than 18°C and only slightly miscible above this temperature.

A general schematic diagram of a standard solvent extraction process is given in Figure 1 [9, p.5]. The systems are operated in either batch or continuous mode and consist of four basic process steps: (1) extraction, (2) separation, (3) desorption, and (4) solvent recovery.

In the first step, solids are loaded into an extraction vessel and the vessel is purged with an inert gas. Solvent is then added and mixed with the solids. Designs of vessels used for the extraction stage vary from countercurrent continuous-flow systems to batch mixers. The ratio of solvent-to-solids also varies, but normally remains within a range from 2:1 to 5:1. Solvent selection may also be

**Figure 1**  
**General Schematic of a Standard Solvent Extraction Process**



consideration. Ideally, a hydrophilic (having an affinity for water) solvent or mixture of hydrophilic/hydrophobic (lacking an affinity for water) solvents is mixed with the solids. This hydrophilic solvent or solvent mixture will dewater the solids and solubilize organic materials. Subsequent extractions may use only hydrophobic solvents. The contact time and type of solvent used are contaminant-specific and are usually selected during treatability studies.

Depending on the type of contaminated medium being treated, three phases may exist in the extractor: solid, liquid, and vapor. Separation of solids from liquids can be achieved by allowing solids to settle and pumping the contaminant-containing solvent to the solvent recovery system. If gravity separation is not sufficient, filtration or centrifugation may be necessary. Residual solids will normally go through additional solvent washes within the same vessel (for batch systems) or in duplicate reaction vessels until cleanup goals are achieved. The settled solids retain some solvent which must be removed. This is often accomplished by thermal desorption.

Solvent recovery occurs in the final process step. Contaminant-laden solvent, along with the solvent vapors removed during the desorption or raffinate stripping stage, are transferred to a distillation system. To facilitate separation through volatilization and condensation, low boiling point solvents are used for extraction. Condensed solvents are normally recycled to the extractor; this conserves solvent and reduces costs. Water may be evaporated or discharged from the system, and still bottoms, which contain high boiling point contaminants, are recovered for future treatment.

In Figure 2, a general schematic diagram of an LG extraction process is shown [9, p.7]. The same basic steps associated with standard solvent processes are used with LG systems; however, operating conditions are different. Increased pressure and temperature are required in order for the solvent to take on LG characteristics.

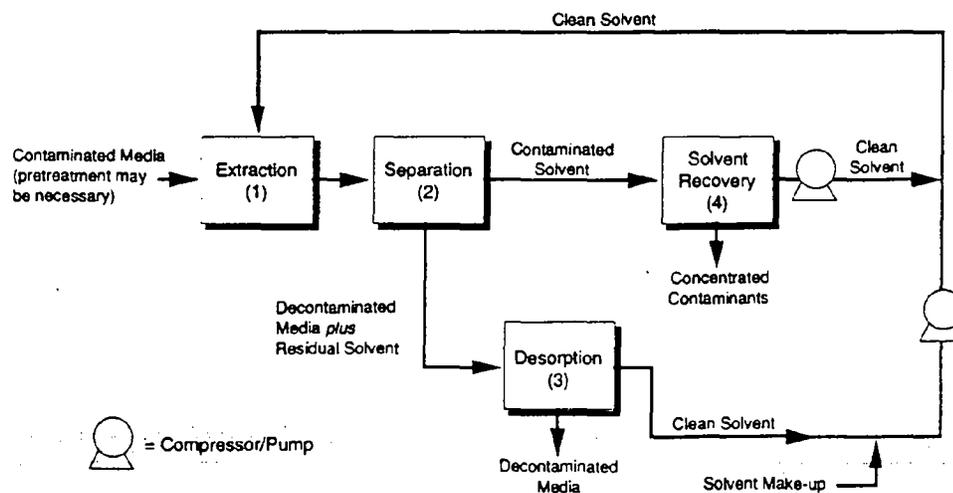
Pumps or screw augers move the contaminated feed through the process. In the extractor, the slurry is vigorously mixed with the hydrophobic solvent. The extraction step can involve multiple stages, with feed and solvent moving in countercurrent directions.

The solvent/solids slurry is pumped to a decanting tank where phase separation occurs. Solids settle to the bottom of the decanter and are pumped to a desorber. Here, a reduction in pressure vaporizes the solvent, which is recycled, and the decontaminated slurry is discharged.

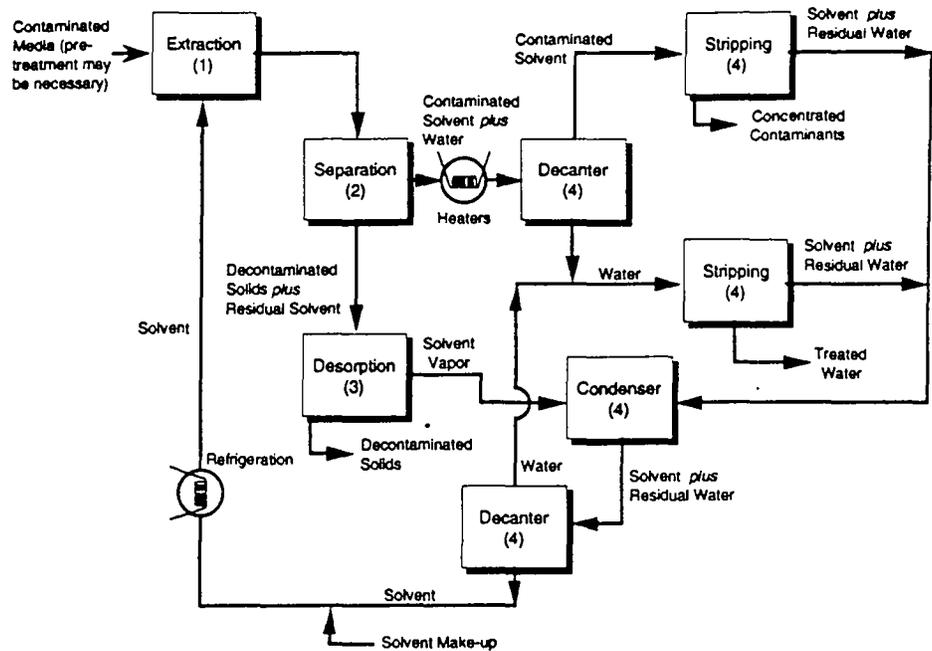
Contaminated solvent is removed from the top of the decanter and is directed to a solvent recovery unit. A reduction of pressure results in separating organic contaminants from the solvent. The organic contaminants remain in the liquid phase and the solvent is vaporized and removed. The solvent is then compressed and recycled to the extractor. Concentrated contaminants are removed for future treatment.

CST processes use extraction solvents for which solubility characteristics can be manipulated by changing the temperature of the fluid. Such solvents include those binary (liquid-liquid) systems that exhibit an upper CST (sometimes referred to as upper consolute temperature), a

Figure 2  
General Schematic of an LG Solvent Extraction Process



**Figure 3**  
**General Schematic of a CST Solvent Extraction Process**



lower CST (sometimes referred to as lower consolute temperature), or both. For such systems, mutual solubilities of the two liquids increase while approaching the CST. At or beyond the CST, the two liquids are completely miscible in each other. Figure 3 is a general schematic of a typical lower CST solvent extraction process. Again, the same four basic process steps are used; however, the solvent recovery step consists of numerous unit operations [9, p.8].

### Process Residuals

Three main product streams are produced from solvent extraction processes. These include treated solids, concentrated contaminants (usually the oil fraction), and separated water. Each of these streams should be analyzed to determine its suitability for recycle, reuse, or further treatment before disposal. Treatment options include: incineration, dehalogenation, pyrolysis, etc.

Depending on the system used, the treated solids may need to be dewatered, forming a dry solid and a separate water stream. The volume of product water depends on the inherent dewatering capability of the individual process, as well as the process-specific requirements for feed slurring. Some residual solvent may remain in the soil matrix. This can be mitigated by solvent selection, and if necessary, an

additional separation stage. Depending on the types and concentrations of metal or other inorganic contaminants present, post-treatment of the treated solids by some other technique (e.g., solidification/stabilization) may be necessary. Since the organic component has been separated, additional solids treatment should be simplified.

The organic solvents used for extraction of contaminants normally will have a limited effect on mobilizing and removing inorganic constituents such as metals. In most cases, inorganic constituents will be concentrated and remain with the treated solids. If these remain below cleanup levels, no further treatment may be required. Alternatively, if high levels of leachable inorganic contaminants are present in the product solids, further treatment such as solidification/stabilization, soil washing, or disposal in a secured landfill may be required. The exception here is organically bound metals. Such metals can be extracted and recovered with the concentrated contaminant (oil) fraction. High concentrations of specific metals, such as lead, arsenic, and mercury, within the oil fraction can restrict disposal and recycle options.

Concentrated contaminants normally include organic contaminants, oils and grease (O&G), naturally occurring organic substances found in the feed solids, and some extraction fluid. Concentration factors may reduce the

overall volume of contaminated material to 1/10,000 of the original waste volume depending on the volume of the total extractable fraction. The highly-concentrated waste stream which results is either destroyed or collected for reuse. Incineration has been used for destruction of this fraction. Dechlorination of contaminants such as PCBs remains untried, but is a possible treatment. Resource recovery may also be a possibility for waste streams which contain useful organic compounds.

Use of hydrophilic solvents with moisture-containing solids produces a solvent/water mixture and clean solids. The solvent and water mixture are separated from the solids by physical means such as decanting. Some fine solids may be carried into the liquid stream. The solvent is normally separated from the water by distillation [10]. The water produced via distillation will contain water-soluble contaminants from the feed solids, as well as trace amounts of residual solvent and fines which passed through the separation stage. If the feed solids were contaminated with emulsifying agents, some organic contaminants may also remain with the water fraction. Furthermore, the volume of the water fraction can vary significantly from one site to another, and with the use of dewatering as a pretreatment. Hence, treatment of this fraction is dependent upon the concentration of contaminants present in the water and the flowrate and volume of residual water. In some cases, direct discharge to a publicly owned treatment works (POTW) or stream may be acceptable; alternatively, onsite aqueous treatment systems may be used to treat this fraction prior to discharge.

Solvent extraction units are designed to operate without air emissions. Nevertheless, during a recent SITE Demonstration Test, solvent concentrations were detected in 2 of 23 samples taken from the offgas vent system [11]. Corrective measures were taken to remedy this. In addition, emissions of dust and fugitive contaminants could occur during excavation and materials handling operations.

### Site Requirements

Solvent extraction units are transported by trailers. Therefore, adequate access roads are required to get the units to the site. Typical commercial-scale units of 25 to 125 tons per day (tpd) require a setup area of 1,500 to 10,000 square feet [12]. NFPA recommends an exclusion zone of 50 feet around solvent extraction systems operating with flammable solvents [8, p. 4-61].

Standard 440V three-phase electrical service is needed. Depending on the type of system used, between 50 and 10,000 gallons per day (gpd) of water must be available at the site [12]. The quantity of water needed is vendor and site specific.

Contaminated soils or other waste materials are hazardous and their handling requires that a site safety plan be developed to provide for personnel protection and special

handling measures. Storage should be provided to hold the process product streams until they have been tested to determine their acceptability for disposal or release. Depending upon the site, a method to store waste that has been prepared for treatment may be necessary. Storage capacity requirements will depend on waste volume.

Onsite analytical equipment for conducting O&C analyses and a gas chromatograph capable of determining site-specific organic compounds for performance assessment will shorten analytical turnaround time and provide better information for process control.

### Performance Data

Full-scale and pilot-scale performance data are currently available from only a few vendors: CF Systems, Resources Conservation Company (RCC), Terra-Kleen Corporation, and Dehydro-Tech Corporation. Lab-scale performance data are also available from these and other vendors. Data from Superfund Innovative Technology Evaluation (SITE) demonstrations are peer-reviewed and have been acquired in independently verified tests with stringent quality standards. Likewise, performance data

**Table 3**  
Contaminant Concentrations in Typical Solids Treated by CF Systems' Process at Port Arthur, Texas Refinery

Compound	mg/kg (ppm)	BDAT
Benzene	BDL	14
Ethylbenzene	BDL	14
Toluene	BDL	14
Xylenes	1.5	22
Naphthalene	2.2	42
Phenanthrene	3.4	34
2-Methylphenol	BDL	6.2
Anthracene	BDL	28
Benzo(a)anthracene	BDL	28
Pyrene	1.6	36
Chrysene	BDL	15
Benzo(a)pyrene	BDL	12
Phenol	BDL	3.6
4-Methylphenol	BDL	6.2
Bis(2-E.H.)phthalate	BDL	7.3
Di-n-butyl phthalate	BDL	3.6

BDL below detection limits.

from remedial actions at Superfund sites or EPA sponsored treatability tests are assumed to be valid. The quality of other data has not been determined.

The CF Systems' 25-tpd commercial unit treated refinery sludge at Port Arthur, Texas, and operated with an on-line availability of greater than 90 percent. Extraction efficiencies for BTX and polynuclear aromatic hydrocarbon (PAH) compounds were greater than 99 percent. As demonstrated by Table 3, the typical level of organics in the treated solids met or exceeded the EPA Best Demonstrated Available Technology (BDAT) standards required for these listed refinery wastes [13].

Pilot-scale activities include the United Creosoting Superfund Site treatability study and the SITE demonstration at New Bedford Harbor, Massachusetts. During the spring of 1989, CF Systems conducted a pilot-scale treatability study for EPA Region VI and the Texas Water Commission at the United Creosoting Superfund Site in Conroe, Texas. The treatability study's objective was to evaluate the effectiveness of the CF Systems process for treating soils contaminated with pentachlorophenol (PCP), dioxins, and creosote-derived organic contaminants, such as PAHs. Treatment data from the field demonstration (Table 4) show that the total PAH concentration in the soil was reduced by more than 95 percent. Untreated soil had total PAH concentrations ranging from 2,879 to 2,124 mg/kg [13].

The SITE demonstration was conducted during the fall

**Table 4**  
CF Systems' Performance Data at United Creosote Superfund Site

Compound	Feed Soil (mg/kg)	Treated Soil (mg/kg)	Reduction (percent)
<b>PAHs</b>			
Acenaphthene	360	3.4	99
Acenaphthylene	15	3.0	80
Anthracene	330	8.9	97
Benzo(a)anthracene	100	7.9	92
Benzo(a)pyrene	48	12	75
Benzo(b)fluoranthene	51	9.7	81
Benzo(g,h,i)perylene	20	12	40
Benzo(k)fluoranthene	50	17	66
Chrysene	110	9.1	92
Dibenzo(a,h)anthracene	ND	4.3	NA
Fluoranthene	360	11	97
Fluorene	380	3.8	99
Indeno(1,2,3-cd)pyrene	19	11	58
Naphthalene	140	1.5	99
Phenanthrene	590	13	98
Pyrene	360	11	97
<b>Total PAH concentration</b>	<b>2879</b>	<b>122.6</b>	<b>96</b>

Notes: mg/kg on a dry weight basis. ND indicates not detected. NA indicates not applicable.

**Table 5**  
Extraction of New Bedford Harbor Sediments Using CF Systems' Process

Test #	Initial PCB Concentration (ppm)	Final PCB Concentration (ppm)	Reduction (Percent)	Number of Passes Through Extractor
1	350	8	98	9
2	288	47	84	1
3	2,575	200	92	6

**Table 6**  
B.E.S.T.® Process Data from the General Refining Superfund Site

Metals	Initial Concentration (mg/kg)	Product Solids Metal (ppm)	TCLP Levels (ppm)
As	<0.6	<0.5	<0.0
Ba	239	410	<0.03
Cr	6.2	21	<0.05
Pb	3,200	23,000	5.2
Se	<4.0	<5.0	0.008

of 1988 to obtain specific operating and cost information for making technology evaluations for use at other Superfund sites. Under the SITE Program, CF Systems demonstrated an overall PCB reduction of more than 90 percent (see Table 5) for harbor sediments with inlet concentrations up to 2,575 ppm [14, p.6]. An extraction solvent blend of propane and butane was used in this demonstration.

The ability of the RCC full-scale B.E.S.T.® process to separate oil feedstock into product fractions was evaluated by the EPA at the General Refining Superfund Site near Savannah, Georgia, in February 1987. The test was conducted with the assistance of EPA's Region X Environmental Services Division in cooperation with EPA's Region IV Emergency Response and Control Branch [15, p.1]. The site was operated as a waste oil reclamation and re-refining facility from the early 1950s until 1975. As a result of those activities, four acidic oily sludge ponds with high levels of heavy metals (Pb= 200 to 10,000 ppm, Cu= 83 to 190 ppm) and detectable levels of PCBs (2.9 to 5 ppm) were produced. The average composition of the sludge from the four lagoons was 10 percent oil, 20 percent solids, and 70 percent water by weight [15, p.13]. The transportable 70-tpd B.E.S.T.® unit processed approximately 3,700 tons of sludge at the General Refining Site. The treated solids from this unit were backfilled to the site, product oil was recycled as a fuel oil blend, and the recovered water was pH adjusted

**Table 7**  
**Summary of Results from the SITE Demonstration of the RCC B.E.S.T.<sup>®</sup> Process**  
**(Averages from Three Runs)**

Parameter	Transect 28 Sediment			Transect 6 Sediment		
	PCBs <sup>1</sup>	PAHs	Triethylamine	PCBs	PAHs	Triethylamine
Concentration in Untreated Sediment, mg/kg	12.1	550	NA	425	70,900	NA
Concentration in Treated Solids, mg/kg	0.04	22	45.1	1.8	510	103
Removal from Sediment, percent	99.7	96.0	NA	99.6	99.3	NA
Concentration in Oil Product, mg/kg	NA <sup>1</sup>	NA <sup>1</sup>	NA <sup>1</sup>	2,030	390,000	733 <sup>2</sup>
Concentration in Water Product, mg/L	<0.003	<0.01	1.0	<0.001	<0.01	2.2

NA Not applicable.

<sup>1</sup> The Transect 28 oil product was sampled at the end of the last run conducted on Transect 28 material. When the oil was sampled, there was not sufficient oil present for oil polishing (using the solvent evaporator to remove virtually all of the triethylamine for the oil). Excess triethylamine was therefore left in the oil.

<sup>2</sup> This oil product was sampled following oil polishing.

and transported to a local industrial wastewater treatment facility. Test results (Table 6) showed that the heavy metals were mostly concentrated in the solids product fraction. Toxicity Characteristic Leaching Procedure (TCLP) test results showed heavy metals to be in stable forms that resisted leaching, illustrating a potential beneficial side effect when metals are treated by the process [4, p.13].

During the summer of 1992 a SITE demonstration was conducted to test the ability of the B.E.S.T.<sup>®</sup> system to remove PAHs and PCBs from contaminated sediments obtained from the Grand Calumet River. The pilot-scale B.E.S.T.<sup>®</sup> system was primarily contained on two skids and had an average daily capacity of 90 pounds of contaminated sediments. As Table 7 demonstrates, more than 96 percent of the PAHs and greater than 99 percent of the PCBs initially present in the sediments collected from Transect 6 and Transect 28 of the Grand Calumet River were removed [16].

Terra-Kleen Corporation has compiled remedial results for its solvent extraction system at three sites; Treband Superfund site, in Tulsa, Oklahoma; Sand Springs Substation site; Sand Springs, Oklahoma; and Pinette's Salvage Yard Superfund site, Washburn, Maine. PCBs were the primary contaminant at each of these sites. Table 8 summarizes the performance at the Treband site. Preliminary results from the Pinette's Salvage Yard site are given in Table 9 [17].

The Carver-Greenfield (C-G) Process<sup>®</sup>, developed by Dehydro-Tech Corporation, was evaluated during a SITE demonstration at an EPA research facility in Edison, New Jersey. During the August 1991 test, about 640 pounds of drilling mud contaminated with indigenous oil and elevated levels of heavy metals were shipped to EPA in Edison, New Jersey from the PAB Oil Site in Abbeville, Louisiana. The pilot-scale unit was trailer-mounted and

capable of treating about 100 lbs/hr of contaminated drilling mud. The process removed about 90 percent of the indigenous oil (as measured by solids/oil/water analysis). The indigenous total petroleum hydrocarbon (TPH) removals were essentially 100 percent for both runs [18, p. 1].

E. S. Fox Limited has determined performance data for the Extraksol<sup>®</sup> Process developed by Sanivan Group of Montreal, Quebec, Canada. Performance data on contaminated soils and refinery wastes for the 1 ton per hour (tph) mobile unit are shown in Table 10 [19]. The process uses a proprietary solvent that reportedly achieved removal efficiencies up to 99 percent (depending on the number of extraction cycles and the type of soil) on solids with contaminants such as PCBs, O&G, PAHs, and PCP.

RCRA Land Disposal Restrictions (LDRs) that require treatment of wastes to BDAT levels prior to land disposal may sometimes be determined to be applicable or relevant and appropriate requirements (ARARs) for CERCLA response actions. The solvent extraction technology can produce a treated waste that meets treatment levels set by BDAT, but may not reach these treatment levels in all cases. The ability to meet required treatment levels is dependent upon the specific waste constituents and the waste matrix. In cases where solvent extraction does not meet these levels, it still may, in certain situations, be selected for use at the site if a treatability variance establishing alternative treatment levels is obtained. EPA has made the treatability variance process available in order to ensure that LDRs do not unnecessarily restrict the use of alternative and innovative treatment technologies. Treatability variances may be justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.3-06FS, September, 1990) [20], and Superfund LDR Guide #6B, "Obtaining a

**Table 8**  
**Terra-Kleen Soil Restoration Unit PCB Removal at**  
**Treband Superfund Site<sup>1</sup>**

Initial Level (ppm)	Final Level (ppm)	Site Goal (ppm)	Reduction (percent)
740	77	<100	89.6
810	3	<100	99.6
2,500	93	<100	96.3

<sup>1</sup> Soil type: sand and concrete dust.

**Table 9**  
**Terra-Kleen Soil Restoration Unit PCB Removal at**  
**Pinette's Salvage Yard NPL Site<sup>1</sup>**

Initial Level (ppm)	Final Level (ppm)	Site Goal (ppm)	Reduction (percent)
41.8	2.7	<5.0	93.5
76.9	4.31	<5.0	94.4
381	3.59	<5.0	99.1

<sup>1</sup> Full scale data. Soil type: glacial till (gravel, sand, silt, and grey marine clay).

Soil and Debris Treatability Variance for Removal Actions\* (OSWER Directive 9347.3-06BFS, September 1990) [21]. Another approach would be to use other treatment techniques in series with solvent extraction to obtain desired treatment levels.

## Technology Status

As of October 1992, solvent extraction has been chosen as the selected remedy at eight Superfund sites. Two of these, General Refining, Georgia and Treband Warehouse, Oklahoma were emergency responses that have been completed. The other sites include Norwood PCBs, Massachusetts; O'Conner, Maine; Pinette's Salvage Yard, Maine; Ewan Property, New Jersey; Carolina Transformer, North Carolina; United Creosoting, Texas [22, p. 51].

Solvent extraction systems are at various stages of development. The following is a brief discussion of several systems that have been identified.

CF Systems uses liquefied hydrocarbon gases such as propane and butane as solvents for separating organic contaminants from soils, sludges, and sediments. To date, the CF Systems process has been used in the field at three Superfund sites; nine petrochemical facilities and remediation sites; and a centralized treatment, storage, and dis-

**Table 10**  
**Summary of 1-tph Extrasol<sup>®</sup>**  
**Process Performance Data**

Contaminant Matrix	In (ppm)	Out (ppm)	Reduction (percent)
O&G Clayey Soil	1,800	182	89.9
O&G Oily Sludge	72,000	2,000	97.2
O&G Fuller's Earth	313,000	3,700	98.8
PAH Clayey Soil	332	55	83.4
PAH Oily Sludge	240	10	95.8
PCB Clayey Soil	150	14	90.7
PCB Clayey Soil	54	4.4	91.8
PCP Porous Gravel	81.4	<0.21	99.7
PCP Activated Carbon	744	83	88.8

Note: Treated concentrations are based on criteria to be met and not process efficiency

posal (TSD) facility. The CF Systems solvent extraction technology is available in several commercial sizes and the Mobile Demonstration Unit is available for onsite treatability studies. CF Systems has supplied three commercial-scale extraction units for the treatment of a variety of wastes [23, p.3-12]. A 60-tpd treatment system was designed to extract organic liquids from a broad range of hazardous waste feeds at ENSCO's El Dorado, Arkansas, incinerator facility. A commercial-scale extraction unit is installed at a facility in Baltimore, Maryland, to remove organic contaminants from a 20 gallons-per-minute (gpm) wastewater stream. A PCU-200 extraction unit was installed and successfully operated at the Star Enterprise (Texaco) refinery in Port Arthur, Texas. This unit was designed to treat listed refinery wastes to meet or exceed the EPA's BDAT standards. A 220 tpd extraction unit is currently being designed for use at the United Creosoting Superfund site in Conroe, Texas.

RCC's B.E.S.T.<sup>®</sup> system uses aliphatic amines (typically triethylamine) as the solvent to separate and recover contaminants in either batch or continuous operation [4, p.2]. It can extract contaminants from soils, sludges, and sediments. In batch mode of operation, a pumpable waste is not required. RCC has a transportable B.E.S.T.<sup>®</sup> pilot-scale unit available to treat soils and sludges. This pilot-scale equipment was used at a Gulf Coast refinery treating various refinery waste streams and treated PCB-contaminated soils at an industrial site in Ohio during November of 1989. A full-scale unit with a nominal capacity of 70 tpd was used to clean 3,700 tons of PCB-contaminated petroleum sludge at the General Refining Superfund Site in Savannah, Georgia, in 1987 [16].

Terra-Kleen Corporation's Soil Restoration Unit was developed for remedial actions involving soil, debris, and sediments contaminated with organic compounds. The

Soil Restoration Unit is a mobile system which uses various combinations of up to 14 patented solvents, depending upon target contaminants present. These solvents are non-toxic and not listed hazardous wastes [17].

Dehydro-Tech Corporation's C-G Process is designed for the cleanup of Superfund sites with sludges, soils, or other water-bearing wastes containing hazardous compounds, including PCBs, polycyclic aromatics, and dioxins. A transportable pilot-scale system capable of treating 30 to 50 lbs/hr of solids is available. Over 80 commercial C-G Process facilities have been licensed in the past 30 years to solve industrial waste disposal problems. More than half of these plants were designed to dry and remove oil from slaughterhouse waste (rendering plants) [12].

NuKEM Development Company/ENSR developed a technique to remove PCBs from soils and mud several years ago. Their solvent extraction method involves acidic conditions, commercially available reagents to prepare the soil matrix for exposure to the solvent, and ambient temperatures and pressures [24]. NuKEM Development Company/ENSR is not currently marketing this technology for the treatment of contaminated soils and sludges. Another application being reviewed is the treatment of refinery sludges (K wastes and F wastes). The Solvent Extraction Process (SXP) system developed for treating these wastes has six steps; acidification, dispersion, extraction, raffinate solvent recovery, stabilization/filtration, and distillation. A pilot-scale SXP system has performed tests on over 20 different sludges. According to the vendor, preliminary cost estimates for treating 5,000 tons per year of a feed with 10 percent solids and 10 percent oil appear to be less than \$300 per ton [25].

The Extraksol® process was developed in 1984 by Sanivan Group, Montreal, Quebec, Canada [26, p.35]. It is applicable to treatment of contaminated soils, sludges, and sediments [26, p.45]. The 1-tph unit is suitable for small projects with a maximum of 300 tons of material to be treated. A transportable commercial scale unit, capable of processing up to 8 tph, was constructed by E.S. Fox Ltd. At present, the assembled unit is available for inspection at the fabricator's facility in Welland, Ontario, Canada. [19].

The Low Energy Extraction Process (LEEP), developed by ART International, Inc., is a patented solvent extraction process that can be used on-site for decontaminating soils, sludges and sediments. LEEP uses common organic solvents to extract and concentrate organic pollutants such as PCB, PAH, PCP, creosotes, and tar derived chemicals [27, p.250]. Bench-scale studies were conducted on PCB contaminated soils and sediments, base neutral contaminated soils and oil refinery sludges. ART has designed and constructed a LEEP Pilot Plant with a nominal solids throughput of 200 lbs/hr [12]. The pilot plant has been operational since March 1992. Recently, a 13 tph (dry basis) commercial facility capable of treating soil contaminated with up to 5 percent tar was completed for a former manufactured gas plant site.

Phønix Miljø, Denmark has developed the Soil Regeneration Plant, a 10 tph transportable solvent extraction process. This process consists of a combined liquid extraction and steam stripping process operating in a closed loop. A series of screw conveyors is used to transfer the contaminated soil through the process. Contaminants are removed from soil in a countercurrent extraction process. A drainage screw separates the soil from the extraction liquid. The extraction liquid is distilled to remove contaminants and is then recycled. The soil is steam heated to remove residual contaminants before exiting the process [28].

Cost estimates for solvent extraction range from \$50 to \$900 per ton [12]. The most significant factors influencing costs are the waste volume, the number of extraction stages, and operating parameters such as labor, maintenance, setup, decontamination, demobilization, and lost time resulting from equipment operating delays. Extraction efficiency can be influenced by process parameters such as solvent used, solvent/waste ratio, throughput rate, extractor residence time, and number of extraction stages. Thus, variation of these parameters, in particular hardware design and/or configuration, will influence the treatment unit cost component but should not be a significant contributor to the overall site costs.

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## Engineering Bulletin In Situ Soil Flushing

### Purpose

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

### Abstract

In situ soil flushing is the extraction of contaminants from the soil with water or other suitable aqueous solutions. Soil flushing is accomplished by passing the extraction fluid through in-place soils using an injection or infiltration process. Extraction fluids must be recovered and, when possible, are recycled. The method is potentially applicable to all types of soil contaminants. Soil flushing enables removal of contaminants from the soil and is most effective in permeable soils. An effective collection system is required to prevent migration of contaminants and potentially toxic extraction fluids to uncontaminated areas of the aquifer. Soil flushing, in conjunction with in situ bioremediation, may be a cost-effective means of soil remediation at certain sites [1, p. vi] [2, p. 11].\* Typically, soil flushing is used in conjunction with other treatments that destroy contaminants or remove them from the extraction fluid and groundwater.

Soil flushing is a developing technology that has had limited use in the United States. Typically, laboratory and field treatability studies must be performed under site-specific conditions before soil flushing is selected as the remedy of choice. To

\* [reference number, page number]

date, the technology has been selected as part of the source control remedy at 12 Superfund sites. This technology is currently operational at only one Superfund site; a second is scheduled to begin operation in 1991 [3][4]. EPA completed construction of a mobile soil-flushing system, the In Situ Contaminant/Treatment Unit, in 1988. This mobile soil-flushing system is designed for use at spills and uncontrolled hazardous waste sites [5].

This bulletin provides information on the technology applicability, the technology limitations, a description of the technology, the types of residuals resulting from the use of the technology, site requirements, the latest performance data, the status of the technology, and sources of further information.

### Technology Applicability

In situ soil flushing is generally used in conjunction with other treatment technologies such as activated carbon, biodegradation, or chemical precipitation to treat contaminated groundwater resulting from soil flushing. In some cases, the process can reduce contaminant concentrations in the soil to acceptable levels, and thus serve as the only soil treatment technology. In other cases, in situ biodegradation or other in situ technologies can be used in conjunction with soil flushing to achieve acceptable contaminant removal efficiencies. In general, soil flushing is effective on coarse sand and gravel contaminated with a wide range of organic, inorganic, and reactive contaminants. Soils containing a large amount of clay and silt may not respond well to soil flushing, especially if it is applied as a stand-alone technology.

A number of chemical contaminants can be removed from soils using soil flushing. Removal efficiencies depend on the type of contaminant as well as the type of soil. Soluble (hydrophilic) organic contaminants often are easily removed from soil by flushing with water alone. Typically, organics with octanol/water partition coefficients ( $K_{ow}$ ) of less than 10 ( $\log K_{ow} < 1$ ) are highly soluble. Examples of such compounds include lower molecular weight alcohols, phenols, and carboxylic acids [6].

Low solubility (hydrophobic) organics may be removed by selection of a compatible surfactant [7]. Examples of such compounds include chlorinated pesticides, polychlorinated biphenyls (PCBs), semivolatiles (chlorinated benzenes and polynuclear aromatic hydrocarbons), petroleum products (gasoline;

jet fuel, kerosene, oils and greases), chlorinated solvents (trichloroethene), and aromatic solvents (benzene, toluene, xylenes and ethylbenzene) [8]. However, removal of some of these chemical classes has not yet been demonstrated.

Metals may require acids, chelating agents, or reducing agents for successful soil flushing. In some cases, all three types of chemicals may be used in sequence to improve the removal efficiency of metals [9]. Many inorganic metal salts, such as carbonates of nickel, zinc, and copper, can be flushed from the soil with dilute acid solutions [6]. Some inorganic salts such as sulfates and chlorides can be flushed with water alone.

In situ soil flushing has been considered for treating soils contaminated with hazardous wastes, including pentachlorophenol and creosote from wood-preserving operations, organic solvents, cyanides and heavy metals from electroplating residues, heavy metals from some paint sludges, organic chemical production residues, pesticides and pesticide production residues, and petroleum/oil residues [10, p. 13][11, p. 8][7][12].

The effectiveness of soil flushing for general contaminant groups [10, p. 13] is shown in Table 1. Examples of constituents within contaminant groups are provided in Reference 10, "Technology Screening Guide For Treatment of CERCLA Soils and Sludges." Table 1 is based on currently available information or professional judgment where definitive information is

**Table 1**  
**Effectiveness of Soil Flushing on General Contaminant Groups**

Contaminant Groups		Effectiveness
Organic	Halogenated volatiles	■
	Halogenated semivolatiles	▼
	Nonhalogenated volatiles	▼
	Nonhalogenated semivolatiles	■
	PCBs	▼
	Pesticides (halogenated)	▼
	Dioxins/Furans	▼
	Organic cyanides	▼
	Organic corrosives	▼
Inorganic	Volatile metals	▼
	Nonvolatile metals	■
	Asbestos	□
	Radioactive materials	▼
	Inorganic corrosives	▼
	Inorganic cyanides	▼
Reactive	Oxidizers	▼
	Reducers	▼
■ Demonstrated Effectiveness: Successful treatability test at some scale completed.		
▼ Potential Effectiveness: Expert opinion that technology will work.		
□ No Expected Effectiveness: Expert opinion that technology will not work.		

currently inadequate or unavailable. The demonstrated effectiveness of the technology for a particular site or waste does not ensure that it will be effective at all sites or that the treatment efficiency achieved will be acceptable at other sites. For the ratings used in this table, demonstrated effectiveness means that, at some scale, treatability was tested to show that, for that particular contaminant and matrix, the technology was effective. The ratings of potential effectiveness and no expected effectiveness are based upon expert judgment. Where potential effectiveness is indicated, the technology is believed capable of successfully treating the contaminant group in a particular matrix. When the technology is not applicable or will probably not work for a particular combination of contaminant group and matrix, a no-expected-effectiveness rating is given. Other sources of general observations and average removal efficiencies for different treatability groups are the Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.3-06FS) [13], and Superfund LDR Guide #68, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.3-07FS) [14].

Information on cleanup objectives, as well as the physical and chemical characteristics of the site soil and its contaminants, is necessary to determine the potential performance of this technology. Treatability tests are also required to determine the feasibility of the specific soil-flushing process being considered. If bench-test results are promising, pilot-scale demonstrations should be conducted before making a final commitment to full-scale implementation. Table 2 contains physical and chemical soil characterization parameters that should be established before a treatability test is conducted at a specific site. The table contains comments relating to the purpose of the specific parameter to be characterized and its impact on the process [15, p. 715] [16, p. 90] [17].

Soil permeability is a key physical parameter for determining the feasibility of using a soil-flushing process. Hydraulic conductivity (K) is measured to assess the permeability of soils. Soils with low permeability ( $K < 1.0 \times 10^{-5}$  cm/sec) will limit the ability of flushing fluids to percolate through the soil in a reasonable time frame. Soil flushing is most likely to be effective in permeable soils ( $K > 1.0 \times 10^{-3}$  cm/sec), but may have limited application to less permeable soils ( $1.0 \times 10^{-5}$  cm/sec  $< K < 1.0 \times 10^{-3}$  cm/sec). Since there can be significant lateral and vertical variability in soil permeability, it is important that field measurements be made using the appropriate methods.

Prior to field implementation of soil flushing, a thorough groundwater hydrologic study should be carried out. This should include information on seasonal fluctuations in water level, direction of groundwater flow, porosity, vertical and horizontal hydraulic conductivities, transmissivity and infiltration (data on rainfall, evaporation, and percolation).

Moisture content can affect the amount of flushing fluids required. Dry soils will require more flushing fluid initially to mobilize contaminants. Moisture content is also used to calculate pore volume to determine the rate of treatment [15].

The concentration and distribution of organic contami-

**Table 2**  
**Characterization Parameters**

Parameter	Purpose and Comment
Soil permeability $\geq 1.0 \times 10^{-3}$ cm/sec $< 1.0 \times 10^{-3}$ cm/sec	Affects treatment time and efficiency of contaminant removal Effective soil flushing Limited soil flushing
Soil structure	Influences flow patterns (channeling, blockage)
Soil porosity	Determines moisture capacity of soil at saturation (pore volume)
Moisture content	Affects flushing fluid transfer requirements
Groundwater hydrology	Critical in controlling the recovery of injected fluids and contaminants
Organics Concentration Solubility Partition coefficient	Determine contaminants and assess flushing fluids required, flushing fluid compatibility, changes in flushing fluid with changes in contaminants.
Metals Concentration Solubility products Reduction potential Complex stability constants	Concentration and species of constituents will determine flushing fluid compatibility, mobility of metals, post treatment.
Total Organic Carbon (TOC)	Adsorption of contaminants on soil increases with increasing TOC. Important in marine wetland sites, which typically have high TOC.
Clay content	Adsorption of contaminants on soil increases with increasing clay content.
Cation Exchange Capacity (CEC)	May affect treatment of metallic compounds.
pH, buffering capacity	May affect treatment additives required, compatibility with equipment materials of construction, wash fluid compatibility.

nants and metals are key chemical parameters. These parameters determine the type and quantity of flushing fluid required as well as any post-treatment requirements. The solubility and partition coefficients of organics in water or other solutions are also important in the selection of the proper flushing fluids. The species of metal compounds present will affect the solubility and leachability of heavy metals.

High humic content and high cation exchange capacity tend to reduce the removal efficiency of soil flushing. Some organic contaminants may adsorb to humic materials or clays in soils and, therefore, are difficult to remove during soil flushing. Similarly, the binding of certain metals with clays due to cationic exchange makes them difficult to remove with soil flushing. The buffering capacity of the soil will affect the amount required of some additives, especially acids. Precipitation reactions (resulting in clogging of soil pores) can occur due to pH changes in the flushing fluid caused by the neutralizing effect of soils with high buffering capacity. Soil pH can affect the speciation of metal compounds resulting in changes in the solubility of metal compounds in the flushing fluid.

### Limitations

Generally, remediation times with this technology will be lengthy (one to many years) due to the slowness of diffusion processes in the liquid phase. This technology requires hydraulic control to avoid movement of contaminants offsite. The hydrogeology of some sites may make this difficult or impossible to achieve.

Contaminants in soils containing a high percentage of silt- and clay-sized particles typically are strongly adsorbed and difficult to remove. Also, soils with silt and clay tend to be less permeable. In such cases, soil flushing generally should not be considered as a stand-alone technology.

