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Remediation Technologies Screening Matrix

Reference Guide

14508

A Joint Project
of the

U.S. Environmental Protection Agency

and the

U.S. Air Force

7-93

THE CIVIL ENGINEER

Headquarters United States Air Force

AF/CEVR

Environmental Restoration Division

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REMEDIATION TECHNOLOGIES SCREENING MATRIX

Reference Guide

Version I

A Joint Project
of the

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Technology Innovation Office
Washington, DC 20460

and

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NOTICE

Preparation of the *Remediation Technologies Screening Matrix Reference Guide* has been funded by the United States Environmental Protection Agency (EPA) under contract number 68-W2-0004. The document is the result of a joint project by EPA and the U.S. Air Force and is intended to be used in conjunction with the *Remediation Technologies Screening Matrix* developed under the same project. Both documents were developed with extensive input from professionals in the field and have been subjected to administrative review by the sponsoring agencies. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The development of the *Remediation Technologies Screening Matrix* and accompanying *Reference Guide* was jointly sponsored by the U.S. Air Force and the U.S. Environmental Protection Agency (EPA). Both the Air Force and EPA are committed to encouraging further development and use of innovative technologies that offer efficient and cost-effective alternatives for site remediation.

The *Matrix* and *Reference Guide* support this effort by summarizing the strengths and limitations of innovative, as well as conventional, technologies for the remediation of soils, sediments, sludges; groundwater; and air emissions/off-gases. They provide information that will assist Air Force and EPA site project managers responsible for screening technologies for potential use at their sites.

The *Matrix* and *Reference Guide* were developed with extensive input from professionals in the field. More than 30 technical experts—site remediation technology researchers, technology developers, and technology users from Federal agencies, State governments, universities, and the private sector—participated in the process. This included attending a two-day workshop at Tyndall Air Force Base, Florida, in March 1993, to identify appropriate technologies and processes to be included in the Matrix and to evaluate them based on the participants' collective experience and expertise.

The Air Force and EPA gratefully acknowledge the significant contribution these professionals, who are listed at the end of Chapter 1, have made to this important project.

The selection and use of innovative technologies to clean up hazardous waste sites is increasing rapidly and new technologies continue to emerge. The Air Force and EPA plan to issue periodic updates of the *Matrix* and *Reference Guide* to help site project managers keep pace with the ever changing range of technology options available.

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CHAPTER 1: INTRODUCTION

This *Reference Guide* provides additional information to increase the usability of the *Remediation Technologies Screening Matrix*. Together, the *Reference Guide* and *Matrix* can help site remediation project managers narrow the field of remediation alternatives and identify potentially applicable technologies for more detailed assessment and evaluation prior to remedy selection. In addition, the documents can be used to guide the selection of focused technology field demonstrations and specific technologies to highlight in subsequent technical data sheets, design manuals, and cost studies.

The *Reference Guide* and *Matrix* are intended as **general references only**. Additional information to support identification of potentially applicable technologies can be obtained by consulting published references, contacting technology experts, and conducting treatability studies. **The *Matrix* and *Reference Guide* are not designed to be used as the sole basis for remedy selection.**

Most of the technologies and processes included are innovative. Most have been developed to full-scale—commercial units are available or are expected shortly. However, many have had limited full-scale application, and comprehensive cost and performance data may not be available. In addition, site-specific factors—such as geology, depth to contamination, particle size, organic content, pH, moisture content, and soil-solvent reactions—may be critical in determining the potential effectiveness of a technology. In addition, Federal, State, and local laws may affect the applicability of technologies at some sites.

Depending on site-specific requirements, more than one technology or process may be needed to achieve remediation goals at a site. Many of the remedial technologies in the *Matrix* and *Reference Guide* may be used in combination with others in "treatment trains" to accomplish site cleanup. For example, "treatment trains" may be used to reduce the volume of contaminated material, to prevent the release of volatile contaminants during excavation and mixing, or to address multiple contaminants within the same matrix. Following are examples of "treatment trains" that have been selected for use at Superfund sites:

- Soil washing, followed by bioremediation, incineration, or solidification/stabilization of soil fines;
- Thermal desorption, followed by incineration, solidification/stabilization, or dehalogenation to treat PCBs;
- Soil vapor extraction, followed by various processes to remove semivolatile organics;
- Solvent extraction, followed by solidification/stabilization, soil washing, or incineration of extracted contaminants and solvents; and
- Bioremediation, followed by solidification/stabilization of inorganics.

Forty-eight technologies—including *in situ* and *ex situ* biological, thermal, and physical/chemical processes—have been chosen for inclusion in the *Matrix* and *Reference Guide* (see Table 1). In addition to treatment technologies, processes designed to be used primarily for containment, waste separation, and enhanced recovery have been included to provide a broad range of remedial options. The *Matrix* and *Reference Guide* do not include every technology option available. Many other innovative technologies have been developed. Depending on site-specific conditions, some of these may provide additional options for site project managers. As a general rule, technologies included in the *Matrix* are commercially available or are likely to be within a year.

The technologies in the *Matrix* are evaluated against 13 factors that address specific cost, performance, technical, developmental, and institutional issues (see Table 2). These screening factors were chosen to assist site project managers identify applicable technologies for media and contaminants of concern at their sites.

It is important to recognize that information about innovative technologies is rapidly evolving. After using the *Matrix* and *Reference Guide* to identify potentially applicable technologies, it is essential that site project managers consult qualified professionals, who can evaluate each in light of the most up-to-date information and site-specific conditions prior to remedy selection.

Participation of Technical Experts

The *Matrix* and *Reference Guide* were developed with extensive input from technical experts. They included professionals representing all segments of the remediation community—site remediation technology researchers, technology developers, and technology users from Federal agencies, State governments, universities, and the private sector (see Table 3).

More than 30 experts participated in an intensive workshop, March 2-3, 1993, at Tyndall Air Force Base, Florida. Based on their collective experience and expertise, they selected appropriate technologies and processes to be included in the *Matrix*, identified the contaminant groups addressed by each technology, and developed the list of factors against which the technologies are evaluated.

Workshop participants then separated into three small groups and focused on the technologies in their individual areas of specialization—biological processes, themal processes, physical/chemical processes—to develop the ratings for each of the technologies shown on the *Matrix*. Each technical expert had the opportunity to review draft documents independently and provide written comments as well.

In light of the rapidly growing range of innovative technologies, workshop participants identified a number of full- and pilot-scale technologies, in addition to those in the *Matrix*, that may provide additional options for project managers to consider, depending on site-specific conditions. Among the full-scale technologies are air-phase resin adsorption, reverse osmosis/ultra membrane filtration, kerfing, cavitation/oxidation, melting/smelting, and high-temperature halogenated reduction. At the pilot and bench scale are molten salt, molten metal, electrokinetics, fungal remediation, solar soil detoxification, biocurtains, and electron beam technology. As these technologies are applied in the field and more information about them becomes available, they may be included in future editions of the *Remediation Technologies Screening Matrix* and *Reference Guide*.

Contents

This chapter describes the development and limitations of the *Matrix* and *Reference Guide*. It also contains definitions for each of the technologies and processes rated in the *Matrix* (see Table 1). The

13 factors applied to technologies in the *Matrix* are defined in Table 2. The participation of technical experts in developing the *Matrix* and *Reference Guide* also is described in this chapter, and all participants are listed in Table 3.

Chapter 2 describes the system used to evaluate technologies, including an explanation of each possible rating (see Table 4).

Chapter 3 provides information about each of the technologies and processes evaluated in the *Matrix*. Included is a discussion of the contaminant groups treated by the technology and other issues that should be considered in determining its potential applicability and effectiveness. The ratings for each technology are presented and supplemental information is provided, as needed. For example, factors that could limit the suitability and effectiveness of each technology are discussed.

Two Appendices provide additional information. Appendix A contains a list of reference materials, including field demonstration reports and case studies, that site project managers may wish to consult for more detailed information about various technologies. Appendix B lists examples of contaminants included in each contaminant group used in the *Matrix*.

TABLE 1: DEFINITION OF MATRIX TECHNOLOGIES/PROCESSES

Soils, Sediments, Sludges

Technology	Status	Description
	In Situ Biological Processes	
Biodegradation	Full-scale/ Innovative	The activity of naturally occurring microbes is stimulated by circulating water-based solutions through contaminated soils to enhance *in situ* biological degradation of organic contaminants. Nutrients, oxygen, or other amendments may be used to enhance biodegradation and contaminant desorption from subsurface materials.
Bioventing	Full-scale/ Innovative	Oxygen is delivered to contaminated unsaturated soils by forced air movement (either extraction or injection of air) to increase oxygen concentrations and stimulate biodegradation. The system also may include the injection of contaminated gases, using the soil system for remediation.
	In Situ Physical/Chemical Processes	
Soil Vapor Extraction	Full-scale/ Innovative	Vacuum is applied through extraction wells to create a pressure gradient that induces gas-phase volatiles to diffuse through soil to extraction wells. The process includes a system for handling off-gases. This technology also is known as *in situ* soil venting, *in situ* volatilization, enhanced volatilization, or soil vacuum extraction.
Soil Flushing	Pilot-scale/ Innovative	Water, or water containing an additive to enhance contaminant solubility, is applied to the soil or injected into the groundwater to raise the water table into the contaminated soil zone. Contaminants are leached into the groundwater, which is then extracted and captured/treated/removed.
Solidification/Stabilization	Full-scale/ Conventional	Contaminants are physically bound or enclosed within a stabilized mass (solidification), or chemical reactions are induced between the stabilizing agent and contaminants to reduce their mobility (stabilization).
Pneumatic Fracturing	Pilot-scale/ Innovative	Pressurized air is injected beneath the surface to develop cracks in low permeability and over-consolidated sediments, opening new passageways that increase the effectiveness of many *in situ* processes and enhance extraction efficiencies.
	In Situ Thermal Processes	
In Situ Vitrification	Pilot-scale/ Innovative	Electrodes for applying electricity, or joule heating, are used to melt contaminated soils and sludges, producing a glass and crystalline structure with very low leaching characteristics.
Thermally Enhanced Soil Vapor Extraction	Full-scale/ Innovative	Steam/hot air injection or electric/radio frequency heating is used to increase the mobility of volatiles and facilitate extraction. The process includes a system for handling off-gases.

Technology	Status	Description
	Ex Situ Biological Processes (assuming excavation)	
Slurry Phase Biological Treatment	Full-scale/ Innovative	An aqueous slurry is created by combining soil or sludge with water and other additives. The slurry is mixed to keep solids suspended and microorganisms in contact with the soil contaminants. Nutrients, oxygen, and pH in the bioreactor may be controlled to enhance biodegradation. Upon completion of the process, the slurry is dewatered and the treated soil is disposed.
Controlled Solid Phase Biological Treatment	Full-scale/ Innovative	Excavated soils are mixed with soil amendments and placed in above-ground enclosures that have leachate collection systems and some form of aeration. Processes include prepared treatment beds, biotreatment cells, soil piles, and composting. Moisture, heat, nutrients, oxygen, and pH may be controlled to enhance biodegradation.
Landfarming	Full-scale/ Conventional	Contaminated soils are applied onto the soil surface and periodically turned over or tilled into the soil to aerate the waste.
	Ex Situ Physical/Chemical Processes (assuming excavation)	
Soil Washing	Full-scale/ Innovative	Contaminants sorbed onto soil particles are separated from soil in an aqueous-based system. The wash water may be augmented with a basic leaching agent, surfactant, pH adjustment, or chelating agent to help remove organics and heavy metals.
Solidification/Stabilization	Full-scale/ Conventional	Contaminants are physically bound or enclosed within a stabilized mass (solidification), or chemical reactions are induced between the stabilizing agent and contaminants to reduce their mobility (stabilization).
Dehalogenation (Glycolate)	Full-scale/ Innovative	An alkaline polyethylene glycolate (APEG) reagent is used to dehalogenate halogenated aromatic compounds in a batch reactor. Potassium polyethylene glycolate (KPEG) is the most common APEG reagent. Contaminated soils and the reagent are mixed and heated in a treatment vessel. In the APEG process, the reaction causes the polyethylene glycol to replace halogen molecules and render the compound non-hazardous. For example, the reaction between chlorinated organics and KPEG causes replacement of a chlorine molecule and results in a reduction in toxicity.
Dehalogenation (BCD)	Full-scale/ Innovative	Contaminated soil is screened, processed with a crusher and pug mill, and mixed with sodium bicarbonate. The mixture is heated in a rotary reactor to decompose and partially volatilize the contaminants.
Solvent Extraction (Chemical Extraction)	Full-scale/ Innovative	Waste and solvent are mixed in an extractor, dissolving the organic contaminant into the solvent. The extracted organics and solvent are then placed in a separator, where the contaminants and solvent are separated for treatment and further use.

Technology	Status	Description
Chemical Reduction/ Oxidation	Full-scale/ Innovative	Reduction/oxidation chemically converts hazardous contaminants to non-hazardous or less toxic compounds that are more stable, less mobile, and/or inert. The reducing/oxidizing agents most commonly used are ozone, hydrogen peroxide, hypochlorites, chlorine, and chlorine dioxide.
Soil Vapor Extraction	Full-scale/ Innovative	A vacuum is applied to a network of above-ground piping to encourage volatilization of organics from the excavated media. The process includes a system for handling off-gases.
Ex Situ Thermal Processes (assuming excavation)		
Low-Temperature Thermal Desorption	Full-scale/ Innovative	Wastes are heated to 200°-600°F (93°-315°C) to volatilize water and organic contaminants. A carrier gas or vacuum system transports volatilized water and organics to the gas treatment system.
High-Temperature Thermal Desorption	Full-scale/ Innovative	Wastes are heated to 600°-1,000°F (315°-538°C) to volatilize water and organic contaminants. A carrier gas or vacuum system transports volatilized water and organics to the gas treatment system.
Vitrification	Full-scale/ Innovative	Contaminated soils and sludges are melted at high temperature to form a glass and crystalline structure with very low leaching characteristics.
Incineration	Full-scale/ Conventional	High temperatures, 1,600°- 2,200°F (871°-1,204°C), are used to volatilize and combust (in the presence of oxygen) organic constituents in hazardous wastes.
Pyrolysis	Pilot-scale/ Innovative	Chemical decomposition is induced in organic materials by heat in the absence of oxygen. Organic materials are transformed into gaseous components and a solid residue (coke) containing fixed carbon and ash.
Other Processes		
Natural Attenuation	Conventional	Natural subsurface processes—such as dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface materials—are allowed to reduce contaminant concentrations to acceptable levels. Sampling and sample analysis throughout the process are required.
Excavation and Off-Site Disposal	Conventional	Contaminated material is removed and transported to permitted off-site treatment and disposal facilities. Pre-treatment may be required.

Groundwater

Technology	Status	Description
		In Situ Biological Processes
Oxygen Enhancement with Hydrogen Peroxide	Full-scale/ Innovative	A dilute solution of hydrogen peroxide is circulated throughout a contaminated groundwater zone to increase the oxygen content of groundwater and enhance the rate of aerobic degradation of organic contaminants by naturally occurring microbes.
Co-Metabolic Processes	Pilot-scale/ Innovative	Water containing dissolved methane and oxygen is injected into groundwater to enhance methanotrophic biological degradation.
Nitrate Enhancement	Pilot-scale/ Innovative	Solubilized nitrate is circulated throughout groundwater contamination zones to provide electron acceptors for biological activity and enhance the rate of degradation of organic contaminants by naturally occurring microbes.
Oxygen Enhancement with Air Sparging	Full-scale/ Innovative	Air is injected under pressure below the water table to increase groundwater oxygen concentrations and enhance the rate of biological degradation of organic contaminants by naturally occurring microbes.
		In Situ Physical/Chemical Processes
Slurry Walls	Full-scale/ Conventional	These subsurface barriers consist of a vertically excavated trench filled with a slurry. The slurry, usually a mixture of bentonite and water, hydraulically shores the trench to prevent collapse and forms a filter cake to reduce groundwater flow.
Passive Treatment Walls	Pilot-scale/ Innovative	A permeable reaction wall is installed across the flow path of a contaminant plume, allowing the plume to passively move through the wall. The halogenated compounds are degraded by reactions with a mixture of porous media and a metal catalyst.
Hot Water or Steam Flushing/Stripping	Pilot-scale/ Innovative	Steam is forced into an aquifer through injection wells to vaporize volatile and semivolatile contaminants. Vaporized components rise to the unsaturated zone where they are removed by vacuum extraction and then treated. This variety of processes includes Contained Recovery of Oily Waste (CROW), Steam Injection and Vacuum Extraction (SIVE), *In Situ* Steam Enhanced Extraction (ISEE), and Steam Enhanced Recovery Process (SERP).
Hydrofracturing (enhancement)	Pilot-scale/ Innovative	Injection of pressurized water through wells cracks low permeability and over-consolidated sediments. Cracks are filled with porous media that serve as avenues for bioremediation or improve pumping efficiency.
Air Sparging	Full-scale/ Innovative	Air is injected into saturated matrices creating an underground air stripper that removes contaminants through volatilization.
Directional Wells (enhancement)	Full-scale/ Innovative	Drilling techniques are used to position wells horizontally, or at an angle, in order to reach contaminants not accessible via direct vertical drilling.

Technology	Status	Description
Dual Phase Extraction	Full-scale/ Innovative	A high vacuum system is applied to simultaneously remove liquid and gas from low permeability or heterogeneous formations.
Vacuum Vapor Extraction	Pilot-scale/ Innovative	Air is injected into a well, lifting contaminated groundwater in the well and allowing additional groundwater flow into the well. Once inside the well, some of the volatile organic compounds in the contaminated groundwater are transferred from the water to air bubbles which rise and are collected at the top of the well by vapor extraction. The partially treated groundwater is never brought to the surface; it is forced into the unsaturated zone, and the process is repeated. Contaminant concentrations gradually are reduced with each repetition of the process.
Free Product Recovery	Full-scale/ Conventional	Undissolved liquid-phase organics are removed from subsurface formations, either by active methods (e.g., pumping) or a passive collection system.
Ex Situ Biological Processes (assuming pumping)		
Bioreactors	Full-scale/ Innovative	Contaminants in extracted groundwater are put into contact with microorganisms through attached or suspended biological systems. In suspended systems, such as activated sludge, contaminated groundwater is circulated in an aeration basin where a microbial population aerobically degrades organic matter and produces new cells. In attached systems, such as rotating biological contactors and trickling filters, microorganisms are established on an inert support matrix to aerobically degrade groundwater contaminants.
Ex Situ Physical/Chemical Processes (assuming pumping)		
Air Stripping	Full-scale/ Conventional	Volatile organics are partitioned from groundwater by increasing the surface area of the contaminated water exposed to air. Aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration.
Carbon Adsorption (Liquid Phase)	Full-scale/ Conventional	Groundwater is pumped through a series of canisters containing activated carbon to which dissolved organic contaminants adsorb. Periodic replacement or regeneration of saturated carbon is required.
UV Oxidation	Full-scale/ Innovative	Ultraviolet (UV) radiation, ozone, and/or hydrogen peroxide are used to destroy organic contaminants as water flows into a treatment tank. An ozone destruction unit is used to treat off-gases from the treatment tank.
Other Processes		
Natural Attenuation	Conventional	Natural subsurface processes—such as dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface materials—are allowed to reduce contaminant concentrations to acceptable levels. Sampling and sample analysis throughout the process are required.

Air Emissions/Off-Gas Treatment Processes

Technology	Status	Description
Carbon Adsorption (Vapor Phase)	Full-scale/ Conventional	Carbon, processed into hard granules or pellets, is used to capture molecules of gas-phase pollutants. The granulated activated carbon (GAC) may be contained in a packed bed through which contaminated emissions/off-gases flow. When the carbon has been saturated with contaminants, it can be regenerated in place, removed and regenerated at an off-site facility, or disposed.
Catalytic Oxidation (non-halogenated)	Full-scale/ Conventional	Trace organics in contaminated air streams are destroyed at lower temperatures, 842°F (450°C), than conventional combustion by passing the air/VOC mixture through a catalyst designed for non-halogenated compounds.
Catalytic Oxidation (halogenated)	Full-scale/ Conventional	Trace organics in contaminated air streams are destroyed at lower temperatures, 842°F (450°C), than conventional combustion by passing the air/VOC mixture through a catalyst designed for halogenated compounds.
Biofiltration	Full-scale/ Innovative	Vapor-phase organic contaminants are pumped through a soil bed and sorb to the soil surface where they are degraded by microorganisms in the soil. Specific strains of bacteria may be introduced into the filter and optimal conditions provided to preferentially degrade specific compounds.
Thermal Oxidation	Full-scale/ Conventional	Organic contaminants are destroyed in a high temperature 1,832°F (1,000°C) combustor.

TABLE 2: DEFINITION OF SCREENING FACTORS

Factor	Definition
Overall Cost	Design, construction, and operation and maintenance (O&M) costs of the core process that defines each technology, exclusive of mobilization, demobilization, and pre- and post-treatment costs. (For *ex situ* soil, sediment, and sludge technologies, it is assumed that excavation costs average $50/ton ($55.00/metric ton). For *ex situ* groundwater technologies, it is assumed that pumping costs average $0.25/1,000 gallons ($0.07/1,000 liters).)
Capital or O&M Intensive?	Is this technology capital (Cap)-intensive, with significant costs for design and construction; O&M-intensive, with significant costs for labor, operation, maintenance, and repair; both; or neither?
Commercial Availability	Number of vendors that can design, construct, and maintain the technology.
Typically Part of a Treatment Train?	Is additional treatment necessary, after the use of this technology, to clean up the contaminated media? (Excludes treatment of off-gases.)
Residuals Produced (<u>S</u>olid, <u>L</u>iquid, <u>V</u>apor)?	If use of the technology produces residuals that require management, are they solids, liquids, or vapors?
Minimum Contaminant Concentration Achievable	Minimum contaminant concentration achievable by the technology, measured in milligrams per kilogram (mg/kg) for soil technologies, micrograms per liter (µg/L) for groundwater, and mg/kg and micrograms per kilogram (µg/kg) for air emissions/off-gases.
Addresses Toxicity, Mobility, or Volume?	What parameter(s) of the contaminated media — toxicity, mobility, or volume — is the technology primarily designed to address?
Long-Term Effectiveness/Permanence?	Does use of the technology maintain protection of human health and the environment, over time, after cleanup objectives have been met?
Time To Complete Cleanup	Time required to clean up a "standard" site using the technology. ("Standard" site is 20,000 tons (18,200 metric tons) for soil and 1 million gallons (3,785,000 liters) for groundwater.)
System Reliability/Maintainability	Degree of system reliability and level of maintenance required when using the technology.
Awareness of Remediation Consulting Community	Degree to which the technology is known to remediation consultants.
Regulatory/Permitting Acceptability	Degree to which use of the technology is acceptable to regulating and permitting agencies.
Community Acceptability	Degree to which use of the technology is acceptable to the public.

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CHAPTER 2: RATING SYSTEM

The purpose of the Rating System is to provide the framework and factors for screening the technologies included in the *Remediation Technologies Screening Matrix.*

The system is comprised of 13 factors that address specific cost, performance, technical, developmental, and institutional issues (see Table 2). The intention is to give site project managers an overview of a range of factors for use in identifying potentially applicable technologies and processes.

It is important to remember that the *Matrix* provides basic, representative information only. The impact of site-specific conditions cannot be reflected. For example, the cost of a technology may depend on the size of the cleanup and physical and chemical characteristics of the waste.

Five of the factors in the system pose performance-related questions. Answers to these questions are shown in the *Matrix* and are presented in Chapter 3 in the discussion of each technology or process.

The remaining eight factors—Overall Cost, Commercial Availability, Minimum Contaminant Concentration Achievable, Time To Complete Cleanup, System Reliability/Maintainability, Awareness of Remediation Consulting Community, Regulatory/Permitting Acceptability, and Community Acceptability—involve a comparative rating. Technologies are assigned one of four possible ratings: Better, Average, Worse, or Inadequate Information. Table 4, which begins on the next page, identifies the rating levels for these eight factors. The levels were defined by the technical experts who participated in the *Matrix* development workshop, based on their collective experience and expertise.

Three of the rating levels are differentiated in the *Matrix* by shape, as well as color, to facilitate black-and-white reproduction:

Better = Square = Blue
Average = Circle = White
Worse = Triangle = Yellow

The letter "I" indicates there is Inadequate Information with which to rate the technology or process; "NA" is used if the factor is Not Applicable to the technology or process. Ratings for individual technologies and processes are discussed in Chapter 3.

TABLE 4: DEFINITION OF RATING LEVELS

FACTORS AND DEFINITIONS	INADEQUATE INFORMATION (I)	WORSE (Triangle)	AVERAGE (Circle)	BETTER (Square)
Overall Cost Design, construction, and operations and maintenance (O&M) costs of the core process that defines each technology, exclusive of mobilization, demobilization, and pre- and post-treatment. (For *ex situ* soil, sediment, and sludge technologies, it is assumed that excavation costs average $50/ton ($55.00/metric ton). For *ex situ* groundwater technologies, it is assumed that pumping costs average $0.25/1,000 gallons ($0.07/1,000 liters).)	There is insufficient information with which to rate the technology in this category.	More than $300/ton ($330/metric ton) for soils; More than $10/1,000 gal. ($2.64/1,000 liters) for groundwater; More than $25/lb. ($11.33/kg) for air emissions and off-gases	$100-$300/ton ($110-$330/metric ton); $3.00 -$10.00/1,000 gal. ($0.79-$2.64/1,000 liters); $7-$25/lb. ($3.17-$11.33/kg)	Less than $100/ton ($110/metric ton); Less than $3.00/1,000 gal. ($0.79/1,000 liters); Less than $7/lb. ($3.17/kg)
Commercial Availability Number of vendors that can design, construct, and maintain the technology.	There is insufficient information with which to rate the technology in this category.	Less than 2 vendors	2-4 vendors	More than 4 vendors
Minimum Contaminant Concentration Achievable Minimum contaminant concentration level achievable by the technology, measured in milligrams per kilogram for soil technologies, micrograms per liter for groundwater, and milligrams per kilogram and micrograms per kilogram for air emissions and off-gases.	There is insufficient information with which to rate the technology in this category.	More than 50 mg/kg; More than 100 µg/L; More than 250 mg/kg	5-50 mg/kg; 5-100 µg/L; 250 mg/kg-250 µg/kg, but detectable	Less than 5 mg/kg; Less than 5 µg/L; Not detectable

FACTORS AND DEFINITIONS	INADEQUATE INFORMATION (I)	WORSE (Triangle)	AVERAGE (Circle)	BETTER (Square)
Time To Complete Cleanup Time required to clean up a "standard" site using the technology. (The "standard" site is 20,000 tons (18,200 metric tons) for soils and 1 million gallons (3,785,000 liters) for groundwater. Chapter 3 contains a more detailed definition.)	There is insufficient information with which to rate the technology in this category.	More than 3 years for *in situ* soil technologies; More than 1 year for *ex situ* soil technologies; More than 10 years for groundwater technologies	1-3 years; 0.5-1 year; 3-10 years	Less than 1 year Less than 0.5 years Less than 3 years
System Reliability/Maintainability The degree of system reliability and level of maintenance required when using the technology.	There is insufficient information with which to rate the technology in this category.	Low reliability and high maintenance	Average reliability and average maintenance	High reliability and low maintenance
Awareness of Remediation Consulting Community Degree to which the technology is known to remediation consultants.	There is insufficient information with which to rate the technology in this cateogry.	Generally unknown; little information available in technical literature	Moderately known; some information available in technical literature	Generally known; information readily available in technical literature

FACTORS AND DEFINITIONS	INADEQUATE INFORMATION (I)	WORSE (Triangle)	AVERAGE (Circle)	BETTER (Square)
Regulatory/Permitting Acceptability Degree to which use of the technology is acceptable to the regulatory and permitting community.	There is insufficient information with which to rate the technology in this category.	Below average	Average	Above average
Community Acceptability Degree to which use of the technology is acceptable to the public.	There is insufficient information with which to rate the technology in this category.	Serious public involvement is likely and the outcome is uncertain.	Public involvement usually occurs, but the technology is generally accepted.	Minimal opposition from the community is likely.

CHAPTER 3: TECHNOLOGY RATINGS

This chapter provides information about each of the technologies and processes evaluated in the *Matrix.* Included is a discussion of the contaminant groups treated by the technology and other issues that should be considered in determining its potential applicability and effectiveness. The ratings on the *Matrix* for each technology are presented in this chapter, and supplemental information is provided, as needed. For example, factors that could limit the suitability and effectiveness of each technology are discussed.

Conventions

The following conventions were used in preparing the *Remediation Technologies Screening Matrix*:

1. Contaminants identified in the *Matrix* are grouped as follows: (1) halogenated volatiles; (2) halogenated semivolatiles; (3) non-halogenated volatiles; (4) non-halogenated semivolatiles; (5) fuel hydrocarbons; (6) pesticides; and (7) inorganics. These groupings were developed based on a review of EPA's *Technology Screening Guide for Treatment of Soils and Sludges* and *Superfund Treatability Clearing House Abstracts* and with guidance from the technical experts who participated in the development of the *Matrix.* Appendix B contains a list of selected contaminants in each group.

2. While all contaminant groups to which the technology or process is applicable are indicated on the *Matrix*, each technology is evaluated based on the contaminant group(s) that it is primarily designed to treat. If appropriate, additional information on the technology's performance against other contaminants is noted.

3. "Standard" site profiles were developed to provide a baseline for rating the soil and groundwater technologies consistently against the "Time To Complete Cleanup" factor. A calculation of the time required to clean up the "standard" site is shown in the text only when the technology's processing rate was generally known. No "standard" was developed for air emissions/off-gas technologies, because cleanup time is dependent on the primary technology or process they support. Air emissions/off-gas treatment technologies are not rated against the "Time To Complete Cleanup" factor.

   - The "standard" for soil is a normalized site of 1 acre, 10 feet deep (.41 hectare, 3.04 meters deep). Site volume is 20,000 tons (18,200 metric tons).
   - The "standard" for groundwater is a normalized site of 1 acre, 10 feet deep (.41 hectare, 3.04 meters deep) with an average porosity of 30% and a shallow aquifer. Site volume is 1,000,000 gallons (3,785,000 liters).

4. For *ex situ* soil, sediment, and sludge technologies, the ratings in the Overall Cost category include an assumption that excavation costs average $50/ton ($55.00/metric ton). For *ex situ* groundwater technologies, it is assumed that pumping costs average $0.25/1,000 gallons ($0.07/1,000 liters).

The discussion of each technology and process included in the *Matrix* begins on page 21.

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Soils, Sediments, Sludges

IN SITU BIODEGRADATION:

The activity of naturally occurring microbes is stimulated by circulating water-based solutions through contaminated soils to enhance *in situ* biological degradation of organic contaminants. Nutrients, oxygen, or other amendments may be used to enhance biodegradation and contaminant desorption from subsurface materials. Generally, the process includes above-ground treatment and conditioning of the infiltration water with nutrients and an oxygen (or other electron acceptor) source. **In situ biodegradation is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Extensive treatability studies and site characterization may be necessary.
- The circulation of water-based solutions through the soil may increase contaminant mobility and necessitate use of an above-ground system for treating water prior to re-injection or disposal.
- The injection of microorganisms into the subsurface is not recommended. Naturally occurring organisms are generally adapted to the contaminants present.
- Preferential flow paths may severely decrease contact between injected fluids and contaminants throughout the contaminated zones.
- The system should be used only where groundwater is near the surface and where the groundwater underlying the contaminated soils is contaminated.
- The system should not be used for clay, highly layered, or heterogeneous subsurface environments due to oxygen (or other electron acceptor) transfer limitations.
- Bioremediation may not be applicable at sites where there are high concentrations of heavy metals, highly chlorinated organics, or inorganic salts.

Target contaminants for *in situ* biodegradation are non-halogenated volatile and semivolatile organics and fuel hydrocarbons (groups 3, 4, and 5). Halogenated volatiles and semivolatiles and pesticides (1, 2, and 6) also can be treated, but the process may be less effective and may only be applicable to some compounds within these contaminant groups.

1. **Overall Cost** **Rating: Average**

2. **Capital (Cap) or O&M Intensive?** **O&M**

   Various quantities of nutrients or other amendments must be obtained and circulated through contaminated soils, and their concentrations and effects on contaminant degradation rates must be monitored.

3. **Commercial Availability:** **Rating: Better**

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)?** **None**

6. Minimum Contaminant Concentration Achievable: **Rating: Average**

In situ soil biodegradation systems are capable of transforming contaminants into non-hazardous substances. However, the extent of contaminant degradation depends on a variety of parameters, such as the specific contaminants present and their concentrations, and adequate electron acceptors.

7. Addresses Toxicity, Mobility, or Volume? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

In situ biodegradation can permanently destroy selected organic contaminants.

9. Time To Complete Cleanup: **Rating: Worse**

Remediation times are often 4-6 years, depending mainly on the degradation rates of specific contaminants. Less than one year may be required to cleanup some contaminants with relatively short half-lives, but higher molecular weight compounds have much longer half-lives and thus take longer to degrade.

10. System Reliability/Maintainability: **Rating: Worse**

11. Awareness of the Remediation Consulting Community: **Rating: Average**

12. Regulatory/Permitting Acceptability: **Rating: Worse**

There is a risk of increasing contaminant mobility and leaching of contaminants into the groundwater. Regulators often do not accept the addition of nutrients and other amendments to contaminated soils. *In situ* biodegradation has been selected for remedial and emergency response actions at only a few Superfund sites.

13. Community Acceptability: **Rating: Better**

Communities generally prefer technologies that result in contaminant destruction and that do not require excavation.

BIOVENTING:

Oxygen is delivered to contaminated unsaturated soils by forced air movement (either extraction or injection of air) to increase oxygen concentrations and stimulate biodegradation. The system also may include the injection of contaminated gases, using the soil system for remediation. Unlike soil vapor extraction, bioventing employs much lower air flow rates that provide only the amount of oxygen necessary for biodegradation while minimizing volatilization and release of contaminants to the atmosphere. The advantages of gas-phase (as opposed to liquid phase) introduction of oxygen into soils are that gases diffuse more rapidly than liquids into less permeable subsurface formations and much less gas is required to deliver oxygen at levels needed to stimulate biological degradation of contaminants. **Bioventing is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Tests should be conducted to determine soil gas permeability.
- Bioventing is not recommended where there is a high water table (within several feet of the surface), saturated soil lenses, or impermeable soils. Areas with a high water table can be successfully treated by combinging bioventing with a dewatering process.
- Vapors can build up in building basements within the radius of influence of air injection wells. This can be alleviated by extracting air near the structure of concern.
- Low soil moisture content may limit biodegradation and the effectiveness of bioventing, which tends to dry out the soils.
- Monitoring of off-gases at the soil surface may be required.
- Aerobic biodegradation of chlorinated compounds is not very effective unless there is a co-metabolite present.

Bioventing is primarily designed to treat non-halogenated volatile and semivolatile organics and fuel hydrocarbons (3, 4, and 5). Halogenated volatiles and semivolatiles and pesticides (1, 2, and 6) also can be treated, but the process may be less effective and may only be applicable to some compounds within these contaminant groups.

1. Overall Cost **Rating: Better**

Costs for operating a bioventing system typically are \$15 per yard^3 (\$19.50 per meter^3). This technology does not require expensive equipment and can be left unattended for long periods of time. Relatively few personnel are involved in the operation and maintenance of a bioventing system. Typically, quarterly maintenance monitoring is conducted.

2. Capital (Cap) or O&M Intensive? **Neither**

3. Commercial Availability: **Rating: Better**

Bioventing is becoming more commonplace, and most of the hardware components are readily available.

4. Typically Part of a Treatment Train? **No**

5. Residuals Produced (Solid, Liquid, Vapor)? **None**

6. Minimum Contaminant Concentration Achievable: **Rating: Better**

Bioventing is capable of completely transforming contaminants into non-hazardous substances. One of the advantages of bioventing is its ability to biodegrade the non-volatile organics that other vapor extraction technologies that rely on volatilization cannot address.

7. Addresses Toxicity, Mobility, or Volume? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

Bioventing can permanently destroy selected organic contaminants.