Hydrophobic contaminants generally require surfactants or organic solvents for their removal from soil. Complex mixtures of contaminants in the soil (such as a mixture of metals, nonvolatile organics, and semivolatile organics) make it difficult to formulate a single suitable flushing fluid that will consistently and reliably remove all the different types of contaminants from the soil. Frequent changes in contaminant concentration and composition in the vertical and horizontal soil profiles will complicate the formulation of the flushing fluid. Sequential steps with frequent changes in the flushing formula may be required at such complex sites [10, p. 77].

Bacterial fouling of infiltration and recovery systems and treatment units may be a problem particularly if high iron concentrations are present in the groundwater or if biodegradable reagents are being used.

While flushing additives such as surfactants and chelants may enhance some contaminant removal efficiencies in the soil flushing process, they also tend to interfere with the downstream wastewater treatment processes. The presence of these additives in the washed soil and in the wastewater treatment sludge may cause some difficulty in their disposal. Costs associated with additives, and the management of these additives as part of the residuals/wastewater streams, must be carefully weighed against the incremental improvements in soil-flushing performance that they may provide.

## Technology Description

Figure 1 is a general schematic of the soil flushing process [18, p. 7]. The flushing fluid is applied (1) to the contaminated soil by subsurface injection wells, shallow infiltration galleries, surface flooding, or above-ground sprayers. The flushing fluid is typically water and may contain additives to improve contaminant removal.

The flushing fluid percolates through the contaminated soil, removing contaminants as it proceeds. Contaminants are mobilized by solubilization into the flushing fluid, formation of emulsions, or through chemical reactions with the flushing fluid [19].

Contaminated flushing fluid or leachate mixes with groundwater and is collected (2) for treatment. The flushing fluid delivery and the groundwater extraction systems are designed to ensure complete contaminant recovery [7]. Ditches open to the surface, subsurface collection drains, or groundwater recovery wells may be used to collect flushing fluids and mobilized contaminants. Proper design of a fluid recovery system is very important to the effective application of soil flushing.

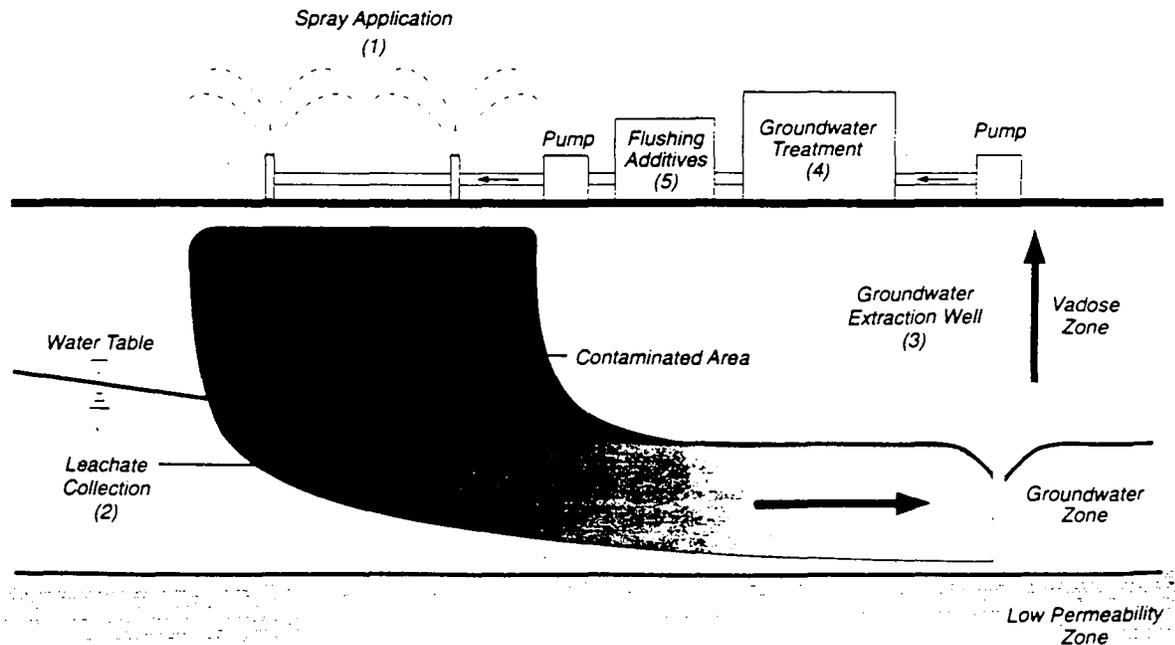
Contaminated groundwater and flushing fluids are captured and pumped to the surface in a standard groundwater extraction well (3). The rate of groundwater withdrawal is determined by the flushing fluid delivery rate, the natural infiltration rate, and the groundwater hydrology. These will deter-

mine the extent to which the groundwater removal rate must exceed the flushing fluid delivery rate to ensure recovery of all reagents and mobilized contaminants. The system must be designed so that hydraulic control is maintained.

The groundwater and flushing fluid are treated (4) using the appropriate wastewater treatment methods. Extracted groundwater is treated to reduce the heavy metal content, organics, total suspended solids, and other parameters until they meet regulatory requirements. Metals may be removed by lime precipitation or by other technologies compatible with the flushing reagents used. Organics are removed with activated carbon, air stripping, or other appropriate technologies. Whenever possible, treated water should be recycled as makeup water at the front end of the soil-flushing process.

Flushing additives (5) are added, as required, to the treated groundwater, which is recycled for use as flushing fluid. Water alone is used to remove hydrophilic organics and soluble heavy-metal salts [9]. Surfactants may be added to remove hydrophobic and slightly hydrophilic organic contaminants [12]. Chelating agents, such as ethylenediaminetetra-acetic acid (EDTA), can effectively remove certain metal compounds. Alkaline buffers such as tetrasodium pyrophosphate can remove metals bound to the soil organic fraction. Reducing agents such as hydroxylamine hydrochloride can reduce iron and manganese oxides that can bind

Figure 1  
Schematic of Soil Flushing System



metals in soil. Insoluble heavy-metal compounds also can be reduced or oxidized to more soluble compounds. Weak acid solutions can improve the solubility of certain heavy metals [9]. Treatability studies should be conducted to determine compatibility of the flushing reagents with the contaminants and with the site soils.

### Process Residuals

The primary waste stream generated is contaminated flushing fluid, which is recovered along with groundwater. Recovered flushing fluids may need treatment to meet appropriate discharge standards prior to release to a local, publicly-owned wastewater treatment works or receiving streams. To the maximum extent practical, this water should be recovered and reused in the flushing process. The separation of surfactants from recovered flushing fluid, for reuse in the process, is a major factor in the cost of soil flushing. Treatment of the flushing fluid results in process sludges and residual solids, such as spent carbon and spent ion exchange resin, which must be appropriately treated before disposal. Air emissions of volatile contaminants from recovered flushing fluids should be collected and treated, as appropriate, to meet applicable regulatory standards. Residual flushing additives in the soil may be a concern and should be evaluated on a site-specific basis.

### Site Requirements

Access roads are required for transport of vehicles to and from the site. Stationary or mobile soil-flushing process systems are located on site. The exact area required will depend on the vendor system selected and the number of tanks or ponds needed for washwater preparation and wastewater treatment.

Because contaminated flushing fluids are usually considered hazardous, their handling requires that a site safety plan be developed to provide for personnel protection and special handling measures during wastewater treatment operations. Fire hazard and explosion considerations should be minimal, since the soil-flushing fluid is predominantly water.

An Underground Injection Control (UIC) Permit may be necessary if subsurface infiltration galleries or injection wells are used. When groundwater is not recycled, a National Pollution Discharge Elimination System (NPDES) or State Pollution Discharge Elimination System (SPDES) permit may be required. Federal, State, and local regulatory agencies should be contacted to determine permitting requirements before implementing this technology.

Slurry walls or other containment structures may be needed along with hydraulic controls to ensure capture of contaminants and flushing additives. Climatic conditions such as precipitation cause surface runoff and water infiltration. Berms, dikes, or other runoff control methods may be required. Impermeable membranes may be necessary to limit infiltration of precipitation, which could cause dilution of flushing solution and loss of hydraulic control. Cold weather freezing must also be considered for shallow infiltration galleries and above-ground sprayers.

### Performance Data

Some of the data presented for specific contaminant removal effectiveness were obtained from publications developed by the respective soil-flushing-system vendors. The quality of this information has not been determined; however it does give an indication of the effectiveness of in situ soil flushing.

Tetrachloroethylene was discharged into the aquifer at the site of a spill in Sindelfingen, Germany. The contaminated aquifer is a high-permeability ( $k=5.10 \times 10^{-4}$  m/sec) layer overlying a clay barrier. Soil flushing was accomplished by infiltrating water into the ground through ditches. The leaching liquid and polluted groundwater were pumped out of eight wells and treated with activated carbon. The treated water was recycled through the infiltration ditches. Within 18 months, 17 metric tons of chlorinated hydrocarbons were recovered [19, p. 565].

Two percolation basins were installed to flush contaminated soil at the United Chrome Products site near Corvallis, Oregon. Approximately 1,100 tons of soil containing the highest chromium concentrations were excavated and disposed of offsite. The resulting pits from the excavations were used as infiltration basins to flush the remaining contaminated soil. The soil-flushing operation for the removal of hexavalent chromium from an estimated 2.4 million gallons of contaminated groundwater began in August 1988. No information on the site soils was provided, but preliminary estimates were that a groundwater equilibrium concentration of 100 mg/L chromium would be reached in 1 to 2 years, but that final cleanup to 10 mg/L would take up to 25 years [20, p. H-1]. Since that time over 8-million gallons of groundwater, containing over 25,000 pounds of chromium, have been removed from the 23 extraction wells in the shallow aquifer. Average monthly chromium concentrations in the groundwater decreased from 1,923 mg/L in August 1988 to 96 mg/L in March 1991 [4].

Waste-Tech Services, Inc. performed two tests of soil-flushing techniques to remove creosote contamination at the Laramie Tie Plant site in Wyoming. The first test involved slowly flooding the soil surface with water to perform primary oil recovery (POR). Soil flushing reduced the average concentration of total extractable organics (TEO) from an estimated initial concentration of 93,000 mg/kg to 24,500 mg/kg, a 74 percent reduction. The second test involved sequential treatment with alkaline agents, polymers, and surfactants. During the 8-month treatment period, average TEO concentrations were reduced to 4,000 mg/kg. This represents an 84 percent reduction from the post-POR concentration (24,500 mg/kg) and a 96 percent reduction from the estimated initial concentration (93,000 mg/kg). The tests were performed in alluvial sands and gravels. The low permeability of adjacent silts and clays precluded soil flushing [22].

Laboratory tests were conducted on contaminated soils from a fire-training area at Volk Air Force Base. Initial concentrations of oil and grease in the soils were reported to be 10,000 and 6,000 mg/kg. A 1.5-percent surfactant solution in water was used to flush soil columns. The tests indicated that 75 to 94 percent of the initial hydrocarbon contamination could be removed by flushing with 12-pore volumes of liquid.

However, field tests were unsuccessful in removing the same contaminants. Seven soil-flushing solutions, including the solution tested in the laboratory studies, were tested in field studies. The flushing solutions were delivered to field test cells measuring 1 foot deep and 1 to 2 feet square. Only three of the seven tests achieved the target delivery of 14-pore volumes. Two of the test cells plugged completely, permitting no further infiltration of flushing solutions. There was no statistically significant removal of soil contaminants due to soil flushing. The plugging of test cells may be related to the use of a surfactant solution. By hydrolyzing in water, surfactants may block soil pores by forming either flocs or surfactant aggregates called micelles. In addition, if the surfactant causes fine soil particles to become suspended in the flushing fluid, narrow passages between soil particles could be blocked. If enough of these narrow passages are blocked along a continuous front, a "mat" is said to have formed, and fluid flow is halted in that area [23] [7].

Resource Conservation Recovery Act (RCRA) Land Disposal Restrictions (LDRs) that require treatment of wastes to best demonstrated available technology (BDAT) levels prior to land disposal may sometimes be determined to be applicable or relevant and appropriate requirements (ARARs) for CERCLA response actions. The soil-flushing technology can produce a treated waste that meets treatment levels set by BDAT, but may not reach these treatment levels in all cases. The ability of the technology to meet required treatment levels is dependent upon the specific waste constituents and the waste matrix. In cases where soil flushing does not meet these levels, it still may, in certain situations, be selected for use at the site if a treatability variance establishing alternative treatment levels is obtained. EPA has made the treatability variance process available in order to ensure that LDRs do not unnecessarily restrict the use of alternative and innovative

treatment technologies. Treatability variances may be justified for handling complex soil and debris matrices. The following guides describe when and how to seek a treatability variance for soil and debris: Superfund LDR Guide #6A, "Obtaining a Soil and Debris Treatability Variance for Remedial Actions" (OSWER Directive 9347.3-06FS) [13], and Superfund LDR Guide #6B, "Obtaining a Soil and Debris Treatability Variance for Removal Actions" (OSWER Directive 9347.3-07FS) [14]. Another approach could be to use other treatment techniques in conjunction with soil flushing to obtain desired treatment levels.

## Technology Status

In situ soil flushing is a developing technology that has had limited application in the United States. In situ soil flushing technology has been selected as one of the source control remedies at the 12 Superfund sites listed in Table 3 [3].

## EPA Contact

Technology-specific questions regarding soil flushing may be directed to:

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Table 3  
 Superfund Sites Using In Situ Soil Flushing

Site	Location (Region)	Primary Contaminants	Status
Byron Barrel & Drum	Genesee County, NY (2)	VOCs (BTX, PCE, and TCE)	Pre-design: finalizing workplan
Goose Farm	Plumsted Township, NJ (2)	VOCs (Toluene, Ethylbenzene, Dichloromethane, and TCE), SVOCs, and PAHs	In design: 30% design phase
Lipari Landfill	Gloucester, NJ (2)	VOCs (Benzene, Ethylbenzene, Dichloromethane, and TCE), SVOCs, PAHs and Chlorinated ethers (bis-2-chloroethylether)	Operational, summer '91
Vineland Chemical	Vineland, NJ (2)	Arsenic and VOCs (Dichloromethane)	Pre-design
Harvey-Knott Drum	_____, DE (3)	Lead	In design: re-evaluating alternative
L.A. Clarke & Son	Spotsylvania, VA (3)	Creosote, PAHs, and Benzene	In design
Ninth Avenue Dump	Gary, IN (5)	VOCs (BTEX, TCE), PAHs, Phenols, Lead, PCBs, and Total Metals	In design: pilot failed
U.S. Aviox	Niles, MI (5)	VOCs (Carbon Tetrachloride, DCA, Ethylbenzene, PCE, TCE, Toluene, TCA, Freon, Xylene, and Chloroform)	Pre-design: re-evaluating alternatives
South Calvacale Street	Houston, TX (6)	PAHs	In design
United Chrome Products	Corvallis, OR (10)	Chromium	Operational since 8/88
Cross Brothers Pail	Pembroke, IL (5)	VOCs (Benzene, PCE, TCE, Toluene, and Xylenes) and PCBs	In design: developing workplan
Bog Creek Farm	Howell Township, NJ (2)	VOCs, Organics	In design: treatment plant completed, dump and treat not installed

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Mr. Clyde Dial	SAIC
Ms. Linda Fiedler	EPA-TIO
Dr. David Wilson	Vanderbilt University
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## **APPENDIX G**

### **ARTICLE ON INCINERATION**

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# Incineration of Hazardous Waste: A Critical Review Update

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Over the last 15 years, concern over improper disposal practices of the past has manifested itself in the passage of a series of federal and state-level hazardous waste cleanup and control statutes of unprecedented scope. As a result, there has been a significant modification of waste management practices. The more traditional and lowest-cost methods of direct landfilling, storage in surface impoundments and deep-well injection are being replaced in large measure by waste minimization at the source of generation, waste reuse, physical/chemical/biological treatment, incineration and chemical stabilization/solidification methods. Of all of the "permanent" treatment technologies, properly designed incineration systems are capable of the highest overall degree of destruction and control for the broadest range of hazardous waste streams. Substantial design and operational experience exists in this area and a wide variety of commercial systems are available. Consequently, significant growth is anticipated in the use of incineration and other thermal destruction methods. The objective of this review is to examine the current state of knowledge regarding hazardous waste incineration in an effort to put these technological and environmental issues into perspective.

Hazardous waste management and remediation of Superfund sites was the environmental issue of the 1980s and will likely continue to be so during the 1990s. Discovery of numerous environmental catastrophes resulting from improper disposal practices in the past has elevated public awareness and concern. Over the last 15 years, this concern has manifested itself in the passage of a series of federal and state-level hazardous waste management and cleanup and control statutes of unprecedented scope and impact. At the federal level, these laws include the Resource Conservation and Recovery Act of 1976 (RCRA) and its subsequent amendments with its "cradle to grave" provisions for controlling the storage, transport, treatment and disposal of hazardous waste. In 1979 the polychlorinated biphenyl (PCB) regulations, promulgated under Section 6(e) of the Toxic Substances Control Act (TSCA), prohibited the further manufacture of PCBs after July 2, 1979. This established limits on PCB use in commerce and established regulations for proper treatment and disposal. Cleanup of uncontrolled waste sites created by

past poor disposal practices was provided for in the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) of 1980. This act established a national fund (Superfund) to assist in remedial actions. The 1986 Superfund Amendments and Reauthorization Act (SARA) not only reauthorized the Superfund program but greatly expanded the provisions and funding of the initial act. In addition, it established a clear preference for remediation technologies that would "permanently" and significantly reduce the volume, toxicity, or mobility of hazardous substances, pollutants and contaminants.

One of the more significant of these statutes was the 1984 amendments and reauthorization of RCRA. Termed the Hazardous and Solid Waste Act (HSWA) of 1984, these amendments established a strict time line for restricting untreated hazardous waste from land disposal. The U.S. Environmental Protection Agency (EPA) promulgated the last of five Congressionally-mandated prohibitions on land disposal of hazardous wastes (the third one-third of the schedule of restricted

hazardous wastes) on June 1, 1990. When fully effective in May 1992, this rule, combined with the previous rulemakings, is expected to require the additional treatment of 7 million tons per year of hazardous waste to levels achievable by the Best Demonstrated Available Technology (BDAT) before it can be land disposed.<sup>1</sup>

These various statutes will continue to drive a significant modification of waste management practices. The more traditional and lowest-cost methods of direct landfilling, storage in surface impoundments and deep-well injection are being replaced, in large measure, by waste minimization at the source of generation, waste reuse, physical/chemical/biological treatment, incineration and chemical stabilization/solidification methods.

Of all of the "permanent" treatment technologies, properly designed incineration systems are capable of the highest overall degree of destruction and control for the broadest range of hazardous waste streams. Substantial design and operational experience exists in these areas and a wide variety of commercial systems are available. Consequently, significant growth is anticipated in the use of incineration and other thermal destruction methods.<sup>2</sup>

While thermal destruction offers many advantages over alternative hazardous waste treatment practices and may help meet the anticipated need for increased waste management capacity, public opposition to the permitting and/or use of thermal destruction operations has been strong in recent years.<sup>3-7</sup> The environmental awareness and activism which spawned the major hazardous waste laws of the 1980s have, in many respects, switched to skepticism over the safety and effectiveness of the technological solutions which the

laws were designed to regulate. Citizen distrust of the waste management facility owners and operators remains strong. The ability of government agencies to enforce compliance is also questioned. Reports of trace quantities of chlorinated dioxins, chlorinated furans and other combustion byproducts in the stack emissions of municipal solid waste and PCB incinerators have raised questions in the minds of some concerning whether the RCRA and other incinerator standards are sufficient to protect public health and the environment. Yet, faced with the specter of complying with the HSWA land disposal restrictions or the prospect of future multimillion dollar environmental damage settlements over contaminated groundwater, waste generators are looking to permanent destruction techniques such as incineration as the preferred alternative.

The objective of this review is to examine the current state of knowledge regarding hazardous waste incineration in an effort to put these technological and environmental issues into perspective. In doing so, it will be important to review:

- Current and emerging regulations and standards for incinerators, industrial boilers and furnaces burning hazardous waste
- Current incineration technology and practice
- Capabilities and limitations of methods for measuring process performance
- Destruction efficiency and emissions characterization of current technology
- Methods for predicting and assuring incinerator performance
- Environmental and public health implications of hazardous waste incineration
- Remaining issues and research needs

While the focus of this paper is on hazardous waste incineration, it is important to understand that many of the same issues relate to the use of hazardous waste as a fuel in industrial boilers and furnaces as well as municipal waste and medical waste incineration. Where possible and appropriate, the performance and emissions of these systems will be compared and contrasted with hazardous waste incinerators.

## Background

### Historical Perspective

Purification by fire is an ancient concept. Its applications are noted in

the earliest chapters of recorded history. The Hebrew word for hell, *Gehenna*, was actually derived from the ancient phrase *ge-ben Hinnom* or the valley of the son of Hinnom, an area outside of Jerusalem which housed the smoldering town dump and was the site of propitiatory sacrifices to Moloch II.<sup>8</sup> Today, waste fires on the ground or in pits are still used throughout the world, including the United States. This includes open burning of agricultural waste as well as the burning of household refuse in some rural areas.

In the Middle Ages, an early waste fire innovation was the "fire wagon," the first mobile incinerator.<sup>9</sup> It was a simple rectangular wooden wagon protected by a clay lining. The horse-drawn wagon traveled the streets and residents threw their refuse into the moving bonfire.

Incineration as we know it today began slightly over 100 years ago when the first municipal waste "destructor" was installed in Nottingham, England.<sup>9</sup> Incineration use in the United States grew rapidly, from the first installation on Governor's Island in New York to more than 200 units in 1921. Most of these were poorly operated batch-fed units, some with steam recovery. Until the 1950s, incinerators and their attendant smoke and odors were accepted as a necessary evil and their operations were generally undertaken in the cheapest possible manner. However, as billowing smoke stacks became less of a symbol of prosperity and air pollution regulations began to emerge, incineration systems improved dramatically.<sup>10</sup> These improvements included continuous feed, improved combustion control, the use of multiple combustion chambers, designs for energy recovery, and the application of air pollution control systems.<sup>11</sup>

Incineration has been employed for the disposal of industrial chemical wastes (hazardous waste) for over 50 years. Initial units borrowed from municipal waste technology, but poor performance and adaptability of these early grate-type units led to the subsequent use of rotary kilns. Many of the earliest rotary kiln facilities were in West Germany. The first rotary kiln unit for industrial wastes in the United States was installed in 1948 at the Dow Chemical Company facility in Midland, Michigan.<sup>12</sup>

### Regulations

The first U.S. federal standards for the control of incineration emissions

were applied to municipal waste combustors under the New Source Performance Standards (NSPS) provisions of the Clean Air Act (CAA) of 1970. The NSPS established a time-averaged (two hours) particulate emission limit of 180 milligrams per dry standard cubic meter (mg/dscm), corrected to 12 percent carbon dioxide (CO<sub>2</sub>), for all incineration units constructed after August 1971 having charging rates greater than 50 tons per day (tpd). On February 11, 1991, the U.S. EPA promulgated more stringent rules for all existing and new municipal waste combustors (MWCs) with unit capacities greater than 225 metric tons per day (Mg/day).<sup>13</sup> This action required the use of good combustion practice (GCP) at all facilities, set lower particulate emissions limits to control metals and established emission limits on nitrogen oxides (NO<sub>x</sub>), organics, hydrogen chloride (HCl), sulfur dioxide (SO<sub>2</sub>) and opacity. The specific limits are a function of the combustion technology used and the facility's size (capacity) and age (new or existing). The February 1991 rules for GCPs and emission limits are summarized in Table I.

The February 1991 MWC rules are to be modified in the near future to comply with the provisions of the November 1990 CAA Amendments. These revisions will include: (1) rules for facilities with capacities less than 225 Mg/day, (2) emission limits for cadmium, lead and mercury, and (3) requirements for the use of the maximum achievable control technology (MACT).<sup>14</sup>

Hazardous waste incineration performance standards were not promulgated until after the passage of RCRA. Technical standards for incinerators were proposed in December 1978, under Section 3004 of RCRA.<sup>15</sup> These standards provided both performance and operating requirements. The performance standards included requirements for acceptable levels of combustion efficiency, destruction efficiency for organic compounds, HCl removal efficiency and an emission limit for particulate matter. Operational standards required semicontinuous monitoring of process variables, such as carbon monoxide (CO), and specific minimum temperature and combustion gas residence time levels. During the allowable comment period on the proposed rules, EPA received extensive comments on the scope of the standards and the adequacy of the combined EPA and industrial data base used to set the standards.

**Table I.** Municipal waste combustor emission standards and guidelines.<sup>13</sup>

DESCRIPTION Capacity (Mg/day)	NSPS <sup>a,b</sup> >225	EMISSION GUIDELINES <sup>c</sup>	
		> 225 to 1,000	>1,000
Opacity (%)	10	10	10
Metal Emissions (As particulate matter, mg/dscm)	34	69	34
Organic Emissions (As total PCDD/PCDF, ng/dscm)	30	125 or 250 <sup>e</sup>	60
NO <sub>x</sub> (ppmv)	180	none	none
HCl (% Reduction/ppmv)	95/25	50/25	90/25
SO <sub>2</sub> (% Reduction/ppmv)	80/30	50/30	70/30
CO (ppmv) <sup>d</sup>	50-150	50-250	50-250

<sup>a</sup> All emission limits are based on standard dry gas corrected to 7% O<sub>2</sub>.

<sup>b</sup> NSPS = New Source Performance Standard.

<sup>c</sup> Applies only to refuse-derived fuel (RDF) stokers and coal/RDF mixed fuel-fired combustors.

<sup>d</sup> CO emission limits depend on the type of MWC technology. GCP requirements also contain limitations on maximum steam load and temperature at the particulate control device inlet.

Based upon the public comment, EPA subsequently proceeded down a three-phased regulatory path:

- Phase I (May 19, 1980). Interim status standards were proposed outlining operating procedures to be followed by existing incinerator facilities.<sup>16</sup>
- Phase II (January 23, 1981). Interim final performance standards were promulgated requiring specific levels of organic hazardous constituent destruction and removal, exhaust gas HCl removal and maximum particulate emission concentration.<sup>17</sup>
- Phase III (June 24, 1982). The interim final standards were amended based on public comment received on the standards that were promulgated on January 23, 1981 and remain in force at this time.<sup>18</sup>

The provisions of the final incinerator standards, which are of greatest importance to this paper, are the performance standards which are now listed in the Code of Federal Regulations (CFR) under 40 CFR 264.343. These standards require that in order to receive a RCRA permit, a facility must attain the following performance levels:

- (1) A 99.99 percent destruction and removal efficiency (DRE) for each principal organic hazardous constituent (POHC) in the waste feed where:

$$DRE = [(W_{in} - W_{out})/W_{in}] \times 100$$

where:  $W_{in}$  = mass feed rate of the principal organic hazardous constituent (POHC) in the waste stream fed to the incinerator, and  
 $W_{out}$  = mass emission rate of the POHC in the stack prior to release to the atmosphere.

- (2) HCl emissions no greater than the larger of either 1.8 kilograms per hour or 1 percent of the HCl in the stack gas prior to entering any pollution control equipment (i.e., 99 percent removal).
- (3) Particulate matter emissions no greater than 180 mg/dscm [0.08 grains per dry standard cubic foot (dscf)] corrected to 7 percent oxygen in the stack gas. The measured particulate matter concentration is multiplied by the following correction factor to obtain the corrected particulate matter emissions:

$$\text{Correction Factor} = 14/(21 - Y)$$

where: Y = measured oxygen concentration in the stack gas on a dry basis (expressed as a percentage).

The concept and selection of POHCs is an important part of the incineration regulations. POHCs, which are to be sampled during "trial burns" to assess attainment of the standards, are to be selected from the organic group of the RCRA Appendix VIII list of hazardous constituents present in the wastes.<sup>17</sup>

Appendix VIII is a list of approximately 400 organic and inorganic hazardous chemicals first published in Part 261 of the May 19, 1980 Federal Register.<sup>16</sup> This list is updated semiannually in 40 CFR 261.

POHC selection is covered by 40 CFR 264.342(b) which suggests that Appendix VIII constituents, which are in the highest concentration in the waste feed and are the most difficult to incinerate, are the most appropriate to be selected as POHCs. Supplementary guidance has also been issued.<sup>19,20</sup> This selection approach, particularly the concept of hazardous compound incinerability and selection of surrogate POHCs, has been the subject of considerable scientific debate. These issues will be examined in greater detail later.

On April 27, 1990, the EPA proposed to amend the hazardous waste incinerator regulations to control the toxic metal and free chloride emissions and improve HCl emissions and residual organic emissions standards.<sup>21</sup> In addition, these amendments would have allowed POHCs to be selected that were not in the normal waste feed or on the RCRA Appendix VIII list if they were demonstrated to be suitable indicators of DRE performance. These amendments would have essentially applied the same approach to hazardous waste incinerators that has since been promulgated for the control of such emissions from boilers and industrial furnaces (BIFs) burning hazardous waste (discussed later). In essence, much of this has already been implemented by EPA permit writers under the "omnibus" authority of HSWA and codified in 40 CFR 270.<sup>32</sup> which states, "Each permit issued under section 3005 of this act shall contain terms and conditions as the Administrator or State Director determines necessary to protect human health and the environment."

It is important to note that in 1980, EPA chose not to apply the incineration standards to the burning of hazardous waste as a fuel in industrial boilers and furnaces.<sup>16</sup> This exemption was based upon a lack of sufficient information on the practice and the fact that energy recovery constituted a beneficial use of wastes. Considerable data have been assembled since the exemption was granted in 1980.

To ensure that low-heating-value hazardous waste was not burned in a boiler or industrial furnace, ostensibly for energy recovery but actually to avoid the cost or regulation of incineration,

the EPA developed a "sham recycling" policy in 1983.<sup>22</sup> That policy held that if a hazardous waste having less than 5,000 to 8,000 Btu/lb heating value were burned in a boiler or industrial furnace, it was not burned for its fuel value but rather to avoid the cost (or regulation) of incineration. With the promulgation of the BIF rule, all BIFs burning hazardous wastes must now meet the new treatment standards (discussed later). Because of this the "sham recycling" policy is being phased out.

On January 4, 1985, EPA revised its rules to state that listed hazardous wastes and sludges are subject to transportation and storage controls prior to their being burned as fuels in boilers and industrial furnaces and prior to their processing or blending to produce a waste-derived fuel.<sup>23</sup> On November 29, 1985, EPA promulgated administrative controls for marketers and burners of hazardous waste fuels that regulated the transportation and storage of any hazardous waste used as a fuel or used to produce a fuel.<sup>24</sup> It also prohibited the burning of hazardous waste fuel in nonindustrial boilers, unless the boiler complied with the standards for hazardous waste incinerators.

On May 6, 1987, the EPA proposed regulations to control the emissions from boilers and industrial furnaces burning hazardous waste.<sup>25</sup> The Agency published a supplement to this proposed rule on October 26, 1989, which requested comment on alternate approaches to addressing issues concerning the control of CO, metals, HCl, particulates and other related issues.<sup>26</sup>

The final rule was promulgated on February 21, 1991 and became effective August 21, 1991.<sup>27</sup> and technical amendments to the final rule were published on August 27, 1991.<sup>28</sup> These regulations control emissions of toxic organic compounds, toxic metals, hydrogen chloride, chlorine gas and particulate matter from boilers and industrial furnaces burning hazardous waste. In addition, this rule subjects owners and operators of these devices to the general facility standards applicable to hazardous waste treatment, storage and disposal facilities. An innovative feature of this BIF rule is that it includes substantive interim status standards which are self-implemented by industry. By August 21, 1992, the facilities were required to conduct a compliance test and provide certification that they were meeting the BIF performance standards. Thus, existing BIF facilities will be operating under emissions standards and other controls

even before they are permitted. However, there are differences between the interim standards and controls and the requirements for permitted facilities. EPA will require the permittee to conduct the RCRA trial burn in due course to ensure compliance with standards given below.

Toxic organic compound emissions are controlled by requiring boilers and industrial furnaces to comply with the same DRE standard currently applicable to hazardous waste incinerators: 99.9999 percent DRE for dioxin-listed waste (EPA Hazardous Waste Nos. F020, F021, F022, F023, F026 or F027) and 99.99 percent DRE for all other hazardous wastes. Compliance with the DRE standard must be demonstrated during a trial burn for each selected POHC. However, facilities may be exempt from the trial burn requirements depending upon the type and quantity of waste burned, the type of facility, and operating conditions. As with hazardous waste incinerators, POHCs are to be selected based on the degree of difficulty of destruction of the organic constituents in the waste and on their concentrations or mass in the waste feed. In most cases, it is believed that these POHCs will be selected from organic compounds contained on the RCRA Appendix VIII list of hazardous constituents. The applicants have the option, however, of proposing compounds that are not in the normal waste feed or not on the RCRA Appendix VIII list if they can demonstrate that those compounds are suitable indicators of DRE performance. Such POHCs need not be toxic or organic compounds. POHC selection will be discussed further under the section labeled "Surrogates."

Products of incomplete combustion (PICs) are controlled by setting limits on parameters that will assure that the device is operated under good combustion conditions. This is accomplished by either limiting the hourly rolling average concentration of the flue gas concentration of CO to 100 parts per million by volume (ppmv), based on standard dry gas corrected to 7 percent oxygen (Tier I), or limiting hydrocarbon (HC) emissions to a maximum of 20 ppmv (Tier II). Furnaces that cannot meet the HC limit because of organic matter in the raw material may establish a higher HC limit by conducting site-specific sampling and analysis and dispersion modeling to demonstrate that annual average ground level concentrations of specific organic compounds do not exceed specified levels for noncarcinogens and

do not pose high risks to the maximum exposed individual (MEI) for carcinogenic compounds. As a part of this analysis, they must also determine the baseline HC contents in the raw material.

Owners and operators of hazardous waste-burning boilers and industrial furnaces equipped with a dry particulate matter control device that operates within the range of 450 to 750°F and furnaces operating under an alternate HC limit must conduct site-specific risk assessments. The assessments are required to demonstrate that emissions of chlorinated dibenzo-p-dioxins and dibenzofurans do not result in an increased lifetime cancer risk to the MEI greater than one in 100,000.

Emission limits based on projected inhalation health risks to a hypothetical MEI have been established for 10 toxic metals which are listed in Table II along with their corresponding unit risk (for carcinogens) or reference air concentration (RAC) (for noncarcinogens) values. RACs for nickel and selenium have been included as well since it is anticipated that these metals will also be regulated in the near future. Limits for the carcinogenic metals are established so that the incremental cancer risk to the MEI is not greater than one in 100,000. These risk assessments are calculated by utilizing dispersion modeling and the unit risk estimates prepared by EPA's Carcinogen Assessment Group (CAG). Unit risk is defined as the incremental cancer risk to an individual exposed for a lifetime (70 years) to ambient air containing one microgram of the compound per cubic meter ( $\mu\text{g}/\text{m}^3$ ) of air.<sup>29</sup>

The limits for the noncarcinogenic metals are based on Reference Doses (RfDs) below which adverse health effects have not been observed. Based on assumptions concerning body weight, volume of air breathed, background levels of the metals from other sources, and the relationship between the oral and inhalation routes of exposure, the RfDs have been used to calculate maximum RACs attributable to noncarcinogenic metal emissions from BIFs. EPA has apportioned 75 percent of the RfD to other nonspecified sources, so the calculated RAC is based on only 25 percent of the RfD. The RAC for lead is set at 10 percent of the national ambient air quality standard. This data and dispersion modeling are then used to back-calculate acceptable emissions.

The metals standards are implemented through a three-tiered approach and compliance with any tier is

acceptable. The tiers are structured to allow higher emission rates (and feed rates) as the owner or operator elects to conduct more site-specific testing and analysis. Under Tier I, it is assumed that all metals fed to the device are emitted. The EPA has developed tables specifying waste feed rate limits for each metal as a function of effective stack height, terrain and land use in the vicinity of the stack assuming reasonable, worst-case dispersion scenarios.

Under Tier II, the owner or operator conducts emission testing to determine the percentage of metals fed that are actually emitted due to partitioning to the bottom ash or to kiln "product" (in the case of cement kilns, for example) and the amount removed by the air pollution control device (APCD). The same tables that were developed for Tier I are used but they now represent metal emission rates instead of metal feed rates.

Under Tier III, the owner or operator conducts metal emissions testing to determine the emission rate for each metal and air dispersion modeling to predict the maximum annual average off-site ground level concentration for each metal to demonstrate that acceptable ambient levels are not exceeded.

The emission of HCl and free chlorine (Cl<sub>2</sub>) are controlled under a three-tiered approach similar to that used for

metals and their RACs are given in Table II. The limit for particulate matter is 180 mg/dscm corrected to 7 percent oxygen, the same as the hazardous waste incinerator standard.

EPA has also promulgated regulations for the incineration of specific wastes. Incineration of PCBs at concentrations of 50 parts per million (ppm) and greater is controlled under TSCA rules, which were initially promulgated in May 1979, and are codified in 40 CFR 761.<sup>30</sup> These rules stipulate that incineration is an acceptable treatment technology. Other disposal alternatives are permitted depending upon the PCB concentrations and waste characteristics. The principal performance standards and operating conditions that incinerators burning PCBs must meet depends upon whether the waste is a liquid or nonliquid. For liquid waste, the following applies:

- (1) The combustion chamber gas residence time must be at least 2 seconds at 1,200°C (+/- 100°C) with a minimum of 3 percent excess oxygen in the stack gas; or  
The combustion chamber gas residence time must be at least 1.5 seconds at 1,600°C (+/- 100°C) with a minimum of 2 percent excess oxygen in the stack gas.

- (2) Combustion efficiency (CE) shall be at least 99.9 percent computed as follows:

$$CE = \frac{\text{Percent CO}_2}{\text{Percent CO}_2 + \text{Percent CO}} \times 100$$

Incinerators burning nonliquid PCB wastes must comply with the following:

- (1) The mass emissions from the incinerator shall be no greater than 0.001 gram (g) PCB per kilogram (kg) of the PCB introduced into the incinerator (which is the same as a DRE of at least 99.9999 percent for the PCBs).
- (2) The CE shall be at least 99.9 percent.

The incineration of wastes containing certain chlorinated dibenzo-p-dioxins, chlorinated dibenzofurans and chlorinated phenols is regulated under RCRA rules promulgated January 14, 1985.<sup>31</sup> This so-called "dioxin rule" limits the incineration of these specific wastes (EPA waste codes F020, F021, F022, F023, F026 or F027), summarized in Table III, to incinerators which have demonstrated the ability to achieve at least 99.9999 percent DRE for chlorinated dioxins or similar compounds during the trial burn.

**Table II.** Summary of toxic metals, HCl and Cl<sub>2</sub> regulated for boilers and industrial furnaces burning hazardous wastes.<sup>27</sup>

CARCINOGENIC			NON-CARCINOGENIC	
Metal	Unit Risk [Cancers/ (μg/m <sup>3</sup> )]	Maximum Permissible Air Concentrations (μg/m <sup>3</sup> ) <sup>a</sup>	Metal	RAC <sup>b</sup> (μg/m <sup>3</sup> )
Cadmium	0.0018	0.0056	Barium	50.00
Beryllium	0.0024	0.0042	Nickel <sup>c</sup>	20.00
Arsenic	0.0043	0.0023	HCl	7.00
Chromium <sup>d</sup>	0.0120	0.00083	Selenium <sup>c</sup>	4.00
			Silver	3.00
			Thallium	0.50
			Cl <sub>2</sub>	0.40
			Antimony	0.30
			Lead	0.09
			Mercury	.08 <sup>e</sup>

<sup>a</sup> These air concentrations apply only if emitted alone and no other carcinogenic metal is emitted. As a practical matter, allowable limits will be even lower, due to the presence of other carcinogens.

<sup>b</sup> RAC = reference air concentration.

<sup>c</sup> Values for nickel and selenium have been included as it is anticipated these metals will be regulated in the future.

<sup>d</sup> Chromium Unit Risk is for Chromium VI (i.e., Cr<sup>6+</sup>).

<sup>e</sup> The RAC for mercury has recently been reduced from 0.30 to 0.08 μg/m<sup>3</sup>. The Agency will use the "omnibus" authority of 40 CFR 270.32 to use revised RACs where the facts warrant.

## Current Incineration Practice

### Incineration Practice

Incineration is an engineered process that employs thermal decomposition via thermal oxidation at high temperature (usually 900°C or greater) to destroy the organic fraction of the waste and reduce volume. Generally, combustible wastes or wastes with significant organic content are considered most appropriate for incineration. Technically, however, any waste with a hazardous organic fraction, no matter how small, is at least a functional candidate for incineration. For instance, significant amounts of contaminated water were being incinerated in the United States during the early 1980s.<sup>32</sup> Contaminated soils are also being incinerated with increasing frequency. EPA, for example, has employed a mobile incinerator to decontaminate 40 tons of Missouri soil which had been contaminated with four pounds of chlorinated dioxin compounds.<sup>33-36</sup>

Following this successful demonstration of mobile incineration, many

**Table III.** Summary of specific dioxin-containing wastes that, if incinerated, must be treated in an incinerator certified capable of achieving a DRE of at least 99.9999%.<sup>31</sup>

EPA Hazardous Waste Number	Description
F020	Wastes (except wastewater and spent carbon from hydrogen chloride purification) from the production or manufacturing use (as a reactant, chemical intermediate, or component in a formulating process) of tri- or tetrachlorophenol, or of intermediates used to produce their pesticide derivatives. (This listing does not include wastes from the production of Hexachlorophene from highly purified 2,4,5-trichlorophenol.)
F021	Wastes (except wastewater and spent carbon from hydrogen chloride purification) from the production or manufacturing use (as a reactant, chemical intermediate, or component in a formulating process) of pentachlorophenol, or of intermediates used to produce its derivatives.
F022	Wastes (except wastewater and spent carbon from hydrogen chloride purification) from the manufacturing use (as a reactant, chemical intermediate, or component in a formulating process) of tetra-, penta-, or hexachlorobenzenes under alkaline conditions.
F023	Wastes (except wastewater and spent carbon from hydrogen chloride purification) from the production of materials on equipment previously used for the production or manufacturing use (as a reactant, chemical intermediate, or component in a formulating process) of tri- and tetrachlorophenols. (This listing does not include wastes from equipment used only for the production or use of Hexachlorophene from highly purified 2,4,5-trichlorophenol.)
F026	Wastes (except wastewater and spent carbon from hydrogen chloride purification) from the production of materials on equipment previously used for the manufacturing use (as a reactant, chemical intermediate, or component in a formulating process) of tetra-, penta-, or hexachlorobenzene under alkaline conditions.
F027	Discarded unused formulations containing tri-, tetra-, or pentachlorophenol or discarded unused formulations containing compounds derived from these chlorophenols. (This listing does not include formulations containing Hexachlorophene synthesized from prepurified 2,4,5-trichlorophenol as the sole component.)

companies have built mobile or transportable incinerators that are actively employed in the remediation of Superfund sites. Some of these are scaled-down, trailer-mounted versions of conventional rotary kiln or fluidized bed incinerators with thermal capacities of 10 to 20 million British thermal units per hour (Btu/h). However, transportable units as large as 120 million Btu/h are also available. Overall, the performance of these mobile systems has been shown to be comparable to equivalent stationary facilities.<sup>34,35</sup> One advantage of mobile systems is that they may be more generally socio-politically acceptable than removal and transportation of cleanup residues to commercial facilities. This may not be true, however, for people living near the site. In the instance of soil decontamination, on-site incineration is commonly more cost-effective than transportation of large amounts of contaminated material to central incineration facilities.

While the exact number of available mobile and transportable units is somewhat dynamic, a 1990 analysis<sup>37</sup> provides a good characterization of this sector of incinerators. At that time, it was reported that 15 companies were operating 30 units which were comprised of 22 rotary kilns, four infrared conveyors and four circulating beds. A more recent survey<sup>38</sup> showed that as of March 1992, mobile and transportable incinerators were in various stages of

remediating 2,139,700 tons of contaminated soil at 56 sites which are summarized in Table IV. It should be noted that the sites summarized in Table IV include CERCLA-Superfund, RCRA corrective action, RCRA closure, real estate transfer and spill cleanup sites. It does not include underground storage tank (UST) sites. As we continue to remediate the balance of the nation's Superfund sites, the use of mobile/transportable incinerators will likely continue to increase as Records of Decision (RODs) are frequently based on thermal treatment technologies.

Since the promulgation of the RCRA interim status incinerator standards in 1980, a number of surveys and studies have been conducted to assess the quantity and types of hazardous waste generated in the United States, as well as the quantities and types of wastes being managed by various treatment,

storage and disposal facilities. Many of these were conducted during the early- to mid-1980s<sup>39-46</sup> and efforts have continued<sup>47</sup> to refine and update this information.

Perhaps the most up-to-date and comprehensive data available on the generation and management of hazardous waste are contained in the State Capacity Assurance Plans (CAPs). SARA required each state to submit a CAP by October 17, 1989 to EPA demonstrating that it had sufficient in-state capacity or had secured sufficient capacity in other states for managing its hazardous waste. As a part of this plan, each state was required to provide information on hazardous waste generation and management within the state for 1987, 1989, 1995 and 2009. The only year for which amounts are based on actual waste management in these plans is 1987. All other years are projections.

**Table IV.** Summary of mobile/transportable incinerators remediating Superfund and other contaminated soils as of March 1992.<sup>38</sup>

DESCRIPTION	SITES	QUANTITY OF CONTAMINATED SOIL (TONS)
Finished	32	452,200
On-Going	12	845,500
Contracted	12	842,000
Totals	56	2,139,700

Note: Underground storage tank (UST) cleanups are not included.

A review of these various studies has sometimes revealed significant differences in what would seem to be relatively straightforward statistics. While frustrating to those in government and industry who evaluate waste management alternatives and economic impacts, these deficiencies in the data base are not surprising. They have resulted from many factors, such as changes and uncertainties in regulatory definitions of hazardous waste terms, differences in methods and assumptions employed in the various surveys, and incomplete or inaccurate responses by facility owners and operators. Continuing changes in waste generation rates, the number and permit status of facilities which have occurred in response to regulatory changes, and economic factors have also made it difficult to accurately project trends in waste management practice from one point in time to another.

One of the most important factors, however, that has contributed to differences among these estimates is the varying manner in which "exempt waste" has been treated. Waste that otherwise would be defined as hazardous is exempt from RCRA hazardous waste regulations when treated in wastewater treatment plants regulated under the Clean Water Act. Approximately 97 percent (when exempt waste is included) of the hazardous generated in the United States is wastewater<sup>48</sup> and much of this is treated in exempt facilities. One analysis of the CAPs<sup>49</sup> illustrates the impact this can have. Eighteen states included some exempt waste in their estimates of hazardous waste generated in 1987. If this exempt waste had not been included, the total reported for the United States would have been over 40 percent less.

In spite of these deficiencies and limitations, it is possible to construct a reasonable picture of hazardous waste generation and incineration practice from the aggregate of the studies. Total annual hazardous waste generation in the United States was first projected by EPA to be approximately 265 million metric tons (MMT) for 1981 in the so-called Westat mail survey.<sup>43</sup> This was later corroborated in separate studies by the Congressional Budget Office (CBO)<sup>44</sup> and the Congressional Office of Technology Assessment (OTA).<sup>45</sup> EPA estimated 216 MMT were generated in 1987<sup>47</sup> and the CAPs reported that 249.3 MMT were generated for this same period.<sup>49</sup> However, 101.4 MMT of this was exempt waste leaving a balance of 147.9 MMT of non-exempt hazardous waste.

Only a small fraction of this waste (<1 percent) was believed to have been incinerated. EPA estimated that 1.7 MMT was treated in incinerators during 1981.<sup>43</sup> The CBO projected this amount at 2.7 MMT for 1983.<sup>44</sup> EPA estimated that 1.0 MMT were treated at 227 incinerator sites (310 estimated units) during 1987.<sup>21</sup> EPA has also estimated that approximately 1.0 MMT were burned in industrial furnaces<sup>27</sup> while Holloway<sup>50</sup> estimated that 1.0 MMT were burned in industrial boilers per year during the late 1980s. These quantities are in reasonable agreement with the estimates in the CAPs which are summarized in Table V by SARA management category for non-exempt hazardous waste for 1987. The CAPs estimated that 1.3 MMT of hazardous waste were incinerated and 1.2 MMT were burned in BIFs during 1987.

The principal attractions to burning hazardous waste in industrial boilers and furnaces include previous exemption from RCRA incineration standards, projected fuel and waste transportation cost savings, and expected waste disposal cost savings since hazardous waste used as a fuel could be sold (i.e., it had an economic fuel value).

One source of information on waste fuel use in industrial processes was compiled for EPA in 1984.<sup>51</sup> The study synopsis results of a national questionnaire of waste fuel and waste oil use in 1983. The study revealed that there were over 1,300 facilities using hazardous waste-derived fuels (HWDF), accounting for a total of 230 million gallons (0.9 MMT) per year. The chemical industry Standard Industrial Classification (SIC) 28 accounted for 67 percent of this while operating only 12.4 percent of the facilities using HWDF. Other industries employing significant quantities of hazardous waste as fuel included SICs 26 (paper), 29 (petroleum), 32 (stone, clay, glass, concrete), and 33 (primary metals). The majority (69 percent) of the waste was burned in large quantities by a few facilities representing only a small fraction (1.6 percent) of the 1,300 facilities. These included medium- to large-sized industrial boilers, cement and aggregate kilns, and iron-making furnaces.

While waste-code-specific data on HWDF are not readily available, 1983 data indicate that of the HWDF burned, 30 percent was organic solvents and 45 percent was other hazardous organics.<sup>51</sup> Most of this waste was generated

**Table V.** Quantities of non-exempt hazardous wastes generated in the United States, 1987.<sup>49</sup>

SARA Management Category	Quantity (MMT)*	Percent of Total
<b>Recovery:</b>		
Metals	0.4	0.2
Solvents	0.9	0.6
Other	0.1	0.1
Total Recovery	1.4	0.9
<b>Thermal Processes:</b>		
Incineration/Liquids	1.1	0.8
Incineration/Solids	0.2	0.1
Energy Recovery	1.2	0.8
Total Thermal	2.5	1.7
<b>Treatment:</b>		
Aqueous Inorganic	16.8	11.4
Aqueous Organic	36.7	24.8
Other Treatment	58.8	39.7
Sludge Treatment	0.4	0.3
Stabilization	0.6	0.4
Total Treatment	113.3	76.6
<b>Disposal:</b>		
Land Treatment	0.4	0.3
Landfill	3.3	2.3
Deep Well Injection	26.8	18.1
Other Disposal	0.2	0.1
Total Disposal	30.7	20.8
Total Non-Exempt Hazardous Waste	147.9	100

\* MMT = millions of metric tons

This public opposition has created considerable uncertainty for waste generators, equipment manufacturers and commercial waste disposers. This uncertainty plus more stringent regulations are partially responsible for the changes in the numbers of facilities and companies that have remained in the hazardous waste incineration business. Between 1981 and 1987 for instance, almost 100 incinerators withdrew from the RCRA system; they either ceased operation or decided to no longer handle hazardous wastes.<sup>41</sup> Of the 57 companies identified as marketing hazardous waste incinerators in 1981, 23 had either gone out of business, left the hazardous waste incinerator business or put considerably less emphasis on this activity by 1984.<sup>41</sup> By November 8, 1989, (the Congressionally-mandated statutory deadline for permitting all hazardous waste incinerators) an additional 55 incinerator sites had announced that they would close, 120 incinerator sites had been permitted and fifty-five incinerator sites were allowed to continue operation (pending receipt of a permit) while they addressed deficiencies.<sup>39</sup> By December 1991, there were approximately 150 permitted and operating incinerator facilities.<sup>60</sup> In addition, an estimated 925 boilers were burning hazardous wastes as fuel during 1991. Following the promulgation of the "Burning of Hazardous Waste in Boilers and Industrial Furnaces; Final Rule"<sup>27</sup> on February

21, 1991, it was expected that 200 of these would stop burning hazardous waste, 600 would continue to operate under the small-quantity on-site burner exemption (does not require permit) and 125 would continue to operate subject to the interim status and permit standards of the rule. It was also estimated that approximately 75 industrial furnaces would continue to burn hazardous wastes. The regulated universe of these furnaces were estimated to be comprised of 40 cement kilns, 18 light-weight aggregate kilns and 15 halogen acid furnaces.<sup>27</sup> It now appears, however, that a somewhat larger number of cement kilns may wish to burn hazardous waste. As of February 1992, 53 cement facilities had applied for interim status under the BIF rule.<sup>61</sup>

The amount of public opposition to proposed permits for incinerator facilities varies by location and type of waste. On-site facilities that directly serve a single waste generator have greater public acceptance than off-site, commercial incinerators that serve multiple generators in a large market area. Off-site facilities are often not discerned as providing sufficient economic benefits to the local community to offset the perceived risks associated with the importation of wastes from other areas. On-site facilities are more clearly distinguished as being linked to businesses that are important to the local economy, and are generally not perceived as being importers of haz-

ardous waste. Opposition has tended to focus primarily on new off-site commercial facilities and on new applications to burn PCBs, which critics view as particularly hazardous.

In an effort to assess the dilemma of perceived benefits versus public concerns, EPA conducted an assessment in 1985 to determine if there was a need for a change in the approach toward regulating thermal destruction.<sup>3</sup> The major issues reported by citizens included concern for:

- Hazardous material spills in storage, treatment and handling
- Environmental and health impacts
- Poor site selection processes
- Distrust of incinerator owners and operators
- Inability of government agencies to enforce compliance

The study concluded that public opposition to incineration may decline somewhat if regulators address more fully some citizen concerns regarding national regulatory strategy, local community impact, equity of facility siting, public decision-making processes, and especially enforcement plans and capacity. It was also concluded that there is a need to better communicate how health and environmental concerns and priorities are reflected in regulations and standards. Better communication of regulatory

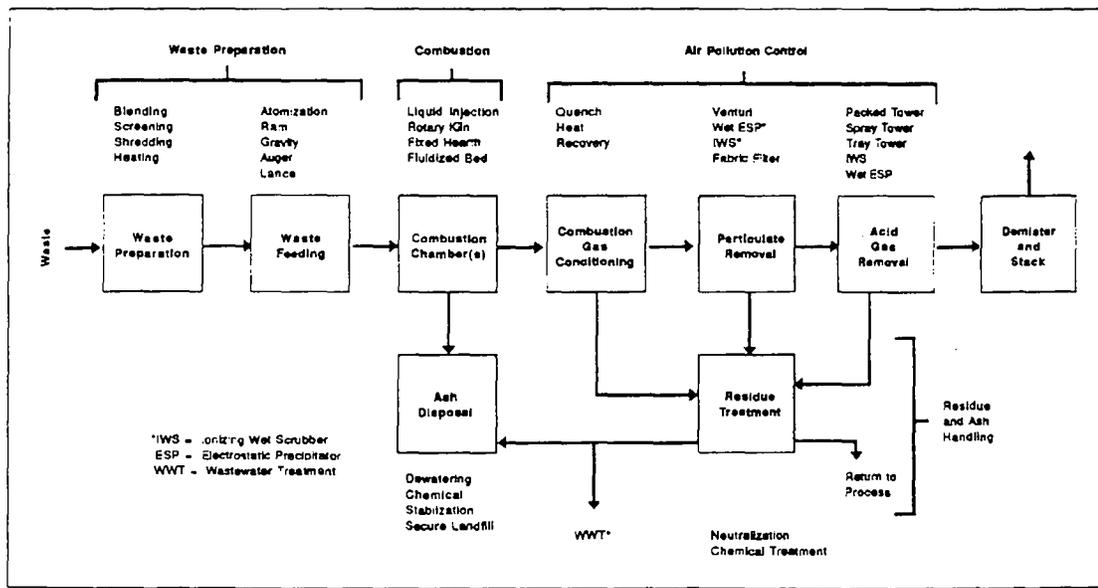


Figure 1. General orientation of incineration subsystems and typical process component options.

on-site and 74 percent of the balance arrived directly from an off-site generator rather than through an intermediary.

Precise information on the exact types of wastes actually going to incineration facilities is not readily available. Many facilities operate on an intermittent basis and handle mixtures of wastes which are difficult to describe in terms of EPA standard waste codes. A 1983 EPA study examined data on 413 waste streams going to 204 incineration facilities in the United States.<sup>32</sup> The major waste streams incinerated were spent nonhalogenated solvents (EPA waste code F003) and corrosive and reactive wastes contaminated with organics (EPA waste codes D002 and D003). Together, these accounted for 44 percent of the waste incinerated. Other prominent wastes included hydrocyanic acid (P063), acrylonitrile bottoms (K011) and nonlisted ignitable wastes (D001). In a separate EPA analysis,<sup>21</sup> 1981 information<sup>43</sup> was utilized to characterize the waste that was treated in incinerators. It was found that the waste was composed of almost 60 different waste codes. Two waste codes - D001, ignitable wastes; and X182, a mixture of U008-acrylic acid, U112-ethyl acetate, U113-ethyl acrylate and P003-acrolein - accounted for 71 percent of the waste. It was also estimated that approximately 44 percent of this waste contained toxic metals and approximately 37 percent contained chlorine. Behmanesh *et al.*<sup>52</sup> examined the quantity and composition of RCRA hazardous wastes incinerated during 1986 and determined the metal-to-halogen ratio of incinerated waste by SIC. He found that the source of the waste streams containing metals was very much different from the bulk of incinerated wastes. In some cases only two or three waste streams contained a significant portion of the total metal loading fed to the incinerator.

While only a small fraction of the

generated hazardous waste is currently managed by incineration, several forces will likely result in the increased use of incineration. Implementation of the HSWA land disposal restriction regulations is expected to increase the quantity of hazardous waste incinerated. This will require an additional 7 million tons per year of hazardous waste that was previously land disposed to now be treated to levels achievable by the BDAT before it can be land disposed.<sup>1</sup> The BDAT treatment levels for many of the scheduled restricted hazardous wastes were based on incineration. In addition, as generator concern for long-term liability increases, incineration will likely continue to become more attractive. EPA has estimated that nearly 8.5 MMT more hazardous wastes could have been thermally destroyed in incinerators and industrial furnaces in 1981 than actually was.<sup>43</sup> Numerous other studies have indicated that the actual use and demand for incineration technologies to manage hazardous waste will increase significantly.<sup>2,44,53-55</sup> Also, there has been a trend toward considering a broader spectrum of waste types that are appropriate for incineration. As the remediation of Superfund sites has demonstrated, wastes contaminated with only relatively low concentrations (hundreds of ppm and lower for some dioxin contaminated sites) of organics and some levels of metals are being treated by incineration. Therefore, a much greater percentage of generated hazardous waste may be managed by incineration in the future.

It is clear that considerable potential exists for expansion of incineration practice. This assumes, however, that sufficient RCRA- and/or TSCA-permitted and mobile/transportable capacity can be made available. This is, of course, a significant issue and one which has been given attention in a number of studies.<sup>2,39-42</sup> Gruber<sup>56</sup> and Highum<sup>57</sup> have examined the existing incineration capacity and found that during 1987 there were 17 operating

commercial hazardous waste incineration facilities and 154 operating on-site hazardous waste incineration facilities with a combined capacity of 4.3 MMT. This information is summarized in Table VI. In addition, it has been reported<sup>56,58</sup> that a number of efforts are under way to bring nonoperating units on line, expand existing capacity and build new facilities which could significantly increase available incineration capacity.

When compared with the quantities of hazardous wastes currently being incinerated, it would appear that the necessary future capacity should be available. This is somewhat misleading, however. First the capacity figures are, for the most part, maximum capacity estimates and it is unlikely that they could be realistically attained. Highum<sup>57</sup> estimated that actual capacity would 30 to 50 percent less (2.2 to 3.0 MMT) than that showed in Table VI. As mentioned earlier, it may be desired to incinerate much greater quantities of waste in the future. It is highly unlikely that all of the nonoperating and planned units will actually be brought on line. While national waste capacity on a tonnage basis may appear to be available, this does not recognize the need for capacity by waste type or location. For example, if much of the available capacity is for liquid waste, there may not be sufficient capacity for sludges and solids. Also, incineration capacity for special wastes such as explosives and mixed wastes, may not be sufficient. Only 13 states had operating commercial incinerators in 1987.<sup>57</sup>

One of the major barriers to increased incineration capacity is public opposition to the permitting and siting of new facilities, especially the off-site commercial facilities which would be necessary to handle much of the solids and sludges which will increasingly require suitable disposal. Public opposition to the permitting of new commercial thermal destruction operations has been very strong in recent years. For example, Greenpeace claims to have been instrumental in preventing the construction or permitting of 44 incinerators.<sup>4</sup> The normal time required for permitting new commercial incineration facilities is at least three years and often much longer. This time factor, and the expense of obtaining a permit, may be greatly increased where public opposition exists. The typical length of time required to obtain a permit for a new industrial incinerator to be located at an existing industrial facility is one to two years.

**Table VI.** Summary of U.S. operating hazardous waste incinerator capacity, 1987.<sup>57</sup>

Description	Number	Capacity* (MMT)
Commercial HWI Facilities	17 <sup>b</sup>	0.9
On-site Incinerator Facilities	154	3.4
<b>Total</b>	<b>171</b>	<b>4.3</b>

\* Capacities as shown are likely maximum capacities. Actual capacities are estimated to be 30% to 50% less.

<sup>b</sup> Includes four industrial furnace facilities that have been permitted as hazardous waste incinerators.

policy, strategy and other activities related to decisions on proposed permits for individual incinerator facilities or units is certainly desirable since improved communication with the public can enhance the credibility of regulatory and enforcement agencies.

### Incineration Technology

Different incineration technologies have been developed for handling the various types and physical forms of hazardous waste. The four most common incinerator designs are liquid injection (sometimes combined with fume incineration), rotary kiln, fixed hearth and fluidized bed incinerators.

The process of selecting and designing hazardous waste incineration systems can be very complex. Fortunately, considerable industrial manufacturing experience exists and many useful design guides have been published.<sup>11,62-65</sup> Thus, while a detailed examination of design principles is beyond the scope of this paper, a generalized review of the most prominent features of incineration systems and important design factors will be helpful in understanding a thermal destructor's operation and emissions performance.

The four major subsystems which may be incorporated into a hazardous waste incineration system are: (1) waste preparation and feeding, (2) combustion chamber(s), (3) air pollution control and (4) residue/ash handling. The normal orientation of these subsystems is shown in Figure 1, along with typical process component options. The selection of the appropriate combination of these components is primarily a function of the physical and chemical properties of the waste stream or streams to be incinerated.

(1) *Waste Preparation and Feeding.* The physical form of the waste determines the appropriate feed method.<sup>62</sup> Liquids are blended, then pumped into the combustion chambers through nozzles or via specially designed atomizing burners. Wastes containing suspended particles may need to be screened to avoid clogging of small nozzle or atomizer openings. While sustained combustion is possible with waste heat content as low as 4,000 Btu/lb, liquid wastes are typically blended to a net heat content of 8,000 Btu/lb or greater, if possible. To incinerate lower heating value wastes, supplementary fuel will normally be required. Blending may be achieved by either mixing the wastes before they are fed to the combustion chamber or by using separate nozzles for different

types of waste, wherein the mixing occurs in the combustion chamber. Blending is also used to control the chlorine content of the waste fed to the incinerator. Wastes with a chlorine content of 70 percent and higher can be incinerated in specially designed incinerators.<sup>66</sup> Blending provides better combustion control and limits the potential for periodic formation of high concentrations of free-chlorine gas in the combustion gases.

Sludges are typically fed using progressive cavity pumps and water cooled lances. Bulk solid wastes may require shredding for control of particle size. They may be fed to the combustion chamber via rams, gravity feed, air-lock feeders, vibratory or screw feeders, or belt feeders. Containerized waste is typically gravity or ram fed.

(2) *Combustion Chambers.* The physical form of the waste and its ash content determine the type of combustion chamber selected. Table VII provides general selection considerations for the four major combustion chamber (incinerator) designs as a function of wastes of different forms.<sup>62</sup> Most incineration systems derive their names from the type of combustion chamber employed.

Liquid injection incinerators or combustion chambers are applicable almost exclusively for pumpable liquid waste. These units (Figure 2) are usually simple, refractory-lined cylinders (either horizontally or vertically aligned) equipped with one or more waste burners. Liquid wastes are injected through the burner(s), atomized to fine droplets and burned in suspension. Burners, as well as separate waste injection nozzles, may be oriented for axial, radial or tangential firing. Improved utilization of combustion space and higher

heat release rates, however, can be achieved with the utilization of swirl or vortex burners or designs involving tangential entry.<sup>67</sup>

Good atomization is critical to achieving high destruction efficiency in liquid combustors. Nozzles have been developed to produce mists with mean particle diameters as low as 1 micron ( $\mu\text{m}$ ),<sup>68</sup> compared to typical oil burners which yield droplets in the 10 to 50  $\mu\text{m}$  range.<sup>69</sup> Atomization may be attained by low pressure air or steam [1 to 10 pounds per square inch gauge (psig)], high pressure air or steam (25 to 100 psig), or mechanical (hydraulic) means using specially designed orifices (25 to 450 psig).

Vertically downward oriented liquid injection incinerators are preferred when wastes are high in inorganic salts and fusible ash content, while horizontal units may be used with low ash waste. In the past, the typical capacity of liquid injection incinerators was roughly  $30 \times 10^6$  Btu/h heat release. However, units as high as  $210 \times 10^6$  Btu/h are now in operation.

Rotary kiln incinerators (Figure 3) are more versatile in the sense that they are applicable to the destruction of solid wastes, slurries and containerized waste as well as liquids. Because of this, these units are most frequently incorporated into commercial off-site incineration facility designs and utilized for Superfund remediation. The rotary kiln is a horizontal cylindrical refractory-lined shell that is mounted on a slight slope. Rotation of the shell provides for transportation of waste through the kiln as well as enhanced mixing of the burning solid waste. The waste may move either concurrent or countercurrent to the gas flow. The residence time of waste solids in the kiln is generally

Table VII. Applicability of major incinerator types to wastes of various physical form.<sup>62</sup>

	Liquid Injection	Rotary Kiln	Fixed Hearth	Fluidized Bed
<b>Solids:</b>				
Granular, homogeneous		X	X	X
Irregular, bulky (pallets, etc.)		X	X	
Low melting point (tars, etc.)	X	X	X	X
Organic compounds with fusible ash constituents		X	X	X
Unprepared, large, bulky material		X	X	
<b>Gases:</b>				
Organic vapor laden	X	X	X	X
<b>Liquids:</b>				
High organic strength aqueous wastes	X	X	X	X
Organic liquids	X	X	X	X
<b>Solids/liquids:</b>				
Waste contains halogenated aromatic compounds (2,200°F minimum)	X	X	X	
Aqueous organic sludge		X		X

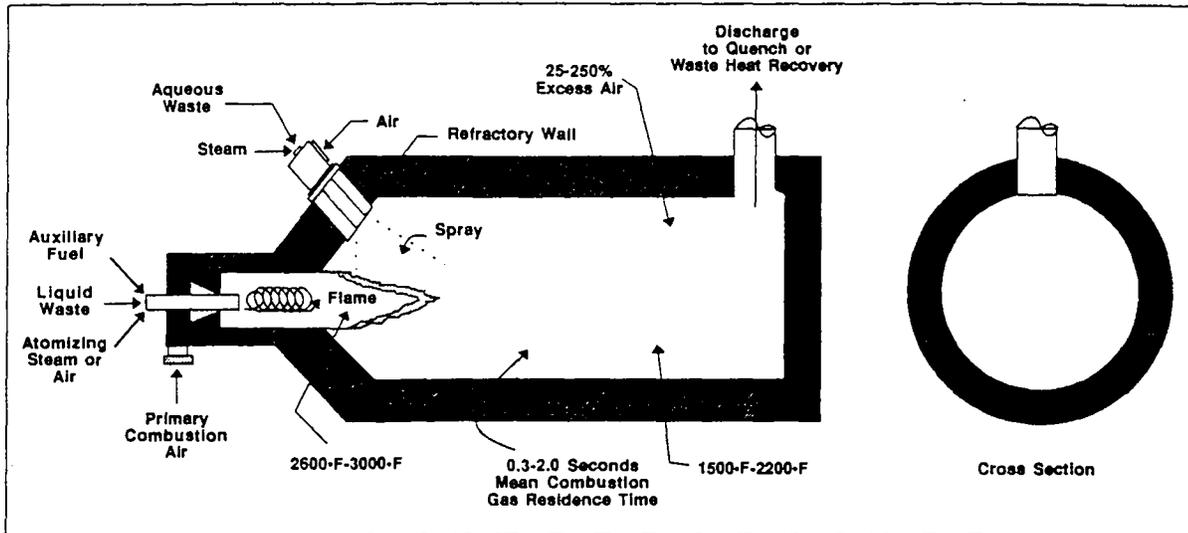


Figure 2. Typical liquid injection combustion chamber.

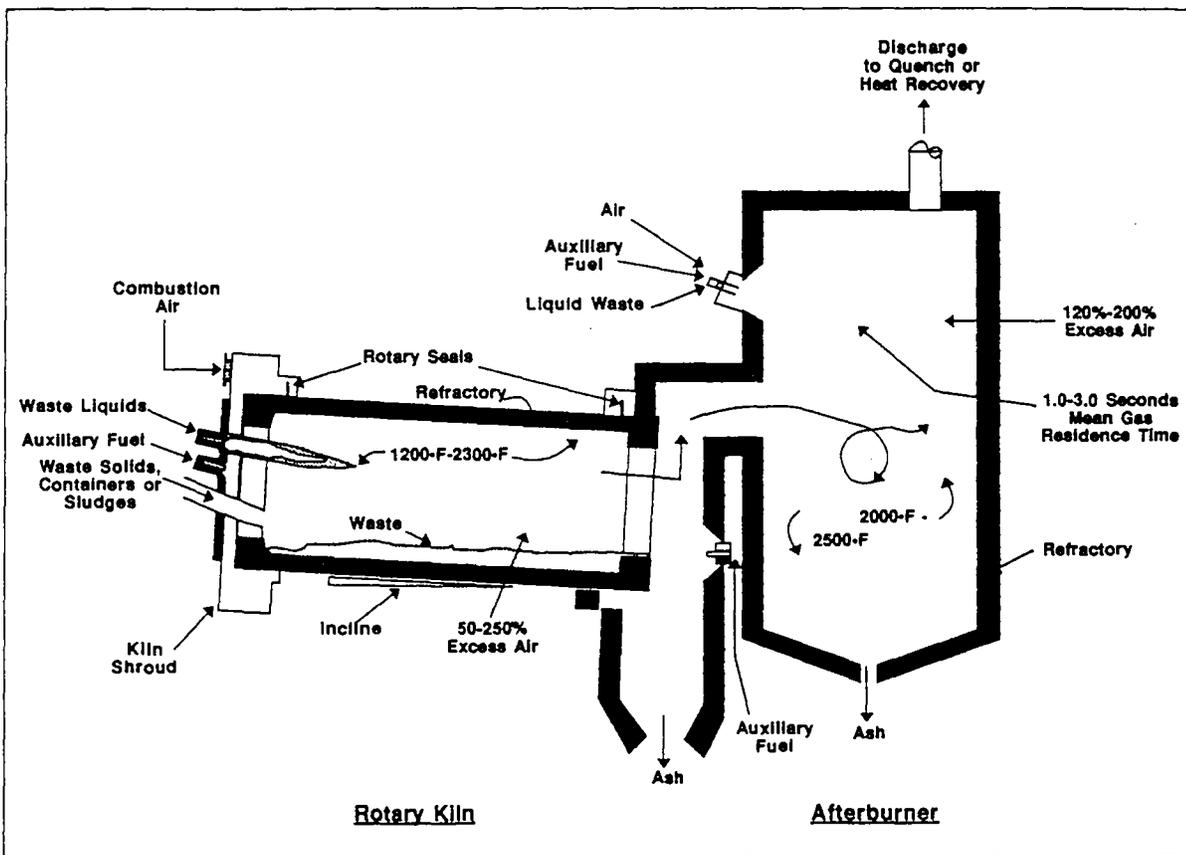


Figure 3. Typical rotary kiln/afterburner combustion chamber.

0.5 to 1.5 hours. This is controlled by the kiln rotation speed (typically 0.5 to 1.0 revolutions per minute), the waste feed rate, and in some instances, the inclusion of internal dams to retard the

rate of waste movement through the kiln. The feed rate is also generally adjusted to limit the amount of waste being processed in the kiln to at most 20 percent of the kiln volume.

The primary function of the kiln is to convert solid wastes to gases, which occurs through a series of volatilization, destructive distillation and partial combustion reactions. An afterburner

is necessary, however, to complete the gas-phase combustion reactions. The afterburner is connected directly to the discharge end of the kiln where the gases exiting the kiln are directed to the afterburner chamber. Some more recent systems have installed a "hot cyclone" between the kiln and afterburner to remove solid particles that might otherwise create slagging problems in the afterburner. The afterburner itself may be horizontally or vertically aligned, and essentially functions much on the same principles as a liquid injection incinerator. In fact, many facilities also fire liquid hazardous waste through separate waste burners in the afterburner. Both the afterburner and kiln are usually equipped with an auxiliary fuel firing system to

bring the units up to temperature and to maintain the desired operating temperatures. On the other hand, some operators make it a practice of firing their aqueous waste streams into the afterburner as a temperature control measure. Rotary kilns have been designed with a heat release capacity as high as  $150 \times 10^6$  Btu/h in the United States. On average, however, units are typically around  $60 \times 10^6$  Btu/h.

Fixed hearth incinerators, also called controlled air, starved air or pyrolytic incinerators, are the third technology in use for hazardous waste incineration today. These units employ a two-stage combustion process, much like rotary kilns (Figure 4). Waste is ram fed or pumped into the first stage or primary chamber, and burned at roughly 50 to

80 percent of stoichiometric air requirements. This starved air condition causes most of the volatile fraction of the waste to be vaporized by the endothermic heat provided by the oxidation of the fixed carbon fraction. The resultant smoke and pyrolytic products consisting primarily of methane, ethane and other hydrocarbons; carbon monoxide and products of combustion pass to the second stage, or secondary chamber. Here, additional air is injected to complete the combustion, which can occur either spontaneously or through the addition of supplementary fuels. The primary chamber combustion reactions and turbulent velocities are maintained at low levels by the starved-air conditions to minimize particulate entrainment and car-

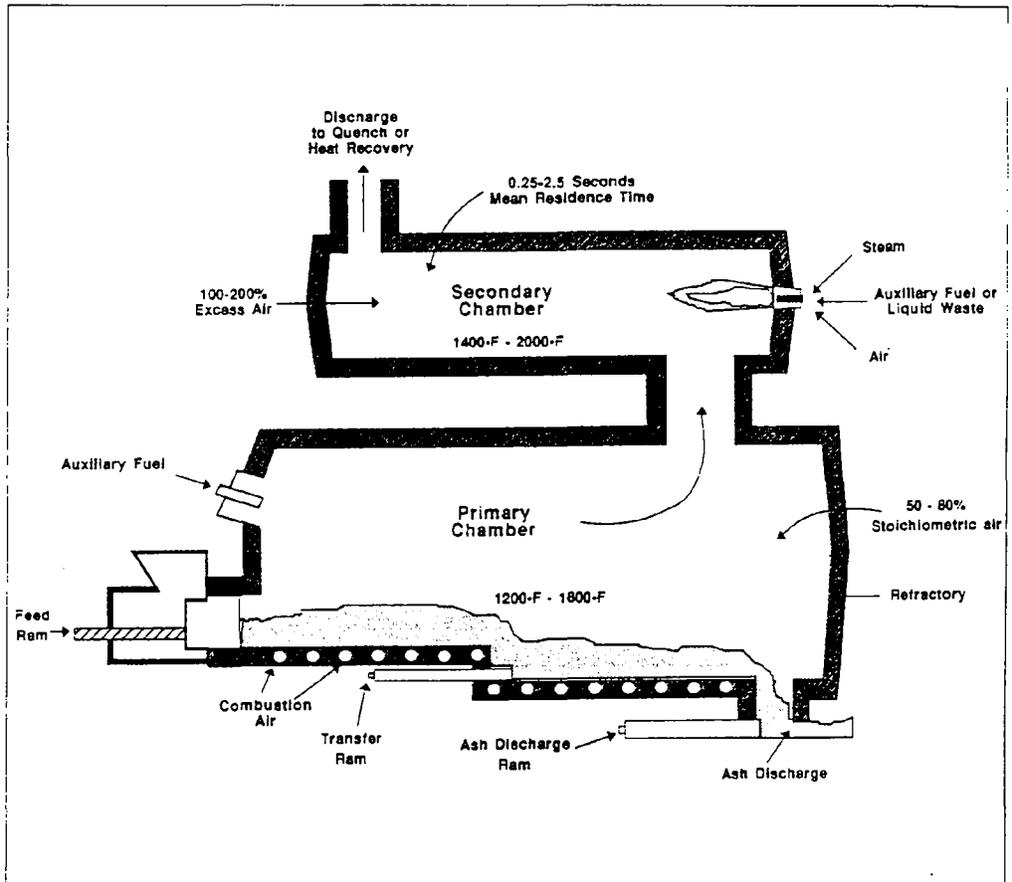


Figure 4. Typical fixed hearth combustion chamber.

ryover. With the addition of secondary air, total excess air for fixed hearth incinerators is in the 100 to 200 percent range.

Fixed hearth units tend to be of smaller capacity than liquid injection or rotary kiln incinerators because of physical limitations in ram-feeding and transporting large amounts of waste material through the combustion chamber. These lower relative capital costs and potentially reduced particulate control requirements make them more attractive than rotary kilns for smaller on-site installations.

Fluidized beds have long served the chemical processing industry as a unit operation and have been used to burn sludge generated by municipal wastewater treatment plants. This type of combustion system has only recently begun to see application in hazardous waste incineration. Fluidized bed incinerators may be either circulating or bubbling bed designs.<sup>70</sup> Both types consist of a single refractory-lined combustion vessel partially filled with particles of sand, alumina, calcium carbonate or other such materials. Combustion air is supplied through a distributor plate at the base of the combustor (Figure 5) at a rate sufficient to fluidize (bubbling bed) or entrain part of the bed material (circulating bed). In the circulating bed design, air velocities are higher and the solids are blown overhead, separated in a cyclone and then returned to the combustion chamber. Operating temperatures are normally maintained in the 1,400 to 1,600°F range and excess air requirements range from 25 to 150 percent.

Fluidized bed incinerators are primarily used for liquids, sludges or shredded solid materials including soil. To allow for good distribution of waste materials within the bed and removal of solid residues from the bed, all solids generally require prescreening or crushing to a size less than 2 inches in diameter. Fluidized bed incinerators offer: high gas-to-solids ratios, high heat transfer efficiencies, high turbulence in both gas and solid phases, uniform temperatures throughout the bed, and the potential for in-situ acid gas neutralization by lime, limestone or carbonate addition. Fluidized beds also have the potential for solids agglomeration in the bed, especially if salts are present in waste feeds.