9. Time To Complete Cleanup: **Rating: Average**

As with all biological technologies, the time required to remediate a site using bioventing is highly dependent upon the specific soil and chemical properties of the contaminated media. The Air Force considers three years as the typical time required for cleaning up most sites.

10. System Reliability/Maintainability: **Rating: Better**

Generally, downtime is minimal and repair parts are readily available.

11. Awareness of the Remediation Consulting Community: **Rating: Average**

Although relatively new, bioventing is receiving increased exposure to the remediation consulting community, particularly its use in conjunction with soil vapor extraction. The Air Force is sponsoring bioventing demonstrations at more than 100 sites.

12. Regulatory/Permitting Acceptability: **Rating: Average**

13. Community Acceptability: **Rating: Better**

The public generally prefers destruction technologies that do not require excavation. In addition, bioventing can eliminate the risks of volatilization of contaminants into the atmosphere.

SOIL VAPOR EXTRACTION (SVE):

Vacuum is applied through extraction wells to create a pressure gradient that induces volatiles to diffuse through the soil to extraction wells. The process includes a system for handling off-gases. This process also is known as *in situ* soil venting, *in situ* volatilization, enhanced volatilization, or soil vacuum extraction. ***In situ* SVE is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- High humic content of soil inhibits contaminant volatilization.
- Heterogeneous soil conditions may result in inconsistent removal rates.
- Low soil permeability limits subsurface air flow rates and reduces process efficiency.

The target contaminant groups for *in situ* SVE are halogenated and non-halogenated volatile organic compounds, and fuel hydrocarbons (1, 3, and 5). The technology is applicable only to volatile compounds with a Henry's law constant greater than 0.01 or a vapor pressure greater than 0.5 units. *In situ* SVE generally applies only to the vadose zone. Treatment of the saturated zone is only possible by artificially lowering the water table. Since SVE is an *in situ* remedy and all contaminants are under vacuum until treatment, the possibility of release is greatly reduced.

1. **Overall Cost** **Rating: Better**

   Data indicates the overall cost for *in situ* SVE is typically under $50/ton, excluding treatment of off-gases and collected groundwater.

2. **Capital (Cap) or O&M Intensive?** **O&M**

3. **Commercial Availability** **Rating: Better**

4. **Typically Part of a Treatment Train?** **No**

   While SVE is considered a stand-alone technology, it also can be used as part of treatment trains to address semivolatiles.

5. **Residuals Produced (Solid, Liquid, Vapor)** **Rating: Liquid**

6. **Minimum Contaminant Concentration Achievable** **Rating: Average**

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Rating: Volume**

8. Long-Term Effectiveness/Permanence? **Yes**

Assuming the characteristics of the treated soil allow for the effective use of *in situ* SVE, the remediation of the targeted contaminants is permanent.

9. Time To Complete Cleanup **Rating: Average**

The time required to remediate a site using *in situ* SVE is highly dependent upon the specific soil and chemical properties of the contaminated media. The "standard" site of 20,000 tons (18,200 metric tons) of contaminated media generally would require 12-36 months.

10. System Reliability/Maintainability **Rating: Better**

Generally, most of the hardware components are readily available. Typical *in situ* SVE systems can be left unattended for long periods of time. The technology has been successfully operated during severe weather conditions.

11. Awareness of Remediation Consulting Community **Rating: Better**

12. Regulatory/Permitting Acceptability **Rating: Better**

In situ SVE has been used at many Superfund and other hazardous waste sites.

14. Community Acceptability **Rating: Better**

SOIL FLUSHING:

Water, or water containing an additive to enhance contaminant solubility, is applied to the soil or injected into the groundwater to raise the water table into the contaminated soil zone. Contaminants are leached into the groundwater. The process includes extraction of the groundwater and capture/treatment/removal of the leached contaminants before the groundwater is re-circulated. **Soil flushing is a pilot-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The technology is applicable only to sites with favorable hydrology, where flushed contaminants and soil flushing fluid can be contained and recaptured.
- Low permeable soils are difficult to treat.
- Surfactants can adhere to soil and reduce effective soil porosity.
- Solvent reactions with soil can reduce contaminant mobility.

The target contaminant groups for soil flushing are halogenated and non-halogenated volatile organic compounds, and inorganics (1, 3, and 7). The technology can be used to treat halogenated and non-halogenated semivolatile organic compounds, fuels, and pesticides (2, 4, 5, and 6), but it may be less effective and may only be applicable to some compounds in these contaminant groups. The addition of compatible surfactants may be used to increase the solubility of some compounds effectively. The technology offers the potential for recovery of metals and can clean a wide range of organic and inorganic contaminants from coarse-grained soils. Soil flushing does introduce potential toxins (e.g., the flushing solution) into the soil, which also may alter the physical/chemical properties of the soil system.

1. **Overall Cost** — **Rating: Inadequate Information**
2. **Capital (Cap) or O&M Intensive?** — **O&M**
3. **Commercial Availability** — **Rating: Better**
4. **Typically Part of a Treatment Train?** — **No**

   Soil flushing can be used as a stand-alone technology for some applications and is capable of reducing contaminant concentrations in the soil to acceptable levels. However, it also can be used in combination with other technologies, such as *in situ* bioremediation.

5. **Residuals Produced (Solid, Liquid, Vapor)** — **Rating: Liquid**

   It is important to ensure that the site has favorable hydrology so that flushed contaminants and soil flushing fluid can be contained and recaptured.

6. **Minimum Contaminant Concentration Achievable** — **Rating: Worse**
7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** — **Rating: Volume**

8. Long-Term Effectiveness/Permanence? Yes

9. Time To Complete Cleanup Rating: Worse

10. System Reliability/Maintainability Rating: Average

11. Awareness of Remediation Consulting Community Rating: Average

12. Regulatory/Permitting Acceptability Rating: Worse

13. Community Acceptability Rating: Average

IN SITU SOLIDIFICATION/STABILIZATION:

Contaminants are physically bound or enclosed within a stabilized mass (solidification), or chemical reactions are induced between the stabilizing agent and contaminants to reduce their mobility (stabilization). ***In situ* solidification/stabilization is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Depth of contaminants.
- Environmental conditions may affect ability to maintain immobilization of contaminants.
- Some processes result in a significant increase in volume (up to double the original volume).
- Certain wastes are incompatible with variations of this process. Treatability studies may be required.

The target contaminant group for *in situ* solidification/stabilization is inorganics (7). The technology has limited effectiveness against halogenated and non-halogenated semivolatile organic compounds, and pesticides (2, 4, and 6). However, systems designed to be more effective in treating organics are being developed and tested. *In situ* solidification/stabilization is relatively simple, uses readily available equipment, and has high throughput rates compared to other technologies.

1. **Overall Cost** **Rating: Better**

2. **Capital (Cap) or O&M Intensive?** **Capital**

3. **Commercial Availability** **Rating: Better**

4. **Typically Part of a Treatment Train?** **No**

   In situ solidification/stabilization is generally considered a stand-alone technology.

5. **Residuals Produced (Solid, Liquid, Vapor)?** **Solid**

   Depending on the original contaminants and the chemical reactions that take place in the *in situ* solidification/stabilization process, the resultant stabilized mass may still have to be treated as a hazardous waste.

6. **Minimum Contaminant Concentration Achievable** **Rating: Not Applicable**

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Mobility**

   In situ solidification/stabilization processes have demonstrated the capability to reduce the mobility of contaminated waste by greater than 95%.

8. **Long-Term Effectiveness/Permanence?** **Inadequate Information**

9. **Time To Complete Cleanup** **Rating: Better**

10. System Reliability/Maintainability **Rating: Better**

11. Awareness of Remediation Consulting Community **Rating: Average**

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Average**

PNEUMATIC FRACTURING:

Pressurized air is injected beneath the surface to develop cracks in low permeability and over-consolidated sediments. These new passageways increase the effectiveness of many *in situ* processes and enhance extraction efficiencies. **Pneumatic fracturing is a pilot-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The technology should not be used in areas of high seismic activity.
- Investigation of possible underground utilities, structures, or trapped free product is required.
- The potential exists to open new pathways for the unwanted spread of contaminants (e.g., dense non-aqueous phase liquids).

Pneumatic fracturing is applicable to the complete range of contaminant groups (1-7) with no particular target group. The technology is used primarily to fracture clays and bedrock, but has applications in aerating sand. Normal operation employs a two-person crew, making 25 - 40 fractures per day with a fracture radius of 15-20 feet (4.6-6.1 meters) to a depth of 50-100 feet (15.2-30.5 meters).

1. **Overall Cost** **Rating: Better**

   The normal cost range for pneumatic fracturing is $5-$10/ton ($5.50-$11.00/metric ton).

2. **Capital (Cap) or O&M Intensive?** **Neither**

3. **Commercial Availability** **Rating: Worse**

   The technology is currently available from only one vendor. Pneumatic fracturing was tested with hot gas injection and extraction in EPA's SITE Demonstration Program in 1992. Results are expected to be published in mid-1993. A phase II demonstration is planned for 1993.

4. **Typically Part of a Treatment Train?** **Yes**

   Pneumatic fracturing is an enhancement technology, designed to increase the efficiency of other *in situ* technologies in difficult soil conditions. The technology is most commonly integrated with vapor extraction, bioremediation, thermal treatment, or soil flushing.

5. **Residuals Produced (Solid, Liquid, Vapor)** **None**

6. **Minimum Contaminant Concentration Achievable** **Rating: Not Applicable**

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Mobility**

   Pneumatic fracturing is designed to increase the mobility through difficult soil conditions. The passageways enhance extraction efficiencies and increase contact between contaminants and soil amendments.

8. Long-Term Effectiveness/Permanence? **Yes**

For longer remediation programs, refracturing efforts may be required at 6-12 month intervals.

9. Time To Complete Cleanup **Rating: Not Applicable**

Pneumatic fracturing is designed to enhance the efficiency of other technologies.

10. System Reliability/Maintainability **Rating: Better**

11. Awareness of Remediation Consulting Community **Rating: Worse**

The technology has been demonstrated in the field, including the one under EPA's SITE program. In addition, numerous bench-scale and theoretical studies have been published.

12. Regulatory/Permitting Acceptability **Rating: Inadequate Information**

13. Community Acceptability **Rating: Inadequate Information**

IN SITU VITRIFICATION:

Electrodes for applying electricity, or joule heating, are used to melt contaminated soils and sludges, producing a glass and crystalline structure with very low leaching characteristics. ***In situ* vitrification is currently in pilot-scale development.** Most of the current work is being sponsored by the Department of Energy (DOE).

The following factors may limit the applicability and effectiveness of the process:

- The process requires homogeneity of the media.
- *In situ* vitrification is only effective to a maximum depth of approximately 30 feet (9 meters).
- Organic and inorganic off-gases must be controlled.
- *In situ* vitrification is limited to operations in the vadose zone.

While *in situ* vitrification is used primarily to encapsulate non-volatile inorganic elements (7), temperatures of approximately 3000°F (1600°C) achieved in the process destroy organic contaminants (1-6) by pyrolysis. The vitrified mass resists leaching for geologic time periods. A vacuum hood placed over the treated area collects off-gases, which are treated before release. The entire process is conducted under a vacuum, greatly reducing the possibility of contaminant release. The high voltage used in the *in situ* vitrification process, as well as control of the off-gases, present some health and safety risks. Recent operational problems involving a sudden gas release at a large-scale test pose some additional technical concerns.

1. Overall Cost **Rating: Worse**

The cost of *in situ* vitrification has been estimated to be approximately $790/ton ($870/metric ton). *In situ* vitrification is a relatively complex, high-energy technology requiring a high degree of skill and training.

2. Capital (Cap) or O&M Intensive? **Both**

3. Commercial Availability **Rating: Worse**

Only one vendor, Battelle Memorial Institute, is licensed at this time by the DOE to perform *in situ* vitrification. Geosafe Corporation, primarily owned by Battelle, holds the exclusive sublicense to perform *in situ* vitrification commercially.

4. Typically Part of a Treatment Train? **No**

In situ vitrification is normally considered a stand-alone technology.

5. Residuals Produced (Solid, Liquid, Vapor) **Liquid**

6. Minimum Contaminant Concentration Achievable **Rating: Not Applicable**

In situ vitrification is designed to encapsulate target contaminants rather than reduce contaminant concentration levels. However, destruction of the organic contaminants present in the treated media does occur because of temperatures achieved in the process.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Mobility**

In situ vitrification is designed to reduce the mobility of the contaminated wastes within the media. The vitrified mass has high resistance to leaching and has strength properties better than those of concrete. The monolith formed has hydration properties similar to those of obsidian, which hydrates at rates of less than 1 millimeter/10,000 years.

8. Long-Term Effectiveness/Permanence? **Yes**

Studies indicate that the glass and crystalline product of *in situ* vitrification permanently immobilizes hazardous inorganics and will retain its physical and chemical integrity for geologic time periods.

9. Time To Complete Cleanup **Rating: Better**

The time to complete cleanup of a 20,000-ton (18,200-metric ton) site using *in situ* vitrification would be approximately 7 months.

10. System Reliability/Maintainability **Rating: Worse**

During a recent large-scale test, a sudden gas release pressurized the containment hood and splattered molten soil on the stainless steel hood.

11. Awareness of Remediation Consulting Community **Rating: Average**

In situ vitrification has been used in 22 pilot-scale and 10 large-scale tests on media contaminated with inorganics, organics, and/or radioactive wastes. However, dissemination of technical information outside of DOE, Battelle, and Geosafe has been limited to date.

12. Regulatory/Permitting Acceptability **Rating: Worse**

13. Community Acceptability **Rating: Worse**

THERMALLY ENHANCED SVE:

This process uses steam/hot-air injection or electric/radio frequency heating to increase the mobility of volatiles and facilitate extraction. The process includes a system for handling off-gases. **Thermally enhanced SVE is a full-scale technology.** It is designed to treat halogenated and non-halogenated semivolatile organic compounds (2 and 4). Some thermally enhanced SVE technologies also are effective in treating some pesticides (6), depending on the temperatures achieved by the system. The technology can also be used to treat some halogenated and non-halogenated volatile organic compounds and fuels (1, 3, and 5), but effectiveness may be limited.

The following factors may limit the applicability and effectiveness of the process:

- Debris or other large objects buried in the media can cause operating difficulties.
- Use of the technology is limited to a 5° slope or less.
- Performance against certain contaminants varies depending upon the process selected because of the maximum temperature achieved.
- The soil structure at the site may be modified depending upon the process selected.

The thermally enhanced SVE processes used by each vendor are notably different and should be investigated individually for more detailed information. Since thermally enhanced SVE is an *in situ* remedy and all contaminants are under a vacuum during operation, the possibility of contaminant release is greatly reduced.

1. Overall Cost **Rating: Average**

Available data indicates the overall cost for thermally enhanced SVE systems is approximately $50-$75/ton ($55-$82/metric ton), excluding treatment of off-gases and collected groundwater.

2. Capital (Cap) or O&M Intensive? **Both**

3. Commercial Availability **Rating: Average**

4. Typically Part of a Treatment Train? **No**

Thermally enhanced SVE is most commonly used as a stand-alone technology.

5. Residuals Produced (Solid, Liquid, Vapor) **Liquid**

6. Minimum Contaminant Concentration Achievable **Rating: Average**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Volume**

8. Long-Term Effectiveness/Permanence? **Yes**

Assuming the soil characteristics allow for the effective use of thermally enhanced SVE, the remediation of the target contaminants is permanent.

9. Time To Complete Cleanup **Rating: Better**

As with SVE, remediation projects using thermally enhanced SVE systems are highly dependent upon the specific soil and chemical properties of the contaminated media. The "standard" site consisting of 20,000 tons (18,200 metric tons) of contaminated media would require approximately 9 months.

10. System Reliability/Maintainability **Rating: Average**

11. Awareness of Remediation Consulting Community **Rating: Average**

Although thermally enhanced SVE systems have only seen limited use to date, the concept of soil vapor extraction, which is its basis, is well recognized.

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Average**

SLURRY PHASE BIOLOGICAL TREATMENT:

An aqueous slurry is created by combining soil or sludge with water and other additives. The slurry is mixed to keep solids suspended and microorganisms in contact with the soil contaminants. Nutrients, oxygen, and pH in the bioreactor are controlled to enhance biodegradation. Upon completion of the process, the slurry is dewatered and the treated soil is disposed. **Slurry phase biological treatment is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- A slurry phase process is much more complex than a controlled solid phase system.
- Excavation of contaminated soils is required.
- Sizing of materials prior to putting them in the hopper can be difficult and expensive. Non-homogeneous soils can create serious materials handling problems.
- Contaminant loading rates can be slow, depending on the compounds to be treated.
- Dewatering soil fines after treatment and prior to ultimate disposal is part of the process and is very expensive.
- An acceptable method for disposing of wastewaters is required.
- Slurry phase biological treatment systems are still under design to include a broader spectrum of contaminants.

Slurry-phase biological treatment is primarily designed to treat non-halogenated volatile organics and fuel hydrocarbons (3 and 5). Halogenated volatiles and semivolatiles, non-halogenated semivolatiles, and pesticides (1, 2, 4, and 6) also can be treated, but the process may be less effective and may only be applicable to some compounds within these contaminant groups. Many chlorinated organics and pesticides are not very biodegradable and this technology would not be very applicable. Aerobic co-metabolism using methanotrophic bacteria and phenol-degrading bacteria can degrade TCE and the lower chlorinated aliphatics, but do not work well for PCE and higher chlorinated compounds. Anaerobic reductive dechlorination is being investigated to treat the higher chlorinated compounds. Higher ringed polynuclear aromatic (PNA) compounds (greater than 5 rings) are very difficult to degrade.

1. Overall Cost **Rating: Average**

Costs are highly dependant on the extent of preparation required for contaminated material prior to slurrying, the need for post-treatment (such as dewatering), and the need for addition of air emission control equipment.

2. Capital (Cap) or O&M Intensive? **Both**

3. Commercial Availability: **Rating: Average**

Commercial-scale units that are complete cleanup systems are in operation. Most of the advances in this technology are related to the development of materials handling equipment and nutrient formulations.

4. Typically Part of a Treatment Train? **No**

5. Residuals Produced (Solid, Liquid, Vapor)? None

6. Minimum Contaminant Concentration Achievable: Rating: Average

This is highly dependent upon the biodegradability of the contaminants, which is affected by the mix of contaminants in the matrix, initial concentrations, and matrix desorption characteristics.

7. Addresses Toxicity, Mobility, or Volume? Toxicity

8. Long-Term Effectiveness/Permanence? Yes

Slurry phase biodegradation can permanently destroy selected organic contaminants.

9. Time To Complete Cleanup: Rating: Average

Slurry phase biological treatment is relatively rapid compared to other biological treatment processes, particularly for contaminated clays. However, as with other biological technologies, this is highly dependent upon the specific soil and chemical properties of the contaminated media. This technology is particularly applicable where the quantity of material containing recalcitrant compounds is small, and time to complete remediation is a high priority.

10. System Reliability/Maintainability: Rating: Average

11. Awareness of the Remediation Consulting Community: Rating: Average

A substantial amount of information is available on slurry phase bioremediation in the published literature and from vendors.

12. Regulatory/Permitting Acceptability: Rating: Better

The technology has been selected to treat soils and sludges at one Superfund site and has been selected to treat the fines from soil washing at four Superfund sites.

13. Community Acceptability: Rating: Average

Communities generally prefer technologies that do not require excavation, although this technology usually meets with little opposition because it destroys contaminants.

CONTROLLED SOLID PHASE BIOLOGICAL TREATMENT:

Excavated soils are mixed with soil amendments and placed in above-ground enclosures that include leachate collection systems and some form of aeration. Controlled solid phase processes include prepared treatment beds, biotreatment cells, soil piles, and composting. Moisture, heat, nutrients, oxygen, and pH can be controlled to enhance biodegradation. **Controlled solid phase biological treatment is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- A large amount of space is required.
- Excavation of contaminated soils is required.
- Treatability testing should be conducted to determine the biodegradability of contaminants and appropriate oxygenation and nutrient loading rates.
- Solid phase processes have questionable effectiveness for halogenated compounds and may not be very effective in degrading transformation products of explosives.
- These processes require more time to complete cleanup than slurry phase processes.

Solid-phase biological treatment is most effective in treating non-halogenated volatile organics and fuel hydrocarbons (3 and 5). Halogenated volatiles and semivolatiles, non-halogenated semivolatiles, and pesticides (1, 2, 4, and 6) also can be treated, but the process may be less effective and may only be applicable to some compounds within these contaminant groups.

1. **Overall Cost** **Rating: Better**

   Costs are dependent on the contaminant, procedure to be used, need for additional pre- and post-treatment, and need for air emission control equipment. Controlled solid phase processes are relatively simple and require few personnel for operation and maintenance.

2. **Capital (Cap) or O&M Intensive?** **Neither**

3. **Commercial Availability:** **Rating: Better**

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)?** **None**

6. **Minimum Contaminant Concentration Achievable:** **Rating: Average**

   As with other biological treatments, under proper conditions controlled solid phase processes can transform contaminants into non-hazardous substances. However, the extent of biodegradation is highly dependent on the initial concentrations of the the contaminants and their biodegradability, the properties of the contaminated matrix, and the particular treatment system selected.

7. **Addresses Toxicity, Mobility, or Volume?** **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

Controlled solid phase biodegradation can permanently destroy selected organic contaminants.

9. Time To Complete Cleanup: **Rating: Average**

Time to complete cleanup for these systems is primarily a function of the degradation rates of the contaminants being treated. A prepared bed system is mainly limited by available space and the size and cost of the treatment beds.

10. System Reliability/Maintainability: **Rating: Better**

Solid phase systems are relatively simple systems that are easy to operate and maintain.

11. Awareness of the Remediation Consulting Community: **Rating: Better**

12. Regulatory/Permitting Acceptability: **Rating: Better**

Tanks or containers must meet RCRA standards, including requirements for secondary containment. NPDES permits are required for wastewater disposal.

13. Community Acceptability: **Rating: Average**

Communities generally prefer technologies that do not require excavation; however, this technology usually meets with little opposition due to its low cost and destruction of contaminants.

LANDFARMING:

Contaminated soils are applied onto the soil surface and periodically turned over or tilled into the soil to aerate the waste. Although landfarming usually requires excavation of contaminated soils, surface-contaminated soils may sometimes be treated in place without excavation. Landfarming systems are increasingly incorporating liners and other methods to control leaching of contaminants. **Landfarming is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- A large amount of space is required.
- Excavation of contaminated soils usually is required.
- Conditions advantageous for biological degradation of contaminants are largely uncontrolled, which increases the length of time to complete remediation, particularly for recalcitrant compounds.
- Reduction of contaminant concentrations may be caused more by volatilization than biodegradation.

Landfarming is most effective in treating non-halogenated volatile organics and fuel hydrocarbons (3 and 5). Halogenated volatiles and semivolatiles, non-halogenated semivolatiles, and pesticides (1, 2, 4, and 6) also can be treated, but the process may only be applicable to some compounds in these groups.

1. Overall Cost **Rating: Better**

Landfarming is a very simple process and does not require control of moisture, oxygen, pH, or other parameters. Most of the system operations, such as tilling, can be done by relatively unskilled personnel.

2. Capital (Cap) or O&M Intensive? **Neither**

3. Commercial Availability: **Rating: Better**

Numerous full-scale operations have been used, particularly by the petroleum industry.

4. Typically Part of a Treatment Train? **No**

5. Residuals Produced (Solid, Liquid, Vapor)? **None**

6. Minimum Contaminant Concentration Achievable: **Rating: Average**

As with other biological treatments, under proper conditions, landfarming can transform contaminants into non-hazardous substances. However, removal efficiencies are a function of contaminant type and concentrations, soil type, temperature, moisture, waste loading rates, application frequency, aeration, volatilization, and other factors.

7. Addresses Toxicity, Mobility, or Volume? **Toxicity**

8. Long-Term Effectiveness/Permanence? Yes

Landfarming can permanently destroy selected organic contaminants.

9. Time To Complete Cleanup: **Rating: Worse**

This is primarily a function of the degradation rates of the contaminants being treated.

10. System Reliability/Maintainability: **Rating: Better**

These systems require regular tilling to aerate the soil and periodic chemical analyses of waste constituents in the soil. Potential for failure is minimal unless there is excessive rainfall or degradation rates are not achieved.

11. Awareness of the Remediation Consulting Community: **Rating: Better**

Numerous full-scale landfarming applications have been operated over the last ten years.

12. Regulatory/Permitting Acceptability: **Rating: Average**

The acceptability of this technology varies by State. Permitting of landfarm operations is becoming more difficult.

13. Community Acceptability: **Rating: Average**

Communities generally prefer technologies that do not require excavation; however, this technology usually meets with little opposition due to its low cost and destruction of contaminants.

SOIL WASHING:

Contaminants sorbed onto soil particles are separated from soil in an aqueous-based system. The wash water may be augmented with a basic leaching agent, surfactant, pH adjustment, or chelating agent to help remove organics or heavy metals. **Soil washing is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Fine soil particles (silts, clays) are difficult to remove from washing fluid.
- Complex waste mixtures (e.g., metals with organics) make formulating washing fluid difficult.
- High humic content in soil inhibits desorption.

The target contaminant groups for soil flushing are halogenated and non-halogenated semivolatile organic compounds, fuel hydrocarbons, and inorganics (2, 4, 5, and 7). The technology can be used but may be less effective against halogenated and non-halogenated volatile organic compounds and pesticides (1, 3, and 6). The technology offers the potential for recovery of metals and can clean a wide range of organic and inorganic contaminants from coarse-grained soils. As an *ex situ* remedy, the excavation associated with soil washing poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. Overall Cost **Rating: Average**

Average cost for use of this technology, including excavation, is approximately $120-$200 per ton ($132-$220/metric ton), depending on the target waste quantity and concentration.

2. Capital (Cap) or O&M Intensive? **Both**

3. Commercial Availability **Rating: Average**

4. Typically Part of a Treatment Train? **Yes**

Soil washing is most commonly used in combination with the following technologies: bioremediation, incineration, and solidification/stabilization.

5. Residuals Produced (Solid, Liquid, Vapor) **Rating: Solid, Liquid**

Depending on the process used, the washing agent and soil fines are residuals that require further treatment.

6. Minimum Contaminant Concentration Achievable **Rating: Average**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Volume**

8. Long-Term Effectiveness/Permanence? Yes

When contaminated fines have been separated, coarse-grain soil can usually be returned clean to the site. It should stay clean unless re-contaminated.

9. Time To Complete Cleanup Rating: Better

The time to complete cleanup of the "standard" 20,000-ton (18,200-metric ton) site using soil washing would be less than 3 months.

10. System Reliability/Maintainability Rating: Average

11. Awareness of Remediation Consulting Community Rating: Average

12. Regulatory/Permitting Acceptability Rating: Average

13. Community Acceptability Rating: Better

SOLIDIFICATION/STABILIZATION:

Contaminants are physically bound or enclosed within a stabilized mass (solidification), or chemical reactions are induced between the stabilizing agent and contaminants to reduce their mobility (stabilization). ***Ex situ* solidification/stabilization is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Environmental conditions may affect the long-term immobilization of contaminants.
- Some processes result in a significant increase in volume (up to double the original volume).
- Certain wastes are incompatible with different processes. Treatability studies may be required.

The target contaminant group for *ex situ* solidification/stabilization is inorganics (7). The technology has limited effectiveness against halogenated and non-halogenated semivolatile organic compounds and pesticides (2, 4, and 6). However, systems designed to be more effective against organic contaminants are being developed and tested. *Ex situ* solidification/stabilization is relatively simple, uses readily available equipment, and has high throughput rates compared to other technologies. As an *ex situ* remedy, the excavation associated with solidification/stabilization poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. Overall Cost **Rating: Better**

Ex situ solidification/stabilization processes are among the most mature remediation technologies. Representative overall costs from more than a dozen vendors indicate an approximate cost of under \$100/ton (\$110/metric ton), including excavation.

2. Capital (Cap) or O&M Intensive? **Capital**

3. Commercial Availability **Rating: Better**

4. Typically Part of a Treatment Train? **No**

Ex situ solidification/stabilization is generally considered a stand-alone technology. However, it is often used in combination with other technologies, such as solvent extraction, bioremediation, soil washing, and soil vapor extraction.

5. Residuals Produced (Solid, Liquid, Vapor) **Solid**

Depending upon the original contaminants and the chemical reactions that take place in the *ex situ* solidification/stabilization process, the resultant stabilized mass may have to be handled as a hazardous waste.

6. Minimum Contaminant Concentration Achievable **Rating: Not Applicable**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Mobility**

Ex situ solidification/stabilization processes have demonstrated capability to reduce the mobility of contaminated waste by greater than 95%.

8. Long-Term Effectiveness/Permanence? **Inadequate Information**

9. Time To Complete Cleanup **Rating: Better**

Remediation of the "standard" site consisting of 20,000 tons (18,200 metric tons) would require less than 1 month.

10. System Reliability/Maintainability **Rating: Better**

11. Awareness of Remediation Consulting Community **Rating: Better**

12. Regulatory/Permitting Acceptability **Rating: Average**

While CERCLA includes preference for treatment of contaminants, solidification/stabilization technologies generally face minimal difficulty in obtaining the necessary regulatory/permitting approvals and have been selected for use at many Superfund sites.

13. Community Acceptability **Rating: Average**

Public resistance to most solidification/stabilization technologies has been minimal and the technology is normally accepted.

DEHALOGENATION (GLYCOLATE):

An alkaline polyethylene glycolate (APEG) reagent is used to dehalogenate halogenated aromatic compounds in a batch reactor. Potassium Polyethylene Glycolate (KPEG) is the most common APEG reagent. Contaminated soils and the reagent are mixed and heated in a treatment vessel. In the APEG process, the reaction causes the polyethylene glycol to replace halogen molecules and render the compound non-hazardous. For example, the reaction between chlorinated organics and KPEG causes replacement of a chlorine molecule and results in a reduction in toxicity. **Dehalogenation (glycolate) is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The technology is generally not cost effective for large waste volumes.
- Media water content above 20% requires excessive reagent volume.
- Concentrations of chlorinated organics greater than 5% require large volumes of reagent.
- The resultant soil has poor physical characteristics.

The target contaminant groups for glycolate dehalogenation are halogenated semivolatile organic compounds and pesticides (2 and 6). The technology can be used but may be less effective against selected halogenated volatile organic compounds (1). APEG dehalogenation is one of the few processes available other than incineration that has been successfully field tested in treating PCBs. The technology is amenable to small-scale applications. As an *ex situ* remedy, the excavation associated with dehalogenation (APEG/KPEG) poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. Overall Cost **Rating: Worse**

2. Capital (Cap) or O&M Intensive? **Both**

3. Commercial Availability **Rating: Average**

4. Typically Part of a Treatment Train? **No**

Dehalogenation (APEG/KPEG) is generally considered a stand-alone technology. However, it can be used in combination with other technologies.

5. Residuals Produced (Solid, Liquid, Vapor) **Liquid**

Treatment of the wastewater generated by the process may include chemical oxidation, biodegradation, carbon adsorption, or precipitation.

6. Minimum Contaminant Concentration Achievable **Rating: Better**

Dehalogenation (glycolate) has been used to successfully treat contaminant concentrations of PCBs from less than 2 mg/kg to reportedly as high as 45,000 mg/kg.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Rating: Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

9. Time To Complete Cleanup **Rating: Worse**

10. System Reliability/Maintainability **Rating: Worse**

11. Awareness of Remediation Consulting Community **Rating: Average**

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Average**

The technology has greater public acceptance than incineration.

DEHALOGENATION (BASE-CATALYZED DECOMPOSITION):

Contaminated soil is screened, processed with a crusher and pug mill, and mixed with sodium bicarbonate. The mixture is heated at 630°F (333°C) in a rotary reactor to decompose and partially volatilize the contaminants. **Dehalogenation (BCD) is a full-scale technology.** However, it has had very limited use.

The following factors may limit the applicability and effectiveness of the process:

- If the influent matrix includes heavy metals and certain non-halogenated volatiles, they will not be destroyed by the process.
- High clay and moisture content will increase treatment costs.

The target contaminant groups for dehalogenation (BCD) are halogenated semivolatile organic compounds and pesticides (2 and 6). The technology can be used to treat halogenated volatile organic compounds (1), but may be less effective and applicable to only some compounds within this group. The dehalogenation (BCD) process was developed by EPA's Risk Reduction Engineering Laboratory (RREL), in cooperation with the Naval Civil Engineering Laboratory (NCEL), as a clean, inexpensive way to remediate soils and sediments contaminated with chlorinated organic compounds, especially PCBs. As an *ex situ* remedy, the excavation associated with dehalogenation (BCD) poses a potential health and safety risk to site workers, through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. Overall Cost **Rating: Inadequate Information**

Use of this technology has been so limited that no reliable data on cost are available.

2. Capital (Cap) or O&M Intensive? **Rating: Inadequate Information**

3. Commercial Availability **Rating: Worse**

As of November 1992, no U.S. vendors were licensed to use the technology.

4. Typically Part of a Treatment Train? **No**

Dehalogenation (BCD) is generally considered a stand-alone technology. However, it can be used in combination with other technologies.

5. Residuals Produced (Solid, Liquid, Vapor) **Vapor**

6. Minimum Contaminant Concentration Achievable **Rating: Inadequate Information**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

9. Time To Complete Cleanup Rating: Inadequate Information

10. System Reliability/Maintainability Rating: Inadequate Information

11. Awareness of Remediation Consulting Community Rating: Worse

12. Regulatory/Permitting Acceptability Rating: Inadequate Information

13. Community Acceptability Rating: Inadequate Information

SOLVENT EXTRACTION:

Waste and solvent are mixed in an extractor, dissolving into the solvent. The extracted organics and solvent are then placed in a separator, where the contaminants and solvent are separated for treatment and further use. **Solvent extraction is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Organically bound metals can be extracted along with the target organic pollutants, which restricts handling of the residuals.
- The presence of detergents and emulsifiers can unfavorably influence the extraction performance.
- Traces of solvent may remain in the treated solids; the toxicity of the solvent is an important consideration.
- Solvent extraction is generally least effective on very high molecular weight organic and very hydrophilic substances.
- Some soil types and moisture content levels will adversely impact process performance.

The target contaminant groups for solvent extraction are halogenated and non-halogenated semivolatile organic compounds and pesticides (2, 4, and 6). The technology can be used to treat halogenated and non-halogenated volatile organic compounds, and fuels (1, 3, and 5), but it may be less effective and may be applicable to only some compounds in these groups. As an *ex situ* remedy, the excavation associated with solvent extraction poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. **Overall Cost** **Rating: Worse**

2. **Capital (Cap) or O&M Intensive?** **Both**

3. **Commercial Availability** **Rating: Average**

4. **Typically Part of a Treatment Train?** **Yes**

   Solvent extraction is commonly used in combination with other technologies, such as solidification/stabilization, incineration, or soil washing, depending upon site-specific conditions. It also can be used as a stand-alone technology, in some instances.

5. **Residuals Produced (Solid, Liquid, Vapor)** **Liquid**

   Organically bound metals can be extracted along with the target organic contaminants, thereby creating residuals with special handling requirements. Traces of solvent may remain within the treated soil matrix, so the toxicity of the solvent is an important consideration.

6. **Minimum Contaminant Concentration Achievable** **Rating: Average**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Volume**

Solvent extraction does not destroy wastes, but is a means of separating the contaminants, thereby reducing the volume of hazardous waste to be treated.

8. Long-Term Effectiveness/Permanence? **Yes**

The treated media is usually returned to the site after having met Best Demonstrated Available Technology (BDAT) and other standards.

9. Time To Complete Cleanup **Rating: Worse**

10. System Reliability/Maintainability **Rating: Average**

11. Awareness of Remediation Consulting Community **Rating: Average**

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Average**

With enclosed systems and dust control measures during soil (feed) preparation, solvent extraction appears to pose little threat to the community.