Regardless of the incinerator type selected, the chemical and thermodynamic properties of the wastes determine the sizing of the combustion chamber and its operating conditions

(temperature, excess air, flow rates) and determine the nature of air pollution control and ash/residue handling systems. Elemental composition and moisture content data are necessary to determine stoichiometric combustion air requirements and to predict combustion gas flow and composition. These parameters are important in determining combustion temperature and residence time, the efficiency of waste/fuel/air mixing, and the type and size of air pollution control equipment. Typical operating temperatures, gas (and solid) residence times, and excess air rates for each of the four major incinerator types are indicated in Figures 2-5. It is important to understand, however, that significant deviation from these values has been observed in actual field practice without detrimental effect on waste destruction and removal efficiency.<sup>71</sup>

(3) *Air Pollution Control.* Following the incineration of hazardous wastes, combustion gases typically need to be further treated in an air pollution control system. The presence of chlorine or other halogens in the waste will generally signal a need for a scrubbing or absorption step for combustion gases to remove HCl and other haloacids. Ash in the waste is not destroyed in the combustion process. Depending on its composition, ash will either exit as bottom ash, at the discharge end of a kiln or hearth for example, and/or as

particulate matter suspended in the combustion gas stream (fly ash). Particulate emissions from most hazardous waste combustion systems generally have particle diameters down to less than one micron and require high efficiency collection devices to meet the RCRA or state emission standards.

One of the most commonly employed air pollution control systems for hazardous waste facilities is a quench (gas cooling and conditioning) followed by high-energy venturi scrubber (particulate removal), a packed tower absorber (acid gas removal) and a demister (visible vapor plume reduction). Facilities handling low ash, low halogen content liquid waste streams have been able to operate without any control, however.

Venturi scrubbers involve the injection of a scrubbing liquid (usually water or a water/caustic solution) into the exhaust gas stream as it passes through a high velocity constriction, or throat. The liquid is atomized into fine droplets which entrain fine particles and a portion of the absorbable gases in the gas stream. The major advantage of venturi scrubbers is their reliability and relative simplicity of operation. On the other hand, maintaining the significant pressure drop across the venturi throat (60 to 120 inches of water column) required for efficient hazardous waste combustion particulate matter control represents a significant percentage of

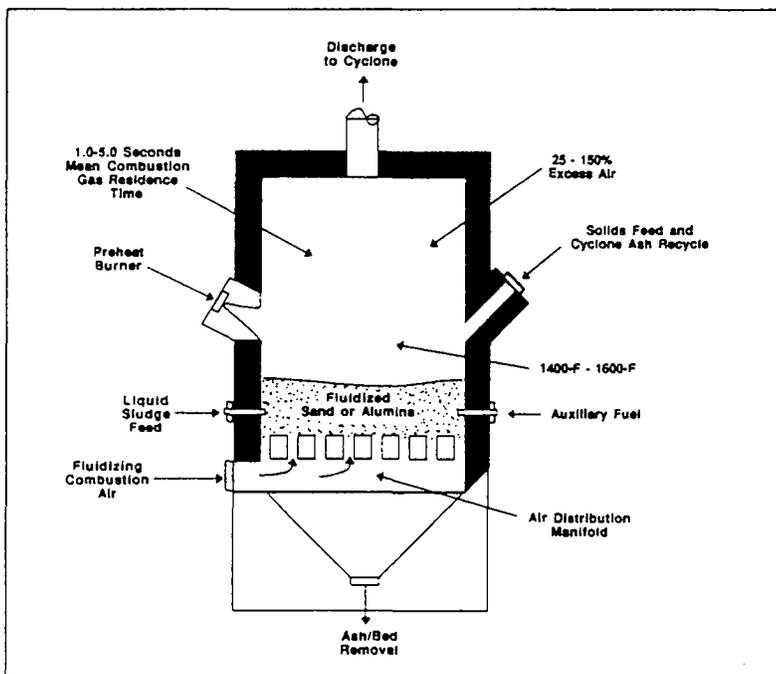


Figure 5. Typical fluidized bed combustion chamber.

the total cost of operation of incineration facilities employing venturi scrubbing. Also, venturi scrubbers may not be very effective in controlling the emission of fine particulates such as metal aerosols.

Acid gas removal is generally accomplished in packed bed or plate tower scrubbers. Packed bed scrubbers are generally vessels filled with randomly-oriented packing material such as polyethylene saddles or rings. The scrubbing liquid is fed to the top of the vessel, with the gas flowing in either concurrent, countercurrent or cross-flow modes. As the liquid flows through the bed, it wets the packing material and thus provides the interfacial surface area for mass transfer with the gas phase which is required for effective acid gas absorption.

Like packed bed scrubbers, plate scrubbers also rely on absorption for the removal of contaminants. The basic design is a vertical cylindrical column with a number of plates or trays inside. The scrubbing liquid is introduced at the top plate and flows successively across each plate as it moves downward to the liquid outlet at the tower bottom. Gas comes in at the bottom of the tower and passes through openings in each plate before leaving through the top. Gas absorption is promoted by the breaking up of the gas phase into small bubbles which pass through the volume of liquid on each plate.

Packed bed or plate tower scrubbers are commonly used at liquid injection incinerator facilities, where absorption of soluble gaseous pollutants [HCl & sulfur oxides (SO<sub>x</sub>)] is often most important and particulate control is less critical. At rotary kiln or fixed hearth facilities, or liquid injection facilities where high ash content wastes are incinerated, however, venturi scrubbers are often used in series with packed bed or plate tower scrubbers.

Many designs have begun to incorporate waste heat boilers as a substitute for gas quenching and as a means of energy recovery.<sup>72,73</sup> Wet electrostatic precipitators (ESP), ionizing wet scrubbers (IWS), collision scrubbers, spray dryer absorbers (SDA), and fabric filters (FF) are also being incorporated into newer systems.<sup>74</sup> This is largely due to their high removal efficiencies for small particles and lower pressure drop.

(4) *Residue and Ash Handling.* The inorganic components of hazardous wastes are not destroyed by incineration. These materials exit the incineration system either as bottom ash from

the combustion chamber, as contaminants in scrubber waters and other air pollution control residues, and in small amounts in air emissions from the stack. Residues generated from the incineration of hazardous waste must be managed carefully.

Ash is commonly either air-cooled or quenched with water after discharge from the combustion chamber. From this point, ash is frequently accumulated on-site in storage lagoons or in containers prior to disposal in a permitted hazardous waste land disposal facility. Dewatering or chemical fixation/stabilization may also be applied to meet the Land Disposal Restriction (LDR) regulations prior to disposal.

Air pollution control residues are generated from the combustion gas quenching, particulate removal, and acid gas absorption steps in an incineration system. These residues are typically aqueous streams containing entrained particulate matter, absorbed acid gases (usually as HCl), salts, and trace amounts of organic contaminants. These streams are often collected in sumps or recirculation tanks where the acids are neutralized with caustic and returned to the process. Eventually, a portion or all of these waters must be discharged for treatment and disposal. Many facilities discharge neutralized waters to settling lagoons or to a chemical precipitation step to allow for suspended contaminants to be concentrated and ultimately sent to land disposal. Depending upon the nature of the dissolved contaminants and their concentration after treatment, waters may either be returned to the process or discharged to sewers. One alternative to the management of aqueous residue streams is to use dry scrubber systems which do not generate any wastewater.

#### Measuring Process Performance

Proper and accurate measurement of the emissions from incineration systems is a critical issue. Great demands have been placed upon sampling and analysis technology by the RCRA incinerator regulations. Fortunately, significant progress has been made in adapting measurement methods to the rigors of specific compound identification and the level of detection and accuracy which are necessary to assess compliance with the RCRA incineration standards. These methods will rarely be a limitation in assessing incinerator performance if proper attention is given to quality assurance and quality control, if adequate advanced

planning is conducted, and if experienced personnel are involved in the sampling and analysis activities.

Performance measurement may have any of the following three purposes: (1) to establish initial or periodic compliance with performance standards (e.g., trial burns), (2) to routinely monitor process performance and direct process control (e.g., continuous monitoring), and (3) to conduct performance measurements for research and equipment development purposes.

Nearly all the methods employed in assessing regulatory compliance are official methods which have been standardized and published in the *Federal Register* or EPA guidance documents. Routine performance monitoring for process control often involves the use of continuous monitors for emissions and facility-specific engineering parameters (e.g., temperature, pH, kiln rotation). Research and equipment assessment investigations may involve any of the aforementioned techniques in combination with standard and occasional nonstandard sampling and analysis techniques designed for rapid screening of performance or for ultra-sensitive detection of specific materials.

#### Performance Measurement

Figure 6 illustrates sampling points which may be involved in assessing incinerator performance. In the case of trial burn activities, the main focus of sampling activities is on the collection of waste feed and stack emission samples. Ash and air pollution control system residues are also sampled and analyzed. Sampling of input/output streams around individual system components (e.g., scrubbers) may also be conducted in research testing or equipment evaluation studies.

The main focus of analytical activities is on POHCs, particulates, metals and HCl. Stack gas analysis may be extended to a determination of other organic compound emissions. In the case of particulate emissions, the size distribution of stack particles may also be of interest. The size of emitted particulate affects its transportation and fate in the atmosphere and can influence the fate of particles relative to inhalation, an important factor in health effects assessment. Few hazardous waste incinerator tests have actually collected particle size data, primarily due to time and funding limitations.

EPA has provided guidance on the types and methods of sampling and analysis to be used in trial burns designed to measure facility compliance

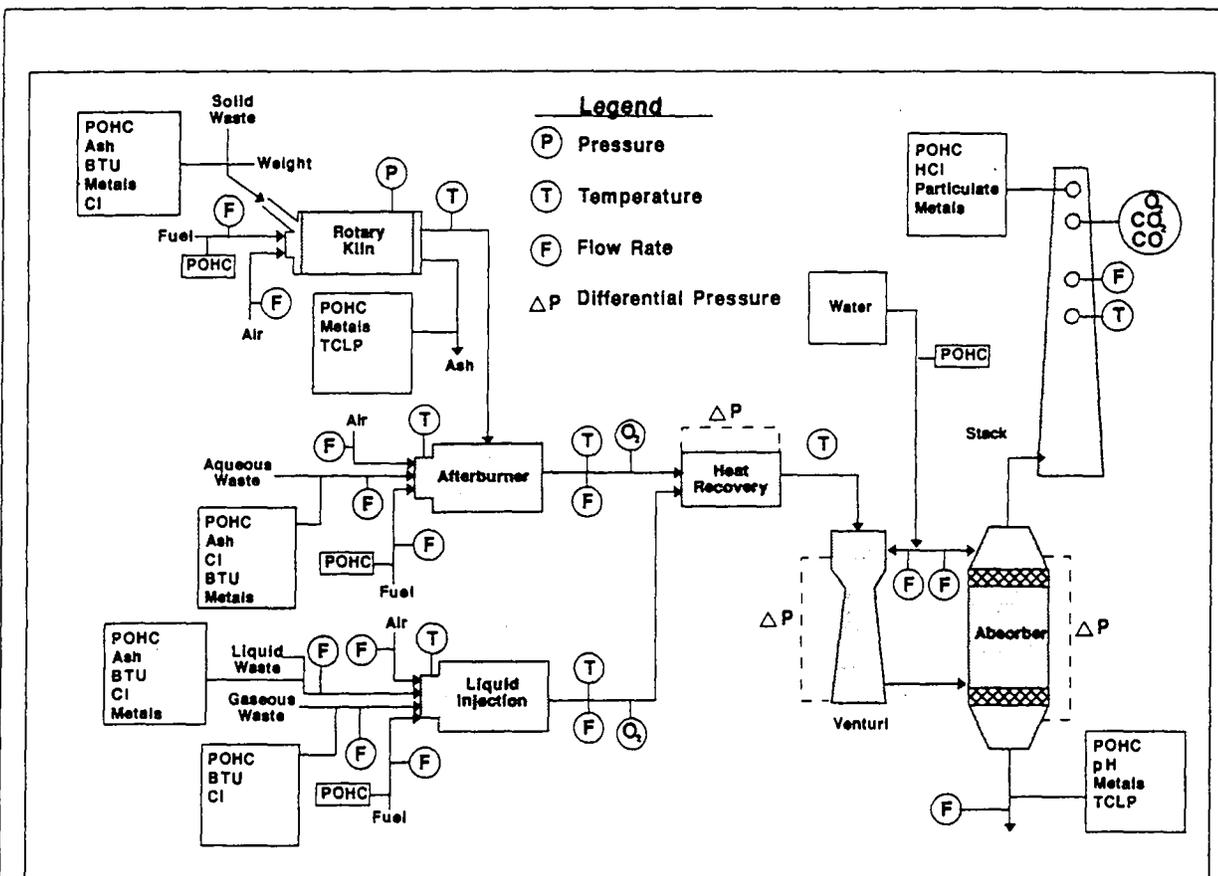


Figure 6. Potential sampling points for assessing incinerator performance.

with the RCRA incinerator standards.<sup>19,20,29,75-79</sup> Johnson<sup>80,81</sup> has provided additional information on this subject. The first guidance manual for hazardous waste incinerator permitting,<sup>19</sup> issued in 1983, is being updated and should be available in the near future. Similar guidance has been provided for PCB incinerators.<sup>82</sup> Table VIII outlines sampling methods typically involved in RCRA trial burns. For any trial burn, at any one set of operating conditions and waste feed conditions, three replicate runs (i.e., identical as possible) are usually recommended to obtain a representative assessment of incinerator performance.<sup>75</sup>

The sampling method numbers in Table VIII refer to methods identified in EPA guidance documents and reports.<sup>76,78,83,84</sup> These materials expand upon and augment the information in EPA SW-846, "Test Methods for Evaluating Solid Waste: Physical/Chemical Methods"<sup>85,86</sup> and "Samplers and Sampling Procedures for Hazardous Waste Streams."<sup>87</sup> EPA has also developed a computerized data base which provides a reference directory pertaining to the availability and reliability of sampling and analysis methods for potentially designated POHCs.<sup>88</sup>

An expanded version of this reference directory is under development.<sup>89</sup> Along with 40 CFR, Part 60, Appendix A, these references are the best sources from which to identify sampling methods to be used in incinerator performance evaluations.

Analytical methods for specific hazardous compounds are often of greatest interest. Analytical methods for Appendix VIII compounds<sup>16</sup> in these references are generally based upon high-resolution fused-silica-capillary column gas chromatography (GC) in combination with mass spectrometry (MS) for specific compound detection. High-performance liquid chromatography (HPLC) is recommended for determination of compounds that are inappropriate for detection by GC/MS. Application of analytical methods has been evaluated for 240 of the approximately 400 Appendix VIII compounds.<sup>90,94</sup> These methods have shown acceptable precision in determining most of the compounds. Detection limits in synthetic samples were on the order of 1 to 10 nanograms per injection, but detection in actual waste samples will be dependent upon the nature of interferences in the waste matrix.

While all emissions from hazardous

waste incinerators are important, the greatest interest is most often placed on stack emissions. The accuracy and reliability of stack sampling results are central to the entire issue of incinerator performance and environmental safety. Existing methods have been the subject of substantial research, validation and debate. Procedures are now in place that provide assurance that measurement of these emissions are valid.<sup>84</sup>

Stack emissions are sampled to determine stack gas flow rate, HCl, particulate concentration, metals and the concentration of organic compounds of interest. Determination of stack gas flow rate and particulate emissions is performed using the conventional stack sampling method commonly referred to as Method 5. This method encompasses EPA Methods 1 through 5 and is defined in detail in 40 CFR Part 60, Appendix A. HCl emissions are sampled by modifying the Method 5 train to include a caustic impinger. A specialized sampling and analytical method has also been developed to further speciate and quantify hydrogen halide and halogen emissions<sup>92</sup> and is specified in the EPA "Methods Manual for Compliance with BIF Regulation"<sup>84</sup> as Method 0050.

**Table VIII.** Sampling methods and analysis parameters.

Sample	Sampling frequency for each run	Sampling method <sup>a</sup>	Analysis parameter <sup>b</sup>	
1. Liquid waste feed	Grab sample every 15 min	S004	V&SV-POHCs, Cl, ash, ult. anal., viscosity, HHV, metals	
2. Solid waste feed	Grab sample from each drum	S006, S007	VS&V-POHCs, Cl, ash, HHV, metals	
3. Chamber ash	Grab one sample after all runs are completed	S006	V&SV-POHCs, TCLP <sup>c</sup> , HHV, TOC, metals	
4. Stack gas	Composite	Method 0010 (3h) (MM5)	SV-POHCs	
	Composite	Method 5 <sup>f</sup>	Particulate, H <sub>2</sub> O	
	Composite	Method 0011	Formaldehyde	
	Composite	Method 0050	HCl, Cl <sub>2</sub>	
	Composite	Method 0030 (2h) (VOST)	V-POHCs	
	Composite in Tedlar gas bag	Method 0040	V-POHCs <sup>d</sup>	
	Composite	Method 3 (1-2 h)	CO <sub>2</sub> and O <sub>2</sub> by Orsat	
	Continuous	CEM	CO, CO <sub>2</sub> , O <sub>2</sub> , SO <sub>2</sub>	
5. APCD Effluent (liquid)	Grab sample every 1/2 h	Composite	Method 0012	Trace metals <sup>e</sup>
		S004	V&SV-POHCs, Cl, pH, metals	
6. APCD Residue (solid)	Grab sample every 1/2 h	S006	V&SV-POHCs, metals	

<sup>a</sup> VOST denotes volatile organic sampling train; MM5 denotes EPA Modified Method 5; SXXX denotes sampling methods found in "Sampling and Analysis Methods for Hazardous Waste Combustion"<sup>83</sup>; CEM denotes Continuous Emission Monitor (usually nondispersive infrared).

<sup>b</sup> V-POHCs denotes volatile principal organic hazardous constituents (POHCs); SV-POHCs denotes semivolatile POHCs; HHV denotes higher heating value; TOC denotes Total Organic Carbon.

<sup>c</sup> Gas bag samples may be analyzed for V-POHCs only if VOST samples are saturated and not quantifiable or if the target POHC is too volatile for VOST.

<sup>d</sup> TCLP - toxicity characteristic leaching procedure<sup>92</sup>.

<sup>e</sup> Metals captured by the Multiple Metals Sampling Train<sup>84</sup>.

<sup>f</sup> Method 5 can be combined with Method 0050 or Method 0012.

The technology of incinerator stack sampling for trace organic compounds is sophisticated. While the basic technology is well developed, many pitfalls await those who attempt the job without sufficient knowledge or experience. Sampling a stack effluent for organics to determine DRE may require one to four (or more) separate methods. This depends on the number and characteristics of compounds to be quantified and the detection limits required to prove a DRE of 99.99 to 99.9999 percent or establish levels of incomplete combustion byproducts. Special attention must be given to sampling rate and duration in planning for emission tests. This will ensure that a sufficient amount of sample is collected to meet detection limit objectives and allow for all necessary analyses to be completed.<sup>75</sup>

The seven methods most often used for hazardous waste incinerator sampling are: (1) Modified Method 5 (MM5). (Method 0010), (2) Method 5 (M5), (3) Volatile Organic Sampling

Train (VOST). (Method 0030), (4) Gas bags. (Method 0040), (5) Method 0050, (6) Multiple Metals Sampling Train. (Method 0012), and (7) Method 0011.

The MM5 train is used to capture semivolatile (boiling point 100°C to 300°C) and nonvolatile (boiling point >300°C) organic compounds. The MM5 is merely a simple modification of the M5 train involving insertion of a sorbent module (XAD-2 resin) between the filter and the first impinger.<sup>93</sup> It is recommended that a separate M5 train for particulate determination be used in tandem with the MM5 train since drying of the filter for particulate determination may invalidate analysis of organic compounds on the filter.<sup>75</sup> Like the M5, the MM5 involves isokinetic traversing of the stack with a sampling probe. Water-cooled sample probes are necessary for sampling hot combustion gases in regions ahead of quenching. Where it is desirable to collect larger amounts of sample for more extensive analysis or lower detection limits, the much larger Source

Assessment Sampling System (SASS) may be used instead of the MM5.<sup>75</sup> SASS involves single point (pseudo-isokinetic) sampling at a rate of 110 to 140 L/min (4 to 5 cfm) compared to the 14 to 28 L/min (0.5 to 1 cfm) rate of the MM5. The same sorbent resin (XAD-2) is also used. Because of its more convenient sample size, portability and multi-point isokinetic sampling, the MM5 train is generally preferred over the SASS train.

The VOST is used for volatile organic compounds (boiling point 30°C to 132°C). This method was developed by EPA in 1981 to enable detection of stack concentrations of volatile organic compounds as low as 0.1 ng/L.<sup>94</sup> This detection limit was deemed necessary to demonstrate greater than 99.99 percent DRE for volatile organic compounds at concentrations as low as 100 ppm in the waste feed. The VOST system involves drawing a stack gas sample through two sorbent tubes in series. The first tube contains Tenax resin and the second contains Tenax and acti-

vated charcoal. Up to six pairs of sorbent tubes operating at one L/min for 20 minutes each may be needed to achieve DRE confirmation.<sup>95</sup> For higher stack gas concentrations, however, the VOST may be operated at lower flow rates with fewer pairs of tubes.

Various types of gas sampling bags may also be used to sample for volatile organic compounds. These are generally appropriate only for higher organic concentrations. The accuracy of sampling with this method is a function of the sampling and storage characteristics of the bags.<sup>96</sup> The use of extensive quality assurance and quality control procedures is required with both plastic bags and the VOST to avoid sample contamination in the field and in transit.<sup>97</sup> This problem was not fully appreciated in some of the early field tests employing the VOST.

Both the MMS and VOST sampling methods have been subjected to laboratory and field validation studies for selected compounds.<sup>98-100</sup> These studies have demonstrated that excellent results are possible with these methods. It is important to note, however, that modifications of these methods may be required for certain POHC compounds which become chemically or physically altered in the sampling systems. Highly water-soluble compounds (e.g., acetonitrile) and water-reactive compounds (e.g., phthalic anhydride), for instance, present special challenges to current sampling methods.

Method 0050 is used to collect HCl and Cl<sub>2</sub> in stack gases. It collects the emission samples isokinetically and can be combined with Method 5 for particulate determination. The Multiple Metals Sampling Train is used to determine the total chromium, cadmium, arsenic, nickel, manganese, beryllium, copper, zinc, lead, selenium, phosphorus, thallium, silver, antimony, barium and mercury in incinerator stack emissions. The stack sample is withdrawn isokinetically from the source with particulate emissions collected in the probe and on a heated filter and gaseous emissions collected in a series of chilled impingers containing an aqueous solution of dilute nitric acid combined with dilute hydrogen peroxide in each of two impingers, and acidic potassium permanganate solution in each of two impingers. Method 0011 is used to collect formaldehyde in stack emissions.

#### Process Monitoring

Measurement of a wide variety of incinerator operating parameters may

be necessary to maintain thermal destruction conditions which are equivalent to those observed during a successful trial burn. These measures are used as indicators of the performance of the incineration system and serve as input to automatic and manual process control strategies. There are many potential measurements, including such parameters as combustion temperature, waste feed rate, oxygen and CO concentration in the stack, gas flow rate at strategic points and scrubber solution pH. These parameters and their use are described in detail in a number of resource documents.<sup>19,20,62,75</sup>

Continuous emission monitors (CEMs) are required or often used in measuring combustion gas components such as CO, CO<sub>2</sub>, oxygen (O<sub>2</sub>), NO<sub>x</sub> and HC. More recently, some consideration has been given to the utilization of HCl and opacity CEMs as well. If properly interpreted, combustion gas components may indicate the completeness of the thermal destruction reaction. These methods typically require extraction of gas samples from the gas stream of interest and measurement with a remote instrument. Some parameters, such as CO and O<sub>2</sub>, may be measured in-situ (in the stack). Table IX summarizes monitor type and

available concentration measurement ranges for a number of CEMs,<sup>101</sup> some of which are required by the RCRA regulations. These CEMs are, however, commercially available at varying stages of development.

EPA has promulgated performance specifications for continuous emission monitoring of carbon monoxide, oxygen and hydrocarbons for incinerators, boilers and industrial furnaces burning hazardous waste.<sup>84</sup> Performance specifications for CO and O<sub>2</sub> are given in Table X. Monitoring HC is based on extracting a sample through a heated sample line to a flame ionization detector (FID). Unheated systems may also be used on an interim basis if a gas conditioning system is provided that reduces the moisture content of the sample gas entering the FID to less than 2 percent.

#### Emissions from Hazardous Waste Incineration

Ideally, the primary products from combustion are carbon dioxide, water vapor and inert ash. In reality, what appears outwardly to be a straightforward, simple process is actually an extremely complex one involving thousands of physical interactions and chemical reactions, reaction kinetics, catalysis, combustion aerodynamics and

Table IX. Summary of continuous emission monitors.<sup>101</sup>

Pollutant	Monitor type	Expected concentration range	Available range*
O <sub>2</sub>	Paramagnetic Electrocatalytic (e.g., zirconium oxide)	5-14%	0-25%
CO <sub>2</sub>	NDIR <sup>b</sup>	2-12%	0-21%
CO	NDIR	0-100 ppmv	0-5000 ppmv
HCl	NDIR	0-50 ppmv	0-10000 ppmv
Opacity	Transmissometer	0-10%	0-100%
NO <sub>x</sub>	Chemiluminescence	0-4000 ppmv	0-10000 ppmv
SO <sub>2</sub>	Flame photometry Pulsed fluorescence NDUV <sup>c</sup>	0-4000 ppmv	0-5000 ppmv
SO <sub>3</sub>	Colorimetric	0-100 ppmv	0-50 ppmv
Organic compounds	Gas chromatography (FID) <sup>d</sup> Gas chromatography (ECD) <sup>e</sup> Gas chromatography (PID) <sup>f</sup> IR absorption UV absorption	0-50 ppmv	0-100 ppmv
HC	FID	0-50 ppmv	0-100 ppmv

\* For available instruments only. Higher ranges are possible through dilution.

<sup>b</sup> Nondispersion infrared.

<sup>c</sup> Nondispersion ultraviolet.

<sup>d</sup> Flame ionization detector.

<sup>e</sup> Electron capture detector.

<sup>f</sup> Photo-ionization detector.

**Table X.** Performance specifications for CO and O<sub>2</sub> monitors.<sup>a</sup>

Parameter	CO monitors		O <sub>2</sub> monitors
	Low range	High range	
Calibration drift (CD) 24 hours	≤ 6 ppm <sup>a</sup>	≤ 90 ppm	≤ 0.5% O <sub>2</sub>
Calibration error (CE)	≤ 10 ppm <sup>a</sup>	≤ 150 ppm	≤ 0.5% O <sub>2</sub>
Response time	≤ 2 min	≤ 2 min	≤ 2 min
Relative accuracy <sup>b</sup> (RA)	( <sup>c</sup> )	( <sup>c</sup> )	(incorporated in CO and RA calculation)

<sup>a</sup> For Tier II, CD and CE are ≤3% and ≤5% of twice the permit limit, respectively.

<sup>b</sup> Expressed as the sum of the mean absolute value plus the 95% confidence interval of a series of measurements.

<sup>c</sup> The greater of 10% of the Performance Test Method (PTM) or 10 ppm.

heat transfer. This is further complicated by the complex and fluctuating nature of the waste feed to the process. While combustion and incineration devices are designed to optimize the chances for completion of these reactions, they never completely attain the ideal. Rather, small quantities of a multitude of other products may be formed, depending on the chemical composition of the waste and the combustion conditions encountered. These products, along with potentially unreacted components of the waste, comprise the emissions from the incinerator.

Hydrogen chloride and small amounts of chlorine, for example, are formed from the incineration of chlorinated hydrocarbons. Hydrogen fluoride (HF) is formed from the incineration of organic fluorides, and both hydrogen bromide (HBr) and bromine (Br<sub>2</sub>) are formed from the incineration of organic bromides.<sup>102</sup> Sulfur oxides, mostly as SO<sub>2</sub>, but also including 1 to 5 percent sulfur trioxide (SO<sub>3</sub>), are formed from the sulfur present in the waste material and auxiliary fuel. Highly corrosive phosphorus pentoxide (P<sub>2</sub>O<sub>5</sub>) is formed from the incineration of organo-phosphorus compounds. In addition, oxides of nitrogen may be formed by fixation of nitrogen from nitrogen compounds present in the waste material or in the combustion air. Suspended particulate emissions are also produced and include particles of mineral oxides and salts from the mineral constituents in the waste material. A wide range of organic compounds may also be formed in trace amounts from the incomplete thermal destruction of organic compounds in the waste and auxiliary fuel.

Prior to the 1980s, there were only limited data available on waste destruction performance and pollutant emissions from hazardous waste thermal destruction devices. Studies by EPA and others in the 1970s employed a variety of evolving trace organic pollutant sampling and analysis techniques and were often targeted only toward measuring macro-destruction and combustion efficiencies<sup>103-105</sup> rather than the destruction and removal of specific organics and characterization of the emissions. During the early 1980s, however, EPA conducted a substantial program of performance testing at thermal destruction facilities. The testing was designed to estimate the environmental impact of these operations and to provide information on the ability of these facilities to destroy organics and control emissions. The test facilities, test procedures, and performance results have been summarized<sup>106</sup> for the facilities tested (incinerators, industrial boilers, and industrial process kilns). Complete test reports have been published for the incinerators,<sup>107</sup> industrial boilers,<sup>108,109</sup> and cement/aggregate kilns<sup>110,111</sup> tested. These data as well as trial burn results from fourteen additional RCRA incinerators, have been summarized in an EPA report, "Permit Writer's Guide to Test Burn Data-Hazardous Waste Incineration."<sup>112</sup> EPA has conducted additional testing to further investigate the characterization and control of particulate matter, metals, HCl, total mass emissions, and PICs from hazardous waste incinerators<sup>113-115</sup> and cement kilns.<sup>116,117</sup> In addition, numerous trial burns have since been conducted for hazardous waste incinerators in com-

pliance with the RCRA permitting requirements.

The following sections discuss this information in five areas:

- (1) DRE, particulate emissions and HCl control
- (2) Metal emissions
- (3) Combustion byproduct emissions
- (4) Dioxin and furan emissions
- (5) Ash and air pollution control residue quality

### DRE, Particulate Emissions and HCl Control

Tables XI, XII and XIII summarize waste destruction efficiency, HCl and particulate emissions results for incinerators, industrial boilers, and cement kilns tested by EPA in the early 1980s. Information from 14 trial burns are also included in Table XI. The tables also summarize certain process operating parameters, as well as emissions of CO, and O<sub>2</sub> and, in some instances, NO<sub>x</sub> and SO<sub>x</sub>.

These data reveal that well operated incinerators, industrial boilers and process kilns are capable of achieving 99.99 (the RCRA performance standard) to >99.999 percent DREs. In many cases the target POHC was below the detection limit and the calculated DRE was a maximum value assuming the stack gas concentration of the POHC equalled the detection limit. All of the incinerators tested by EPA achieved this level of performance for candidate POHC compounds in concentrations greater than 1,200 parts per million (ppm) in the waste feed.<sup>118</sup> Candidate POHC compounds between 200 and 1,200 ppm frequently were not destroyed to a 99.99 percent DRE and no compounds below 200 ppm in the waste feed met the RCRA DRE limit. In fact, regression analysis of the pooled data suggested that statistically significant correlations (correlation coefficients were 0.76 and 0.84) existed between compound penetration (1-DRE) and compound feed concentration, showing that DRE increased with waste feed concentration.<sup>118</sup>

This phenomenon, which has been observed in tests of other thermal destruction devices, was not anticipated. A number of possible explanations have been advanced.<sup>2,107</sup> The most frequently stated theory postulates that at the very low stack emission concentrations (<1 ng/L) necessary to demonstrate greater than 99.99 percent DRE for a sub-1,200 ppm compound, sufficient amounts of that compound may

**Table XI.** Incinerator performance and stack emissions data (data reported as averages for each facility).<sup>107,112</sup>

Facility Type	O <sub>2</sub> (%)	CO (ppm)	HC (ppm)	DRE (%)	Particulate (mg/m <sup>3</sup> )	HCl control (%)
Commercial rotary kiln/liquid incinerator	10.5	6.2	1.0	99.999	152	99.4
Commercial fixed hearth, two-stage incinerator	11.4	6.9	1.0	99.994	400	98.3
On-site two-stage liquid incinerator	8.1	9.4	6.0	99.994	143	99.7
Commercial fixed hearth, two-stage incinerator	11.0	327.7	18.7	99.997	60	b
On-site liquid injection incinerator	13.2	11.9	1.0	99.999	186	b
Commercial two-stage incinerator	10.2	1.1	1.3	99.998	902	b
On-site rotary kiln incinerator	9.7	554.0	61.7	99.999	23	99.9
Commercial two-stage fixed hearth incinerator	13.4	26.8	1.8	99.996	168	98.3
On-site rotary kiln	c	794.5	NA*	99.998	184	99.7
On-site liquid injection incinerator	9.7	66.3	7.8	99.994	95	b
On-site rotary kiln incinerator	10.7	5.8	NA	99.996	404	99.9
On-site rotary kiln incinerator	14.1	323.0	NA	99.996	NA	99.8
On-site liquid injection incinerator	12.4	31.9	1.9	99.999	163	98.6
On-site liquid injection incinerator	9.3	1.0	NA	99.996	40	b
On-site fluidized bed incinerator	3.6	67.4	NA	99.996	259	b
On-site fixed hearth incinerator	12.9	ND <sup>d</sup>	NA	99.999	93	b
On-site liquid injection incinerator	4.5	358.0	NA	99.995	99	b
On-site liquid injection incinerator	3.6	28.4	NA	99.998	12	99.3
Commercial rotary kiln incinerator	9.4	8.0	0.5	99.999	172	99.9
On-site liquid injection incinerator	3.1	779.3	NA	99.999	88	99.6
On-site liquid furnace incinerator	6.4	56.3	NA	99.999	4	99.9
On-site fixed hearth incinerator	13.5	5.0	NA	99.999	150	98.4

\* NA = not available.

<sup>b</sup> HCl emissions <4 lb/h.

<sup>c</sup> Reported only as a range (3.1-16.7%)

<sup>d</sup> ND = Not detected.

**Table XII.** Summary of boiler performance (data reported as averages for each facility).<sup>108</sup>

Facility Type	Load (%)	O <sub>2</sub> (%)	Residence time (s)	Average volumetric heat release rate (kW/m <sup>3</sup> )	DRE <sup>d</sup>	W/F <sup>a</sup> (%)	NO <sub>x</sub> (ppm) <sup>b</sup>	CO (ppm) <sup>b</sup>
Watertube stoker	100	6-16	1.2	509	99.98	40	163-210	900-1200
Packaged firetube	25	4-6	0.8	739	99.991	0.1-0.5	40-65	47-88
Field erected watertube	26	10	2	78	99.999	37	61-96	18-21
Converted stoker	78	4-6	1.1	339	99.998	18-48	193-250	75-127
Packaged watertube	36-73	6-7	1.1-0.5	960	99.995	19-56	164-492	83-138
Converted watertube	53	7-11	2	107	99.98	8.7-10.1	243-328	109-139
Modified firetube	44	8	0.4	807	99.998	100	67-74	146-170
Tangentially fired watertube	100	6	2	180	99.991	2.4-4.3	393-466	142-201
Packaged watertube	65	2	1.8	343	99.998	8.2	64-78	46-750
							410-1125 <sup>c</sup>	
Packaged firetube	50-100	3-8	0.7-0.3	1240	99.999	100	85-203	20-135
Packaged watertube	82	4	1.8	269	99.999	49	154-278	102-119

<sup>a</sup> W/F = waste heat input as a percent of total heat input.

<sup>b</sup> Range of average values across individual sites and runs including baseline.

<sup>c</sup> Higher values are for high nitrogen content waste firing.

<sup>d</sup> Mass weighted average for all POHCs in the waste > 100 ppm.

actually be formed as an incomplete combustion or recombination byproduct from other compounds in the wastes to effect a reduction of the calculated DRE below 99.99 percent. Others argue that limitations of current stack sampling and analysis techniques for such low levels of trace organic compounds are responsible.

From a regulatory standpoint, however, this is not currently perceived as

an issue. Few, if any, of the low concentration compounds in the wastes identified in the EPA test program would have actually been selected as POHCs in trial burns if existing EPA guidance on POHC selection was employed. It is also important to note that even though DRE declines with lower initial compound concentrations in the waste, the absolute amount of compound emitted also declines. In fact,

the DRE versus concentration correlation noted previously actually predicts that the net emissions resulting from a reduced DRE for a 100 ppm compound will actually be slightly less than those for a 99.99 percent DRE for the compound at 1000 ppm in the waste.

Table XII indicates that industrial boilers, particularly the larger watertube units, typically attain 99.99 percent DRE. Cement kilns, lime kilns

## FEATURE

**Table XIII.** Summary of industrial kiln performance and stack emissions data (data reported as averages for each facility).<sup>110,111</sup>

Facility Type	Test <sup>a</sup>	DRE (%)	Particulate (kg/Mg) <sup>c</sup>	HCl (kg/h)	NOx (ppm)	SO <sub>2</sub> (ppm)	W/F (%) <sup>b</sup>
Wet process cement kiln (non-atomized waste)	W	99.200	0.27	0.36	68	450	25
	B	—	0.26	0.09	136	279	—
Wet process cement kiln (atomized waste)	W	99.996	0.27	2.1	478	265	15
	B	—	0.26	0.6	371	636	—
Dry process cement kiln (non-atomized waste)	W	99.998	—	11.5	814	19	45
	B	—	—	1.3	620	7	—
Dry process cement kiln (atomized waste)	W	99.992	—	0.47	486	27	15
	B	—	—	0.25	680	27	—
Lime kiln (atomized waste)	W	99.997	0.11	0.20	446	596	30
	B	—	0.10	0.09	386	553	—
Shale aggregate kiln (atomized waste)	W	>99.99	0.33	2.1	—	—	100
Clay aggregate kiln (atomized waste)	W	99.998	0.58	0.023	162	1130	59
Clay products kiln (atomized waste)	W	>99.99	0.002	0.84	—	—	100

<sup>a</sup> W = waste testing, B = baseline (fossil fuel only).

<sup>b</sup> W/F = waste fuel heat input expressed as a percent of total heat input.

<sup>c</sup> Particulate emissions are expressed as kg particulate per metric ton (Mg) of product produced (e.g., cement, lime).

and light-weight aggregate kilns with good combustion control and waste atomization all met or exceeded the 99.99 percent DRE (Table XIII).

All incinerators and industrial process kilns tested met or approached the RCRA HCl removal standard of 99 percent. The industrial boilers tested typically had no controls for HCl, but none exceeded the 1.8 kg/h emission standard because wastes with low net chlorine content were employed.

Achieving the RCRA particulate emission standard of 180 mg/dscm was a problem for a number of the incinerators tested by EPA. Four of the eight units tested failed to meet the RCRA standard. Two of those facilities were marginally above the emission limit and could likely meet the standard with minor operating adjustments. The remaining two facilities appeared to need significant design and/or operational changes.<sup>119</sup> In some cases, failure of the particulate emission standard may be attributed to dissolved neutralization salts in mist carryover from alkaline acid gas scrubbers. It is clear, however, that the particulate emission standard of 180 mg/dscm is achievable if proper air pollution control is provided since at least 150 hazardous waste incinerators have now demonstrated this during their trial burns.