CHEMICAL REDUCTION/OXIDATION:

Reduction/oxidation chemically converts hazardous contaminants to non-hazardous or less toxic compounds that are more stable, less mobile, and/or inert. The reducing/oxidizing agents most commonly used for treatment of hazardous contaminants are ozone, hydrogen peroxide, hypochlorites, chlorine, and chlorine dioxide. A combination of these reagents, or combining them with ultraviolet (UV) oxidation, makes the process more effective. **Chemical reduction/oxidation is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Incomplete oxidation or formation of intermediate contaminants may occur depending upon the contaminants and oxidizing agents used.
- The process is not cost effective for high contaminant concentrations due to the large amounts of oxidizing agent required.
- Oil and grease in the media should be minimized to optimize process efficiency.

The target contaminant group for chemical reduction/oxidation is inorganics (7). The technology can be used but may be less effective against non-halogenated volatile and semivolatile organic compounds, fuel hydrocarbons, and pesticides (3, 4, 5, and 6). As an *ex situ* remedy, the excavation associated with chemical reduction/oxidation poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. Overall Cost	**Rating: Average**
2. Capital (Cap) or O&M Intensive?	**Neither**
3. Commercial Availability	**Rating: Better**
4. Typically Part of a Treatment Train?	**Yes**
5. Residuals Produced (Solid, Liquid, Vapor)	**Solid**
6. Minimum Contaminant Concentration Achievable	**Rating: Not Applicable**
7. Addresses Toxicity (T), Mobility (M), or Volume (V)?	**Toxicity, Mobility**

Oxidation chemically converts inorganics to non-hazardous or less toxic compounds that are more stable, less mobile, or inert.

8. Long-Term Effectiveness/Permanence?	**Inadequate Information**
9. Time To Complete Cleanup	**Rating: Better**
10. System Reliability/Maintainability	**Rating: Better**

11. Awareness of Remediation Consulting Community **Rating: Average**

Chemical reduction/oxidation is a well established technology used for disinfection of drinking water and wastewater, and is a common treatment for cyanide wastes. Enhanced systems are now being used more frequently to treat hazardous wastes in soils.

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Average**

SOIL VAPOR EXTRACTION (SVE):

A vacuum is applied to a network of above-ground piping to encourage volatilization of organics from the excavated media. The process includes a system for handling off-gases. The process is very similar to *in situ* SVE. ***Ex situ* SVE is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- High humic content of soil inhibits volatilization.
- The technology is incompatible with certain soil types.

The target contaminant groups for *ex situ* SVE are halogenated and non-halogenated volatile organic compounds (1 and 3). An advantage of the technology over its *in situ* counterpart is the increased number of passageways formed via the excavation process. However, as an *ex situ* remedy, the excavation associated with SVE poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. Overall Cost **Rating: Better**

The overall cost for *ex situ* SVE is under $100/ton ($110/metric ton), including the cost of excavation, but excluding treatment of off-gases and collected groundwater.

2. Capital (Cap) or O&M Intensive? **Neither**

3. Commercial Availability **Rating: Better**

4. Typically Part of a Treatment Train? **No**

5. Residuals Produced (Solid, Liquid, Vapor) **Liquid**

6. Minimum Contaminant Concentration Achievable **Rating: Average**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Volume**

8. Long-Term Effectiveness/Permanence? **Yes**

Assuming the characteristics of the treated soil allow for the effective use of *ex situ* SVE, the remediation of the targeted contaminants is permanent.

9. Time To Complete Cleanup **Rating: Average**

The time required to remediate a site using *ex situ* SVE is highly dependent upon the specific soil and chemical properties of the contaminated media. Cleanup of the "standard" site consisting of 20,000 tons (18,200 metric tons) of contaminated media would require 12-36 months.

10. System Reliability/Maintainability **Rating: Better**

Generally, most of the hardware components are relatively well developed with repair parts readily available to minimize downtime. Typical *ex situ* SVE systems can be left unattended for long periods of time.

11. Awareness of Remediation Consulting Community **Rating: Better**

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Average**

LOW TEMPERATURE THERMAL DESORPTION:

Wastes are heated from 200°-600°F (93°-315°C) to volatilize water and organic contaminants. A carrier gas or vacuum system transports volatilized water and organics to the gas treatment system. Low temperature thermal desorption systems are physical separation processes and are not designed to destroy organics. The bed temperatures and residence times designed into these systems will volatilize selected contaminants, but typically not oxidize them. **Low temperature thermal desorption is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- There are specific feed size and materials handling requirements that can impact applicability or cost at specific sites.
- Dewatering may be necessary to achieve acceptable soil moisture content levels.
- Highly abrasive feed potentially can damage the processor unit.

The target contaminant groups for low temperature thermal desorption systems are halogenated and non-halogenated volatile organic compounds and fuels (1, 3, and 5). The technology can be used to treat halogenated and non-halogenated semivolatile organic compounds and pesticides (2, 4, and 6) but may be less effective. As an *ex situ* remedy, the excavation associated with low temperature thermal desorption poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. Overall Cost **Rating: Better**

Approximate overall cost is less than $100/ton ($110/metric ton). Low temperature thermal desorption is relatively labor intensive. The skill and training level required for most of the operating personnel is minimal.

2. Capital (Cap) or O&M Intensive? **Both**

3. Commercial Availability **Rating: Better**

There are at least five vendors actively promoting the technology and most of the hardware components for low temperature thermal desorption systems are readily available off the shelf. The engineering and configuration of the systems are similarly refined, such that once a full-scale system is designed, little or no prototyping is required.

4. Typically Part of a Treatment Train? **Yes**

Low temperature thermal desorption is frequently used in combination with incineration, solidification/stabilization, or dechlorination, depending upon site-specific conditions.

5. Residuals Produced (Solid, Liquid, Vapor) **Liquid**

6. Minimum Contaminant Concentration Achievable **Rating: Better**

The technology has proven it can produce a final contaminant concentration level below 5 mg/kg for the target contaminants identified.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Volume**

8. Long-Term Effectiveness/Permanence? **Yes**

Treatment using low temperature thermal desorption is considered to be permanent.

9. Time To Complete Cleanup **Rating: Better**

Cleanup of the "standard" site consisting of 20,000 tons (18,200 metric tons) would require less than 2 months.

10. System Reliability/Maintainability **Rating: Average**

Daily maintenance checks are required for all thermal desorption technologies. Generally, most of the hardware components are relatively well developed with repair parts readily available to minimize downtime. Normal maintenance concerns include temperature control, waste feed system, dust and particulate collection, and fouling of the heat transfer surfaces with polymers.

11. Awareness of Remediation Consulting Community **Rating: Better**

Low temperature thermal desorption systems have been demonstrated in the EPA SITE Demonstration Program.

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Average**

HIGH TEMPERATURE THERMAL DESORPTION:

Wastes are heated to 600°-1,000°F (315°-538°C) to volatilize water and organic contaminants. A carrier gas or vacuum system transports volatilized water and organics to the gas treatment system. High temperature thermal desorption systems are physical separation processes and are not designed to destroy organics. Bed temperatures and typical residence times will cause selected contaminants to volatilize, but not oxidize. **High temperature thermal desorption is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- There are specific feed size and materials handling requirements that can impact applicability or cost at specific sites.
- Dewatering may be necessary to achieve acceptable soil moisture content levels.
- Highly abrasive feed can potentially damage the processor unit.

High temperature thermal desorption systems have varying degrees of effectiveness against the full spectrum of organic contaminants. The target contaminants are halogenated and non-halogenated semivolatile organic compounds, and pesticides (2, 4, and 6). Halogenated and non-halogenated volatiles and fuels (1, 3, and 5) also may be treated, but treatment may be less effective. As an *ex situ* remedy, the excavation associated with high temperature thermal desorption poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations.

1. **Overall Cost** **Rating: Average**

   Approximate overall cost is between $100 and $300/ton ($110 and $330/metric ton).

2. **Capital (Cap) or O&M Intensive?** **Both**

3. **Commercial Availability** **Rating: Better**

   There are at least five vendors actively promoting the technology and most of the hardware components for high temperature thermal desorption systems are readily available off the shelf. The engineering and configuration of the systems are similarly refined, such that once a full-scale system is designed, little or no prototyping is required.

4. **Typically Part of a Treatment Train?** **Yes**

   High temperature thermal desorption is frequently used in combination with incineration, solidification/stabilization, or dechlorination, depending upon site-specific conditions.

5. **Residuals Produced (Solid, Liquid, Vapor)** **Liquid**

6. Minimum Contaminant Concentration Achievable **Rating: Better**

The technology has proven it can produce a final contaminant concentration level below 5 mg/kg for the target contaminants identified.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Volume**

8. Long-Term Effectiveness/Permanence? **Yes**

Treatment using high temperature thermal desorption is considered to be permanent.

9. Time To Complete Cleanup **Rating: Better**

The time to complete cleanup of the "standard" 20,000-ton (18,200-metric ton) site using high temperature thermal desorption is just over 4 months.

10. System Reliability/Maintainability **Rating: Average**

Daily maintenance checks are required for all thermal desorption technologies. Generally, most of the hardware components are relatively well developed with repair parts readily available to minimize downtime. Normal maintenance concerns include temperature control, waste feed system, dust and particulate collection, and fouling of the heat transfer surfaces with polymers.

11. Awareness of Remediation Consulting Community **Rating: Average**

High temperature thermal desorption has been demonstrated in the EPA SITE Demonstration Program.

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Average**

VITRIFICATION:

Contaminated soils and sludges are melted at high temperature to form a glass and crystalline structure with very low leaching characteristics. Non-volatile inorganic elements are encapsulated in a vitreous slag while organic contaminants are destroyed by pyrolysis. ***Ex situ* vitrification is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Organic and inorganic off-gases need to be controlled.
- Use or disposal of the resultant vitrified slag is required.
- Accessibility to a sufficient power supply is needed.

Ex situ vitrification is applicable to the full range of contaminant groups, but inorganics (7) is the target contaminant group. Metals are encapsulated in the vitrified mass, resisting leaching for geologic time periods. The excavation associated with *ex situ* vitrification poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations. The high energy required for the *ex situ* vitrification process also is a health and safety concern when using the technology.

1. Overall Cost **Rating: Worse**

Approximate overall cost is $700/ton ($770/metric ton). *Ex situ* vitrification is a relatively complex, high-energy technology requiring a high degree of specialized skill and training.

2. Capital (Cap) or O&M Intensive? **Both**

3. Commercial Availability **Rating: Average**

Five vendors are known to be actively promoting their own proprietary *ex situ* vitrification technology processes.

4. Typically Part of a Treatment Train? **No**

Ex situ vitrification is normally considered a stand-alone technology. However, its potential for use in treating the solid residuals from other technologies, such as incinerator ash, is receiving increasing attention.

5. Residuals Produced (Solid, Liquid, Vapor) **Liquid**

6. Minimum Contaminant Concentration Achievable **Rating: Not Applicable**

Vitrification is designed to encapsulate target contaminants, rather than reduce contaminant concentrations. However, destruction of.the organic contaminants present in the treated media does occur because of temperatures achieved in the process.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? Mobility

Ex situ vitrification is most effective in reducing the mobility of the contaminated wastes within the media. The vitrified mass has high resistance to leaching and possess strength properties better than those of concrete. The monolith formed has hydration properties similar to those of obsidian, which hydrates at rates of less than 1 mm/10,000 years.

8. Long-Term Effectiveness/Permanence? Yes

Studies indicate that the glass and crystalline product of *ex situ* vitrification permanently immobilizes hazardous inorganics and will retain its physical and chemical integrity for geologic time periods.

9. Time To Complete Cleanup Rating: Average

10. System Reliability/Maintainability Rating: Average

11. Awareness of Remediation Consulting Community Rating: Average

12. Regulatory/Permitting Acceptability Rating: Worse

13. Community Acceptability Rating: Worse

INCINERATION:

High temperatures, 1,600°-2,200°F (871°-1,204°C), are used to volatilize and combust (in the presence of oxygen) organic constituents in hazardous wastes. Four common incinerator designs are rotary kiln, liquid injection, fluidized bed, and infrared incinerators. The destruction and removal efficiency (DRE) for properly operated incinerators often exceeds the 99.99% requirement for hazardous waste and can be operated to meet the 99.9999% requirement for PCBs and dioxins. **All four incinerator types have been used successfully at full scale.**

The following factors may limit the applicability and effectiveness of the process:

- There are specific feed size and materials handling requirements that can impact applicability or cost at specific sites.
- The presence of volatile metals and salts may affect performance or incinerator life.
- Volatile metals, including lead and arsenic, leave the combustion unit with the flue gases or in bottom ash and may have to be removed prior to incineration.
- Metals can react with other elements in the feed stream, such as chlorine or sulfur, forming more volatile and toxic compounds than the original species.
- Sodium and potassium can attack the brick lining and form a sticky particulate that fouls heat transfer surfaces.

The target contaminant groups for incineration are all halogenated and non-halogenated semivolatile organic compounds and pesticides (2, 4, and 6). The technology also may be used to treat halogenated and non-halogenated volatile organics and fuels (1, 3, and 5) but may be less effective. As an *ex situ* remedy, the excavation associated with incineration poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations. If an off-site incinerator is used, the potential risk of transporting the hazardous waste through the community must be considered.

1. Overall Cost — Rating: Worse

Incineration costs are highly dependent upon the size of the contaminated site and the type of incinerator technology used. The cost to incinerate approximately 20,000 tons (18,200 metric tons) of contaminated media would be greater than $300/ton ($330/metric ton).

2. Capital (Cap) or O&M Intensive? — Both

The capital expenditures associated with incinerators is relatively high. Materials handling, control of bed temperatures and residence times, and system maintenance make the technology O&M-intensive as well.

3. Commercial Availability — Rating: Better

Incineration is one of the most mature remediation technologies and its use at Superfund sites is increasing. There are well over a dozen mobile, transportable, or off-site incinerator vendors, and as many or more incinerator manufacturers.

4. Typically Part of a Treatment Train? **No**

Incineration is normally considered a stand-alone technology. However, incineration can be used in combination with other technologies, such as soil washing, thermal desorption, and solvent extraction, depending upon site-specific conditions.

5. Residuals Produced (Solid, Liquid, Vapor) **Liquid, Solid**

6. Minimum Contaminant Concentration Achievable **Rating: Better**

The technology has proven it can produce a final contaminant concentration level below 5 mg/kg for the target contaminants identified.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Toxicity**

Incinerators primarily reduce toxicity by destroying the contaminants, but the process also accomplishes volume reduction.

8. Long-Term Effectiveness/Permanence? **Yes**

The result of incineration is the destruction of organic wastes, permanently reducing the risk to human health and the environment.

9. Time To Complete Cleanup **Rating: Better**

The time to complete cleanup of the "standard" 20,000-ton (18,200-metric ton) site using incineration would be less than 3 months.

10. System Reliability/Maintainability **Rating: Average**

Daily maintenance checks are required for all incinerator designs. Generally, most of the hardware components are relatively well developed and repair parts are readily available to minimize downtime. Normal maintenance concerns include temperature control, waste feed system, dust and particulate collection, and fouling of the heat transfer surfaces.

11. Awareness of Remediation Consulting Community **Rating: Better**

12. Regulatory/Permitting Acceptability **Rating: Average**

Incineration, primarily off-site, has been selected or used as the remedial action at more than 150 Superfund sites. Incineration is subject to a series of technology-specific regulations, including the following federal requirements: CAA (Air Emissions), TSCA (PCB Treatment and Disposal), NEPA (HW Generation, Treatment, Storage and Disposal), NPDES (Discharge to Surface Waters), NCA (Noise), and RCRA (Emissions).

13. Community Acceptability **Rating: Worse**

PYROLYSIS:

Chemical decomposition is induced in organic materials by heat in the absence of oxygen. Organic materials are transformed into gaseous components and a solid residue (coke) containing fixed carbon and ash. **Pyrolysis is currently pilot scale.**

The following factors may limit the applicability and effectiveness of the process:

- There are specific feed size and materials handling requirements that impact applicability or cost at specific sites.
- The technology requires a low soil moisture content.
- Highly abrasive feed can potentially damage the processor unit.

The target contaminant groups for pyrolysis are all halogenated and non-halogenated semivolatile organic compounds and pesticides (2, 4, and 6). The technology also may be used to treat halogenated and non-halogenated volatile organics and fuels (1, 3, and 5) but may be less effective. As an *ex situ* remedy, the excavation associated with pyrolysis poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, normally would be required during excavation operations.

1. **Overall Cost** **Rating: Worse**

   Overall cost for remediating approximately 20,000 tons (18,200 metric tons) of contaminated media is expected to exceed $300/ton ($330/metric ton).

2. **Capital (Cap) or O&M Intensive?** **Both**

3. **Commercial Availability** **Rating: Worse**

   Pyrolysis is in the early stages of development.

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)** **Solid, Liquid**

6. **Minimum Contaminant Concentration Achievable** **Rating: Better**

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Toxicity**

   Pyrolysis primarily reduces toxicity by destroying the contaminants.

8. **Long-Term Effectiveness/Permanence?** **Yes**

   The result of pyrolysis is the destruction of the target contaminated wastes, which permanently reduces the risk to human health and the environment.

9. Time To Complete Cleanup — Rating: Better

10. System Reliability/Maintainability — Rating: Inadequate Information

11. Awareness of Remediation Consulting Community — Rating: Worse

Pyrolysis is still relatively unknown due to its early stage of development.

12. Regulatory/Permitting Acceptability — Rating: Average

13. Community Acceptability — Rating: Worse

NATURAL ATTENUATION:

Natural subsurface processes—such as dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface materials—are allowed to reduce contaminant concentrations to acceptable levels.
Natural attenuation is not a "technology" per se, and there is significant debate among technical experts about its use at hazardous waste sites. Consideration of this option requires modeling and evaluation of contaminant degradation rates to determine feasibility, and special approvals may be needed. In addition, sampling and sample analysis must be conducted throughout the process to confirm that degradation is proceeding at rates consistent with meeting cleanup objectives. It has been included in the *Matrix* and this *Guide* for completeness only.

Natural attenuation is not the same as "no action," although it often is perceived as such. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) requires evaluation of a "no action" alternative, but does not require evaluation of natural attenuation. Natural attenuation is considered in the Superfund program on a case-by-case basis, and guidance on its use is still evolving. It has been selected at Superfund sites where, for example, PCBs are strongly sorbed to deep subsurface soils and are not migrating; where removal of dense non-aqueous phase liquids (DNAPLs) has been determined to be technically impracticable (Superfund is developing technical impracticability (TI) guidance); and where it has been determined that active remedial measures would be unable to significantly speed remediation time frames. Where contaminants are expected to remain in place over long periods of time, as in the first two examples, TI waivers must be obtained. In all cases, extensive site characterization is required.

The attitude toward natural attenuation varies among agencies. The Air Force carefully evaluates the potential for use of natural attenuation at its sites. However, EPA accepts its use only in certain special cases.

Natural attenuation involves no excavation or handling of contaminated materials. Therefore, site workers require no protective equipment and there is no risk to the community from excavation and transportation of contaminated materials. There are potential risks, however, from migration of contaminants to areas where groundwater is being used.

The following factors may limit the applicability and effectiveness of the process:

- Data must be collected to determine model input parameters.
- Although commercial services for evaluating natural attenuation are widely available, the quality of these services varies widely among the many potential suppliers. Highly skilled modelers are required.
- Intermediate degradation products may be more mobile and more toxic than the original contaminant.
- Natural attenuation should be used only where there are no impacts on potential receptors.
- Contaminants may migrate before they are degraded.
- The site may have to be fenced and may not be available for re-use until contaminant levels are reduced.
- If free product exists, it may have to be removed.
- Some inorganics can be immobilized, such as mercury, but they will not be degraded.

Target contaminants for natural attenuation are non-halogenated volatile and semivolatile organics and fuel hydrocarbons (groups 3, 4, and 5). Halogenated volatiles and semivolatiles and pesticides (1, 2, and 6) also can be allowed to naturally attenuate, but the process may be less effective and may only be applicable to some compounds within these contaminant groups.

1. **Overall Cost** **Rating: Better**

   There are no capital or O&M costs associated with natural attenuation. However, there are costs for modeling contamination degradation rates to determine whether natural attenuation is a feasible remedial alternative, and there are costs for subsurface sampling and sample analysis (potentially extensive) to determine the extent of contamination and confirm contaminant degradation rates and cleanup status. Skilled labor hours are required to conduct the modeling, sampling, and analysis.

2. **Capital (Cap) or O&M Intensive?** **Neither**

3. **Commercial Availability:** **Rating: Better**

   Many potential suppliers can perform the modeling, sampling, and sample analysis required for justifying and monitoring natural attenuation. However, the quality of services provided varies widely.

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)?** **None**

6. **Minimum Contaminant Concentration Achievable:** **Rating: Inadequate Information**

   The extent of contaminant degradation depends on a variety of parameters, such as contaminant types and concentrations, temperature, moisture, and availability of nutrients/electron acceptors (e.g., oxygen, nitrate).

7. **Addresses Toxicity, Mobility, or Volume?** **Toxicity**

8. **Long-Term Effectiveness/Permanence?** **Yes**

9. **Time To Complete Cleanup:** **Rating: Worse**

   Natural attenuation does not involve active remedial measures. Subsurface environments are often oxygen limited in regards to the needs of microorganisms that can degrade organic contaminants. Without active measures to increase the oxygen supply (or supply of other electron acceptors), biodegradation can be slow.

10. **System Reliability/Maintainability:** **Rating: Better**

    Natural attenuation requires no equipment to maintain.

11. Awareness of the Remediation Consulting Community: Rating: Average

A large amount of information is available on subsurface processes that affect contaminant transport and transformation. In addition, subsurface transport and fate models are available to estimate times required for natural attenuation to attain cleanup goals. However, natural attenuation is considered a viable alternative only for a limited number of contaminated sites.

12. Regulatory/Permitting Acceptability: Rating: Worse

Because it involves no active remedial measures, natural attenuation is not well accepted by the regulatory community. However, regulatory/permitting acceptance may be possible where alternative remedial options are technically or economically infeasible and where a very strong scientific case can be made predicting its success and protectiveness.

13. Community Acceptability: Rating: Worse

The public generally prefers active remedial alternatives.

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EXCAVATION AND OFF-SITE DISPOSAL:

Contaminated material is removed and transported to permitted off-site treatment and/or disposal facilities. Some pre-treatment of the contaminated media usually is required in order to meet land disposal restrictions. Excavation and off-site disposal is applicable to the complete range of contaminant groups (1-7) with no particular target group. Although excavation and off-site disposal alleviates the contaminant problem at the site, it does not treat the contaminants.

The following factors may limit the applicability and effectiveness of the process:

- Generation of fugitive emissions may be a problem during operations.
- The distance from the contaminated site to the nearest disposal facility will affect cost and may affect community acceptability.
- Depth and composition of the media requiring excavation must be considered.
- Applicable Land Ban Restrictions must be considered.

The type of contaminant and its concentration level will impact off-site disposal requirements. Most hazardous wastes must be treated to meet either RCRA or non-RCRA treatment standards prior to land disposal. Excavation poses a potential health and safety risk to site workers through skin contact and air emissions. Personal protective equipment, at a level commensurate with the contaminants involved, is normally required during excavation operations. Additionally, transportation to the off-site facility introduces a potential risk to the community via accidental releases.

1. **Overall Cost** **Rating: Worse**

   Cost estimates for excavation and disposal range from $272 to $463/ton ($300 to $510/metric ton). These estimates include excavation/removal, transportation, and disposal at a RCRA permitted facility. Excavation and off-site disposal is a relatively simple process, with proven procedures. It is a labor-intensive practice with little potential for further automation.

2. **Capital (Cap) or O&M Intensive?** **Neither**

   No capital investment is required and once disposal is completed, no O&M costs are incurred.

3. **Commercial Availability** **Rating: Better**

   Several manufacturers produce heavy equipment and hazardous waste transport containers.

4. **Typically Part of a Treatment Train?** **No**

   Excavation and off-site disposal is considered a stand-alone remediation option. Excavation also is an integral first step in the use of many treatment technologies.

5. **Residuals Produced (Solid, Liquid, Vapor)** **Not Applicable**

6. Minimum Contaminant Concentration Achievable **Rating: Not Applicable**

This process does not treat the contaminants. However, some pre-treatment of the contaminated media usually is required before approval is granted for off-site disposal.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Mobility**

The mobility of the contaminated media is reduced. This is accomplished by moving the media from the unsecured site to a disposal facility that will physically contain it.

8. Long-Term Effectiveness/Permanence? **No**

Since excavation and off-site disposal does not treat the contaminants, no long-term effectiveness or permanence is achieved without some other additional treatment.

9. Time To Complete Cleanup **Rating: Better**

The excavation of 20,000 tons (18,200 metric tons) of contaminated soil would require about 2 months. Disposal of the contaminated media is dependant upon the availability of adequate containers to transport the hazardous waste to a RCRA permitted facility.

10. System Reliability/Maintainability **Rating: Better**

Adequately maintained heavy earth moving equipment has a minimal probability of failure.

11. Awareness of Remediation Consulting Community **Rating: Better**

Prior to 1984, excavation and off-site disposal was the most common method for cleaning up hazardous waste sites. Excavation is the initial component in *ex situ* treatments. As a consequence, the remediation consulting community is very familiar with this remediation option.

12. Regulatory/Permitting Acceptability **Rating: Worse**

CERCLA includes a statutory preference for treatment of contaminants, and excavation and off-site disposal is now less acceptable than in the past. The disposal of hazardous wastes is governed by the Resource Conservation and Recovery Act (RCRA) (40 CFR Parts 261-265), and the U.S. Department of Transportation regulates the transport of hazardous materials (49 CFR Parts 172-179, 49 CFR Part 1387, and DOT-E 8876).

13. Community Acceptability **Rating: Better**

Groundwater

OXYGEN ENHANCEMENT WITH HYDROGEN PEROXIDE:

A dilute solution of hydrogen peroxide is circulated throughout a contaminated groundwater zone to increase the oxygen content of groundwater and enhance the rate of aerobic degradation of organic contaminants by naturally occurring microbes. For best results, factors that must be considered include redox conditions, saturation rates, presence of nutrient trace elements, pH, temperature, and permeability of the subsurface materials. **Oxygen enhancement with hydrogen peroxide is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- A groundwater circulation system must be created so that contaminants do not escape from zones of active biodegradation.
- Where the subsurface is heterogeneous, it is very difficult to circulate the hydrogen peroxide solution throughout every portion of the contaminated zone. Higher permeability zones are cleaned up much faster because groundwater flow rates are greater.
- High iron content of subsurface materials can rapidly reduce concentrations of hydrogen peroxide.
- Amended hydrogen peroxide can be consumed very rapidly near the injection well, which creates two significant problems: biological growth can be limited to the region near the injection well, limiting adequate contamination/microorganism contact throughout the contaminated zone; and biofouling of wells can retard the input of nutrients.
- A surface treatment system, such as air stripping or carbon adsorption, may be required to treat extracted groundwater prior to re-injection or disposal.

Oxygen enhancement with hydrogen peroxide is primarily designed to treat non-halogenated volatile and semivolatile organics and fuel hydrocarbons (3, 4, and 5). Halogenated volatiles and semivolatiles and pesticides (1, 2, and 6) also can be treated, but the process may be less effective and only applicable to some compounds within these groups.

1. **Overall Cost** **Rating: Average**

2. **Capital (Cap) or O&M Intensive?** **O&M**

   O&M costs can be significant because a continuous source of hydrogen peroxide must be delivered to the contaminated groundwater.

3. **Commercial Availability:** **Rating: Better**

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)?** **None**

6. Minimum Contaminant Concentration Achievable: **Rating: Better**

As with other biological treatments, under proper conditions, oxygen enhancement with hydrogen peroxide can completely transform contaminants into non-hazardous substances.

7. Addresses Toxicity, Mobility, or Volume? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

Enhancement of biological degradation with hydrogen peroxide can permanently destroy selected organic contaminants.

9. Time To Complete Cleanup: **Rating: Average**

As with all biodegradation processes, remediation projects are highly dependent upon the specific soil and chemical properties of the contaminated media.

10. System Reliability/Maintainability: **Rating: Worse**

Maintenance of sufficient hydrogen peroxide concentrations to promote biological activity throughout contaminated zones has proven to be very difficult.

11. Awareness of the Remediation Consulting Community: **Rating: Better**

12. Regulatory/Permitting Acceptability: **Rating: Average**

13. Community Acceptability: **Rating: Better**

Communities generally prefer *in situ* remedies because the possibility of contaminant releases is greatly reduced. In addition, this technology can permanently destroy groundwater contaminants.

CO-METABOLIC PROCESSES:

Water containing dissolved methane and oxygen is injected into groundwater to enhance methanotrophic biological degradation. This class of microorganisms can degrade chlorinated solvents, such as vinyl chloride and TCE, by co-metabolism. Co-metabolism is one form of secondary substrate transformation in which enzymes produced for primary substrate oxidation are capable of degrading the secondary substrate fortuitously, even though the secondary substrates do not afford sufficient energy to sustain the microbial population. **Development of co-metabolic processes is at the pilot scale.**

While development of *ex situ* bioreactors for methanotrophic TCE biodegradation is progressing well, *in situ* application has not yet been demonstrated at a practical scale. A field demonstration project has been conducted at DOD's Moffett Naval Air Station and another is being conducted at DOE's Savannah River Site.

The following factors may limit the applicability and effectiveness of the process:

- This technology is still under development.
- Where the subsurface is heterogeneous, it is very difficult to circulate the methane solution throughout every portion of the contaminated zone. Higher permeability zones are cleaned up much faster because groundwater flow rates are greater.

Target contaminants for co-metabolic processes are halogenated volatile and semivolatile organics (1 and 2). Non-halogenated organics, fuel hydrocarbons, and pesticides (3, 4, 5, and 6) also can be treated, but the process may be less effective and only applicable to some compounds within these groups.

1. **Overall Cost** — **Rating: Average**

2. **Capital (Cap) or O&M Intensive?** — **O&M**

   O&M costs can be significant because a continuous source of methane solution must be delivered to the contaminated groundwater.

3. **Commercial Availability:** — **Rating: Worse**

   The development of this technology is still at the pilot-scale level.

4. **Typically Part of a Treatment Train?** — **No**

5. **Residuals Produced (Solid, Liquid, Vapor)?** — **None**

6. **Minimum Contaminant Concentration Achievable:** — **Rating: Better**

   As with other biological treatments, this is highly dependent upon the biodegradability of the contaminants. Under proper conditions, co-metabolic processes can remove virtually all of selected contaminants.

7. **Addresses Toxicity, Mobility, or Volume?** — **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

Co-metabolic biodegradation can permanently destroy selected contaminants.

9. Time To Complete Cleanup: **Rating: Average**

10. System Reliability/Maintainability: **Rating: Worse**

This technology has not yet been demonstrated to be effective at full commercial scale.

11. Awareness of the Remediation Consulting Community: **Rating: Worse**

12. Regulatory/Permitting Acceptability: **Rating: Inadequate Information**

13. Community Acceptability: **Rating: Inadequate Information**

NITRATE ENHANCEMENT:

Solubilized nitrate is circulated throughout groundwater contamination zones to provide electron acceptors for biological activity and enhance the rate of degradation of organic contaminants by naturally occurring microbes. **Development of nitrate enhancement is still at the pilot scale.**

The following factors may limit the applicability and effectiveness of the process:

- This technology has been found to be effective on only a narrow spectrum of contaminants to date.
- Where the subsurface is heterogeneous, it is very difficult to circulate the nitrate solution throughout every portion of the contaminated zone. Higher permeability zones will be cleaned up much faster because groundwater flow rates are greater.

Target contaminants for the process are non-halogenated volatile and semivolatile organics and fuel hydrocarbons (3, 4, and 5). Nitrate enhancement has primarily been used to remediate groundwater contaminated by BTEX. Halogenated volatiles and semivolatiles and pesticides (1, 2, and 6) also should be treatable, but the process has had only limited use and the potential effectiveness and applicability to specific compounds in these groups is not known.

1. Overall Cost **Rating: Better**

The costs of supplying solubilized nitrate is less expensive than similar costs for hydrogen peroxide or methane solutions.

2. Capital (Cap) or O&M Intensive? **Neither**

3. Commercial Availability: **Rating: Worse**

4. Typically Part of a Treatment Train? **No**

5. Residuals Produced (Solid, Liquid, Vapor)? **None**

6. Minimum Contaminant Concentration Achievable: **Rating: Better**

As with other biological treatments, this is highly dependent upon the biodegradability of the contaminants. Under proper conditions, nitrate enhancement can remove virtually all of selected contaminants.

7. Addresses Toxicity, Mobility, or Volume? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

Nitrate enhancement can permanently destroy selected contaminants.

10. Time To Complete Cleanup: **Rating: Average**

As with other *in situ* biodegradation processes, the success of this technology is highly dependent upon soil and chemical properties.

10. System Reliability/Maintainability: **Rating: Average**

11. Awareness of the Remediation Consulting Community: **Rating: Worse**

12. Regulatory/Permitting Acceptability: **Rating: Worse**

Many states prohibit nitrate injection into groundwater because nitrate is regulated through Drinking Water Standards.

13. Community Acceptability: **Rating: Average**

Communities generally prefer *in situ* remedies because the possibility of contaminant release is minimal, and they prefer technologies that permanently destroy contaminants.

OXYGEN ENHANCEMENT WITH AIR SPARGING:

Air is injected under pressure below the water table to increase groundwater oxygen concentrations and enhance the rate of biological degradation of organic contaminants by naturally occurring microbes. Air sparging increases mixing in the saturated zone, which increases the contact between groundwater and soil. The ease and low cost of installing small-diameter air injection points allows considerable flexibility in the design and construction of a remediation system. **Oxygen enhancement with air sparging is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- A permeability differential, such as a clay layer, above the air injection zone can reduce the effectiveness of air sparging.
- Where vertical air flow is restricted due to the presence of less permeable strata, sparging can push contaminated groundwater away from the injection point. In these cases, a groundwater recovery system may be needed.
- Vapors may rise through the vadose zone and be released into the atmosphere.
- Since air sparging increases pressure in the vadose zone, vapors can build up in building basements, which are generally low pressure areas.

Oxygen enhancement with air sparging is primarily designed to treat non-halogenated volatile and semivolatile organics and fuel hydrocarbons (3, 4, and 5). Halogenated volatiles and semivolatiles and pesticides (1, 2, and 6) also can be treated, but the process may be less effective and only applicable to some compounds within these groups.

1. **Overall Cost** **Rating: Better**

   The technology employs the same concepts as bioventing, except that air is injected below the water table to promote the remediation of groundwater.

2. **Capital (Cap) or O&M Intensive?** **Neither**

   Equipment is readily available and the process is simple to operate. It does not require maintaining concentrations of chemical solutions in the subsurface to provide adequate electron acceptors for biological activity.

3. **Commercial Availability:** **Rating: Better**

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)?** **None**

6. Minimum Contaminant Concentration Achievable: **Rating: Better**

As with other biological treatments, this is highly dependent upon the biodegradability of the contaminants. Under proper conditions, air sparging can remove virtually all of selected contaminants.

7. Addresses Toxicity, Mobility, or Volume? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

Air sparging can permanently destroy selected contaminants.

9. Time To Complete Cleanup: **Rating: Average**

10. System Reliability/Maintainability: **Rating: Better**

11. Awareness of the Remediation Consulting Community: **Rating: Average**

Although oxygen enhancement with air sparging is relatively new, the related technology, bioventing, is rapidly receiving increased attention from remediation consultants.

12. Regulatory/Permitting Acceptability: **Rating: Average**

13. Community Acceptability: **Rating: Better**

Communities generally prefer *in situ* remedies because the possibility of contaminant release is minimal, and they prefer technologies that permanently destroy contaminants.

SLURRY WALLS (containment only):

These subsurface barriers consist of a vertically excavated trench that is filled with a slurry. The slurry, usually a mixture of bentonite and water, hydraulically shores the trench to prevent collapse and forms a filter cake to reduce groundwater flow. Slurry walls often are used where the waste mass is too large for practical treatment and where soluble and mobile constituents pose an imminent threat to a source of drinking water. **Slurry walls are a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The technology only contains the contaminants to a specific area.
- Soil-bentonite backfills are not able to withstand attack by strong acids, bases, salt solutions, and some organic chemicals.
- There is the potential for the slurry walls to degrade or deteriorate over time.