In fact, it appears that the technology exists to reduce particulate emissions to substantially lower levels. In a test of a full-scale PCB incinerator equipped with a spray dryer/baghouse

followed by an ionizing wet scrubber,<sup>114</sup> particulate emissions averaged 20 mg/dscm for one test condition and 109 mg/dscm for a second test condition. In another test of a full-scale hazardous waste incinerator<sup>115</sup> equipped with a venturi/packed-bed wet scrubber system, the particulate emissions averaged 48 mg/dscm. The particulate emissions from a pilot-scale hazardous waste incinerator<sup>113</sup> ranged from 17 to 64 mg/dscm when it was equipped with an ESP. When this system was equipped with a Hydro-Sonic<sup>®</sup> wet scrubber, the particulate emissions averaged 10 mg/dscm.

No significant changes in particulate emissions were observed for industrial boilers and certain of the industrial process kilns when they fired waste fuels compared to emissions for fossil fuels only.<sup>120,121</sup> Some increased emissions were observed in kilns employing electrostatic precipitators for particulate control. These increases were attributed to changes in the electrical resistivity of the particles due to the presence of increased chloride levels. Adjustments in ESP operation should correct this in most cases.

### Metal Emissions

Metals are of possible concern in waste incineration because of their presence in many hazardous wastes and because of possible adverse health effects from human exposure to emissions. Those metals posing carcinogenic

risk include arsenic, cadmium, chromium and beryllium. Among the non-carcinogenic toxic metals are antimony, barium, lead, mercury, silver and thallium. It is anticipated that the noncarcinogenic toxic metals, nickel and selenium, will also be regulated in the near future.

Incineration may change the form of metal fractions in waste streams, but it will not destroy the elemental metals. As a result, metals are expected to emerge from the combustion zone essentially in the same total quantity as the input. The principal environmental concern therefore centers around where and in what physical or chemical form the metals exit the combustion system, i.e., bottom ash, APCD residues or stack emissions.

Most interest has traditionally focused on stack emissions of metals. Increasing attention, however, is now being given to the quality of residuals from incineration of metal-bearing hazardous wastes since disposal of these materials has become subject to LDR Rules under HSWA.

Metals present in the feed to combustion devices exit via several pathways. The mechanisms which control the behavior of metals during incineration are similar to those of other types of combustion systems. Much of the early knowledge on metal behavior in combustion systems was based on coal combustion research.<sup>122-126</sup>

The inorganic portion of wastes contains most of the metals and metal

species.<sup>127</sup> Much of the inorganic material remains inert during incineration and forms ash particles.<sup>128</sup> Particulate from hazardous waste incinerators is composed mostly of oxides of silicon, iron, calcium and aluminum. Typically from 1 to 10 percent of the particulate is RCRA regulated metals.<sup>107</sup> A small fraction of this ash is entrained by the combustion gases, while the remainder travels through the primary combustion chamber and exits as bottom ash. Some metals and metal species are volatile and will vaporize at the conditions found in incinerators.<sup>129</sup>

Vaporized metals can condense homogeneously into condensation nuclei that grow into a very fine fume, or they can condense heterogeneously onto existing flue gas particulate.<sup>130</sup> In both mechanisms, the tendency is to enrich (be found at higher "per mass" concentration) in fine particulate.<sup>131</sup> Under another mechanism, metal species may react to form new compounds such as metal chlorides, fluorides, oxides and reduced species. These new compounds are sometimes more volatile than the original species and therefore vaporize, after which they typically undergo homogeneous condensation.<sup>128,132,133</sup>

EPA has been developing a model to aid in predicting the relative distributions of trace metals in emissions and discharges from incinerators.<sup>132,134</sup> The volatility temperature of the metal is one of the principal input parameters for this model. Volatility temperature is the temperature at which the effective vapor pressure of the metal is  $10^{-6}$  atmospheres. The effective vapor pressure is the sum of the equilibrium vapor pressure of all species containing the metal.

The presence of chlorine can affect the metal species and volatility temperature. This is particularly true for lead and nickel because the chlorides of these metals are more volatile than the species that would exist without chlorine. The volatility temperatures with 10 percent chlorine and without chlorine for the 10 RCRA-regulated metals, plus nickel and selenium, are given in Table XIV.<sup>135</sup> This reflects the quantity of a metal that would vaporize under a given set of conditions. The lower the volatility temperature of the metal, the more volatile it is expected to be.

Until recently, data on metal behavior in hazardous waste incinerators were quite limited. The focus of most emission assessments had historically been on organic compounds. Over the past several years, however, the body of

knowledge on incineration of metal-bearing waste has been expanded significantly. A number of EPA-sponsored studies have examined metals partitioning (distribution among discharge streams) and APCD collection efficiencies.<sup>113-115,132,133,136-140</sup>

As part of its strategy to control metal emissions, EPA has developed conservative estimates for partitioning of metals within combustion processes prior to the APCD.<sup>29</sup> Table XV lists these estimates for two temperatures (1600°F and 2000°F) and two levels of chlorine in the waste feed (0 and 1 percent). Similarly, conservative metal collection efficiencies have been estimated for a number of different APCD types and are listed in Table XVI.<sup>29</sup>

Actual stack data indicate that fabric filter removal efficiencies are far higher than 95% on most metals except mercury. Effective mercury removal requires gas cooling and high efficiency wet scrubbers or carbon and a fabric filter.

As noted in the EPA guidance document on control of metal emissions,<sup>29</sup> the conservative nature of the Tables XV and XVI should be stressed. A multitude of waste feed compositions (for example, metal species concentrations, chlorine concentrations, matrices), incinerator designs (such as combustion chamber and APCD) and operating conditions (like temperature profiles, oxygen concentrations, gas velocities) will be encountered. This

Table XIV. Metal volatility temperatures.<sup>135</sup>

Metal	Without Chlorine		With 10% Chlorine	
	Volatility Temperature (°C)	Principal Species	Volatility Temperature (°C)	Principal Species
Chromium	1613	CrO <sub>2</sub> /CrO <sub>3</sub>	1611	CrO <sub>2</sub> /CrO <sub>3</sub>
Nickel	1210	Ni (OH) <sub>2</sub>	693	NiCl <sub>2</sub>
Beryllium	1054	Be (OH) <sub>2</sub>	1054	Be (OH) <sub>2</sub>
Silver	904	Ag	627	AgCl
Barium	849	Ba (OH) <sub>2</sub>	904	BaCl <sub>2</sub>
Thallium	721	Tl <sub>2</sub> O <sub>3</sub>	138	TlOH
Antimony	660	Sb <sub>2</sub> O <sub>3</sub>	660	Sb <sub>2</sub> O <sub>3</sub>
Lead	627	Pb	-15	PbCl <sub>4</sub>
Selenium	318	SeO <sub>2</sub>	318	SeO <sub>2</sub>
Cadmium	214	Cd	214	Cd
Arsenic	32	As <sub>2</sub> O <sub>3</sub>	32	As <sub>2</sub> O <sub>3</sub>
Mercury	14	Hg	14	Hg

Table XV. Conservative estimates of metals partitioning to APCD<sup>a</sup> as a function of solids<sup>b</sup> temperature<sup>c</sup> (%).<sup>29</sup>

Metal <sup>d</sup>	1600°F		2000°F	
	Cl = 0%	Cl = 1%	Cl = 0%	Cl = 1%
Antimony	100	100	100	100
Arsenic	100	100	100	100
Barium	50	30	100	100
Beryllium	5	5	5	5
Cadmium	100	100	100	100
Chromium	5	5	5	5
Lead	100	100	100	100
Mercury	100	100	100	100
Silver	8	100	100	100
Thallium	100	100	100	100

<sup>a</sup> The remaining percentage is contained in the bottom ash of the incinerator.

<sup>b</sup> Partitioning for liquids is estimated at 100% for all metals.

<sup>c</sup> The combustion gas temperature is estimated to be 100-400°F higher than the solids temperature.

<sup>d</sup> Assumptions: Excess air = 50%; Entrainment = 5%; Waste Metals Content = 100 ppm for each metal. For a given set of combustion chamber conditions, the maximum amount of metal which will be vaporized will become constant as the metal concentration in the solids increase. As a result, higher concentrations of metals are expected to have lower partitioning factors.

## FEATURE

**Table XVI.** Air pollution control devices and their conservatively estimated efficiencies for controlling toxic metals.<sup>29</sup>

APCD	POLLUTANT				
	Ba, Be	Ag	Cr	As, Sb, Cd, Pb, Tl	Hg
*WS	50	50	50	40	30
*VS-20	90	90	90	20	20
*VS-60	98	98	98	40	40
ESP-1	95	95	95	80	0
ESP-2	97	97	97	85	0
ESP-4	99	99	99	90	0
*WESP	97	97	96	95	60
*FF	95	95	95	90	50
*PS	95	95	95	95	80
SD/FF;SD/C/FF	99	99	99	95	90
DS/FF	98	98	98	98	50
*FF/WS	95	95	95	90	50
ESP-1/WS;ESP-1/PS	96	96	96	90	80
ESP-4/WS;ESP-4/PS	99	99	99	95	85
*VS-20/WS	97	97	97	96	80
**WS/IWS	95	95	95	95	85
*WESP/VS-20/TWS	99	99	98	97	90
C/DS/ESP/FF;C/DS/C/ESP/FF	99	99	99	99	98
SD/C/ESP-1	99	99	98	95	85

\* It is assumed that flue gases have been pre-cooled in a quench. If gases are not cooled adequately, mercury recoveries will diminish, as will cadmium and arsenic to a lesser extent.

\*\* An IWS is nearly always used with an upstream quench and packed horizontal scrubber.

C = Cyclone

WS = Wet Scrubber including: Sieve Tray Tower; Packed Tower; Bubble Cap Tower

PS = Proprietary Wet Scrubber Design (A number of proprietary wet scrubbers have come on the market in recent years that are highly efficient on both particulates and corrosive gases. Two such units are offered by Calvert Environmental Equipment Co. and by Hydro-Sonic Systems, Inc.).

VS-20 = Venturi Scrubber, ca. 20-30 in W. G. ΔP

VS-60 = Venturi Scrubber, ca. > 60 in W. G. ΔP

ESP-1 = Electrostatic Precipitator; 1 stage

ESP-2 = Electrostatic Precipitator; 2 stages

ESP-4 = Electrostatic Precipitator; 4 stages

WESP = Wet ESP

IWS = Ionizing Wet Scrubber

DS = Dry Scrubber

FF = Fabric Filter (Baghouse)

SD = Spray Dryer (Wet/Dry Scrubber)

can result in significantly differing partitioning and metals collection efficiency factors. Furthermore, it should be noted that similar emission rates for two different facilities may result in two very different rates of human exposure as a result of site-specific dispersion factors. Emission rates must be translated into exposure rates in order to fully evaluate health impacts.

Since 1988, a number of parametric metals partitioning studies have been carried out at EPA's Incineration Research Facility (IRF) in Jefferson, Arkansas. These studies examined the effects of operating conditions and waste feed characteristics on the behavior of a mixture of metals fed into a pilot-scale rotary kiln incinerator.

While the majority of the metals followed their predicted behavior, some did not.

Arsenic, for example, behaved quite differently from what was expected. The guidance document<sup>29</sup> suggests a conservative assumption of 100 percent arsenic partitioning to flue gas, yet as much as 95 percent of the discharged arsenic in the IRF studies was accounted for by the kiln ash fraction.<sup>137</sup> Lead behavior also differed from expectations; its observed volatility changed significantly between two test series conducted under similar operating conditions. In the first test series, an average of 20 percent of the recovered lead was accounted for by kiln ash. But in the second test series, much

more lead stayed in the kiln ash and that fraction rose to greater than 80 percent.<sup>133</sup> Research is continuing to investigate this occurrence.

Consideration of specific waste feed composition, incinerator operating conditions, APCD type and site-specific dispersion modeling will assist in the prediction of a waste feedrate that will result in acceptable emissions under EPA's current guidance. Unless emission testing is conducted, it is conservatively assumed that 100% of the metals in the feed are emitted to the air. Whether or not this feedrate is economically or practically feasible must be determined on an individual basis. Treatability tests of the waste may be warranted.

### Combustion Byproduct Emissions

The current RCRA incineration standards regulate destruction and removal only for the major hazardous compounds in the waste. One of the concerns expressed by some scientists and environmentalists regarding hazardous waste thermal destruction is the possible impact on human health and the environment of potentially hazardous PIC emissions. While many of the incinerator field tests conducted to date have attempted to quantify byproduct emissions, these data have been criticized as being incomplete and insufficient for the purposes of a full risk assessment.<sup>141,142</sup> Testing has focused largely on identifying Appendix VIII organic compounds only. Comparison of total hydrocarbon emissions with the total quantity of specific organic compounds identified in the emissions has usually revealed that only a relatively small percentage of the total hydrocarbon emissions may have been identified.<sup>143,144</sup> However, major efforts have been conducted to better understand the composition of the total mass emissions.<sup>113,145</sup>

Incomplete combustion byproducts from hazardous waste incineration have been recognized for some time. Early pilot-scale studies of the thermal destruction of the pesticide, Kepone, found emissions of hexachlorobenzene and several other "daughter products" which had been predicted from previous laboratory-scale studies.<sup>146</sup> Similar thermal decomposition studies followed for PCBs<sup>147</sup> and dozens of other compounds.<sup>148-151</sup>

Dellinger<sup>152</sup> has conducted a comprehensive review of the status of research concerning the emission of organic PICs from hazardous waste incinerators (HWIs) and concluded that these emissions were primarily caused

by temporal or spatial excursions from nominal incineration conditions. He further concluded that low temperature due to quenching, residence time short circuits due to non-plug flow and/or unswept recesses, and locally high waste/oxygen concentrations ratios due to poor microscale mixing or overloading were the most likely causes for PIC emissions.

While the RCRA incinerator standards do not specifically regulate incomplete combustion byproducts, this issue has been considered during the regulatory process. The January 1981 Phase I rule proposed that emissions of incomplete combustion byproducts be limited to 0.01 percent of the POHC input to hazardous waste incinerators.<sup>17</sup> Although this proposal was never adopted, the recently proposed amendments to the hazardous waste incineration regulations include a provision to control PICs by setting limits on parameters (CO or HC emissions) which would assure that the device is operated under good combustion conditions.<sup>21</sup> While these amendments have not been promulgated, this approach is being implemented on a national basis by permit writers using the "omnibus" authority (40 CFR 270.32). Researchers, regulators and environmentalists have pursued the question of PICs, including various attempts to analyze actual field performance.<sup>115,144,145,153-155</sup> One of the basic problems in assessing the results of laboratory and, particularly, field studies of PIC emissions is the fact that there is no standardized definition of what a PIC is. While a POHC is defined in the RCRA regulations, a PIC is not. Thus, there is often confusion even among scientists working in the area. Strictly speaking, PICs are organic compounds which are present in the emissions from the incineration process, but which were not present or detectable in the fuel or air fed to the incinerator. In EPA's test program, compounds were considered to be PICs if they were regulated organic compounds (that is listed in Appendix VIII of CFR 40 Part 261) which were detected in stack emissions, but not present in the waste feed at concentrations greater than 100 ppm.<sup>153</sup>

Compounds in the emission stream which are identified as PICs may actually result from any one of the following four phenomena:

- (1) Compounds resulting from the incomplete destruction of the POHCs, such as fragments of the original POHCs.

- (2) New compounds "created" in the combustion zone and downstream as the result of partial destruction followed by radical-molecule reactions with other compounds or compound fragments present. These compounds may also result from the incomplete combustion of non-Appendix VIII compounds in the waste. This aspect may be especially significant where fossil fuel is used in incineration and where waste is fired into conventional industrial furnaces as only a percentage of the heat input.
- (3) An Appendix VIII compound originally present in the feed stream before incineration but not specifically identified as a POHC.
- (4) Compounds from other sources, such as ambient air pollutants in combustion air. In some field tests, compounds identified in the stack emissions as PICs were actually found to have come from contaminants (trihalomethanes) in the potable water used for scrubber water make-up.<sup>153</sup>

Given the complexity of sources of potential PIC compounds, it is not surprising that a consensus PIC definition has been difficult to achieve. Consequently, for the purpose of this review, it seems more productive to examine the issue of combustion byproducts separately from any type of specific definition by ignoring the source or cause of the emission of particular compounds and considering all organic compound emissions (including POHCs) as combustion byproducts (CBPs). An earlier EPA study examined CBPs in this fashion.<sup>144</sup> The study examined field test data from 23 EPA-sponsored emissions tests at thermal destruction facilities. Included were eight incinerators, nine industrial boilers and six industrial kilns. Organic emissions from hazardous waste facilities were compared to emissions when these facilities were burning fossil fuel only. The organic emissions were also compared to organic emissions from municipal solid waste incinerators and coal-fired utility boilers.

This EPA study of thermal destruction systems identified 55 Appendix VIII compounds (28 volatile and 27 semivolatile) in stack emissions. This and other emission data have been used to generate a list (Table XVII)<sup>27</sup> of organics that could potentially be emitted from devices burning hazardous

waste. These compounds were emitted at normalized rates that span over five orders of magnitude, 0.09 to 13,000 nanograms of emissions per kilojoule (ng/kJ) of combustor heat input (one ng/kJ = 2.34 X 10<sup>-6</sup>lb/million Btu). The greatest number of compounds were emitted in the 10 to 100 ng/kJ range. Only nine of the 23 facilities emitted identified hazardous compounds at rates exceeding 100 ng/kJ.

The volatile compounds tended to be detected more often, and in significantly higher concentrations, than the semivolatile compounds. The compounds that occurred most frequently and in the highest concentrations, nine volatile and six semivolatile, are indicated in Table XVII. Emission rates for incinerators, boilers and kilns are shown in Table XVIII for 12 of these compounds for which sufficient data were available for comparison. The data show that values from test run to test run varied considerably. Thus, these data do not allow prediction of levels for all three combustion devices. Many of the volatile compounds showed higher levels for boilers, and semivolatile compounds tended to be higher for incinerators than boilers. However, most of the organic compound mass emitted from hazardous waste incinerators are volatile compounds.<sup>155</sup>

Data were also available from several baseline (no waste firing) tests on boilers and kilns which allowed comparison of emissions from hazardous waste combustion with combustion of other fuels. While there was a wide range in values from test to test, the data suggested that there is little inherent difference between waste and fuel combustion emissions.<sup>144</sup>

Sufficient data for five semivolatile compounds were available to compare their emissions when burning hazardous waste versus their emissions from municipal incinerators and coal-fired power plants. Similar data were not available for volatile compounds. Table XIX presents this comparison. The four phthalate compounds in the table show very similar emission rates from all three sources. The phthalate rates, however, should be viewed with caution since they can be artifacts of laboratory contamination. Naphthalene emissions were lower for power plants than the other two sources. Again, the data suggest that for these compounds there is little inherent difference among the emissions from these different combustion sources.

In most of these studies, however, only a portion of the organic mass emissions has been identified. Many

believe that most of this unidentified mass is non-chlorinated C<sub>1</sub>-C<sub>5</sub> hydrocarbons, many of which tend to be of lesser concern from a risk standpoint. In an EPA test of a full-scale hazardous waste incinerator it was found that most of the organic mass in the stack gas (80.7% average) was C<sub>1</sub>-C<sub>7</sub> volatile compounds.<sup>115</sup> In a test of a full-scale rotary kiln hazardous waste incinerator, EPA attempted to identify the total mass emissions of all organics under both steady and nonsteady state conditions.<sup>145</sup> Between 53 to 91 percent of the organic emissions were identified. Methane and ethylene accounted for 33 to 97 percent of the identified organic emissions. While it is recognized that these results are only

representative of emissions from the particular facility tested, they do support the belief that a large percentage of the organic emissions are the non-chlorinated, low molecular weight hydrocarbons. Additional testing is needed to more completely characterize emissions. However, such testing is very expensive. The described test cost approximately \$700,000.

EPA has analyzed its historical data base on emissions of individual organic compounds from hazardous waste incinerators, boilers and industrial furnaces.<sup>77</sup> This information was used to develop a "reasonable worst-case" emission concentration for specific organic compounds from these devices. For each Appendix VIII compound

identified in the emissions data base, it was assumed that that compound was emitted at its 95th percentile concentration level. This was further expanded by including methane and ethane emissions from fossil fuel combustion and formaldehyde concentration from municipal waste incinerators, also at their 95th percentile concentration. In addition, compounds which had not been detected from hazardous waste combustion but for which health effects data are available were assigned a value of 0.1 ng/L. Table XX provides the 95th percentile concentration level for the major organics that were determined by this approach. It is interesting to note that C<sub>1</sub> and C<sub>2</sub> hydrocarbons account for almost 68 percent of the total organic emissions. Benzene, methylene chloride, chloroform, formaldehyde, chloromethane, 1,2-dichloroethane and toluene accounted for most (over 28 percent) of the balance of the emissions. Again, it should be stressed that these values are reasonable worst-case estimates and actual emissions would likely be lower for most facilities.

**Dioxin and Furan Emissions**

Without doubt, the greatest amount of scientific and public attention has been given to one class of incinerator combustion byproducts, the dioxins and furans. Dioxins are members of a family of organic compounds known chemically as dibenzo-p-dioxins. This family is characterized by a three-ring nucleus consisting of two benzene rings interconnected by a pair of oxygen atoms. The structural formula of the dioxin nucleus and the convention used in numbering its substituent positions are shown in Figure 7.<sup>156</sup> Usually, the

**Table XVII.** Organics that could potentially be emitted from devices burning hazardous waste.<sup>27</sup>

Volatile Compounds	Semivolatile Compounds
Benzene*	Bis(2-ethylhexyl)phthalate*
Toluene*	Naphthalene*
Carbon tetrachloride*	Phenol*
Chloroform*	Diethylphthalate*
Methylene chloride*	Butylbenzylphthalate*
Trichloroethylene*	Dibutyl phthalate*
Tetrachloroethylene*	2,4-Dimethylphenol
1,1,1-Trichloroethane*	o-Dichlorobenzene
Chlorobenzene*	m-Dichlorobenzene
cis-1,4-Dichloro-2-butene	p-Dichlorobenzene
Bromochloromethane	Hexachlorobenzene
Bromodichloromethane	2,4,6-Trichlorophenol
Bromoform	Fluoranthene
Bromomethane	o-Nitrophenol
Methylene bromide	1,2,4-Trichlorobenzene
Methyl ethyl ketone	o-Chlorophenol
	Pentachlorophenol
	Pyrene
	Dimethyl phthalate
	Mononitrobenzene
	2,6-Toluene diisocyanate

\* Most frequently detected organics.

**Table XVIII.** Emission rates of specific compounds from incinerators, boilers, and kilns, ng/kJ.<sup>2,144</sup>

	Incinerators		Boilers		Industrial Furnace Kilns	
	Mean	Range	Mean	Range	Mean	Range
Benzene	87	2-980	30	0-300	580	290-1,000
Toluene	1.6	1.5-4.1	280	0-1,200	b	b
Carbon tetrachloride	0.8	0.3-1.5	1.8	0-7.2	b	b
Chloroform	3.8	0.5-8.4	120	0-1,700	b	b
Methylene chloride	2.2	0-9.6	180	0-5,800	b	b
Trichloroethylene	5.2	2.3-9.1	1.2	0-13	1.3	0.7-2.8
Tetrachloroethylene	0.3	0-1.3	63	0-780	b	b
1,1,1-Trichloroethane	0.3	0-1.3	7.5	0-66	2.4	(One value)
Chlorobenzene	1.2	0-6.0	63	0-1,000	152	33-270
Naphthalene	44	0.7-150	0.6	0.3-2.1	b	b
Phenol	7.8	0-16	0.3	0-0.8	0.02	0-0.05
Diethylphthalate	3.7	2.8-4.8	0.4	0.04-1.6	b	b

\* Expressed as ng of emission per kJ of combustor heat input (1 ng/kJ = 2.34 × 10<sup>-9</sup>lb/MM Btu).

<sup>b</sup> No data.

**Table XIX.** Semivolatile compound emission rates from hazardous waste combustion, municipal incinerators, and coal power plants, ng/kJ.<sup>a,144</sup>

	Hazardous Waste		Municipal Waste		Coal Power Plant	
	Mean	Range	Mean	Range	Mean	Range
Naphthalene	17	0.3-150	71	0.4-400	0.5	0.06-1.8
Bis(2-ethylhexyl)phthalate	4.6	0-21	4.6	0.4-12	7.6	0.2-24
Diethylphthalate	1.2	0.04-4.8	0.5	0-0.9	2.8	0.4-5.7
Butylbenzophthalate	3.7	0.7-23	b	b	0.5	0.3-1.0
Dibutylphthalate	0.3	0-1.1	3.9	1.5-7.6	3.0	0.09-8.7

<sup>a</sup> Expressed as ng of emission per kJ of combustor heat input (1 ng/kJ = 2.34 × 10<sup>-6</sup>lb/MM Btu).

<sup>b</sup> No data.

**Table XX.** Reasonable worst case emissions of specific organics from incinerators, boilers and industrial furnaces burning hazardous wastes.<sup>77</sup>

	Carcinogenic (Y/N)	Emission <sup>c</sup> (ng/L)	Percent of Total (%)
C2 Hydrocarbons	N	17000	43.3
C1 Hydrocarbons	N	9600	24.5
Benzene	Y	4928	12.6
Methylene Chloride <sup>a</sup>	Y	1755	4.5
Chloroform	Y	1407	3.6
Formaldehyde	Y	892	2.3
Chloromethane	Y	807	2.1
1,2-Dichloroethane	Y	714	1.8
Toluene	N	551	1.4
Tetrachloroethylene	Y	297	0.76
Chlorobenzene <sup>b</sup>	N	195	0.50
2,4,5-Trichlorophenol	N	144	0.37
Naphthalene <sup>b</sup>	N	130	0.33
Carbon Tetrachloride	Y	99.5	0.25
o-Dichlorobenzene	N	95	0.24
p-Dichlorobenzene	N	86	0.22
Trichloroethylene	Y	81.8	0.21
bis(2-Ethylhexyl) Phthalate	Y	77.7	0.20
1,2,4-Trichlorobenzene	N	77	0.20
1,1,1-Trichloroethane <sup>b</sup>	N	64	0.16
1,1,2-Trichloroethane	Y	36.7	0.094
Methyl Ethyl Ketone	N	33.2	0.085
Phenol	N	33.1	0.084
1,1-Dichloroethylene	Y	31.6	0.081
Diethyl Phthalate	N	31	0.079
1,1,2,2-Tetrachloroethane	Y	17	0.043
Vinyl Chloride	Y	14	0.036
Pentachlorophenol	N	9.3	0.024
Hexachlorobenzene	Y	8.95	0.023
Dibutyl Phthalate <sup>b</sup>	N	3.6	0.0092
1,1-Dichloroethane	Y	3.37	0.0086
Butylbenzyl Phthalate <sup>b</sup>	N	3	0.0076
Bromomethane	N	2.13	0.0054
Dichlorodifluoromethane	N	1.22	0.0031
Benzo(a)Anthracene	Y	1.10	0.0028
2,4-Dichlorophenol	N	0.50	0.0013
Acetonitrile	N	0.26	0.00066
TCDF	Y	0.00141	0.000036
PCDD	Y	0.10246	0.00026
Other Carcinogens	Y	4.6	0.0117
Other Noncarcinogens	N	2.8	0.007
Totals		39240	

<sup>a</sup> May be due to laboratory contamination.

<sup>b</sup> Values estimated from Reference 126.

<sup>c</sup> 95th percentile concentration levels.

term "dioxin" refers to the chlorinated congeners of dibenzo-p-dioxin. Theoretically, one to eight chlorine atoms can occur at dioxin substituent positions such that 75 chlorinated dioxin congeners are possible.

Furans are members of a family of organic compounds known chemically as dibenzofurans. They have a similar structure to the dibenzo-p-dioxins except that the two benzene rings in the nucleus are interconnected with a five-member ring containing only one oxygen atom. The structural formula of the furan nucleus and the convention used in numbering its substituent positions are shown in Figure 8.<sup>156</sup> As with dioxins, the term "furan" normally refers to the chlorinated congeners of dibenzofurans. Theoretically, 135 chlorinated furan congeners are possible. From a human health hazard viewpoint, the polychlorinated dibenzo-p-dioxin (PCDD) and the polychlorinated dibenzofuran (PCDF) compounds (specifically, their "tetra" and "penta" forms) are the most significant. Polychlorinated, as used here, means the compound contains four or more chlorine atoms.

Initially, most concern was focused on 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD). Over the last 20 years, many studies have been conducted to elucidate the toxic effects of 2,3,7,8-TCDD. The data from these studies are summarized in a number of reviews.<sup>157-161</sup> While these data have not answered all of the questions, the data do show that 2,3,7,8-TCDD can produce a variety of toxic effects, including cancer and reproductive effects, in laboratory animals at very low doses. While some reports in the literature suggest that the chemical can produce similar effects in humans, more definitive information is needed.<sup>162</sup> Fingerhut *et al.*<sup>163</sup> recently conducted a study of mortality among 5,172 workers at 12 plants in the United States that produced chemicals contaminated with TCDD and did not find a significant increase in cancers for this group.

For risk assessment purposes, EPA currently classifies 2,3,7,8-TCDD as a "B2" carcinogen with a potency of 1.6 × 10<sup>5</sup> (mg/kg-d)<sup>-1</sup>, by far the most potent carcinogen yet evaluated by the Agency.<sup>159</sup> The B2 category is one of five categories that EPA uses to group the weight of evidence of the carcinogenicity of a chemical for humans. These are further defined below:<sup>164</sup>

Group A: There is sufficient evidence from epidemiologic studies to support a causal association between exposure to the chemical agent and cancer.

Group B1: The weight of evidence of carcinogenicity based on animal studies is "sufficient" but there is limited evidence of carcinogenicity from epidemiologic studies.

Group B2: The weight of evidence of carcinogenicity based on animal studies is "sufficient" but there is "inadequate evidence" or "no data" from epidemiologic studies.

Group C: There is limited evidence of carcinogenicity in animal studies but no human data.

Group D: Not classified as to human carcinogenicity because there is inadequate human and animal evidence of carcinogenicity or no data available.

Group E: Not a human carcinogen.

The compound 2,3,7,8-TCDD is also the most potent reproductive toxin yet evaluated by the Agency, with a RfD of 1 pg/kg-d.<sup>159</sup> More recently, it has been suggested by some scientists that the Agency's health standards for this chemical are not supported by the latest scientific evidence. The U.S. EPA has undertaken a review to reassess the toxicity of 2,3,7,8-TCDD which might result in a revision of risks assigned to it.<sup>165</sup>

In order to address the risks posed by other chlorinated dibenzo-p-dioxins and chlorinated dibenzofurans (CDDs and CDFs), in the spring of 1987 the EPA first adopted an interim procedure for estimating the hazard and dose-response of complex mixtures containing CDDs and CDFs in addition to

2,3,7,8-TCDD.<sup>166</sup> This procedure was based upon a set of derived toxicity equivalency factors (TEFs) which permit the conversion of any CDD/CDF congener into an equivalent concentration of 2,3,7,8-TCDD or Toxicity Equivalents (TEQs). In 1989, the EPA updated this procedure by adopting the International TEFs (I-TEFs/89) which are given in Table XXI.<sup>162</sup> As can be seen in the table, the relative toxicities of the other 209 congeners of dioxins and furans range from 0 to 50 percent of the toxicity of 2,3,7,8-TCDD. Therefore, the combined toxicity of a mixture of PCDD/PCDFs is highly dependent on the specific isomers that constitute that mixture.

With the exception of analytical standards, dioxins and furans are not intentionally made for any purpose. They can, however, be created as by-products in the manufacture of other chemicals (such as some pesticides) or as a result of incomplete combustion or the recombination of exhaust products from the burning of mixtures containing certain chlorinated organic compounds. Since the first published report of PCDD and PCDF emissions from a municipal solid waste incinerator by Olie *et al.*<sup>167</sup> a large number of studies have been carried out to examine this phenomenon. Some of this initial work was reported by Buser *et al.*,<sup>168</sup> Eiceman *et al.*,<sup>169</sup> Karasek,<sup>170</sup> Bumb *et al.*,<sup>171</sup> Cavallaro *et al.*,<sup>172</sup> and Lustenhouwer *et al.*<sup>173</sup> Over the past 10 years, numerous studies have continued to investigate this issue and PCDD/PCDFs have been the focus of many national and international symposia and conferences.<sup>174</sup>

A large part of the interest has been placed on municipal solid waste incineration. A number of excellent summaries of municipal solid waste incinerator emission data have been prepared.<sup>175-178</sup> EPA has reviewed PCDD/PCDF emissions data for a broad range of combustion sources, including fossil fuel and wood combustion and a wide range of industrial furnaces,<sup>156</sup> and has reported the results of emissions testing at 13 additional facilities.<sup>179</sup>

EPA full-scale hazardous waste tests have examined dioxin/furan emissions at six incinerators,<sup>107</sup> five industrial boilers,<sup>180</sup> two cement kilns<sup>181,182</sup> and a lime kiln<sup>183</sup> employing hazardous waste as a fuel. Data are also available from test burns at one incinerator burning pentachlorophenol (PCP) waste<sup>184</sup> and three PCB incinerators.<sup>185,186</sup> Dioxin/furan emission data are also available from a pilot-scale treatability

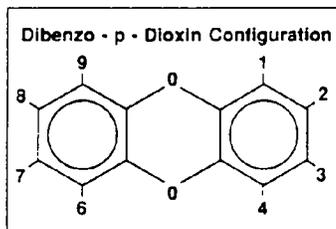


Figure 7. Structural formula of the dioxin nucleus.

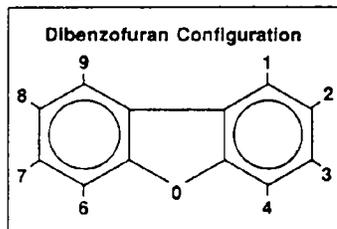


Figure 8. Structural formula of the furan nucleus.

Table XXI. International toxicity equivalency factors/89 (I-TEFs/89).<sup>162</sup>

Compound	I-TEFs/89
Mono-, Di-, and TriCDDs	0
2,3,7,8-TCDD	1
Other TCDDs	0
2,3,7,8-PeCDD	0.5
Other PeCDDs	0
2,3,7,8-HxCDDs	0.1
Other HxCDDs	0
2,3,7,8-HpCDD	0.01
Other HpCDDs	0
OCDD	0.001
Mono-, Di-, and TriCDFs	0
2,3,7,8-TCDF	0.1
Other TCDFs	0
1,2,3,7,8-PeCDF	0.05
2,3,4,7,8-PeCDF	0.5
Other PeCDFs	0
2,3,7,8-HxCDFs	0.1
Other HxCDFs	0
2,3,7,8-HpCDFs	0.01
Other HpCDFs	0
OCDF	0.001

test of PCB-contaminated soil from a Superfund site.<sup>187</sup> More recent dioxin/furan emission data are available for municipal waste combustors (MWCs) and medical waste incinerators (MWIs) as a result of EPA testing to support the development of regulations for these sources.<sup>188-190</sup> Dioxin/furan emissions from all of these sources are summarized in Table XXII. In addition, these emissions are expressed in I-TEQs/89 in both concentration and mass per year.

No 2,3,7,8-TCDD was detected in any of the 10 full-scale hazardous waste

incinerators or three industrial furnaces burning hazardous or PCB waste. The compound 2,3,7,8-TCDD was detected at the detection level of 0.002 ng/dscm in one series of tests at Industrial Boiler D and at .003 ng/dscm for the pilot-scale treatability tests. Detectable levels of PCDD or PCDF were found at five of the hazardous waste incinerators and all five of the industrial boilers. No PCDD or PCDF was found at any of the three industrial furnaces. By comparison, 2,3,7,8-TCDD, PCDDs and PCDFs have been

detected frequently in MWI and MWC emissions at levels that are three to four orders of magnitude higher than emissions reported from HWIs, industrial boilers and industrial furnaces burning hazardous wastes.

Recent testing<sup>188,190</sup> has demonstrated, however, that through the combination of good combustion practices and flue gas cleaning, dioxin/furan emissions from MWCs can be dramatically reduced to levels that are about the same as to somewhat higher than those reported for hazardous waste

**Table XXII.** Dioxin/furan emissions from thermal destruction facilities (ng/dscm @ 7% O<sub>2</sub>).

Facility Type <sup>a</sup>	Sample (Waste) <sup>b</sup>	2378-TCDD	PCDD	PCDF	I-TEQs/89 <sup>c</sup>		Ref.
					ng/dscm	g/yr <sup>d</sup>	
HWI (Commercial, Rotary Kiln, Liquid Injection)	FG <sup>e</sup> (HW)	ND <sup>f</sup>	ND	ND	ND	ND	107
HWI (Confidential)	FG/FA (HW)	ND	22	70	17.7	1.95	107
HWI (On-site Liquid Injection)	FG (HW)	ND	ND	7.3	0.93	0.02	107
HWI (On-site Liquid Injection)	FG (HW)	ND	ND	ND	ND	ND	107
HWI (Commercial, Two Chamber, Liquid Injection and Hearth)	FG/FA (HW)	ND	ND	1.7	0.57	0.02	107
HWI (On-site Kiln and Liquid Injection in Parallel)	FG (HW)	ND	ND	ND	ND	ND	107
HWI (Liquid Injection, Incinerator Ship)	FG/FA (PCB)	ND	ND	ND	0.3	0.16	185
HWI (Fixed Hearth)	FG/FA (PCP)	ND	ND	ND	ND	ND	184
HWI (Liquid Injection)	FG/FA (PCB)	ND	0.64	9.9	1.63	0.81	186
HWI (Rotary Kiln/Liquid Injection)	FG/FA (PCB)	ND	0.18	2.1	0.39	0.12	186
HWI (Pilot-scale Rotary Kiln)	FG/FA (PCB)	.003	.108	3.18	.073	.001	187
Cement Kiln	FG (HW)	ND	ND	ND	ND	ND	181
Cement Kiln	FG (HW)	ND	ND	ND	ND	ND	182
Lime Kiln	FG/FA (HW)	ND	ND	ND	ND	ND	183
Industrial Boiler/A (Watertube Stoker)	FG/FA (PCP)	ND	75.5	NR <sup>g</sup>	10.5	0.84	180
Industrial Boiler/D (Converted Stoker)	FG/FA (HW)	ND-.002	0.64-0.8	0.24-5.5	0.45	0.12	180
Industrial Boiler/E (Packaged Watertube)	FG/FA (HW)	ND	ND	0.14	0.01	0.0026	180
Industrial Boiler/M (Tangentially Fired Watertube)	FG/FA (HW)	ND	ND	0.81	0.11	NA <sup>h</sup>	180
Industrial Boiler/L (Packaged Watertube)	FG/FA (HW)	ND	1.1	2.5	0.336	NA	180
MWC/A	FG/FA (MW)	0.5	41.2	202	22.22	24.70	179
MWC/B	FG/FA (MW)	20.2	4980	9022	2628.9	729.79	179
MWC/C	FG/FA (MW)	NR	35.8	93.3	9.07	NA	179
MWC/D	FG/FA (MW)	0.6	552	117	140.2	74.00	179
MWC/E	FG/FA (MW)	12.4	3344	4122	1704	142.66	179
MWC/F	FA/FA (MW)	NR	163	194	34.8	NA	179
MWC/Mass Burn (SDA/FF) <sup>i</sup>	FG/FA (MW)	NA	1.01	1.19	0.079	NA	188
MWC/Mass Burn (SDA/ESP) <sup>j</sup>	FG/FA (MW)	NA	15.6	60.4	1.159	NA	188
MWC/Refuse Derived Fuel (SDA/FF)	FG/FA (MW)	NA	0.271	0.375	0.005	NA	188
MWI/A (Lime Injection/FF)	FG/FA (Mdw)	0.11	92.78	1655	10.81	0.14	189
MWI/B (Venturi/Packed Beed)	FG/FA (Mdw)	0.07	62.88	342	7.59	0.30	189
MWI/K (No APCD)	FG/FA (Mdw)	12.3	3000	14300	435.18	3.84	189
MWI/W (No APCD)	FG/FA (Mdw)	3.79	714	3740	123.16	1.44	189

<sup>a</sup> HWI = Hazardous Waste Incinerator; MWI = Medical Waste Incinerator; MWC = Municipal Waste Combustor.