Slurry walls are applicable to the full range of contaminant groups (1-7), with no particular target group.

1. **Overall Cost** — **Rating: Better**

2. **Capital (Cap) or O&M Intensive?** — **Capital**

3. **Commercial Availability** — **Rating: Better**

   Slurry walls have been used for decades, so the equipment and methodology are readily available and well known. The process of designing the proper mix of wall materials to contain specific contaminants is relatively new, however.

4. **Typically Part of a Treatment Train?** — **Not Applicable**

5. **Residuals Produced (Solid, Liquid, Vapor)** — **Not Applicable**

6. **Minimum Contaminant Concentration Achievable** — **Rating: Not Applicable**

   The technology does not treat the contaminants. It is a containment system only.

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** — **Mobility**

   Slurry walls are most effective in reducing the overall mobility of the contaminated media. The technology has demonstrated its effectiveness in containing greater than 95% of the contaminated groundwater.

8. **Long-Term Effectiveness/Permanence?** — **Inadequate Information**

   Slurry walls have been used for decades as long-term solutions for controlling seepage of uncontaminated water. In contaminated environments, however, their long-term effectiveness is very dependent on contaminant types and concentrations, and has not been proven.

9. Time To Complete Cleanup **Rating: Better**

The only time involved in employing this technology is the excavation and backfilling of the trench, and some monitoring activities.

10. System Reliability/Maintainability **Rating: Better**

11. Awareness of Remediation Consulting Community **Rating: Better**

Slurry walls have been used for decades, so the methodology is well known.

12. Regulatory/Permitting Acceptability **Rating: Worse**

13. Community Acceptability **Rating: Average**

PASSIVE TREATMENT WALLS:

A permeable reaction wall is installed across the flow path of a contaminant plume, allowing the plume to passively move through the wall. The halogenated compounds are degraded by reactions with a mixture of porous media and a metal catalyst. **Development of passive treatment walls is at the pilot scale.**

The following factors may limit the applicability and effectiveness of the process:

- The technology is applicable only in relatively shallow aquifers because the trench must be constructed down to the level of the bedrock or an impermeable clay.
- Passive treatment walls are often only effective for a short time because they lose their reactive capacity, requiring replacement of the reactive medium.

The target contaminant groups for passive treatment walls are halogenated volatile and semivolatile organic compounds, and inorganics (1, 2, and 7). The technology can be used, but may be less effective, in treating some non-halogenated volatile and semivolatile organics and fuel hydrocarbons (3, 4, and 5).

1. Overall Cost **Rating: Inadequate Information**

2. Capital (Cap) or O&M Intensive? **Capital**

3. Commercial Availability **Rating: Worse**

This technology currently is available from only one vendor, Envirometal Technologies (Canada).

4. Typically Part of a Treatment Train? **No**

5. Residuals Produced (Solid, Liquid, Vapor) **Solid**

6. Minimum Contaminant Concentration Achievable **Rating: Inadequate Information**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Toxicity**

Passive treatment walls are most effective in reducing the overall toxicity of the contaminated media.

8. Long-Term Effectiveness/Permanence? **Inadequate Information**

Theoretically, passive treatment walls are a destructive technology capable of meeting or exceeding maximum concentration limits (MCLs) for drinking water. This would permanently reduce the risk to human health and the environment from the treated groundwater. However, there has been insufficient field data available to confirm its long-term effectiveness and permanence.

9. Time To Complete Cleanup **Rating: Worse**

11. System Reliability/Maintainability **Rating: Inadequate Information**

The system requires consistent control of pH levels. When the pH level within the passive treatment wall rises, it reduces the reaction rate and can inhibit effectiveness of the wall.

11. Awareness of Remediation Consulting Community **Rating: Worse**

Data has been developed by the U.S. Air Force, University of Waterloo, and Envirometal Technologies but has received limited dissemination in the technical literature to date.

12. Regulatory/Permitting Acceptability **Rating: Inadequate Information**

13. Community Acceptability **Rating: Inadequate Information**

HOT WATER OR STEAM FLUSHING/STRIPPING:

Steam is forced into an aquifer through injection wells to vaporize volatile and semivolatile contaminants. Vaporized components rise to the unsaturated zone where they are removed by vacuum extraction and then treated. This variety of processes includes Contained Recovery of Oily Waste (CROW), Steam Injection and Vacuum Extraction (SIVE), *In Situ* Steam Enhanced Extraction (ISEE), and Steam Enhanced Recovery Process (SERP). **Hot water or steam flushing/stripping is a pilot-scale technology.**

The following factor may limit the applicability and effectiveness of the process:

- Soil type will significantly impact process effectiveness.

The target contaminant groups for hot water or steam flushing/stripping are halogenated and non-halogenated semivolatile organic compounds and fuels (2, 4, and 5). The technology can be used to treat halogenated and non-halogenated volatile organic compounds (1 and 3), but may be less effective.

1. Overall Cost	**Rating: Average**
2. Capital (Cap) or O&M Intensive?	**Capital**
3. Commercial Availability	**Rating: Average**

Four vendors are promoting hot water or steam flushing/stripping processes. The CROW system appears to be the most developed of the four.

4. Typically Part of a Treatment Train?	**Yes**
5. Residuals Produced (Solid, Liquid, Vapor)	**Liquid, Vapor**
6. Minimum Contaminant Concentration Achievable	**Rating: Average**
7. Addresses Toxicity (T), Mobility (M), or Volume (V)?	**Volume**
8. Long-Term Effectiveness/Permanence?	**Yes**
9. Time To Complete Cleanup	**Rating: Better**
10. System Reliability/Maintainability	**Rating: Worse**
11. Awareness of Remediation Consulting Community	**Rating: Worse**
12. Regulatory/Permitting Acceptability	**Rating: Average**
13. Community Acceptability	**Rating: Average**

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HYDROFRACTURING (enhancement):

Pressurized water is injected through injection wells to crack low permeability and over-consolidated sediments. Cracks are filled with porous media that serve as avenues for bioremediation or improved pumping efficiency. **Hydrofracturing is a pilot-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The technology should not be used in areas of high seismic activity.
- Investigation of possible underground utilities, structures, or trapped free product is required.
- The potential exists to open new pathways for the unwanted spread of contaminants (e.g., DNAPLs).

Hydrofracturing is applicable to the complete range of contaminant groups (1-7) with no particular target group. The technology has seen widespread use in the water-well construction industry, but is relatively new at remediating hazardous waste sites.

1. Overall Cost **Rating: Average**

2. Capital (Cap) or O&M Intensive? **Neither**

3. Commercial Availability **Rating: Inadequate Information**

4. Typically Part of a Treatment Train? **Yes**

Hydrofracturing is an enhancement technology, designed to increase the efficiency of other *in situ* technologies in difficult subsurface conditions.

5. Residuals Produced (Solid, Liquid, Vapor) **None**

6. Minimum Contaminant Concentration Achievable **Rating: Not Applicable**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Mobility**

Hydrofracturing is designed to increase the mobility through difficult soil conditions. The passageways create enhanced extraction efficiencies and allow for a more thorough distribution of *in situ* remediation technologies.

8. Long-Term Effectiveness/Permanence? **Yes**

9. Time To Complete Cleanup **Rating: Better**

10. System Reliability/Maintainability **Rating: Better**

12. Awareness of Remediation Consulting Community **Rating: Worse**

The technology has been used in three EPA SITE Program demonstrations.

12. Regulatory/Permitting Acceptability **Rating: Better**

13. Community Acceptability **Rating: Average**

AIR SPARGING:

Air is injected into a saturated matrices creating an underground stripper that removes contaminants through volatilization. The technology is designed to operate at high air flow rates in order to effect volatilization (as opposed to the lower air flow rates used to increase groundwater oxygen concentrations to stimulate biodegradation). Air sparging must operate in tandem with SVE systems that capture volatile contaminants stripped from the saturated zone. **Air sparging is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Depth of contaminants and specific site geology must be considered.
- Pressure levels must be designed for site-specific conditions.
- Channeling of the air flow can occur.
- Using air sparging without SVE could create a net positive subsurface pressure that could induce contaminant migration beyond the contaminated zone.

The target contaminant groups for air sparging are halogenated and non-halogenated volatile organic compounds and fuels (1, 3, and 5). Only limited information is available on the process.

1. Overall Cost	**Rating: Better**
2. Capital (Cap) or O&M Intensive?	**Neither**
3. Commercial Availability	**Rating: Better**
4. Typically Part of a Treatment Train?	**Yes**

Air sparging must operate in tandem with SVE systems that capture volatile contaminants stripped from the saturated zone.

5. Residuals Produced (Solid, Liquid, Vapor)	**Vapor**
6. Minimum Contaminant Concentration Achievable	**Rating: Average**
7. Addresses Toxicity (T), Mobility (M), or Volume (V)?	**Volume**
8. Long-Term Effectiveness/Permanence?	**Yes**
9. Time To Complete Cleanup	**Rating: Better**
10. System Reliability/Maintainability	**Rating: Better**
11. Awareness of Remediation Consulting Community	**Rating: Average**

12. Regulatory/Permitting Acceptability **Rating: Better**

13. Community Acceptability **Rating: Better**

DIRECTIONAL WELLS (enhancement):

Drilling techniques are used to position wells horizontally, or at an angle, to reach contaminants not accessible via direct vertical drilling. **Directional well technology is at full-scale development.**

The following factors may limit the applicability and effectiveness of this technology:

- Well failures are possible during system installation.
- Potential exists for the wells to collapse.

Directional well technology is applicable to the complete range of contaminant groups (1-7) with no particular target group.

1. Overall Cost	**Rating: Inadequate Information**
2. Capital (Cap) or O&M Intensive?	**Neither**
3. Commercial Availability	**Rating: Worse**
4. Typically Part of a Treatment Train?	**Yes**
5. Residuals Produced (Solid, Liquid, Vapor)	**Solid, Liquid**
6. Minimum Contaminant Concentration Achievable	**Rating: Not Applicable**
7. Addresses Toxicity (T), Mobility (M), or Volume (V)?	**Rating: Not Applicable**
8. Long-Term Effectiveness/Permanence?	**Yes**
9. Time To Complete Cleanup	**Rating: Better**
10. System Reliability/Maintainability	**Rating: Average**
11. Awareness of Remediation Consulting Community	**Rating: Average**
12. Regulatory/Permitting Acceptability	**Rating: Better**
13. Community Acceptability	**Rating: Better**

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DUAL PHASE EXTRACTION:

A high vacuum system is applied to simultaneously remove liquid and gas from low permeability or heterogeneous formations. The vacuum extraction well includes a screened section in the zone of contaminated soils and groundwater. As the vacuum is applied to the well, soil vapor is extracted, and groundwater is entrained by the extracted vapors. Once above grade, the extracted vapors and groundwater are separated and treated. **Dual phase extraction is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Depending upon the specific site geology, the technology may have limited effectiveness.
- Dual phase extraction is not applicable to *in situ* recovery of metals.
- Unless it is combined with other technologies, such as bioremediation, air sparging, or bioventing, the technology is not applicable to certain long-chained hydrocarbons.
- Combination with complementary technologies (*e.g.* pump-and-treat) may be required to recover groundwater from high yielding aquifers.

The target contaminant groups for dual phase extraction are halogenated and non-halogenated volatile organic compounds and fuel hydrocarbons (1, 3, and 5).

1. **Overall Cost** **Rating: Average**

2. **Capital (Cap) or O&M Intensive?** **O&M**

3. **Commercial Availability** **Rating: Better**

4. **Typically Part of a Treatment Train?** **Yes**

   Dual phase extraction is generally combined with bioremediation, air sparging, or bioventing when the target contaminants include long-chained hydrocarbons. It also can be used with pump-and-treat technologies to recover groundwater from high yielding aquifers.

5. **Residuals Produced (Solid, Liquid, Vapor)** **Liquid, Vapor**

6. **Minimum Contaminant Concentration Achievable** **Rating: Average**

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Volume**

8. **Long-Term Effectiveness/Permanence?** **Yes**

9. **Time To Complete Cleanup** **Rating: Average**

   Use of dual phase extraction with bioremediation, air sparging, or bioventing can shorten the cleanup time at a site.

10. System Reliability/Maintainability Rating: Average

11. Awareness of Remediation Consulting Community Rating: Better

12. Regulatory/Permitting Acceptability Rating: Average

13. Community Acceptability Rating: Better

VACUUM VAPOR EXTRACTION:

Air is injected into a well, lifting contaminated groundwater in the well and allowing additional groundwater flow into the well. Once inside the well, some of the volatile organic compounds in the contaminated groundwater are transferred from the water to air bubbles which rise and are collected at the top of the well by vapor extraction. The partially treated groundwater is never brought to the surface; it is forced into the unsaturated zone, and the process is repeated. As groundwater circulates through the treatment system *in situ*, contaminant concentrations are gradually reduced. **Vacuum vapor extraction is a pilot-scale technology.**

A variation of this process, called UVB, has been used at numerous sites in Germany and has been introduced recently into the United States.

Stanford University has developed another variation of this process, an in-well sparging system, which is currently being evaluated as part of the U.S. Department of Energy's Integrated Technology Demonstration Program. The Stanford system combines air-lift pumping with a vapor stripping technique.

The following factors may limit the applicability and effectiveness of the process:

- Shallow aquifers may limit process effectiveness.
- Depth of the saturated and unsaturated zones and soil permeability must be considered.

The target contaminant groups for vacuum vapor extraction are halogenated volatile and semivolatile organic compounds, and fuels (1, 2, and 5). Variations of the technology may allow for its effectiveness against some non-halogenated volatile and semivolatile organic compounds, pesticides, and inorganics (3, 4, 6, and 7).

1. Overall Cost **Rating: Average**

2. Capital (Cap) or O&M Intensive? **Capital**

3. Commercial Availability **Rating: Worse**

This process has been used extensively in Germany, but technologies based on the process have only recently been introduced in the United States.

4. Typically Part of a Treatment Train? **No**

5. Residuals Produced (Solid, Liquid, Vapor) **Liquid, Vapor**

6. Minimum Contaminant Concentration Achievable **Rating: Better**

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Volume**

8. Long-Term Effectiveness/Permanence? **Yes**

9. Time To Complete Cleanup **Rating: Average**

10. System Reliability/Maintainability **Rating: Better**

11. Awareness of Remediation Consulting Community **Rating: Worse**

Awareness of this process is limited in the United States but can be expected to increase as development and demonstration of technologies based on the process continue.

12. Regulatory/Permitting Acceptability **Rating: Average**

13. Community Acceptability **Rating: Better**

FREE PRODUCT RECOVERY:

Undissolved liquid-phase organics are removed from subsurface formations, either by active methods (*e.g.*, pumping) or a passive collection system. This process is used primarily in cases where a fuel hydrocarbon lens is floating on the water table. The free product is generally drawn up to the surface via a pumping system. Following recovery, it can be disposed, re-used directly in an operation not requiring high-purity materials, or purified prior to re-use. **Free product recovery is a full-scale technology.**

The following factor may limit the applicability and effectiveness of the process:

- Depending upon the specific site geology, the technology may have limited effectiveness.

The target contaminant groups for free product recovery are non-halogenated semivolatiles and fuel hydrocarbons (4 and 5).

1. Overall Cost	**Rating: Better**
2. Capital (Cap) or O&M Intensive?	**Neither**
3. Commercial Availability	**Rating: Better**
4. Typically Part of a Treatment Train?	**No**
5. Residuals Produced (Solid, Liquid, Vapor)	**Liquid**

Free product recovered in this process can be disposed, re-used directly in an operation not requiring high-purity materials, or purified prior to re-use.

6. Minimum Contaminant Concentration Achievable	**Rating: Not Applicable**
7. Addresses Toxicity (T), Mobility (M), or Volume (V)?	**Volume**
8. Long-Term Effectiveness/Permanence?	**Yes**
9. Time To Complete Cleanup	**Rating: Better**
10. System Reliability/Maintainability	**Rating: Average**
11. Awareness of Remediation Consulting Community	**Rating: Better**
12. Regulatory/Permitting Acceptability	**Rating: Better**
13. Community Acceptability	**Rating: Better**

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BIOREACTORS:

Contaminants in extracted groundwater are put into contact with microorganisms through attached or suspended biological systems. In suspended growth systems, such as activated sludge, contaminated groundwater is circulated in an aeration basin where a microbial population aerobically degrades organic matter and produces new cells. The new cells form a sludge, which is settled out in a clarifier, and the sludge biomass is recycled to the aeration basin. In attached growth systems, such as rotating biological contactors and trickling filters, microorganisms are established on an inert support matrix to aerobically degrade groundwater contaminants. The microbial population may either be derived from the contaminant source or from an inoculum of organisms specific to a contaminant. Attached and suspended systems often are used together. **Bioreactors are full-scale technologies.**

The following factors may limit the applicability and effectiveness of the process:

- Solid residuals from sludge processes may require treatment or disposal.
- Skilled, competent microbiologists are required to start and maintain the biological systems.
- Metals may need to be removed prior to treatment in the bioreactors.
- The precipitation of iron may clog treatment systems.
- Treatability studies should be conducted to determine if contaminants are biodegradable and to estimate the rate of biodegradation.
- Air pollution controls may need to be applied if there is volatilization from activated sludge processes.
- Low temperatures significantly decrease biodegradation rates, resulting in longer cleanup times or increased costs for heating.

Bioreactors are used primarily to treat non-halogenated volatile and semivolatile organics and fuel hydrocarbons (3, 4, and 5). Halogenated volatiles and semivolatiles and pesticides (1, 2, and 6) also can be treated, but the process may be less effective and may be applicable only to some compounds within these groups. Successful pilot-scale field studies have been conducted on some halogenated compounds, such as chlorobenzene and dichlorobenzene isomers.

1. **Overall Cost** **Rating: Better**

   Costs are highly dependent on the contaminants and their concentrations in the influent stream. Biological treatment has often been found to be more economical than carbon adsorption.

2. **Capital (Cap) or O&M Intensive?** **Capital**

3. **Commercial Availability** **Rating: Better**

   This is a well developed technology that has been used for many years in the treatment of municipal wastewater. Equipment and materials are readily available.