<sup>b</sup> Information in parentheses describes waste feed; HW = hazardous waste; PCB = polychlorinated biphenyls; PCP = pentachlorophenol waste; Mdw = medical waste; MW = municipal waste.

<sup>c</sup> Calculated by the International Toxicity Equivalency Factor/89 (I-TEF/89) method. If isomer specific data was not available, homologue data were considered to be composed of the most toxic isomers.

<sup>d</sup> Assumes 8160 operating hours per year.

<sup>e</sup> FG = flue gases analyzed; FA = flue gas particulate analyzed.

<sup>f</sup> ND = not detected.

<sup>g</sup> NR = not reported.

<sup>h</sup> NA = Not available.

<sup>i</sup> SDA/FF = spray dryer absorber/fabric filter.

<sup>j</sup> ESP = electrostatic precipitator.

incinerators. On February 11, 1991, the emission standards for new MWCs and guidelines for existing facilities were promulgated and became effective on August 12, 1991.<sup>13</sup> The specific dioxin/furan stack emission limits are a function of the facility's size and age and range from 30 to 250 ng/dscm of total PCDDs and PCDFs (see Table I). It is expected that current efforts to develop emission standards for MWCs<sup>191</sup> may also result in design and operational improvements which will effect a reduction of dioxin/furan emissions from these facilities as well.

From a human health risk viewpoint, the mass of toxicity equivalents emitted is the best indication of the threat posed by these emissions. However, calculation requires identification of all of the specific isomers given in Table XXI. If isomer-specific data are not available, homologue data are considered to be comprised of the most toxic isomers. With the exception of the MWCs and three of the MWCs<sup>188</sup> in Table XXII, isomer-specific data were not available and the I-TEQs/89 are, therefore, conservative.

Using an even more conservative approach, risk assessment calculations for dioxin/furan emissions from two HWIs burning PCBs concluded that these emissions did not pose a significant risk based on excess lifetime cancer risk to the MEI of  $1.8 \times 10^{-5}$  and  $3.9 \times 10^{-7}$ .<sup>186</sup> Dioxin/furan emissions levels from these two facilities are at the high end of the range of emissions measured from hazardous waste incinerators. The lower levels of emissions found at other facilities burning hazardous waste are not believed to create a significant risk to human health.

#### Ash and Air Pollution Control Residue Quality

Facilities which incinerate hazardous waste containing significant ash or halogen contents will generate combustion chamber bottom ash and various types of residues collected by subsequent APCDs. Operators must assess these materials to determine proper methods of disposal.

Since APCDs using wet collection methods predominates incinerator practice, fly ash and haloacids (like HCl) are often collected in aqueous effluents from a scrubber, absorber or wet ESP. The principal contaminants of interest in these APCD residues and incinerator bottom ash are heavy metals and trace levels of undestroyed organic material.

Currently under RCRA, the incineration of a listed hazardous waste results in the generation of ashes and residues which bear the same listed-waste code as the parent waste. This "derived from" rule has been challenged in court, however, and is under review. Currently, these "derived from" listed-waste ashes and residues are subject to LDR regulations, which specify a concentration level that must be met or a treatment technology that must be applied prior to placement of the materials in landfills. Further, facilities incinerating any hazardous waste must determine if the materials generated during such incineration exhibit any of the four hazardous characteristics defined in the regulations (i.e., ignitability, corrosivity, reactivity and toxicity). Among the more comprehensive of the tests for hazardous characteristics is the Toxicity Characteristic Leaching Procedure (TCLP),<sup>192</sup> designed to measure the concentration of a number of contaminants in a waste extract.

Some characterization data are available for combustion chamber ash and air pollution control residues which were generated by the incineration of a wide variety of wastes under a wide variety of conditions. Combustion chamber ash and scrubber water were analyzed for several of the incinerators tested by EPA as part of the incineration Regulatory Impact Analysis (RIA) program.<sup>107</sup> In additional testing, 10 incinerators were sampled to characterize ash and residues.<sup>193</sup> Incinerator ash and residues were also characterized as part of BDAT incineration tests under both RCRA and CERCLA,<sup>194-201</sup> as well as during demonstration testing under the Superfund Innovative Technology Evaluation (SITE) program.<sup>202</sup>

In the RIA study,<sup>107</sup> incinerator ash and scrubber waters were analyzed for organic constituents. Only two facilities had ash concentrations of organic compounds at levels greater than 35 µg/g. When organic compounds were detected, they tended to be toluene, phenol or naphthalene at concentrations less than 10 µg/g. The same compounds were also detected in scrubber waters, usually at concentrations below 20 µg/L.

The results of the 10-incinerator test program generally confirmed the RIA results.<sup>195</sup> While more organic compounds were detected across all of the facilities (19 volatile and 24 semivolatile organic compounds), levels in ash were typically at or well below 30 µg/g. More compounds were detected in

scrubber waters across the 10 facilities than in the RIA study (nine volatiles and five semivolatiles) and in higher concentrations. Semivolatiles ranged from 0 to 100 µg/L, while volatile compounds were much higher (0 to 32 mg/L).

Combustion chamber ash and scrubber waters were also analyzed for metals in these studies. Detected concentrations varied widely and were a function of facility operating conditions, residue processing and the amount of metal in the input waste stream, among other variables. Metals most frequently detected in the ash were chromium, zinc, copper, nickel, lead, arsenic and silver.<sup>203</sup>

While the majority of the metals in the TCLP extracts of the residues were at concentrations below the standards which define a waste as characteristically hazardous, disposal of the material is often subject to more restrictive LDR standards which are not always met. When compared to the most stringent of the "land ban" treatment standards, ash and scrubber wastewater from conventional incinerators yielded TCLP extracts which often exceeded the limits, particularly those for metals. Among metals which most frequently exceeded these limits were arsenic, nickel and lead. This suggests that wastes subject to land disposal standards may require further treatment (such as stabilization or precipitation) prior to disposal.<sup>204</sup> High-temperature "slagging" incinerators have shown some promise in producing ash with reduced metal leachability.<sup>204,205</sup>

Overall, the data indicate that very small amounts of residual organic compounds remain in incinerator ash and APCD residues. Thus, destruction and removal efficiencies reported for incinerators are almost entirely the result of destruction, rather than removal, of organic compounds. Levels of metals in ashes and APCD residues, and in their TCLP extracts, varied widely but generally do not appear to exhibit RCRA toxicity characteristics. In contrast, some TCLP extracts are likely to exceed the more restrictive standards associated with the LDR rules. It should be recognized that the available data represent short-term samples from less than 10 percent of the total hazardous waste incinerator population in the United States. Use of these data to project residue and ash quality for specific waste/incinerator combinations is not possible. Metals and organic concentrations are highly waste- and facility-specific and will

parameters are based on equipment manufacturers' design and operating specifications. They are set independently of trial burn results and are not linked with the automatic waste feed cutoff.

Operating conditions (such as combustion temperature and O<sub>2</sub> and CO in stack emissions) must be used as surrogates for continued high destruction performance after the trial burn since there is currently no real-time method to determine DRE for specific POHCs. DRE can only be determined with certainty via expensive, multi-day testing procedures. Similarly, parameters related to the specific APCD are used as surrogates to assure HCl removal and particulate control. Although, CEMs are available for HCl monitoring. Analytical results often take weeks or months to generate. EPA believes the current permitting approach is reasonable and protective of human health and the environment. But many argue that the availability of additional real-time monitoring techniques to detect process upsets and alert operators to automatically take corrective action would significantly increase public acceptance of thermal destruction technology.

Two general classes of performance estimation techniques exist. The first of these involves the use of compounds which are either identified in the waste or added to it to serve as "surrogates" for the destruction of other important compounds in the waste. The second approach involves the use of indicator emissions such as CO or unburned hydrocarbons to mirror waste destruction efficiency. A combination of both concepts are currently used to some extent in incinerator permitting.

### Surrogates

The surrogates concept involves identifying an easily detected organic compound or compounds which are more difficult to thermally destroy than any of the other hazardous compounds in the waste feed mixture. It is then assumed that if destruction efficiency for this compound is known for a given facility then all other compounds in the waste will be destroyed to at least that degree. Therefore, this concept involves developing an incinerability ranking of compounds.

The RCRA permit guidance for selecting POHCs in wastes actually employs this approach along with other considerations. It is recommended that a group of POHCs be chosen based on a variety of considerations including

incinerability, concentration in the feed and compound structure. Identifying compound incinerability has proven difficult, however, and sometimes unreliable. EPA originally suggested the use of compound heat of combustion ( $\Delta H_C$ ) as a ranking of compound incinerability.<sup>19</sup> This ranking method has received considerable criticism<sup>206</sup> and alternative methods, some of which have also been criticized, have been proposed. These ranking approaches have been reviewed and compared by Dellinger.<sup>207</sup> They include autoignition temperature,<sup>208</sup> theoretical flame mode kinetics,<sup>209</sup> experimental flame failure modes,<sup>210</sup> ignition delay time,<sup>211</sup> and gas-phase (nonflame) thermal stability.<sup>206,212,213</sup> The rankings of compounds by each of these indices were compared to their observed incinerability in actual waste incineration tests in 10 pilot- and field-scale units.<sup>207</sup> Each index failed to adequately predict field results except for the nonflame thermal stability method. This method, based on experimentally determined thermal stability for mixtures of compounds under low oxygen concentration conditions, showed a statistically significant correlation for the compounds evaluated.

While the low oxygen thermal stability (TSLoO<sub>2</sub>) concept appears promising, bench-scale data are only available for approximately half of the Appendix VIII organic compounds. Correlation for other important Appendix VIII compounds over a range of compound concentrations is needed to fully understand the potential utilization of this incinerability ranking approach. In recent tests carried out at both pilot- and full-scale levels, the TSLoO<sub>2</sub> (or "pyrolytic") Incinerability Ranking Index was investigated.<sup>214,215</sup> Only a limited amount of data could be obtained (given EPA's funding limitations). Consequently, making definitive statistical comparisons was difficult. Nevertheless, an analysis of that data (as contrasted to the data gathered at bench-scale on the roughly 160 compounds aforementioned) led to the following three general conclusions:<sup>216</sup>

- (1) The pyrolytic-based thermal stability ranking of POHC incinerability yielded statistically significant correlations at the 97.5 percent confidence level for each test series at the pilot facility and 90 percent for the full-scale facility. In contrast, the  $\Delta H_C$  Index achieved statistically significant correla-

tions at the 90 percent confidence level in only two of six test series.

- (2) Some differences between predicted and observed results using the TSLoO<sub>2</sub> ranking were likely due to PIC formation. Other discrepancies were particularly notable for benzene in the pilot-scale tests and for toluene in the full-scale tests, both of which were considerably more destructible (or "fragile") than predicted. These results disagree with typical observations for other field studies.
- (3) The full-scale tests consistently showed sulfur hexafluoride (SF<sub>6</sub>) to be significantly more "stable" (resistant to destruction) than the other POHCs, supporting its potential as an incinerability surrogate.

As a result of uncertainty over incinerability rankings, the use of "additives" is being considered for overcoming the limitations of the POHC compound approach. This concept involves the addition of a single, well-characterized compound or small group (or "soup") of compounds to a waste stream, with subsequent continuous monitoring of the emissions of the compound(s) to serve as a measure of destruction performance. Compounds such as various freons<sup>217,218</sup> and SF<sub>6</sub> have been proposed.<sup>219-221</sup> In a recent EPA study,<sup>222</sup> a mixture of four stable POHCs (as predicted by the TSLoO<sub>2</sub> Ranking) and SF<sub>6</sub> were fed to a pilot-scale rotary kiln system which was operated at different temperatures and oxygen concentrations. In all cases where the SF<sub>6</sub> DRE was 99.99 percent or greater, the individual POHC DREs exceeded 99.99 percent. However, there is also some evidence that SF<sub>6</sub> may not always be a conservative indicator of organic destruction for all cases such as the low oxygen failure mode. Conceptually, these types of materials would appear to be good additives since they rarely occur in hazardous wastes, can be detected in emissions using on-line instruments and are not likely to be formed as PICs.

Combustion byproducts formation has caused difficulty in interpreting incinerability data for mixtures of conventional POHC candidate compounds.<sup>219,223,224</sup> While laboratory-scale studies have shown some promise, earlier attempts in correlating field incinerator performance with additives behavior have generally been inconclusive. Additional testing is

needed, beyond the recent pilot- and full-scale tests highlighted previously.

#### Performance Indicators

Carbon monoxide and total unburned hydrocarbons are emitted from all combustion systems in varying amounts. Because CO is the final combustion intermediate prior to the formation of CO<sub>2</sub> in an ideal combustion process, it has been used in the determination of combustion efficiency. Measured unburned hydrocarbon emission values do not include all incompletely combusted hydrocarbons. Rather, this is an instrumentation-derived value resulting from the passage of gaseous emissions through a hydrogen Flame Ionization Detector (FID), which is commonly used with gas chromatographs. The FID responds to the number of carbon-hydrogen and carbon-carbon bonds in residuals in the combustion gas but not to carbon-halogen bonds. Nonetheless, because it does not respond to oxidized products such as O<sub>2</sub>, CO, CO<sub>2</sub>, and H<sub>2</sub>O, it has traditionally been used as an indicator of residual fuel emissions.

The use of CO and HC as indicators of the degree of combustion completion in hazardous waste incineration has been studied by several groups<sup>210,219,225,226</sup> and criticized by others.<sup>224,227</sup> Waterland obtained pilot-scale data which indicated correlations of the fractional penetration of POHCs (1-DRE/100) with CO and HC.<sup>225</sup> Kramlich *et al.*<sup>210</sup> and LaFond *et al.*<sup>228</sup> found that increases in CO preceded increases in the penetration of POHCs in a laboratory-scale turbulent flame reactor as parameters such as air/fuel ratio, atomization and degree of thermal quenching were varied. At the same time, HC tended to increase as POHC penetration increased. In a test of a pilot-scale circulating fluidized bed combustor, Chang *et al.*<sup>219</sup> indicated that penetration of combustion byproducts appeared to be correlated with HC and that there were no instances of high combustion byproducts penetration without a corresponding increase in CO. The converse was not true; increases in CO were observed on some occasions without a corresponding increase in combustion byproduct penetration. POHC destruction efficiency was high throughout this series of tests and did not appear to correlate well with either HC or CO. Although critical of the use of CO as a surrogate for POHC DRE or as an indicator of incinerator performance, Daniels *et al.*<sup>227</sup> presented data obtained from a full-scale rotary kiln. In five out of six cases the data

indicated increased POHC penetration with increased CO concentration.

Analysis of the pooled data from the early 1980s EPA incinerator test program revealed that there was no absolute level of mean combustion temperature, mean gas-phase residence time or carbon monoxide emission concentration which correlated with achieving a 99.99 percent DRE.<sup>107</sup> Residence times ranged from 0.1 to 6.5 seconds in the facilities tested, and temperatures ranged from 648 to 1,450°C. Carbon monoxide levels were as high as 600 ppmv, but at most plants ranged from 5 to 15 ppmv. It was concluded that the relationships between DRE and these parameters are, in all likelihood, facility-specific and that waste characteristics, waste atomization and combustion chamber mixing likely play equally important roles in achieving high DREs. Timing, funding and facility constraints, however, did not allow for collection of sufficient performance data under varying conditions at each site tested to allow quantification of such relationships. In particular, few of the test conditions produced DREs significantly below 99.99 percent.

Dellinger<sup>224</sup> has suggested that one reason for difficulties in correlating CO with DRE is that the assumed rapid oxidation of hydrocarbons to CO may not be correct for complex hazardous wastes containing large halogenated and heteroatom molecules. For these wastes, formation of stable and/or refractory intermediate organic reaction products may delay the production of CO. This delay would tend to distribute or move the CO production maximum relative to fuel (waste) destruction efficiency and would tend to negate the usefulness of CO measurement in the region of 99.99 percent DRE. Hall *et al.*<sup>226</sup> have conducted laboratory studies of CO formation versus compound destruction for several complex mixtures and found no correlation.

The Clean Air Act regulations currently requires the continuous monitoring of opacity using transmissometers for many types of facilities (such as cement kilns) and the continuous emission monitoring of MWCs is also required. Furthermore, it appears that opacity can be correlated to mass particulate emissions on a site specific basis. Thus, the possibility exists for using continuous opacity monitoring (COM) to monitor mass particulate emissions.

#### Predicting Performance

Based on current knowledge, it would appear that no single perform-

ance indicator or surrogate is sufficient as a predictor of organic compound destruction in incinerators. While low oxygen thermal stability data show promise as a predictor of relative compound incinerability, the data base is still not sufficient to extend this concept to universal POHC selections or to the development of standard POHC soups for trial burns or compliance monitoring. Data on additives are also insufficient to project a DRE correlation. EPA's Science Advisory Board (SAB) did conclude that the concept of using CO and/or HC concentrations to ensure that PIC emissions from combustion devices burning hazardous waste are below levels of public health concern was reasonable.<sup>142</sup> Even though it was observed that there was not a universal correlation between CO and PIC emissions, it was found that when CO was low, PICs were also low. On the other hand, when CO was high, PICs may or may not be high. Consequently, CO should be a good conservative indicator of combustion performance.<sup>21</sup> While attempts to correlate performance with single indicators and surrogates have not been entirely successful, taken in appropriate combination with other indicators they are useful as real-time indicators of the onset of process failure.

One of the additional limitations placed upon attempts to correlate surrogates and indicators with DRE and emissions of PICs is the lack of a significant data base on incinerator operation under failure or upset conditions. A failure condition can be defined as a normal or accidental operational deviation which results in failure of the facility to achieve the RCRA performance standards such as a 99.99 percent DRE. Most of the field incinerator data used to make HC and CO correlations has been taken under steady-state operating conditions, although there are some full-scale emissions data available for non-steady state operation.<sup>115,145</sup> The impact of events that could be indicative of failure (such as nozzle clogging, kiln overcharging, and CO and HC emissions spikes) has not been adequately quantified. This is largely because of limitations on test time and funding and, in particular, permit constraints which prohibit off-design operation of facilities. EPA has, however, conducted some failure-mode testing at its bench- and pilot-scale research facilities in Cincinnati, Ohio, Research Triangle Park, North Carolina and Jefferson, Arkansas. And some testing has shown that there is little change in POHC DRE over significant

operating ranges or under "apparent" failure conditions.<sup>214,222,229-232</sup>

In July 1990, EPA and the Occupational Safety and Health Administration established a joint task force to review safety and health issues at hazardous waste incineration facilities nationwide. The task force inspected 29 facilities. While the focus of this inspection was to evaluate compliance with safety and RCRA standards, a significant number of waste feed cutoffs and emergency safety vent openings were also noted at some facilities.<sup>233</sup> EPA is, therefore, conducting additional failure-mode testing at its bench- and pilot-scale research facilities in Research Triangle Park, North Carolina and Jefferson, Arkansas to assess the impact of these events.

A series of pilot-scale incineration tests were recently conducted at the IRF to assess the impact on emissions in situations that would trigger a waste feed cutoff.<sup>234</sup> Seven tests were performed corresponding to high CO spikes, reduced pressure drop across the venturi scrubber and decreased scrubber liquor flow to the packed-column scrubber. None of the modes tested caused significant increases in POHC, trace metal, or HCl emissions.

EPA has also conducted nonsteady-state operational assessments at three boilers employing hazardous waste as a fuel.<sup>235</sup> The impact of typical nonsteady-state operating conditions (such as start-up, soot blowing and load change) upon DRE and emission of combustion byproducts, CO and HC was studied. While elevated CO emissions were observed at two of the sites under off-design operation, attempts to correlate DRE with CO, NO<sub>x</sub> and O<sub>2</sub> emissions were unsuccessful. This was largely because 99.99 percent DRE was achieved under both good and off-design operation. The testing, however, acknowledged some of the difficulties in conducting off-design studies. In some cases, the duration of the process transient to be studied may be shorter than the sampling time required to collect a sufficient sample to assess DRE. The large volume and high surface area (boiler tubes) in boilers tended to delay emissions of organics from one off-design test to the next, making it difficult to separate cause and effect.

This so-called "hysteresis effect" has been tested more thoroughly and found to be much less of a problem in determining true DREs than originally thought.<sup>236</sup> In this test of a full-scale boiler, the operating parameters were set in an attempt to maximize the hysteresis effect by operating the boiler in

a "sooting" mode. It was found that while hysteresis did occur, the magnitude was compound-specific and small so that it would have little effect in determining the DRE. The mass of pollutants emitted during hysteresis ranged from 5.5 percent for monochlorobenzene to 10.5 percent for trichloroethylene of the mass of these same pollutants that were emitted during normal sampling operation.<sup>237</sup> This would have the net effect of changing a 99.99% DRE calculated under normal sampling procedures to 99.9895% for monochlorobenzene and to 99.9890 for trichloroethylene.

### Environmental and Public Health Implications

Regardless of the apparent capabilities of hazardous waste incinerators to meet or exceed the RCRA performance standards, the ultimate public test involves demonstration that there is no unacceptable increase in public health risk from the emissions to the environment. While any of the emissions from an incinerator may potentially be of environmental interest, most attention has been directed toward air pollution emissions. This is because they appear to represent the most important source of off-site human exposure and there is no opportunity for secondary containment or treatment of emissions once they leave the stack. Ash and scrubber residues, however, are lower in volume and can be contained, examined and if necessary, treated prior to discharge or disposal. In addition to chronic exposure to recurring emissions, there are also environmental and public health impacts which could result from potential single-event or catastrophic emissions at incineration facilities.

### Risks from Single-Event Emissions

As with any industrial facility, there are risks from potential accidents at incineration facilities such as fires, explosions, spills of raw waste, physical injuries, acute exposure to waste, or accidental releases to the environment. These events are probabilistic in nature and their evaluation in a risk assessment is handled differently from continuous pollutant emissions from stacks. For instance, the U.S. Department of Transportation maintains statistics on the frequency of releases of cargo from vehicular accidents involving trucks. For tank trucks of all types, for instance, this is estimated to be 0.35 releases per million miles traveled.<sup>238</sup> Similar values may be identified for

accidents involving storage facilities and transfer operations.

Little specific information on these types of accidents is available for hazardous waste incineration facilities. Often such detail which is not readily available is a matter of legal and court actions and other kinds of settlements protected by privacy. Ingiwersen *et al.*<sup>239</sup> evaluated the potential off-site impacts of five hypothetical accidents at a planned hazardous waste incineration facility. It was estimated that no long-term adverse effects could be expected from chronic exposure for the nearest residents (0.5 miles) and that any effects due to acute exposures to the HCl emissions from the accidents were expected to be short-term and reversible. Actual accidents at an operating European facility have been documented;<sup>240</sup> seven accidents occurred over an 11-year period. One employee was injured and no off-site effects were reported for any of the incidents, which generally involved storage and handling operations. In the absence of accident data specific for incineration facilities, statistics from related industrial practices are probably adequate in assessing these risks.

### Methods for Assessing Risks from Recurring Emissions

The major concern of this discussion is the risk associated with recurring air pollution emissions from incinerators. The assessment of risk to human health rather than environmental damage is generally believed to be of greatest interest. Four general steps are involved in assessing the impact on public health from stack emissions from an incinerator:<sup>241</sup>

- (1) Identify the health effects of constituents of concern as a function of concentration level.
- (2) Predict the concentrations of these constituents to which the public may be exposed.
- (3) Estimate the health impact of these concentration exposures.
- (4) Conduct an uncertainty analysis.

Identification of the constituents of concern in stack emissions and the health effects of these constituents is, of course, a function of the waste streams and incineration facility of interest. In general, any of the constituents in Appendix VIII of the RCRA standards are of possible interest. Other compounds which may be found in combustion emissions (certain polynuclear aromatics, polycyclic aromatic

compounds and heavy metals) may also be of concern. The major health effects of concern are for low-level chronic exposure to these materials. These effects are generally carcinogenicity, mutagenicity, teratogenic or target organ toxicity such as nephrotoxicity, immunotoxicity and behavioral effects.

Predicting the potential levels of human exposure to pollutants requires information on the frequency, intensity, duration and continuity of exposure.<sup>241</sup> Exposure assessment generally requires the use of mathematical models which simulate the transport and dispersion of emissions from the stack to the exposed population. EPA has developed approximately 10 models suitable for regulatory application and more than 20 additional models have been submitted to EPA by private developers for possible use. EPA has issued guidelines which recommend the air quality modeling techniques that should be used. Table XXIV lists specific models that are recommended for selected applications in simple terrain.<sup>242,243</sup> Simple terrain, as used here, is considered to be an area where terrain features are all lower in elevation than the top of the stack of the source(s) in question.

Of the air dispersion models available, EPA has most often used the Industrial Source Complex Long-Term (ISCLT) Model for predicting annual average concentration for hazardous waste incinerator facility studies.<sup>244-247</sup> The Oak Ridge National Laboratory has linked the ISCLT model with computerized meteorology and population data bases and programs to form the Inhalation Exposure Methodology (IEM).<sup>248,249</sup> The IEM employs U.S. population data and local meteorological data along with ISCLT to estimate air pollutant concentrations and human inhalation exposures in the vicinity of hazardous waste incinerators located anywhere in the United States. The IEM has been used extensively by EPA in assessing regulatory alternatives for hazardous waste incinerators.<sup>250,251</sup>

The exposure information generated by models such as the IEM may then be employed to estimate human health risk. The individuals at highest risk of developing adverse health effects are of most interest. The risk to this "maximally exposed population" is estimated from the modeled exposure at the point of highest annual average pollutant ground-level concentration outside the facility. For each exposed individual, cancer risk is

expressed as the cumulative risk over a 70-year (lifetime) period of continuous exposure.

A variety of models are available to quantify the health risks of chemical pollutants. Carcinogen potency factors have been developed by EPA based on the linearized multistage model.<sup>159</sup> This model is consistent with current understanding of the mechanism of carcinogenesis. For noncarcinogenic effects, no observable adverse effect levels (NOAELs) have been used to derive RfD levels.<sup>252</sup>

There is considerable uncertainty involved in conducting risk assessments. Numerous assumptions must be made regarding pollutant emission levels, pollutant effects, dispersion factors and so on. Only a fraction of the needed tests of the effects of chronic, low-level exposures to environmental pollutants have been done. There is also considerable uncertainty in extrapolating effects from high doses, which cause effects in animals, to low doses in humans. Linearity assumptions are typically used in making such extrapolations. Some investigators have questioned the wisdom of such assumptions, however.<sup>253</sup>

Beyond this, very little is known about how, or even if, this information can be used to estimate the effects of complex mixtures of the substances usually present in incinerator stack emissions. For these reasons and other limitations, most assessments adopt assumptions and risk estimate values which produce an estimate of a worst-case effect. In order to promote consistency in risk assessments, EPA has published in the *Federal Register* a six-part guidance on risk and exposure assessment methodologies.<sup>254</sup> This guidance is an excellent resource to those conducting or evaluating risk assessment studies. In addition, EPA has issued risk assessment guidance manuals to be used in the remedial investigation/feasibility study (RI/FS) process at Superfund sites.<sup>255,256</sup>

#### Overall Risks from Long-Term Air Pollution Emissions from Hazardous Waste Incinerators

Risk assessment and risk management have been used increasingly by industry and government over the past fifteen years in evaluating control technology and regulatory options for managing hazardous waste.<sup>257</sup> The initial 1978 RCRA incineration standards, for instance, were almost entirely design and performance oriented. In the 1981 proposal, however, EPA incorporated risk assessment into what was

Table XXIV. Preferred air quality models for selected applications in simple terrain.<sup>242</sup>

Short Term (1-24 hours)	Land Use	Model <sup>a,b</sup>
Single Source	Rural	CRSTER
	Urban	RAM
Multiple Source	Rural	MPTER
	Urban	RAM
Complicated Sources <sup>c</sup>	Rural/Urban	ISCST
Buoyant Industrial Line Source	Rural	BLP
Long Term (monthly, seasonal or annual)		
Single Source	Rural	CRSTER
	Urban	RAM
Multiple Source	Rural	MPTER
	Urban	CDM 2.0 or RAM <sup>d</sup>
Complicated Sources <sup>c</sup>	Rural/Urban	ISCLT
Buoyant Industrial Line Source	Rural	BLP

<sup>a</sup> CRSTER denotes single source model; RAM denotes Gaussian-plume multiple source air quality algorithm; MPTER denotes multiple point Gaussian dispersion algorithm with terrain adjustment; ISCST/ISCLT denotes industrial source complex short-term and long-term models; BLP denotes buoyant line and point source dispersion model; CDM denotes climatological dispersion model.

<sup>b</sup> Several of these models contain options which allow them to be interchanged. For example, ISCST can be substituted for CRSTER and equivalent, if not identical, concentration estimates obtained. Similarly, for a point source application, MPTER with urban option can be substituted for RAM. Where a substitution is convenient to the user and equivalent estimates are assured, it may be made. The models as listed here reflect the applications for which they were originally intended.

<sup>c</sup> Complicated sources are sources with special problems such as aerodynamic downwash, particle deposition, volume and area sources, etc.

<sup>d</sup> If only a few sources in an urban area are to be modeled, RAM should be used.

called the "best engineering judgement" (BEJ) approach to regulating and permitting incinerators.<sup>17</sup> The operating and performance standards for incinerators were to apply to facilities unless a site-specific risk assessment indicated that a higher degree of control was necessary. The risk assessment proposal, however, was not included in the final rule in 1982, largely because of concern from the regulated community over the uncertainty of risk assessment approaches. Rather, risk assessment and cost-benefit analysis became a more integral part of the development of hazardous waste control technology standards through the conduct of Regulatory Impact Analyses of all proposed standards as required by Executive Order 12291.

Rules promulgated for burning hazardous waste in boilers and industrial furnaces<sup>27</sup> require that emissions testing and health-risk assessments for chlorinated dioxins and furans for certain facilities be done. Emission limits for metals, HCl and Cl<sub>2</sub> are based on projected inhalation health risks to the hypothetical maximum exposed individual. Similar approaches were used in developing the proposed amendments to the hazardous waste incinerator regulations.<sup>21</sup>

A number of risk assessments have been conducted for specific hazardous waste incinerators and for incineration on a national basis. Using the emissions data from eight full-scale incinerator tests,<sup>107</sup> EPA conducted a risk assessment as part of its Incinerator RIA in 1982. The objective was to examine the economic impact of the regulations on the regulated community and to estimate the health and environmental effects of the regulations.<sup>258</sup> The risks due to POHCs, PICs and metal emissions were developed (Table XXV). Since then, numerous other risk assessments have been conducted for facilities burning hazardous waste.

While these results show that the human health risks from emission of organics from most hazardous waste incinerators are low, risks from metal emissions show the greatest potential for cancer risk. The risks from metals

**Table XXV.** Total excess lifetime cancer risk to the maximum exposed individual from incinerator emissions.<sup>258</sup>

POHCs	10 <sup>-10</sup> to 10 <sup>-7</sup>
PICs	10 <sup>-11</sup> to 10 <sup>-7</sup>
Metals	10 <sup>-8</sup> to 10 <sup>-5</sup>
Total	10 <sup>-8</sup> to 10 <sup>-5</sup>

emissions ranged from two to six orders of magnitude higher than values for POHCs and PICs, and dominated the total risk values. Risks from residual POHC and PIC emissions from the incinerators tested were both low. Much more importance has now been given to the control of metal emissions, however, and the risks from these emissions will not exceed acceptable levels if appropriate APCDs and the metal controls promulgated for BIFs<sup>27</sup> are employed.

Taylor *et al.*<sup>259</sup> reported the results of a risk assessment for metal emissions using the same test data but employing somewhat different assumptions. Using the IEM methodology, carcinogenic and noncarcinogenic risks were examined. Interestingly, these results showed even lower cancer risks than the EPA study. Individual lifetime cancer risks for the maximum exposed population ranged from a low of 4.48 x 10<sup>-11</sup> for beryllium to a high of 3.47 X 10<sup>-6</sup> for chromium. Noncarcinogenic risks were also small. All values were well below the respective acceptable daily intake (ADI) values. Lead intake was highest, estimated at 2 percent of the ADI.

Kelly reported similar conclusions for a risk assessment of stack emissions from a hazardous waste incinerator in Biebesheim, West Germany.<sup>260</sup> Maximum ground level air concentrations for 24 metals (and for PCB) were estimated using the IEM. All levels (including PCB) were less than 2 percent of the corresponding continuous exposure limit (CEL) value.

Following the promulgation of the BIF regulations,<sup>28</sup> some communities have become increasingly concerned regarding the burning of hazardous waste in cement kilns. Studies have been conducted to address the risk posed by this practice. Mantus<sup>261</sup> reported that the organic and metal emissions of a well-designed and properly operated

cement kiln burning hazardous waste are not substantially different from the emissions of a cement kiln burning only conventional fuel. Mantus also reported that no increases in adverse health effects were expected due to the use of hazardous waste fuels. The Texas Air Control Board conducted an extensive environmental monitoring study in Midlothian, Texas where two cement plants were burning hazardous waste and reported that no adverse health effects were expected due to emissions from these facilities.<sup>262</sup>

Holton *et al.*<sup>263-265</sup> examined the significance of various exposure pathways for air pollution emissions from three sizes of land-based incinerators located at three hypothetical sites in the United States. For certain organic chemicals, the food chain pathway may be an important contributor to total human exposure. The study concluded, however, that the human health risk from emissions was small for all of the chemicals studied irrespective of the exposure pathway. EPA has recently issued guidance necessary to estimate the health risks that result from exposure to toxic pollutants in combustor emissions by pathways other than inhalation.<sup>266</sup>

Fugitive emissions from peripheral facilities at incinerators (such as storage tanks) were also estimated to be an important contributor to total pollutant emissions.<sup>264,265</sup> Few studies have quantified fugitive emission levels at incinerators, but the ones that did have shown that ambient levels are not a cause for concern.<sup>107,267,268</sup>

The risks associated with incineration of hazardous wastes at sea have been compared to risks from land-based incineration.<sup>238</sup> While risks of marine and terrestrial ecological damage were estimated, the direct human health risks from stack emissions are of greatest interest in this discussion (Table XXVI). The incremental cancer risk to the most

**Table XXVI.** Incremental cancer risk to the most exposed individual by type of stack release.<sup>238</sup>

Systems	PCB Waste	EDC Waste
Ocean-based		
POHCs	1.45 x 10 <sup>-10</sup>	5.51 x 10 <sup>-10</sup>
PICs	1.68 x 10 <sup>-12</sup>	3.36 x 10 <sup>-9</sup>
Metals	6.37 x 10 <sup>-7</sup>	1.06 x 10 <sup>-6</sup>
Total stack	6.37 x 10 <sup>-7</sup>	1.06 x 10 <sup>-6</sup>
Land-based (two sites)		
POHCs	5.13 x 10 <sup>-8</sup>	1.43 x 10 <sup>-7</sup>
PICs	1.79 x 10 <sup>-6</sup>	2.59 x 10 <sup>-8</sup>
Metals	2.65 x 10 <sup>-5</sup>	3.12 x 10 <sup>-5</sup>
Total stack	2.74 x 10 <sup>-5</sup>	3.14 x 10 <sup>-5</sup>

exposed individual was determined for POHCs, PICs and metals for two scenarios: a PCB waste and an ethylene dichloride (EDC) waste. Not surprisingly, the human health risk of stack emissions from ocean incineration were less than those of land-based systems, largely due to distance from population. The land-based incinerator risk values were similar to those estimated in the EPA incinerator RIA. POHC and PIC releases showed low risk, generally one to five orders of magnitude less than those for metals. Risks from metals accounted for from 90 percent to almost all of the identified risk from either system, and they exceeded the  $10^{-6}$  risk level for only the land-based scenario. The study notes, however, that the assumptions used in the assessment overstate the likely levels of carcinogenic metals in the hypothetical wastes used in the assessment and, therefore, likely overestimate emissions and risk levels.

All of these risk assessment studies suggest that stack emissions from incineration of hazardous waste pose little risk to human health. However, as previously stated, the emissions data base upon which many of the assessments were based has been criticized by EPA's Science Advisory Board (SAB) as being insufficient.<sup>141,142</sup> The SAB has recommended that "EPA should conduct more studies to better define whether or not a problem exists with the emission of PICs, the source(s) of the problem if it exists, and how to minimize the problem."<sup>142</sup>

It is not clear, however, that even this level of emissions information will really answer the question of how much absolute risk is associated with incinerator emissions. From the standpoint of the lay public, it may be more useful and productive to compare these emissions with other types of combustion emissions whose risks we have accepted in daily life. Lewtas<sup>269</sup> and others have done interesting work on the comparative cancer potency of complex mixtures of pollutants (for example, power plant emissions, automobile exhaust and cigarette smoke). Using short-term bioassays of organics extracted from actual emissions, the relative cancer potency of emissions has been estimated.

Comparative mutagenic emissions rates, expressed as revertants per mile or joule, have been determined from testing mobile sources and stationary sources, respectively. Experimental work to date suggests that the mutagenic emission rates of wood stoves,

for instance, are as much as four orders of magnitude greater than those for conventional coal-fired utility power plants.<sup>269</sup> Similar sampling and testing are needed for incineration emissions so that their potency can be compared to everyday sources such as wood stoves, oil furnaces and utility power plants. It should be noted, however, that use of comparative mutagenic emissions rates alone does not account for variations in potential human health impact that occur due to differences in exposure level to emissions from sources of different types or as a result of different routes of exposure.

The mass of specific organic emissions from HWIs have been compared<sup>270</sup> to the 1990 Toxics Release Inventory (TRI).<sup>271</sup> The HWI emissions were estimated using "reasonable worst case" assumptions. Comparisons were made for 15 carcinogenic organic and 17 non-carcinogenic compounds. Ratios for all but one of these compound-specific HWI emissions to their corresponding TRI air releases ranged from 0.0003 to 0.746 percent. The total mass emissions (121.7 tons) of all 32 specific organics from HWIs was less than 0.03 percent of the corresponding 1990 TRI air releases (431,600 tons).

In an EPA analysis, the cancer risks from exposures to airborne toxic pollutants were estimated for the total U.S. population.<sup>272</sup> The purpose of this was to provide information to suggest priorities for air toxics control. It is emphasized that the estimated annual cancer cases are not absolute predictions of cancer occurrence and are intended to be used in a relative sense only. About 90 toxic air pollutants and 60 source categories were addressed. Hazardous waste incinerators and industrial boilers and furnaces burning hazardous waste comprised one of the source categories. Estimated incremental annual cancer cases are summarized in Table XXVII. It is interesting to note that emissions from burning hazardous waste accounted for only an incremental 0.3 cancer cases per year or 0.015 percent of the estimated 1,986 incremental annual cancer cases from all 60 sources. Over 56 percent of the cancer cases was due to emissions from motor vehicles. Cancer cases due to source categories such as woodsmoke and gasoline marketing were two to three orders of magnitude higher than those due to burning hazardous waste. In comparison, it is estimated that 330,000 cancer cases were due to tobacco use and 385,000 cancer

cases were due to diet in the U.S. in 1991.<sup>273</sup>

## Conclusions

The body of knowledge concerning hazardous waste incineration has been expanding rapidly since 1980. This review update has examined some of the most significant aspects of this information. A number of conclusions may be drawn on the status of incineration technology, current practice, monitoring methods, emissions and performance, and public health risks. Beyond these, a number of remaining issues and research needs can also be identified.

Based on this review, the following conclusions may be drawn:

- (1) Incineration is a demonstrated, commercially available technology for hazardous waste treatment. Considerable design experience exists, and design and operating guidelines are available covering the engineering aspects of these systems.
- (2) A variety of process technologies exist for the range of hazardous wastes appropriate for thermal destruction. The most common incinerator designs incorporate one of four major combustion chamber designs: liquid injection, rotary kiln, fixed hearth or fluidized bed. The most common air pollution control system involves combustion gas quenching followed by a venturi scrubber (for particulate removal), a packed tower absorber (for acid gas removal) and a mist eliminator. Newer systems have incorporated more efficient air pollution control devices, however, such as wet electrostatic precipitators, ionizing wet scrubbers, spray dryer absorbers, fabric filters and proprietary systems.
- (3) Some of the most recent information for the burning of hazardous waste is provided by the state Capacity Analysis Plans which show that for 1987 about 1.3 MMT of hazardous waste were incinerated in 171 incinerator facilities across the United States. In addition, about 1.2 MMT of hazardous waste were burned in BIFs during this same period.

Ranking Index. Bench-scale data are only available, however, for approximately half of the Appendix VIII organic compounds.

- (18) There appears to be little increased human health risk from hazardous waste incinerator emissions, based on assessments done to date. Metal emissions appear to be most significant in the risk values which have been derived.
- (19) An EPA analysis of 90 toxic air pollutants from 60 industrial categories estimated that the incremental cancer risk from all hazardous waste incinerators, industrial boilers and industrial furnaces burning hazardous waste in the United States at approximately 0.3 cancers per year. This compared to 1,986 additional cancers per year from all 60 categories.
- (20) In spite of the demonstrated destruction capabilities of hazardous waste incinerators and the apparent low incremental risk of emissions, there is considerable public opposition to siting and permitting these facilities. Permits for commercial HWIs require an average of three years, and often much longer, to be finalized. Uncertainty over permitting and public acceptance will likely result in a near-term shortfall in needed capacity for certain geographic areas and for specific waste types such as explosives, mixed waste, and possibly solids and sludges.

**Remaining Issues and Research Needs**

While thermal destruction represents the most effective and widely applicable control technology available today for the disposal of organic hazardous waste, a number of issues remain concerning its use in the long term. These include: destruction effectiveness on untested/unique wastes, control of heavy metal emissions, emissions of combustion byproducts, detection of process failure, real-time performance assurance and the role of innovative technology.

**Destruction Effectiveness on Untested/Unique Wastes**

Most of the performance data which have been used in the development and

assessment of thermal destruction regulations and standards to date have been collected for waste/thermal technology combinations typical of current practice. The character of wastes which are being treated by incineration, however, has begun to change dramatically during recent years. These changes have been strongly influenced by the Land Disposal Restrictions Program required by the Hazardous and Solid Waste Act Amendments of 1984 and influenced by increased emphasis upon remedial action at Superfund sites. This is due to the fact that the BDAT treatment standards for many of the restricted wastes are based on incineration, which is also frequently selected as the remediation technology for Superfund sites. These wastes often: have higher solids and water content, are more complex in their physical and chemical composition, may contain inorganic salts, have lower heating value and/or potentially contain higher levels of hazardous metals and high-hazard organics compared to wastes which were typically incinerated in the past.

To further clarify this issue, the term "untested/unique wastes" emphasizes the wide spectrum of mixed waste organics, plastics, inorganics, and contaminated soil and other debris being found at numerous Superfund sites where industrial wastes from multiple sources had been buried. The term also applies to other, more homogeneous RCRA waste streams such as waste pesticides or industrial chemicals which previously had never been treated by incineration. In either case, not thoroughly understood are the incineration of wastes containing the following: toxic metals in significant concentrations, various organics for which there is a lack of documented incineration experience, and organics absorbed within inorganic matrices where the organic desorption properties have not been fully investigated. Waste containing inorganic salts and other situations, such as where plastics or sludges or light and fluffy materials are involved, potentially present materials-handling problems in an incinerator.

Consequently, while incineration is believed capable of achieving high levels of destruction for hazardous wastes and there is a wealth of successful experience and destruction data for wastes historically incinerated in stationary facilities, situations may still arise where an unfamiliar combination of organics, inorganics, and waste media or soil are considered for incineration. Treatability/performance testing in such situations may be necessary to:

assure the destruction and removal effectiveness for untested wastes, assess process limitations and waste pretreatment requirements, determine the safety or treatment requirements for process residues and improve the ability to predict incinerator performance when fed new waste materials.

**Control of Heavy Metal Emissions**

While the human health risk associated with incinerator emissions appears to be small, metal emissions have been the dominant component of the risk levels identified thus far. Significant progress has been made in better understanding the fate or "partitioning" of metals in the combustion process and the effectiveness of certain APCDs to control metal emissions, but much remains to be done.

Research to understand the incineration behavior of organic/metal mixtures began in earnest only a few years ago. As a result, understanding of metals partitioning is not yet complete. Likewise, at a very early stage of development are the understanding of the importance of the chemical form of the particular metal species (whether pure, oxides, chlorides, alloys or organometallics and their respective valence states) as well as the knowledge concerning the possible influences of the soil matrix and/or inorganic materials (such as lime, portland cement dust and fly ash) that could be added to the incineration process to tie up the metals. In addition, modified operation of conventional rotary kilns such as running at lower temperatures in the primary chamber to "remove" the organics for subsequent destruction in the afterburner may become increasingly attractive. This may be particularly true for treating wastes such as Superfund soils which are contaminated by both organics and metals since more of the metal might remain with the treated/decontaminated soil and not pose an air pollution problem. More testing is required, however, to determine that these modified operating approaches will effectively destroy the organics and decontaminate the soil.

**Emissions of Combustion Byproducts**

Current information suggests that organic combustion byproduct emissions resulting from the incineration of hazardous waste do not represent a significant risk to public health. Some, however, have questioned the completeness or thoroughness of emissions data and, therefore, the adequacy of risk assessments performed using these

data. This issue has emerged as a concern in numerous public meetings on incinerator permits and facility sitings.

There is little doubt that none of the emissions testing efforts conducted to date has identified *all* compounds contained in incinerator stack emissions. It should be noted, however, that the same is true for virtually *any* other source of air (including vehicle emissions) or water pollution; that is the complete character of these other emissions or effluents is also not completely known. While many believe that most of the unidentified organic mass is nonchlorinated, low molecular weight hydrocarbons which are of little concern from a health risk viewpoint, this is not yet sufficiently supported by currently available data. In one full-scale test, however, between 53 to 91 percent of all organics were identified. Methane and ethylene accounted for 33 to 97 percent of the identified emissions.

Because hazardous waste facilities are perceived by some as posing higher risk than many other types of pollution control or industrial facilities, more attention is given to their emissions. Thus, while it is unlikely that any major, highly hazardous components of emissions have been overlooked, the data are not available to satisfactorily prove this to all who may be concerned. The EPA's Science Advisory Board has recommended that EPA should investigate this issue more thoroughly to better define whether or not a problem exists due to the emission of organics, the source(s) of the problem if it exists and how to minimize the problem. On the other hand, the task of finding all potentially hazardous compounds is an open-ended one, ultimately limited by expense.

Most risk assessments conducted to date have been based on inhalation of HWI emissions. For certain situations, the food chain pathway may be an important contributor to total human exposure. Additional effort is needed to investigate this issue both in the form of validating methodologies and applying these methodologies to specific cases.

#### Detection of Process Failure

Another issue related to combustion byproduct emissions is that only a few tests<sup>115, 145, 234</sup> have examined the level and chemical character of emissions for those occasional periods of time when facilities may be operating under upset conditions (transients or failure modes). More experimental work is clearly

needed here. Some testing has shown that there is little change in principal organic hazardous constituent DRE over significant operating ranges or under "apparent" failure conditions. But at the same time, measured or visible emissions of unburned hydrocarbons have typically increased. Research is necessary to determine if these "failure-mode" emissions pose a hazard.

One approach to resolving both the question of data completeness and failure mode impacts is to examine the relative potency of emissions using short-term bioassays and bioassay-directed chemical analysis as a means of more cost-effectively identifying the chemical compounds (perhaps including some previously unidentified) which are primarily causing the potency. While short-term bioassays have their own set of constraints and limitations, they have proven useful in comparing the cancer potency of mixtures of compounds among different combustion sources. Testing a reasonable range of hazardous waste types under "good" and off-design conditions would give an indication of the range of potency of emissions as a function of operational conditions. This would also permit additional comparison with conventional combustion sources such as automobiles, which are more familiar to the general public.

#### Real-Time Performance Assurance

Once the public health significance of incinerator emissions is verified, methods must be available to assure that effective operation is maintained. A variety of surrogates and indicators of incinerator performance have been evaluated and are already being used. None, however, are capable of directly identifying and measuring the emission of specific organics or metals on a "real-time basis" and little evaluation has been done under true failure conditions.

While the TSL<sub>02</sub> Incinerability Ranking Index appears promising, additional laboratory evaluations need to be conducted for many of the remaining hazardous constituent organic compounds. Additional validation studies are needed before this method can be used reliably for POHC designation or as a basis for establishing optimal continuous monitoring systems for specific surrogate compounds. Research has indicated that the additive SF<sub>6</sub> may be a useful way of continuously assuring DRE, but this would probably have to be used in combination with other parameters since there

may be cases where SF<sub>6</sub> is not always a conservative indicator of organic destruction. Additional investigation is needed to fully understand the potential of SF<sub>6</sub> and similar compounds for assuring DRE.

While it may not be possible to find an easily monitored parameter which "correlates" with incinerator performance, it may be possible to identify other parameters and combinations of parameters which might improve the ability to identify the onset of process failure. Research is necessary to examine the suitability of additional real-time monitoring systems and approaches to more reliably predict process failure. Some promising work is under way to develop "real-time" detection monitors for specific organics and metals utilizing Fourier transform infrared (FTIR) spectroscopy<sup>274</sup> and laser technology. Availability and use of such techniques might have a significant and beneficial impact upon public acceptance of these facilities and form a technical basis for more effective compliance monitoring by regulatory agencies. CEMs are also available for HCl and opacity, and utilization of these monitors could possibly help assure the control of HCl and particulates from HWIs on a continuous basis.

#### Role of Innovative Technology

A wide range of innovative hazardous waste technology has emerged since the passage of RCRA.<sup>275, 276</sup> A number of these technologies are thermal destruction processes. The potential destruction capabilities and cost-effectiveness of these processes have been steadily publicized, although many of the techniques must be considered to be only in the developmental stage. Among technologies considered to be new or innovative are pyrolysis, high- and low-temperature plasmas, molten salt, molten glass and molten metal baths. One innovative concept which has been tested and applied to Superfund soils in the past three to five years by Rollins Environmental Services is a patented "rotary reactor."<sup>277</sup> This system utilizes a basic rotary kiln concept, modified by the addition of a mechanically agitated and recycled internal bed of sand or aggregate.

Many argue, particularly in public hearings, that decisions on permitting conventional incineration facilities should be postponed in favor of adopting more innovative approaches, whose inventors or developers often claim higher destruction efficiency at lower cost than conventional systems. For

specific waste streams (such as contaminated soils and PCBs), a number of innovative systems have demonstrated equivalent performance to those of conventional systems. Some systems appear to offer advantages for handling specific, although sometimes limited, waste streams. Considerable uncertainty exists as to the true cost-effectiveness of some systems, since practical field experience and system longevity data are often not yet available to aid in identifying operating limitations.

In order to accelerate the development and use of innovative cleanup technologies at Superfund sites across the country, EPA has established the Superfund Innovative Technology Evaluation (SITE) Program. In a recent report<sup>278</sup> that briefly described 72 demonstration and emerging technologies that were being evaluated under the SITE Program, it was reported that 13 percent of the emerging technologies and 20 percent of the demonstration program technologies were thermal.

Many of these emerging systems will find a role in future hazardous waste management strategies. Policymakers, public officials and industrial decision officials should be careful, however, in delaying action on currently available, demonstrated, thermal destruction systems until the need, benefit and operability of such innovative systems are clearly established.

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Acronyms/Abbreviations

ADI: acceptable daily intake  
 APCD: air pollution control device  
 BDAT: best demonstrated available technology  
 BEJ: best engineering judgment  
 BIFs: boilers and industrial furnaces  
 Btu: British thermal unit  
 Br<sub>2</sub>: bromine  
 CD: calibration drift  
 CAP: Capacity Assurance Plan  
 CO<sub>2</sub>: carbon dioxide  
 CO: carbon monoxide  
 CAG: carcinogen assessment group  
 CDF: chlorinated dibenzofuran  
 CDD: chlorinated dibenzo-p-dioxin  
 Cl<sub>2</sub>: free chlorine  
 CAA: Clean Air Act  
 CFR: Code of Federal Regulations  
 CBP: combustion byproducts  
 CE: combustion efficiency or calibration error  
 ΔHc: compound heat of combustion  
 CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act of 1980  
 CBO: Congressional Budget Office  
 CEM: continuous emission monitors  
 COM: continuous opacity monitoring  
 CEL: continuous exposure limit  
 cfm: cubic feet per minute  
 DRE: destruction and removal efficiency  
 dscf: dry standard cubic foot  
 ECD: electron capture detector  
 ESP: electrostatic precipitator  
 EPA: U.S. Environmental Protection Agency  
 EDC: ethylene dichloride  
 FF: fabric filter  
 FID: flame ionization detector  
 FTIR: Fourier transform infrared  
 GC: gas chromatography  
 GCP: good combustion practice  
 g: gram  
 HSWA: Hazardous and Solid Waste Act of 1984  
 HWDF: hazardous waste derived fuel  
 HWI: hazardous waste incinerator  
 HPLC: high-performance liquid chromatography

HC: hydrocarbon  
 HBr: hydrogen bromide  
 HCl: hydrogen chloride  
 HF: hydrogen fluoride  
 HHV: higher heating value  
 IRF: Incineration Research Facility  
 ISCLT: Industrial Source Complex Long-Term  
 IEM: Inhalation Exposure Methodology  
 I-TEFs/89: International Toxicity Equivalency Factors, 1989  
 IWS: ionizing wet scrubber  
 LDR: Land Disposal Restriction  
 TSL0<sub>2</sub>: low oxygen thermal stability  
 MS: mass spectrometry  
 MACT: maximum achievable control technology  
 MEI: maximum exposed individual  
 MWI: medical waste incinerator  
 M5: Method 5  
 Mg: metric ton (10<sup>6</sup> grams)  
 μg/m<sup>3</sup>: micrograms (10<sup>-6</sup> grams) per cubic meter  
 μm: micron (10<sup>-6</sup> meters)  
 mg/dscm: milligrams per dry standard cubic meter  
 mg/kg-d: milligrams per kilogram per day  
 MMT: million metric tons  
 MMS: modified Method 5  
 MWC: municipal waste combustor  
 ng/dscm: nanograms (10<sup>-9</sup> grams) per dry standard cubic meter  
 ng/kJ: nanograms per kilojoule  
 ng/L: nanograms per liter  
 NSPS: New Source Performance Standards  
 NO<sub>x</sub>: nitrogen oxides  
 NDIR: nondispersion infrared  
 NDUV: nondispersion ultraviolet  
 NOAEL: no observable adverse effect level  
 OTA: Office of Technology Assessment  
 O<sub>2</sub>: oxygen  
 ppm: parts per million  
 ppmv: parts per million by volume  
 PTM: performance test method  
 P<sub>2</sub>O<sub>5</sub>: phosphorus pentoxide  
 PID: photo-ionization detector

pg/kg-d: picograms (10<sup>-12</sup> grams) per kilogram per day  
 PCB: polychlorinated biphenyls  
 PCDF: polychlorinated dibenzofuran  
 PCDD: polychlorinated dibenzo-p-dioxin  
 PCP: pentachlorophenol  
 psig: pounds per square inch gauge  
 ΔP: pressure drop  
 POHC: principal organic hazardous constituent  
 PICs: products of incomplete combustion  
 RODs: Records of Decision  
 RAC: reference air concentration  
 RfD: reference dose  
 RDF: refuse-derived fuel  
 RIA: Regulatory Impact Analysis  
 RA: relative accuracy  
 RI/FS: remedial investigation/feasibility study  
 RCRA: Resource Conservation and Recovery Act of 1976  
 RREL: Risk Reduction Engineering Laboratory  
 SAB: Science Advisory Board  
 SIC: Standard Industrial Classification  
 SASS: Source Assessment Sampling System  
 SD: spray dryer  
 SDA: spray dryer absorber  
 SO<sub>2</sub>: sulfur dioxide  
 SF<sub>6</sub>: sulfur hexafluoride  
 SO<sub>x</sub>: sulfur oxides  
 SO<sub>3</sub>: sulfur trioxide  
 SARA: 1986 Superfund Amendments and Reauthorization Act  
 SITE: Superfund Innovative Technology Evaluation  
 TCDD: tetrachlorodibenzo-p-dioxin  
 TOC: total organic carbon  
 tpd: tons per day  
 TRI: Toxics Release Inventory  
 TCLP: Toxicity Characteristic Leaching Procedure  
 TEF: toxicity equivalency factor  
 TEQ: Toxicity Equivalents  
 TSCA: Toxic Substances Control Act  
 UV: ultraviolet  
 UST: underground storage tank  
 VOST: volatile organic sampling train

## APPENDIX H

### Uncertainty/Sensitivity Analysis

#### Uncertainty Analysis for EEM 1: Excavation/Removal Emission Rate for Benzene from Gasoline-Contaminated Soil

Variable parameters are in bold:

Assumptions:	<b>C</b> =	10 ppm	soil concentration of benzene
	<b>beta</b> =	1.5 g/cm <sup>3</sup>	bulk density of the soil
	<b>A</b> =	2500 m <sup>2</sup>	emitting surface area
	<b>Q</b> =	0.042 m <sup>3</sup> /sec	excavation rate
	<b>Mfrac</b> =	0.15 %/100	moisture by weight

Equations used:

$$ER = ER_{ps} + ER_{diff}$$

$$ER_{ps} = [(P_a)(M_w)(10^6)(E_a)(Q)(ExC)]/[(R)(T)]$$

$$ER_{diff} = [C_s](10,000)(A)/\{[(E_a)/(K_{eq})(K_g)] + [(\pi)(t)/(D_e)(K_{eq})]^{0.5}\}$$

$$C_s = (C)(\beta)(10^{-6})$$

$$E_t = 1 - (\beta/p)$$

$$E_a = 1 - (\beta + (\beta * M_{frac})/p)$$

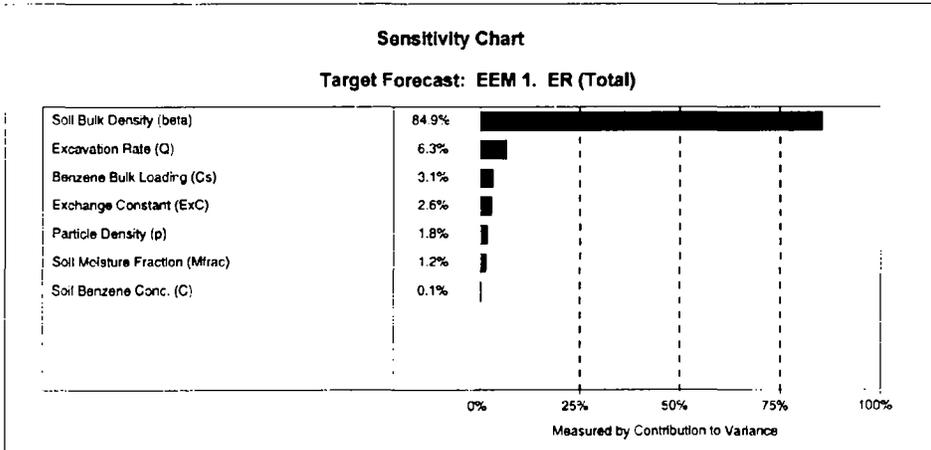
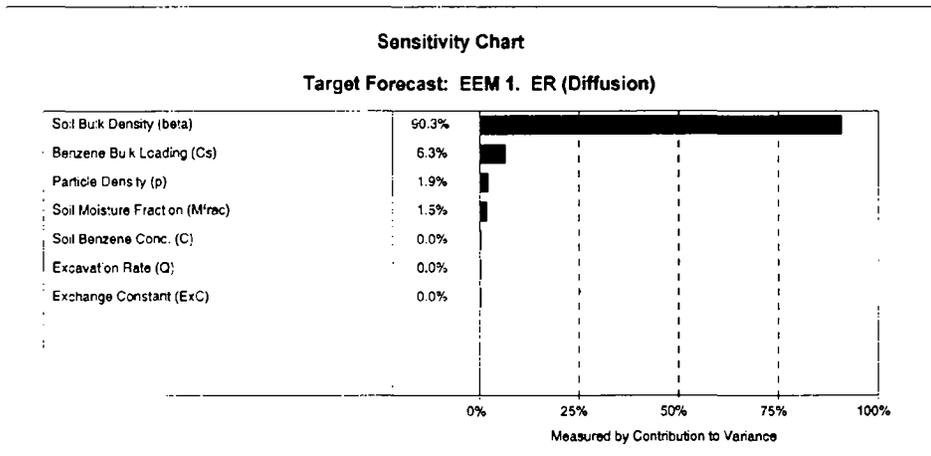
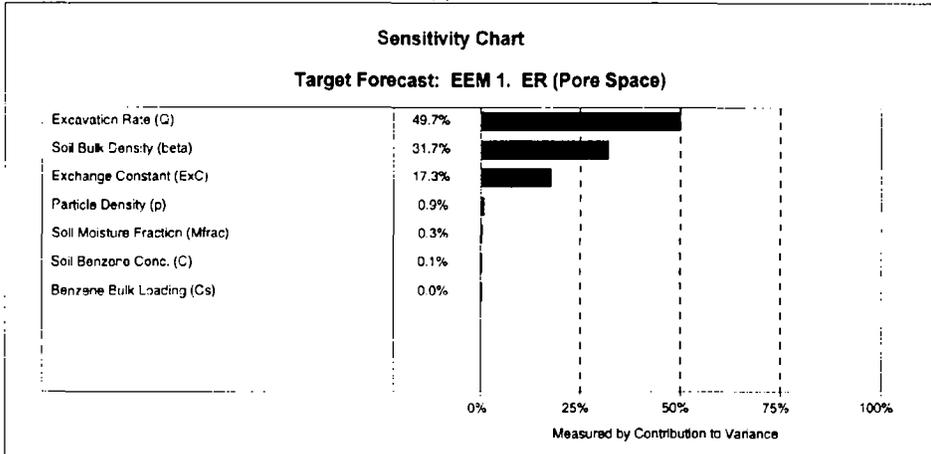
Additional Parameters:

<b>P<sub>a</sub></b> =	95.2 mm Hg	vapor pressure of benzene at ambient temp. (298K)
<b>M<sub>w</sub></b> =	78 g/g-mol	molecular weight
<b>E<sub>a</sub></b> =	0.349057 vol/vol	air-filled porosity
<b>E<sub>t</sub></b> =	0.433962 vol/vol	total porosity
<b>ExC</b> =	0.10 %/100	soil-gas to atmosphere exchange constant
<b>T<sub>a</sub></b> =	298 degrees K	ambient temperature
<b>C<sub>s</sub></b> =	1.50E-05 g/cm <sup>3</sup>	mass loading in bulk soil
<b>K<sub>eq</sub></b> =	1 g/g	equilibrium coefficient
<b>K<sub>g</sub></b> =	0.15 cm/sec	gas phase mass transfer coefficient
<b>t</b> =	60 sec	time to achieve best curve fit
<b>D<sub>e</sub></b> =	0.014872 cm <sup>2</sup> /sec	effective diffusivity in air
<b>p</b> =	2.65 g/cm <sup>3</sup>	particle density

Point Estimates Using the Above Parameters/Equations:

<b>ER<sub>ps</sub></b> =	0.585797 g/sec	emission rate from pore space
<b>ER<sub>diff</sub></b> =	3.263417 g/sec	emission rate from diffusion
<b>ER</b> =	3.849215 g/sec	total emission rate

**EEM 1 Uncertainty/Sensitivity Analysis**  
 Simulation started on 9/27/96 at 12:06:54  
 Simulation stopped on 9/27/96 at 12:09:04



**Forecast: EEM 1. ER (Pore Space)**

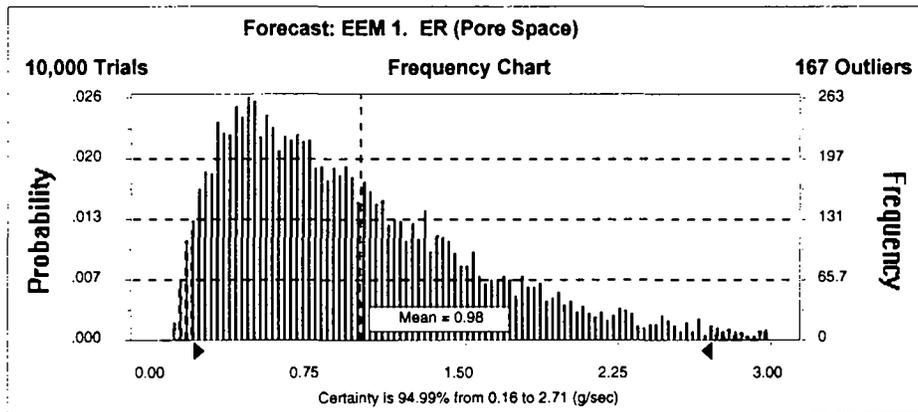
**Cell: B35**

**Summary:**

Certainty Level is 94.99%  
 Certainty Range is from 0.16 to 2.71 (g/sec)  
 Display Range is from 0.00 to 3.00 (g/sec)  
 Entire Range is from 0.07 to 4.48 (g/sec)  
 After 10,000 Trials, the Std. Error of the Mean is 0.01

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	0.98
Median	0.82
Mode	---
Standard Deviation	0.68
Variance	0.46
Skewness	1.35
Kurtosis	5.17
Coeff. of Variability	0.69
Range Minimum	0.07
Range Maximum	4.48
Range Width	4.41
Mean Std. Error	0.01



**Percentiles:**

<u>Percentile</u>	<u>(g/sec)</u>
0%	0.07
10%	0.29
20%	0.42
30%	0.54
40%	0.67
50%	0.82

Forecast: EEM 1. ER (Pore Space) (cont'd)

Cell: B35

<u>Percentile</u>	<u>(g/sec)</u>
60%	0.99
70%	1.20
80%	1.46
90%	1.90
100%	4.48

End of Forecast

**Forecast: EEM 1. ER (Total)**

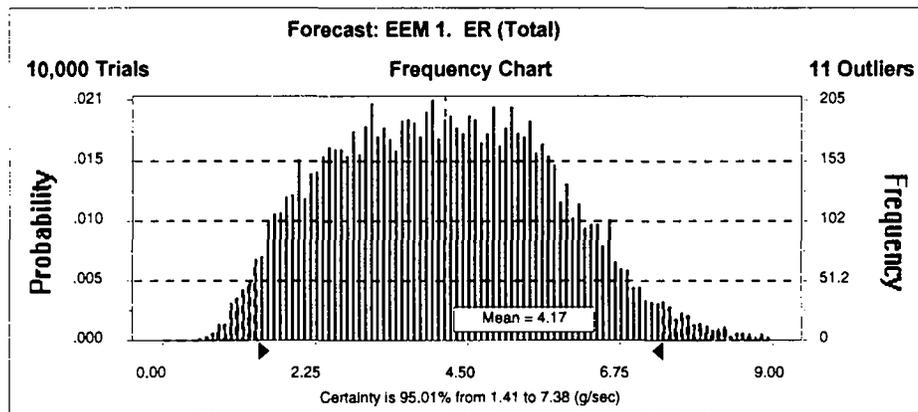
**Cell: B37**

**Summary:**

Certainty Level is 95.01%  
 Certainty Range is from 1.41 to 7.38 (g/sec)  
 Display Range is from 0.00 to 9.00 (g/sec)  
 Entire Range is from 0.59 to 10.30 (g/sec)  
 After 10,000 Trials, the Std. Error of the Mean is 0.02

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	4.17
Median	4.13
Mode	---
Standard Deviation	1.62
Variance	2.62
Skewness	0.21
Kurtosis	2.46
Coeff. of Variability	0.39
Range Minimum	0.59
Range Maximum	10.30
Range Width	9.71
Mean Std. Error	0.02



**Percentiles:**

<u>Percentile</u>	<u>(g/sec)</u>
0%	0.59
10%	2.03
20%	2.62
30%	3.15
40%	3.65
50%	4.13

Forecast: EEM 1. ER (Total) (cont'd)

Cell: B37

<u>Percentile</u>	<u>(g/sec)</u>
60%	4.62
70%	5.11
80%	5.61
90%	6.31
100%	10.30

End of Forecast

**Forecast: Effective Diffusivity (De)**

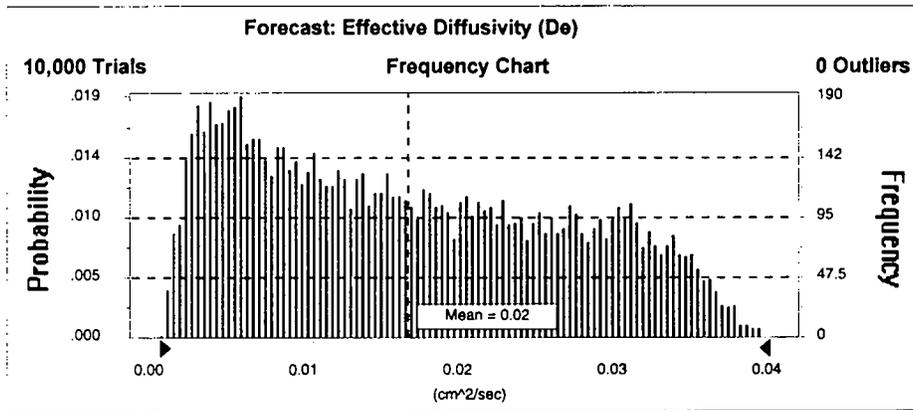
**Cell: B31**

**Summary:**

Display Range is from 0.00 to 0.04 (cm<sup>2</sup>/sec)  
 Entire Range is from 0.00 to 0.04 (cm<sup>2</sup>/sec)  
 After 10,000 Trials, the Std. Error of the Mean is 0.00

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	0.02
Median	0.01
Mode	---
Standard Deviation	0.01
Variance	0.00
Skewness	0.32
Kurtosis	1.92
Coeff. of Variability	0.63
Range Minimum	0.00
Range Maximum	0.04
Range Width	0.04
Mean Std. Error	0.00



**Percentiles:**

<u>Percentile</u>	<u>(cm<sup>2</sup>/sec)</u>
0%	0.00
10%	0.00
20%	0.01
30%	0.01
40%	0.01
50%	0.01
60%	0.02
70%	0.02

**Forecast: Effective Diffusivity (De) (cont'd)**

**Cell: B31**

<u>Percentile</u>	<u>(cm<sup>2</sup>/sec)</u>
80%	0.03
90%	0.03
100%	0.04

End of Forecast

**Forecast: Air-Filled Porosity (Ea)**

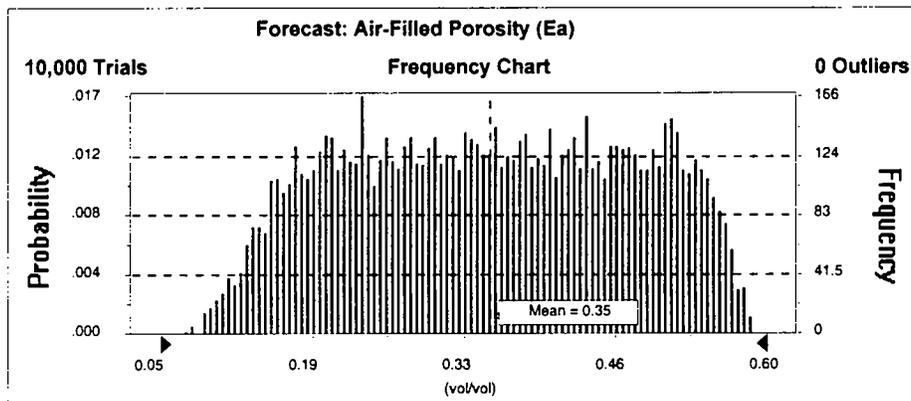
**Cell: B23**

**Summary:**

Display Range is from 0.05 to 0.60 (vol/vol)  
 Entire Range is from 0.07 to 0.59 (vol/vol)  
 After 10,000 Trials, the Std. Error of the Mean is 0.00

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	0.35
Median	0.35
Mode	---
Standard Deviation	0.13
Variance	0.02
Skewness	-0.03
Kurtosis	1.88
Coeff. of Variability	0.37
Range Minimum	0.07
Range Maximum	0.59
Range Width	0.52
Mean Std. Error	0.00



**Percentiles:**

<u>Percentile</u>	<u>(vol/vol)</u>
0%	0.07
10%	0.17
20%	0.22
30%	0.26
40%	0.31
50%	0.35
60%	0.39
70%	0.44

**Forecast: Air-Filled Porosity (Ea) (cont'd)**

**Cell: B23**

<u>Percentile</u>	<u>(vol/vol)</u>
80%	0.48
90%	0.52
100%	0.59

End of Forecast

**Forecast: Total Porosity (Et)**

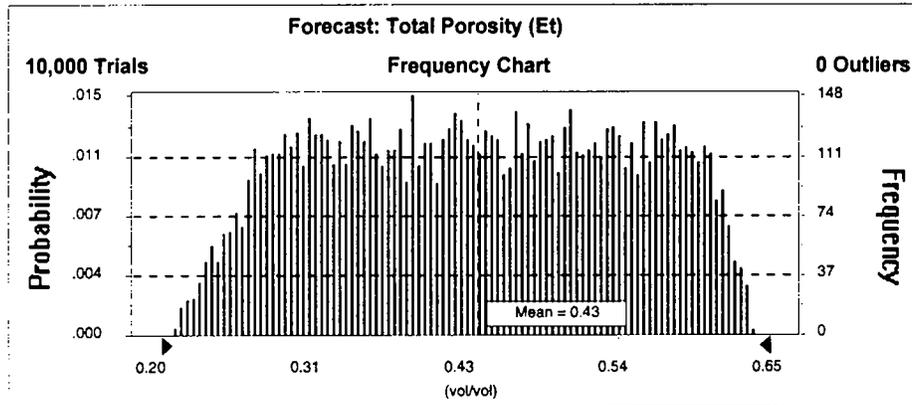
**Cell: B24**

**Summary:**

Display Range is from 0.20 to 0.65 (vol/vol)  
 Entire Range is from 0.21 to 0.64 (vol/vol)  
 After 10,000 Trials, the Std. Error of the Mean is 0.00

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	0.43
Median	0.43
Mode	---
Standard Deviation	0.11
Variance	0.01
Skewness	-0.02
Kurtosis	1.86
Coeff. of Variability	0.25
Range Minimum	0.21
Range Maximum	0.64
Range Width	0.43
Mean Std. Error	0.00



**Percentiles:**

<u>Percentile</u>	<u>(vol/vol)</u>
0%	0.21
10%	0.28
20%	0.32
30%	0.36
40%	0.40
50%	0.43
60%	0.47
70%	0.51

**Forecast: Total Porosity (Et) (cont'd)**

**Cell: B24**

<u>Percentile</u>	<u>(vol/vol)</u>
80%	0.55
90%	0.58
100%	0.64

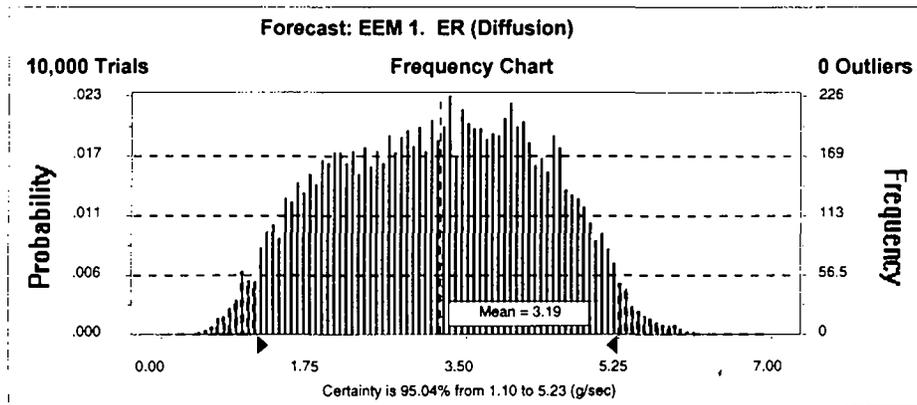
End of Forecast

Summary:

Certainty Level is 95.04%  
 Certainty Range is from 1.10 to 5.23 (g/sec)  
 Display Range is from 0.00 to 7.00 (g/sec)  
 Entire Range is from 0.47 to 6.64 (g/sec)  
 After 10,000 Trials, the Std. Error of the Mean is 0.01

Statistics:

	<u>Value</u>
Trials	10000
Mean	3.19
Median	3.22
Mode	---
Standard Deviation	1.16
Variance	1.35
Skewness	-0.04
Kurtosis	2.13
Coeff. of Variability	0.36
Range Minimum	0.47
Range Maximum	6.64
Range Width	6.17
Mean Std. Error	0.01



Percentiles:

<u>Percentile</u>	<u>(g/sec)</u>
0%	0.47
10%	1.59
20%	2.05
30%	2.46
40%	2.85
50%	3.22

Forecast: EEM 1. ER (Diffusion) (cont'd)

Cell: B36

<u>Percentile</u>	<u>(g/sec)</u>
60%	3.57
70%	3.94
80%	4.28
90%	4.72
100%	6.64

End of Forecast

## Assumptions

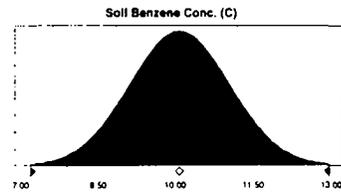
### Assumption: Soil Benzene Conc. (C)

Cell: C5

Normal distribution with parameters:

Mean	10.00
Standard Dev.	1.00

Selected range is from -Infinity to +Infinity  
Mean value in simulation was 10.00



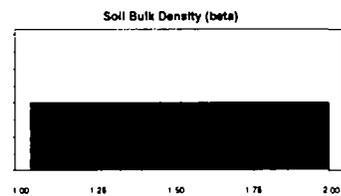
### Assumption: Soil Bulk Density (beta)

Cell: C6

Uniform distribution with parameters:

Minimum	1.00
Maximum	2.00

Mean value in simulation was 1.50



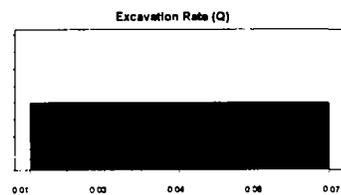
### Assumption: Excavation Rate (Q)

Cell: C8

Uniform distribution with parameters:

Minimum	0.01
Maximum	0.07

Mean value in simulation was 0.04



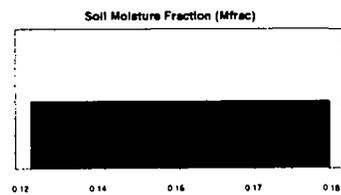
### Assumption: Soil Moisture Fraction (Mfrac)

Cell: C9

Uniform distribution with parameters:

Minimum	0.12
Maximum	0.18

Mean value in simulation was 0.15



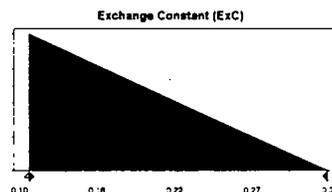
**Assumption: Exchange Constant (ExC)**

**Cell: B25**

Triangular distribution with parameters:

Minimum	0.10
Likeliest	0.10
Maximum	0.33

Selected range is from 0.10 to 0.33  
Mean value in simulation was 0.18



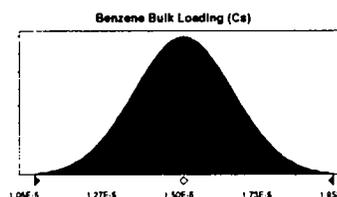
**Assumption: Benzene Bulk Loading (Cs)**

**Cell: B27**

Normal distribution with parameters:

Mean	1.50E-05
Standard Dev.	1.50E-06

Selected range is from -Infinity to +Infinity  
Mean value in simulation was 1.50E-5



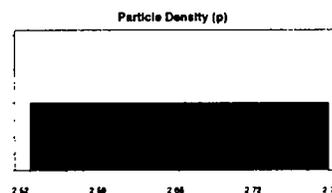
**Assumption: Particle Density (p)**

**Cell: B32**

Uniform distribution with parameters:

Minimum	2.52
Maximum	2.78

Mean value in simulation was 2.65



End of Assumptions

**Uncertainty Analysis for EEM 2: Thermal Desorption  
Emission Rate for Benzene from Gasoline-Contaminated Soil**

Variable parameters are in bold:

Assumptions:	<b>C=</b>	10.00 ppm	soil concentration of benzene
	<b>F=</b>	27200 kg/hr	mass rate of soil treated
	<b>V=</b>	99.50 %	percentage of benzene volatilized
	<b>CE=</b>	99.50 %	percent efficiency of control devices

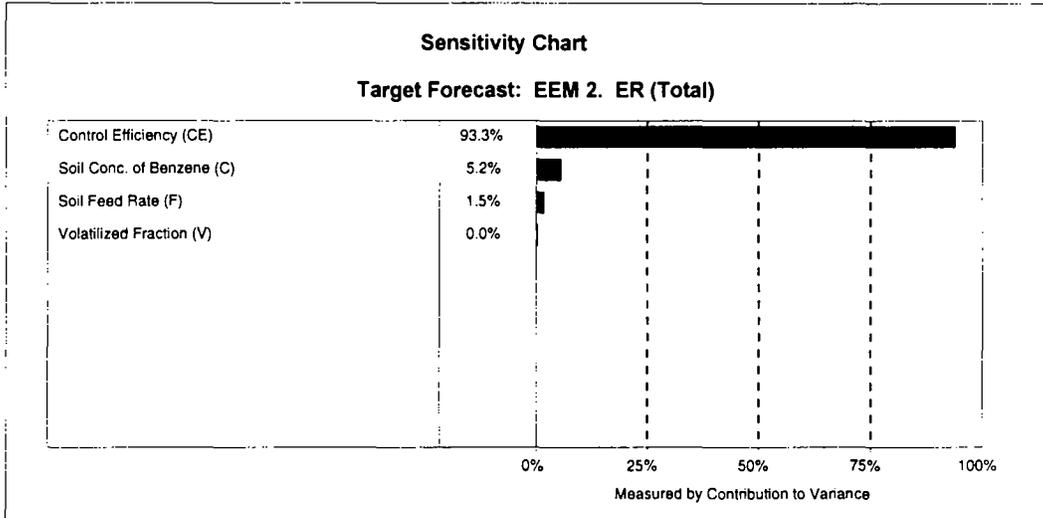
Equations used:

$$ER \text{ (g/hr)} = (C/1000)(F)(V/100)(1-(CE/100))$$

Point Estimate Using the Above Parameters/Equation:

**ER =** 1.353 g/sec total emission rate

**EEM 2 Uncertainty/Sensitivity Analysis**  
Simulation started on 9/27/96 at 12:34:02  
Simulation stopped on 9/27/96 at 12:35:30



**Forecast: EEM 2. ER (Total)**

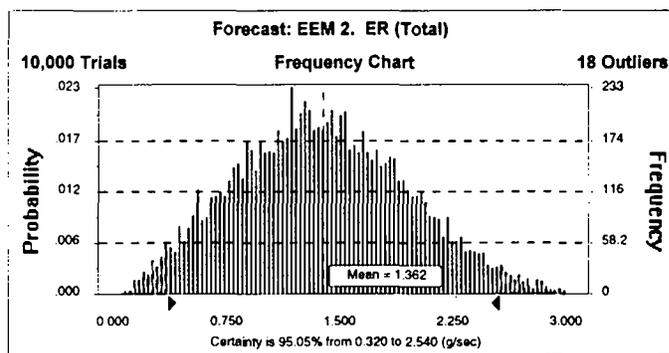
**Cell: B14**

**Summary:**

Certainty Level is 95.05%  
 Certainty Range is from 0.320 to 2.540 (g/sec)  
 Display Range is from 0.000 to 3.000 (g/sec)  
 Entire Range is from 0.030 to 3.552 (g/sec)  
 After 10,000 Trials, the Std. Error of the Mean is 0.006

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	1.362
Median	1.338
Mode	---
Standard Deviation	0.576
Variance	0.331
Skewness	0.21
Kurtosis	2.63
Coeff. of Variability	0.42
Range Minimum	0.030
Range Maximum	3.552
Range Width	3.522
Mean Std. Error	0.006



**Percentiles:**

<u>Percentile</u>	<u>(g/sec)</u>
0%	0.030
10%	0.611
20%	0.849
30%	1.030
40%	1.192
50%	1.338

Forecast: EEM 2. ER (Total) (cont'd)

Cell: B14

<u>Percentile</u>	<u>(g/sec)</u>
60%	1.495
70%	1.665
80%	1.860
90%	2.129
100%	3.552

End of Forecast

## Assumptions

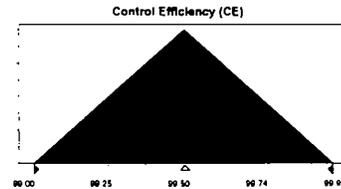
### Assumption: Control Efficiency (CE)

Cell: C8

Triangular distribution with parameters:

Minimum	99.00
Likeliest	99.50
Maximum	99.99

Selected range is from 99.00 to 99.99  
Mean value in simulation was 99.50



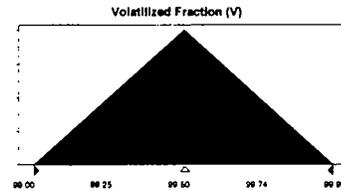
### Assumption: Volatilized Fraction (V)

Cell: C7

Triangular distribution with parameters:

Minimum	99.00
Likeliest	99.50
Maximum	99.99

Selected range is from 99.00 to 99.99  
Mean value in simulation was 99.50



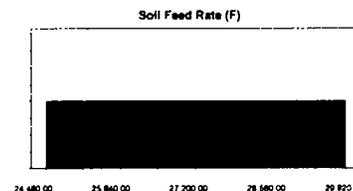
### Assumption: Soil Feed Rate (F)

Cell: C6

Uniform distribution with parameters:

Minimum	24,480.00
Maximum	29,920.00

Mean value in simulation was 27,200.00



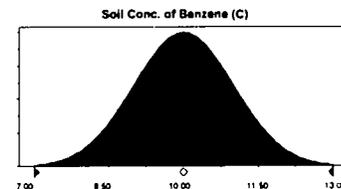
### Assumption: Soil Conc. of Benzene (C)

Cell: C5

Normal distribution with parameters:

Mean	10.00
Standard Dev.	1.00

Selected range is from -Infinity to +Infinity  
Mean value in simulation was 10.00



End of Assumptions

**Uncertainty Analysis for EEM 3: Soil Vapor Extraction  
Emission Rate for Benzene from Gasoline-Contaminated Soil**

Variable parameters are in bold:

Assumptions:

$$\mathbf{Q} = 85 \text{ m}^3/\text{min} \text{ vapor extraction rate}$$

Equations used:

$$ER \text{ (g/sec)} = (C_g)(Q/60)(10^{-6})$$

$$C_g \text{ (ug/m}^3\text{)} = [(P_s)(M_w)(10^9)]/[(R)(T_s)]$$

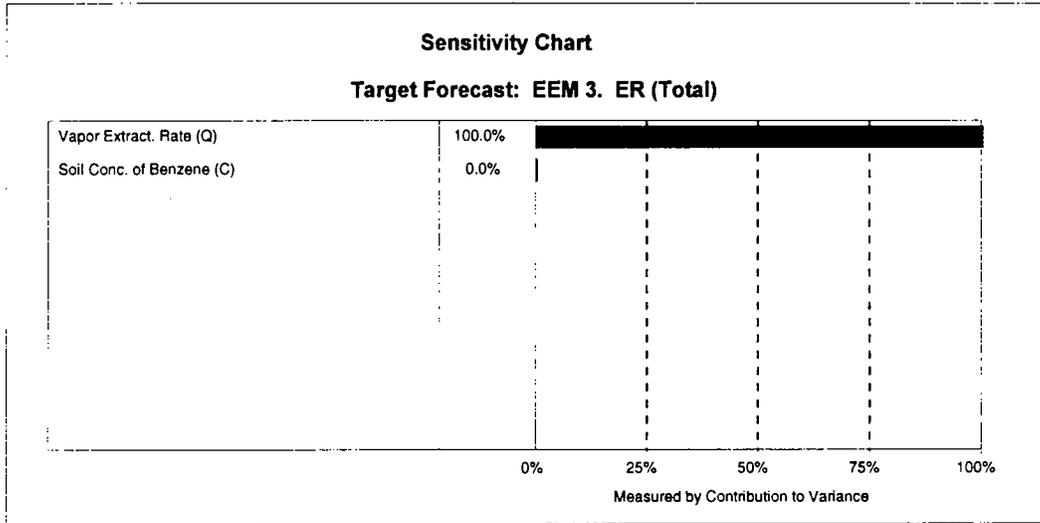
Additional Parameters:

$P_a$	=	95.2 mm Hg	vapor pressure of benzene at ambient temp. (298K)
$P_s$	=	77.1 mmHg	vapor pressure of benzene at soil temp. (293K)
$M_w$	=	78 g/g-mol	molecular weight
$T_a$	=	298 degrees K	ambient temperature
$T_s$	=	293 degrees K	soil temperature

Point Estimates Using the Above Parameters/Equations:

$$\mathbf{ER} = 0.466 \text{ g/sec} \quad \text{total emission rate}$$

**EEM 3 Uncertainty/Sensitivity Analysis**  
Simulation started on 9/27/96 at 12:55:39  
Simulation stopped on 9/27/96 at 12:56:34



**Forecast: EEM 3. ER (Total)**

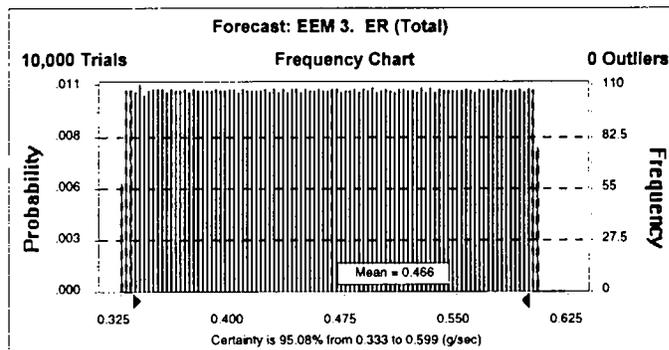
**Cell: B20**

**Summary:**

Certainty Level is 95.08%  
 Certainty Range is from 0.333 to 0.599 (g/sec)  
 Display Range is from 0.325 to 0.625 (g/sec)  
 Entire Range is from 0.326 to 0.606 (g/sec)  
 After 10,000 Trials, the Std. Error of the Mean is 0.001

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	0.466
Median	0.466
Mode	---
Standard Deviation	0.081
Variance	0.007
Skewness	0.00
Kurtosis	1.80
Coeff. of Variability	0.17
Range Minimum	0.326
Range Maximum	0.606
Range Width	0.280
Mean Std. Error	0.001



**Percentiles:**

<u>Percentile</u>	<u>(g/sec)</u>
0%	0.326
10%	0.354
20%	0.382
30%	0.410
40%	0.438
50%	0.466

Forecast: EEM 3. ER (Total) (cont'd)

Cell: B20

<u>Percentile</u>	<u>(g/sec)</u>
60%	0.494
70%	0.522
80%	0.550
90%	0.578
100%	0.606

End of Forecast

## Assumptions

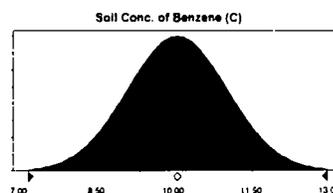
### **Assumption: Soil Conc. of Benzene (C)**

**Cell: C5**

Normal distribution with parameters:

Mean	10.00
Standard Dev.	1.00

Selected range is from -Infinity to +Infinity  
Mean value in simulation was 10.00



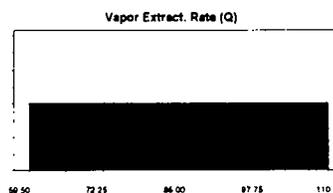
### **Assumption: Vapor Extract. Rate (Q)**

**Cell: C6**

Uniform distribution with parameters:

Minimum	59.50
Maximum	110.50

Mean value in simulation was 85.00



End of Assumptions

**Uncertainty Analysis for EEM 4: In-Situ Biodegradation  
Emission Rate for Benzene from Gasoline-Contaminated Soil**

Variable parameters are in bold:

Assumptions:	<b>C</b> =	10 ppm	soil concentration of benzene
	<b>A</b> =	2500 m <sup>2</sup>	surface area
	<b>D</b> =	5 m	excavation depth
	<b>beta</b> =	1.5 g/cm <sup>3</sup>	bulk density of the soil
	<b>Mfrac</b> =	0.15 %/100	moisture by weight

Equations used:

$$ER \text{ (g/sec)} = (C_g)(Q/60)(10^{-6})$$

$$C_g \text{ (ug/m}^3\text{)} = [(P_s)(M_w)(10^9)]/[(R)(T_s)]$$

$$Q \text{ (m}^3\text{/min)} = (1.0/1440)(S_v)(E_a)$$

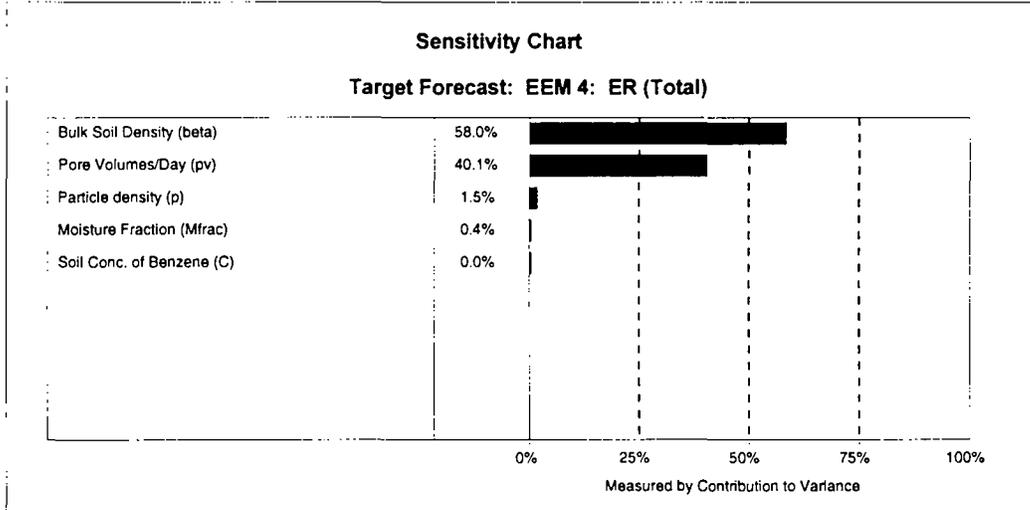
Additional Parameters:

<b>Pa</b> =	95.2 mm Hg	vapor pressure of benzene at ambient temp. (298K)
<b>Ps</b> =	77.1 mmHg	vapor pressure of benzene at soil temp. (293K)
<b>MW</b> =	78 g/g-mol	molecular weight
<b>Ta</b> =	298 degrees K	ambient temperature
<b>Ts</b> =	293 degrees K	soil temperature
<b>Ea</b> =	0.349057 vol/vol	air-filled porosity
<b>p</b> =	2.65 g/cm <sup>3</sup>	particle density
<b>pv</b> =	1.0 vol/vol	number of pore volumes vented per day

Point Estimates Using the Above Parameters/Equations:

<b>Cg</b> =	329131 ug/m <sup>3</sup>	saturated vapor concentration
<b>Q</b> =	3 m <sup>3</sup> /min	exhaust flow rate
<b>ER</b> =	0.017 g/sec	total emission rate

**EEM 4 Uncertainty/Sensitivity Analysis**  
Simulation started on 9/27/96 at 13:13:29  
Simulation stopped on 9/27/96 at 13:15:09



**Forecast: Air-Filled Porosity**

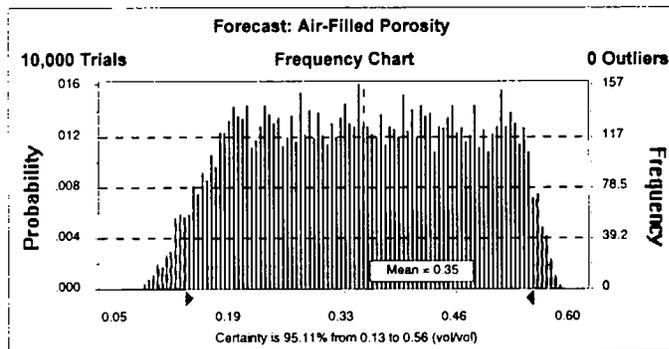
**Cell: B22**

**Summary:**

Certainty Level is 95.11%  
 Certainty Range is from 0.13 to 0.56 (vol/vol)  
 Display Range is from 0.05 to 0.60 (vol/vol)  
 Entire Range is from 0.08 to 0.59 (vol/vol)  
 After 10,000 Trials, the Std. Error of the Mean is 0.00

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	0.35
Median	0.35
Mode	---
Standard Deviation	0.13
Variance	0.02
Skewness	-0.03
Kurtosis	1.88
Coeff. of Variability	0.36
Range Minimum	0.08
Range Maximum	0.59
Range Width	0.52
Mean Std. Error	0.00



**Percentiles:**

<u>Percentile</u>	<u>(vol/vol)</u>
0%	0.08
10%	0.18
20%	0.22
30%	0.26
40%	0.31
50%	0.35

**Forecast: Air-Filled Porosity (cont'd)**

**Cell: B22**

<u>Percentile</u>	<u>(vol/vol)</u>
60%	0.39
70%	0.43
80%	0.48
90%	0.52
100%	0.59

End of Forecast

**Forecast: Saturated Vapor Conc. (Cg)**

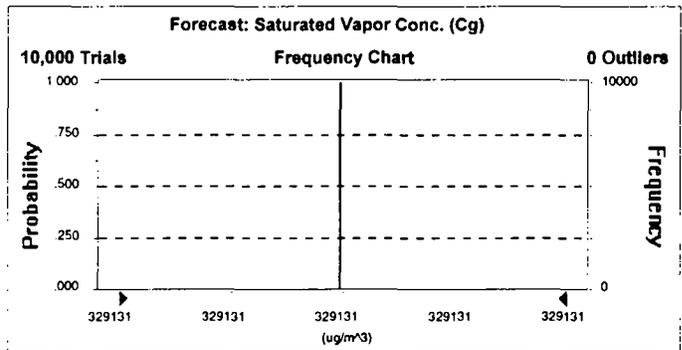
**Cell: B27**

**Summary:**

Display Range is from 329131 to 329131 (ug/m<sup>3</sup>)  
 Entire Range is from 329131 to 329131 (ug/m<sup>3</sup>)  
 After 10,000 Trials, the Std. Error of the Mean is 0

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	329131
Median	329131
Mode	329131
Standard Deviation	0
Variance	0
Skewness	0.00
Kurtosis	+ Infinity
Coeff. of Variability	0.00
Range Minimum	329131
Range Maximum	329131
Range Width	0
Mean Std. Error	0.00



**Percentiles:**

<u>Percentile</u>	<u>(ug/m<sup>3</sup>)</u>
0%	329131
10%	329131
20%	329131
30%	329131
40%	329131
50%	329131
60%	329131
70%	329131

**Forecast: Saturated Vapor Conc. (Cg) (cont'd)**

**Cell: B27**

<u>Percentile</u>	<u>(ug/m<sup>3</sup>)</u>
80%	329131
90%	329131
100%	329131

End of Forecast

**Forecast: Exhaust Flow Rate (Q)**

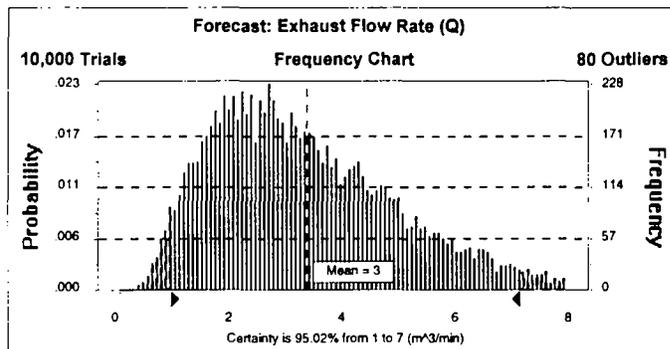
**Cell: B28**

**Summary:**

Certainty Level is 95.02%  
 Certainty Range is from 1 to 7 (m<sup>3</sup>/min)  
 Display Range is from 0 to 8 (m<sup>3</sup>/min)  
 Entire Range is from 0 to 10 (m<sup>3</sup>/min)  
 After 10,000 Trials, the Std. Error of the Mean is 0

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	3
Median	3
Mode	---
Standard Deviation	2
Variance	3
Skewness	0.71
Kurtosis	3.05
Coeff. of Variability	0.50
Range Minimum	0
Range Maximum	10
Range Width	9
Mean Std. Error	0.02



**Percentiles:**

<u>Percentile</u>	<u>(m<sup>3</sup>/min)</u>
0%	0
10%	1
20%	2
30%	2
40%	3
50%	3

**Forecast: Exhaust Flow Rate (Q) (cont'd)**

**Cell: B28**

<u>Percentile</u>	<u>(m<sup>3</sup>/min)</u>
60%	3
70%	4
80%	5
90%	6
100%	10

End of Forecast

**Forecast: EEM 4: ER (Total)**

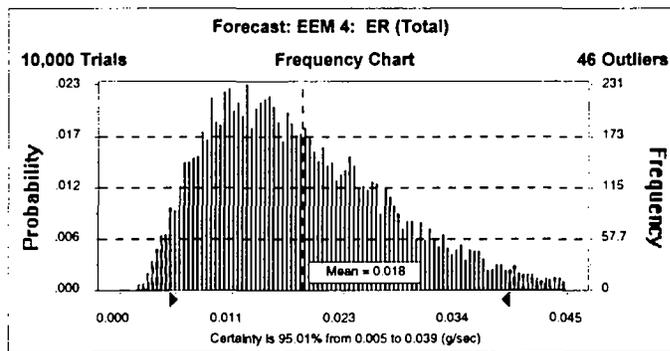
**Cell: B29**

**Summary:**

Certainty Level is 95.01%  
 Certainty Range is from 0.005 to 0.039 (g/sec)  
 Display Range is from 0.000 to 0.045 (g/sec)  
 Entire Range is from 0.002 to 0.052 (g/sec)  
 After 10,000 Trials, the Std. Error of the Mean is 0.000

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	0.018
Median	0.017
Mode	---
Standard Deviation	0.009
Variance	0.000
Skewness	0.71
Kurtosis	3.05
Coeff. of Variability	0.50
Range Minimum	0.002
Range Maximum	0.052
Range Width	0.051
Mean Std. Error	0.000



**Percentiles:**

<u>Percentile</u>	<u>(g/sec)</u>
0%	0.002
10%	0.008
20%	0.010
30%	0.012
40%	0.014
50%	0.017

Forecast: EEM 4: ER (Total) (cont'd)

Cell: B29

<u>Percentile</u>	<u>(g/sec)</u>
60%	0.019
70%	0.022
80%	0.026
90%	0.031
100%	0.052

End of Forecast

**Assumptions**

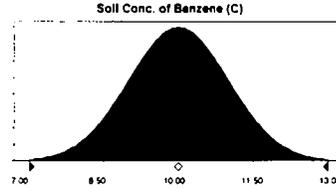
**Assumption: Soil Conc. of Benzene (C)**

**Cell: C5**

Normal distribution with parameters:

Mean 10.00  
Standard Dev. 1.00

Selected range is from -Infinity to +Infinity  
Mean value in simulation was 10.00



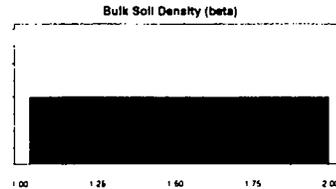
**Assumption: Bulk Soil Density (beta)**

**Cell: C8**

Uniform distribution with parameters:

Minimum 1.00  
Maximum 2.00

Mean value in simulation was 1.50



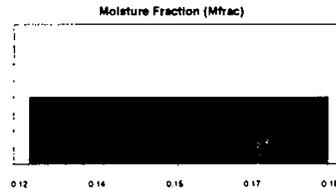
**Assumption: Moisture Fraction (Mfrac)**

**Cell: C9**

Uniform distribution with parameters:

Minimum 0.12  
Maximum 0.18

Mean value in simulation was 0.15



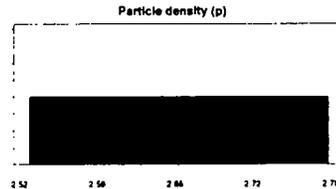
**Assumption: Particle density (p)**

**Cell: B23**

Uniform distribution with parameters:

Minimum 2.52  
Maximum 2.78

Mean value in simulation was 2.65



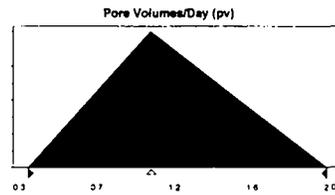
**Assumption: Pore Volumes/Day (pv)**

**Cell: B24**

Triangular distribution with parameters:

Minimum	0.3
Likeliest	1.0
Maximum	2.0

Selected range is from 0.3 to 2.0  
Mean value in simulation was 1.1



End of Assumptions

**Uncertainty Analysis for EEM 5: Ex-Situ Biodegradation  
Emission Rate for Benzene from Gasoline-Contaminated Soil**

Variable parameters are in bold:

Assumptions: continuous slurry process is used.

<b>C</b> =	10 ppm	soil concentration of benzene
<b>Mr</b> =	600 kg/hr	mass feed rate for soil treatment
<b>V</b> =	0.62 %/100	percentage of contaminant volatilized

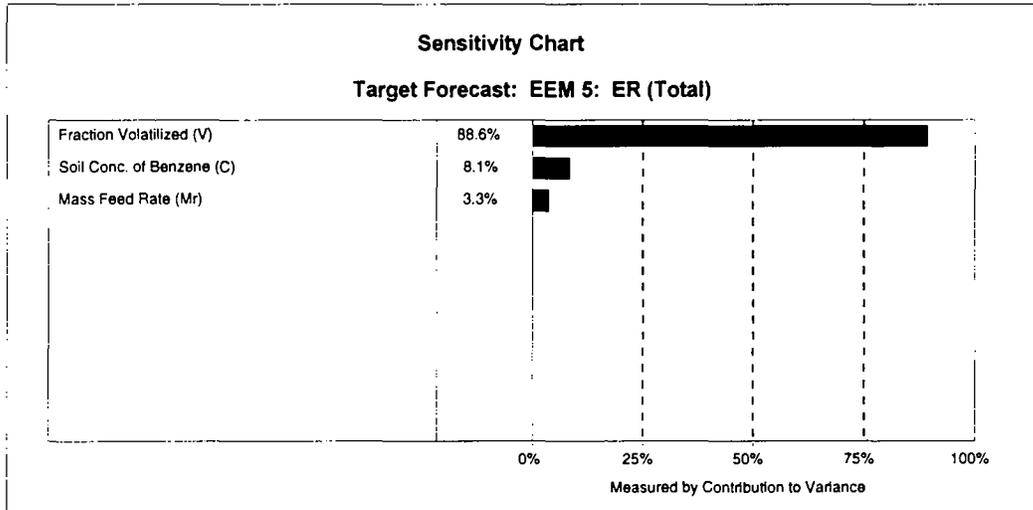
Equations used:

$$ER \text{ (g/hr)} = (C/1000)(Mr)(V)$$

Point Estimate Using the Above Parameters/Equation:

<b>ER</b> =	3.720 g/hr	total emission rate
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**EEM 5 Uncertainty/Sensitivity Analysis**  
Simulation started on 9/27/96 at 13:26:12  
Simulation stopped on 9/27/96 at 13:27:30



**Forecast: EEM 5: ER (Total)**

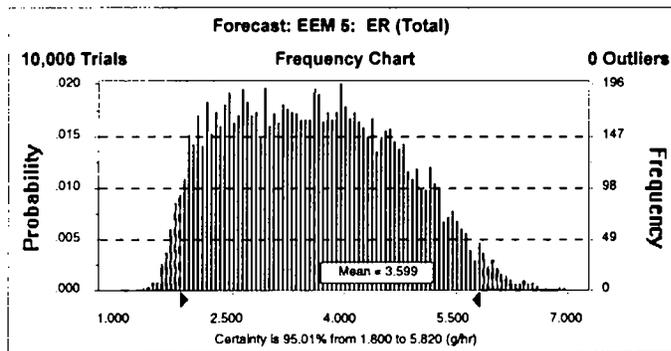
**Cell: B14**

**Summary:**

Certainty Level is 95.01%  
 Certainty Range is from 1.800 to 5.820 (g/hr)  
 Display Range is from 1.000 to 7.000 (g/hr)  
 Entire Range is from 1.312 to 6.999 (g/hr)  
 After 10,000 Trials, the Std. Error of the Mean is 0.011

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	3.599
Median	3.555
Mode	---
Standard Deviation	1.124
Variance	1.263
Skewness	0.24
Kurtosis	2.22
Coeff. of Variability	0.31
Range Minimum	1.312
Range Maximum	6.999
Range Width	5.687
Mean Std. Error	0.011



**Percentiles:**

<u>Percentile</u>	<u>(g/hr)</u>
0%	1.312
10%	2.130
20%	2.487
30%	2.834
40%	3.193
50%	3.555

Forecast: EEM 5: ER (Total) (cont'd)

Cell: B14

<u>Percentile</u>	<u>(g/hr)</u>
60%	3.902
70%	4.251
80%	4.652
90%	5.157
100%	6.999

End of Forecast

## Assumptions

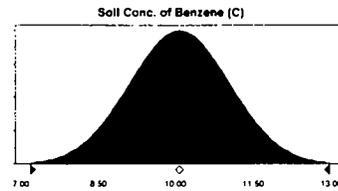
### Assumption: Soil Conc. of Benzene (C)

Cell: C6

Normal distribution with parameters:

Mean	10.00
Standard Dev.	1.00

Selected range is from -Infinity to +Infinity  
Mean value in simulation was 10.00



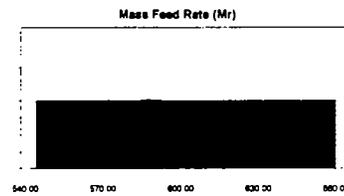
### Assumption: Mass Feed Rate (Mr)

Cell: C7

Uniform distribution with parameters:

Minimum	540.00
Maximum	660.00

Mean value in simulation was 600.00



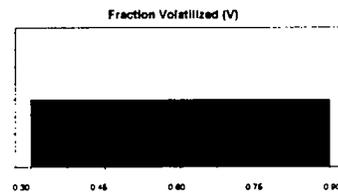
### Assumption: Fraction Volatilized (V)

Cell: C8

Uniform distribution with parameters:

Minimum	0.30
Maximum	0.90

Mean value in simulation was 0.60



End of Assumptions

**Uncertainty Analysis for EEM 6: Incineration**  
**Emission Rate for Benzene from Gasoline-Contaminated Soil**

Variable parameters are in bold:

Assumptions: continuous slurry process is used.

<b>C</b> =	10.00 mg/kg	soil concentration of benzene
<b>CE</b> =	99.5 %	control (destruction & removal) efficiency
<b>Mw</b> =	4500 kg/hr	mass feed rate for soil treatment

Equations used:

$$ER \text{ (g/hr)} = (1 - (DRE/100))(C/1000)(mw)$$

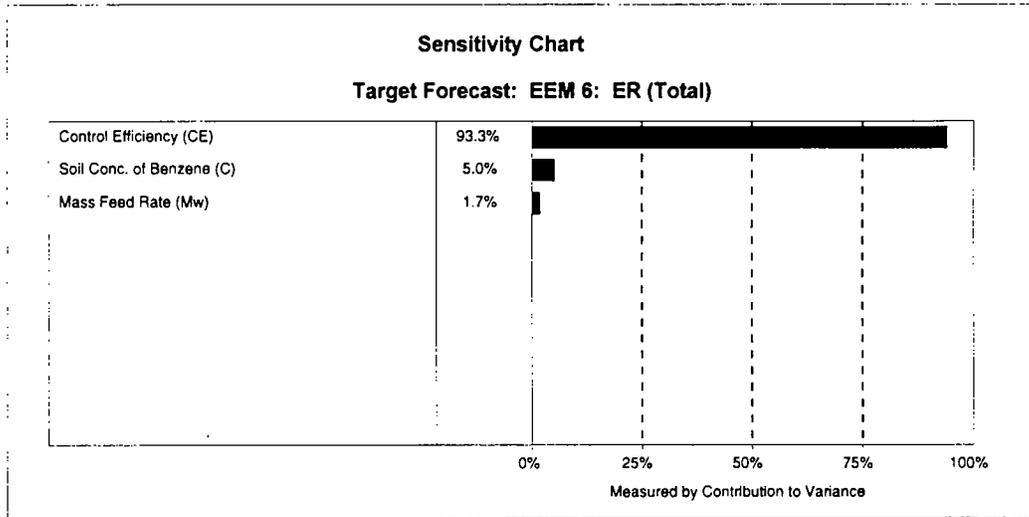
Point Estimate Using the Above Parameters/Equation:

<b>ER</b> =	0.225 g/hr	total emission rate
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**EEM 6 Uncertainty/Summary**

Simulation started on 9/27/96 at 13:44:08

Simulation stopped on 9/27/96 at 13:45:29



**Forecast: EEM 6: ER (Total)**

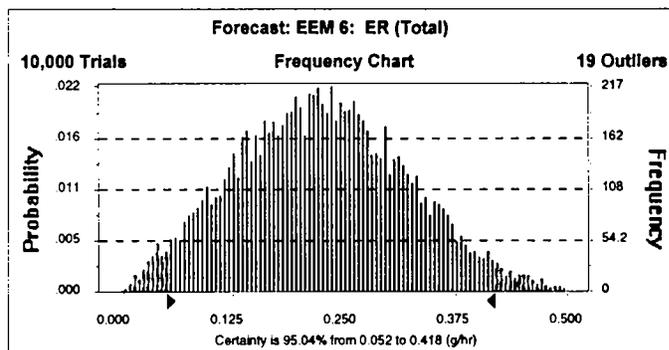
**Cell: B14**

**Summary:**

Certainty Level is 95.04%  
 Certainty Range is from 0.052 to 0.418 (g/hr)  
 Display Range is from 0.000 to 0.500 (g/hr)  
 Entire Range is from 0.008 to 0.554 (g/hr)  
 After 10,000 Trials, the Std. Error of the Mean is 0.001

**Statistics:**

	<u>Value</u>
Trials	10000
Mean	0.227
Median	0.224
Mode	---
Standard Deviation	0.095
Variance	0.009
Skewness	0.19
Kurtosis	2.65
Coeff. of Variability	0.42
Range Minimum	0.008
Range Maximum	0.554
Range Width	0.546
Mean Std. Error	0.001



**Percentiles:**

<u>Percentile</u>	<u>(g/hr)</u>
0%	0.008
10%	0.101
20%	0.141
30%	0.172
40%	0.199
50%	0.224

Forecast: EEM 6: ER (Total) (cont'd)

Cell: B14

<u>Percentile</u>	<u>(g/hr)</u>
60%	0.249
70%	0.276
80%	0.309
90%	0.354
100%	0.554

End of Forecast

Assumptions

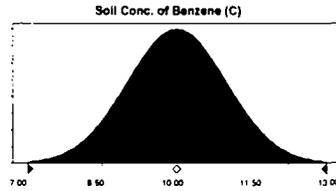
**Assumption: Soil Conc. of Benzene (C)**

Cell: C6

Normal distribution with parameters:

Mean 10.00  
Standard Dev. 1.00

Selected range is from -Infinity to +Infinity  
Mean value in simulation was 10.00



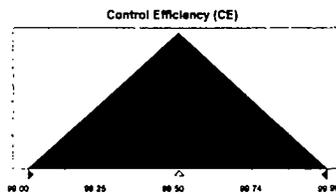
**Assumption: Control Efficiency (CE)**

Cell: C7

Triangular distribution with parameters:

Minimum 99.00  
Likeliest 99.50  
Maximum 99.99

Selected range is from 99.00 to 99.99  
Mean value in simulation was 99.50



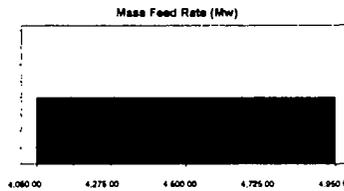
**Assumption: Mass Feed Rate (Mw)**

Cell: C8

Uniform distribution with parameters:

Minimum 4,050.00  
Maximum 4,950.00

Mean value in simulation was 4,500.00



End of Assumptions

**TECHNICAL REPORT DATA**  
(Please read Instructions on the reverse before completin.)

1. REPORT NO. EPA-600/R-97-116		2.	3. RI	
4. TITLE AND SUBTITLE Air Emissions from the Treatment of Soils Contaminated with Petroleum Fuels and Other Substances			5. REPORT DATE October 1997	
			6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) B. Eklund, P. Thompson, A. Inglis, W. Wheelless, and W. Horton (Radian); and S. Roe (Pechan)			8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Radian Corp. E. H. Pechan and Assoc. P. O. Box 201088 2880 Sunrise Blvd, No. 220 Austin, TX 78720 Rancho Cordova, CA 95742			10. PROGRAM ELEMENT NO.	
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16. ABSTRACT The report updates a 1992 report that summarizes available information on air emissions from the treatment of soils contaminated with fuels. Soils contaminated by leaks or spills of fuel products, such as gasoline and jet fuel, are a nationwide concern. Air emissions during remediation are a potential problem because of the volatile nature of many of the fuel components and the remediation processes themselves, which may promote or result in contaminant transfer to the vapor phase. Limited information also is included on air emissions from the treatment of soils contaminated with hazardous wastes. The report will allow staff from state and local regulatory agencies, as well as staff from EPA regional offices, to assess the different options for cleaning up soil contaminated with fuels. Seven general remediation approaches are addressed in this report. For each approach, information is presented about the remediation process, the typical air emission species of concern and their release points, and the available air emissions data. Control technologies for each remediation approach are identified, and their reported efficiencies are summarized. Cost data are given for each remediation approach and for its associated control technologies. Emission estimation methods (EEMs) for each remediation approach are presented along with a brief case study.				
17. KEY WORDS AND DOCUMENT ANALYSIS				
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution Volatility		Air Pollution Control	13B	20M
Petroleum Products Organic Compounds		Stationary Sources	11G	07C
Fuels Estimating		Volatile Organic Compounds (VOCs)	21D, 21I	
Soils Cost Effectiveness			08G, 08M	14A
Contamination			14G	
Emission				
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