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)** **Solids**

6. Minimum Contaminant Concentration Achievable **Rating: Average**

As with other biological treatments, this is highly dependent upon the biodegradability of the contaminants.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

Biological reactors can permanently destroy selected contaminants.

10. Time To Complete Cleanup **Rating: Not Applicable**

As with other pump-and-treat technologies, time to clean up is dependent upon subsurface conditions and the rate of desorption of contaminants from subsurface materials. A bioreactor system can be established to treat extracted groundwater at virtually any rate.

10. System Reliability/Maintainability **Rating: Average**

Suspended systems are more difficult to maintain than attached systems because bacteria must be kept in a form that settles easily. Start-up time can be slow if organisms need to be acclimated to the wastes, however, the existence of cultures that have been previously adapted to specific hazardous wastes can decrease start-up and detention time.

11. Awareness of Remediation Consulting Community **Rating: Average**

Bioreactors have been used for the treatment of municipal wastewaters for many years, but their application to Superfund wastes is relatively new.

12. Regulatory/Permitting Acceptability **Rating: Better**

13. Community Acceptability **Rating: Average**

AIR STRIPPING:

Volatile organics are partitioned from groundwater by greatly increasing the surface area of the contaminated water exposed to air. Types of aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration. **Air stripping is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Potential exists for inorganic or biological fouling of the equipment.
- Consideration should be given to the Henry's Law constant of the VOCs in the water stream, and the type and amount of packing used in the tower.
- Compounds with low volatiles at ambient temperature may require pre-heating of the groundwater.
- Clogging of the stripping column packing material due to inorganics in the groundwater (especially dissolved ferrous iron, which precipitates out as insoluble ferrous hydroxide species upon aeration) and biofouling are common problems. Air strippers must be taken out of service and packing materials acid-washed.

The target contaminant groups for air stripping systems are halogenated and non-halogenated volatile organic compounds (1 and 3). The technology can be used but may be less effective against halogenated and non-halogenated semivolatile organic compounds and fuels (2, 4, and 5).

1. Overall Cost	**Rating: Better**
2. Capital (Cap) or O&M Intensive?	**O&M**
3. Commercial Availability	**Rating: Better**
More than 1,000 air stripping units are in operation in the United States.	
4. Typically Part of a Treatment Train?	**No**
5. Residuals Produced (Solid, Liquid, Vapor)	**Liquid, Vapor**
6. Minimum Contaminant Concentration Achievable	**Rating: Better**
7. Addresses Toxicity (T), Mobility (M), or Volume (V)?	**Volume**
8. Long-Term Effectiveness/Permanence?	**Yes**
9. Time To Complete Cleanup	**Rating: Not Applicable**
10. System Reliability/Maintainability	**Rating: Average**

11. Awareness of Remediation Consulting Community **Rating: Better**

The approach to packed tower design has become standardized. Numerous published and unpublished articles and technical papers are available on the design of air strippers.

12. Regulatory/Permitting Acceptability **Rating: Worse**

13. Community Acceptability **Rating: Average**

CARBON ADSORPTION (LIQUID PHASE):

Groundwater is pumped through a series of canisters containing activated carbon to which dissolved organic contaminants adsorb. The technology requires periodic replacement or regeneration of saturated carbon. **Carbon adsorption (liquid phase) is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The solubility and concentration of the contaminants can impact process performance.
- Metals can foul the system.
- Costs are high if used as the primary treatment on waste streams with high contaminant concentration levels.
- Type and pore size of the carbon, as well as the operating temperature, will impact process performance.

The target contaminant groups for carbon adsorption (liquid phase) are halogenated and non-halogenated semivolatile organic compounds (2 and 4). The technology can be used, but may be less effective in treating halogenated volatile organic compounds, fuel hydrocarbons, pesticides, and inorganics (1, 5, 6, and 7).

1. **Overall Cost** **Rating: Worse**

2. **Capital (Cap) or O&M Intensive?** **O&M**

3. **Commercial Availability** **Rating: Better**

   Adsorption by activated carbon has a long history of use in treating municipal, industrial, and hazardous wastes.

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)** **Solid**

   When the concentration of contaminants in the effluent from the bed exceeds a certain level, the carbon can be regenerated in place, removed and regenerated at an off-site facility, or disposed.

6. **Minimum Contaminant Concentration Achievable** **Rating: Better**

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Volume**

8. **Long-Term Effectiveness/Permanence?** **Yes**

9. **Time To Complete Cleanup** **Rating: Not Applicable**

10. **System Reliability/Maintainability** **Rating: Better**

11. Awareness of Remediation Consulting Community **Rating: Better**

12. Regulatory/Permitting Acceptability **Rating: Better**

Regulatory agencies actively support this technology, which has been used at many Superfund sites.

13. Community Acceptability **Rating: Better**

UV OXIDATION:

Ultraviolet (UV) radiation, ozone, and/or hydrogen peroxide are used to destroy organic contaminants as water flows into a treatment tank. An ozone destruction unit is used to treat off-gas from the treatment tank. **UV oxidation is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The technology cannot be applied on all contaminants.
- The presence of inorganics and naturally occurring soil organics (*e.g.*, humic substances) can adversely affect system performance.

The target contaminant groups for UV oxidation are halogenated volatile and semivolatile organic compounds and pesticides (1, 2, and 6). The technology also can be used, but may be less effective, in treating non-halogenated volatile organics and fuels (3 and 5). The potential for exposure is minimal as the system does not produce air emissions.

1. **Overall Cost** **Rating: Average**

   The cost of this process is highly dependent upon the amount of influent pre-treatment required and the type of processing units needed.

2. **Capital (Cap) or O&M Intensive?** **Capital**

3. **Commercial Availability** **Rating: Better**

   The technology is readily available.

4. **Typically Part of a Treatment Train?** **No**

5. **Residuals Produced (Solid, Liquid, Vapor)** **None**

6. **Minimum Contaminant Concentration Achievable** **Rating: Better**

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Toxicity**

8. **Long-Term Effectiveness/Permanence?** **Yes**

9. **Time To Complete Cleanup** **Rating: Not Applicable**

10. **System Reliability/Maintainability** **Rating: Worse**

11. **Awareness of Remediation Consulting Community** **Rating: Average**

12. Regulatory/Permitting Acceptability **Rating: Average**

Units have been permitted without unusual difficulty.

13. Community Acceptability **Rating: Average**

NATURAL ATTENUATION:

Natural subsurface processe—such as dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface materials—are allowed to reduce contaminant concentrations to acceptable levels.
Natural attenuation is not a "technology" per se, and there is significant debate among technical experts about its use at hazardous waste sites. Consideration of this option requires modeling and evaluation of contaminant degradation rates to determine feasibility, and special approvals may be needed. In addition, sampling and sample analysis must be conducted throughout the process to confirm that degradation is proceeding at rates consistent with meeting cleanup objectives. It has been included in the *Matrix* and this *Guide* for completeness only.

Natural attenuation is not the same as "no action," although it often is perceived as such. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) requires evaluation of a "no action" alternative, but does not require evaluation of natural attenuation. Natural attenuation is considered in the Superfund program on a case-by-case basis, and guidance on its use is still evolving. It has been selected at Superfund sites where, for example, PCBs are strongly sorbed to deep subsurface soils and are not migrating; where removal of dense non-aqueous phase liquids (DNAPLs) has been determined to be technically impracticable (Superfund is developing technical impracticability (TI) guidance); and where it has been determined that active remedial measures would be unable to significantly speed remediation time frames. Where contaminants are expected to remain in place over long periods of time, as in the first two examples, TI waivers must be obtained. In all cases, extensive site characterization is required.

The attitude toward natural attenuation varies among agencies. The Air Force carefully evaluates the potential for use of natural attenuation at its sites. However, EPA accepts its use only in certain special cases.

No handling of contaminated materials is required. Therefore, site workers require no protective equipment. There are potential risks to the commuity from migration of contaminants to areas where groundwater is being used.

The following factors may limit the applicability and effectiveness of the process:

- Data must be collected to determine model input parameters.
- Although commercial services for evaluating natural attenuation are widely available, the quality of these services varies widely among the many potential suppliers. Highly skilled modelers are required.
- Intermediate degradation products may be more mobile and more toxic than the original contaminant.
- Natural attenuation should be used only in low-risk situations.
- Contaminants may migrate before they are degraded.
- The site may have to be fenced and may not be available for reuse until contaminant levels are reduced.
- If free product exists, it may have to be removed.
- Some inorganics can be immobilized, such as mercury, but they will not be degraded.

Target contaminants for natural attenuation are non-halogenated volatile and semivolatile organics and fuel hydrocarbons (groups 3, 4, and 5). Halogenated volatiles and semivolatiles and pesticides (1, 2, and 6) also can be allowed to naturally attenuate, but the process may be less effective and may only be applicable to some compounds within these contaminant groups.

1. **Overall Cost** — **Rating: Better**

2. **Capital (Cap) or O&M Intensive?** — **Neither**

   There are no capital or O&M costs associated with natural attenuation. However, there are costs for modeling contamination degradation rates to determine whether natural attenuation is a feasible remedial alternative, and there are costs for subsurface sampling and sample analysis (potentially extensive) to determine the extent of contamination and confirm contaminant degradation rates and cleanup status. Skilled labor hours are required to conduct the modeling, sampling, and analysis.

3. **Commercial Availability:** — **Rating: Better**

   Many potential suppliers can perform the modeling, sampling, and sample analysis required for justifying and monitoring natural attenuation. However, the quality of services provided varies widely.

4. **Typically Part of a Treatment Train?** — **No**

5. **Residuals Produced (Solid, Liquid, Vapor)?** — **None**

6. **Minimum Contaminant Concentration Achievable:** — **Rating: Inadequate Information**

   The extent of contaminant degradation depends on a variety of parameters, such as contaminant types and concentrations, temperature, moisture, and availability of nutrients/electron acceptors (e.g., oxygen, nitrate).

7. **Addresses Toxicity, Mobility, or Volume?** — **Toxicity**

8. **Long-Term Effectiveness/Permanence?** — **Yes**

9. **Time To Complete Cleanup:** — **Rating: Worse**

   Natural attenuation does not involve active remedial measures. Subsurface environments are often oxygen limited in regards to the needs of microorganisms that can degrade organic contaminants. Without active measures to increase the oxygen supply (or supply of other electron acceptors), biodegradation can be slow.

10. **System Reliability/Maintainability:** — **Rating: Better**

    Natural attenuation requires no equipment to maintain.

11. Awareness of the Remediation Consulting Community: **Rating: Average**

A large amount of information is available on subsurface processes that affect contaminant transport and transformation. In addition, subsurface transport and fate models are available to estimate times required for natural attenuation to attain cleanup goals. EPA's Robert S. Kerr Environmental Research Laboratory sponsored the development of Bioplume II, which models the natural attenuation of BTEX in groundwater, and is working with the Air Force Center for Environmental Excellence to improve it. However, natural attenuation is considered a viable alternative only for a limited number of contaminated sites.

12. Regulatory/Permitting Acceptability: **Rating: Worse**

Because it involves no active remedial measures, natural attenuation is not well accepted by the regulatory community. However, regulatory/permitting acceptance may be possible where alternative remedial options are technically or economically infeasible and where a very strong scientific case can be made predicting its success and protectiveness.

13. Community Acceptability: **Rating: Worse**

The public generally prefers active remedial alternatives.

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Air Emissions/Off-Gases

CARBON ADSORPTION (VAPOR PHASE):

Carbon, processed into hard granules or pellets, is used to capture molecules of gas-phase pollutants. Typically, the granulated activated carbon (GAC) is contained in a packed bed through which contaminated emissions/off-gases flow. When the carbon has been saturated with contaminants, it is regenerated in place, removed and regenerated at an off-site facility, or disposed. **Carbon adsorption (vapor phase) is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- High contaminant concentration levels limit effectiveness.
- Temperature and moisture/humidity must be controlled.

The target contaminant groups for carbon adsorption (vapor phase) are volatile and semivolatile organic compounds, fuel hydrocarbons, and pesticides (1-6). Carbon adsorption (vapor phase) systems are most effective for contaminants with molecular weights between 50 and 200 and boiling points between 75° and 300°F (24° and 149°C).

1. **Overall Cost** **Rating: Better**

2. **Capital (Cap) or O&M Intensive?** **Neither**

3. **Commercial Availability** **Rating: Better**

   Carbon adsorption (vapor phase) has a long history of use and is readily available. Activated carbon producers are able to manufacture carbon adsorption (vapor phase) systems to meet specific applications.

4. **Typically Part of a Treatment Train?** **Not Applicable**

   The definition of this factor is not applicable to this technology. The technology, by design, is the finishing step in treatment processes.

5. **Residuals Produced (Solid, Liquid, Vapor)** **Solid**

   When the concentration of contaminants in the effluent from the bed exceeds a certain level, the carbon can be regenerated in place, removed and regenerated at an off-site facility, or disposed.

6. **Minimum Contaminant Concentration Achievable** **Rating: Better**

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Volume**

8. Long-Term Effectiveness/Permanence? **Yes**

The target contaminants are permanently separated from the vapor stream.

9. Time To Complete Cleanup **Rating: Not Applicable**

Since carbon adsorption (vapor phase) is a support technology used to treat off-gases produced by another remediation technology, the site cleanup time is wholly dependent upon the cleanup time associated with the primary technology.

10. System Reliability/Maintainability **Rating: Better**

Regular maintenance checks are required during operation. Carbon adsorption (vapor phase) is a well developed technology with high reliability.

11. Awareness of Remediation Consulting Community **Rating: Better**

The concepts, theory, and engineering aspects of the technology are well developed and disseminated throughout the remediation consulting community.

12. Regulatory/Permitting Acceptability **Rating: Average**

Carbon adsorption (vapor phase) is a mature technology and has been used without unusual regulatory or permitting difficulty.

13. Community Acceptability **Rating: Better**

CATALYTIC OXIDATION (NON-HALOGENATED):

Trace organics in contaminated air streams are destroyed at lower temperatures, 842°F (450°C), than conventional combustion by passing the air/VOC mixture through a catalyst designed for non-halogenated compounds. **Catalytic oxidation (non-halogenated) is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- If sulfur or halogenated compounds are in the emissions stream, the catalyst can be poisoned/deactivated and require replacement.
- The technology requires operation in the optimum containment range.

The target contaminant groups for catalytic oxidation (non-halogenated) are non-halogenated volatile and semivolatile organic compounds and fuel hydrocarbons (3, 4 and 5). Because the maximum permissible total hydrocarbon concentration is usually limited to control the temperature in the oxidizer and reduce the risk of an explosion, contaminant concentrations over certain levels, typically 3,000 ppm volatile organic compounds, are usually diluted with ambient air. Catalytic oxidation has long been used for emissions control of air/VOC mixtures. An advantage of catalytic oxidation is that it occurs at lower temperatures than thermal oxidation.

1. **Overall Cost** **Rating: Better**

2. **Capital (Cap) or O&M Intensive?** **Neither**

3. **Commercial Availability** **Rating: Better**

   Commercial equipment is in operation, and there are at least five vendors promoting the technology. Some processes are proprietary in nature.

4. **Typically Part of a Treatment Train?** **Not Applicable**

   The definition of this factor is not applicable to this technology. The technology, by design, is the finishing step in treatment processes.

5. **Residuals Produced (Solid, Liquid, Vapor)** **None**

6. **Minimum Contaminant Concentration Achievable** **Rating: Better**

   The process normally begins with very low concentration levels and the technology cleans the emissions to regulatory standards.

7. **Addresses Toxicity (T), Mobility (M), or Volume (V)?** **Toxicity**

8. **Long-Term Effectiveness/Permanence?** **Yes**

9. Time To Complete Cleanup **Rating: Not Applicable**

Since catalytic oxidation (non-halogenated) is a support technology used to treat off-gases produced by another remediation technology, the site cleanup time is wholly dependent upon the cleanup time associated with the primary technology.

10. System Reliability/Maintainability **Rating: Better**

Although there appears to be a low probability of failure, careful monitoring to prevent overheating of the catalyst and daily maintenance are required.

11. Awareness of Remediation Consulting Community **Rating: Better**

12. Regulatory/Permitting Acceptability **Rating: Better**

There are no federal regulations on catalytic oxidation. However California, New Jersey, and Texas regulate this technology, and its use is increasing nationwide. With the trend in regulations to limit emissions from vacuum extraction and air strippers, catalytic oxidation is likely to receive more attention.

13. Community Acceptability **Rating: Better**

CATALYTIC OXIDATION (HALOGENATED):

Trace organics in contaminated air streams are destroyed at lower temperatures, 842°F (450°C), than conventional combustion by passing the air/VOC mixture through a catalyst designed for halogenated compounds. **Catalytic oxidation (halogenated) is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The catalyst can be poisoned/deactivated and require replacement.
- The technology requires operation in the optimum containment range.

The target contaminant group for catalytic oxidation (halogenated) is halogenated volatile and semivolatile organic compounds (1 and 2), but the technology has been evaluated below based only on its use in cleaning media contaminated with TCE and, in some instances, PCE. An advantage of catalytic oxidation is that it occurs at lower temperatures then thermal oxidation.

1. Overall Cost **Rating: Better**

2. Capital (Cap) or O&M Intensive? **Neither**

3. Commercial Availability **Rating: Average**

4. Typically Part of a Treatment Train? **Not Applicable**

The definition of this factor is not applicable to this technology. The technology, by design, is the finishing step in treatment processes.

5. Residuals Produced (Solid, Liquid, Vapor) **None**

6. Minimum Contaminant Concentration Achievable **Rating: Better**

The process normally begins with very low concentrations and the technology cleans the emissions to regulatory standards.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

9. Time To Complete Cleanup **Rating: Not Applicable**

Since catalytic oxidation (halogenated) is a support technology used to treat off-gases produced by another remediation technology, the site cleanup time is wholly dependent upon the cleanup time associated with the primary technology.

10. System Reliability/Maintainability **Rating: Average**

When PCE is present, catalyst deactivation can occur.

11. Awareness of Remediation Consulting Community **Rating: Worse**

The development of a catalytic oxidizer specifically designed to treat halogenated compounds is relatively new and not well known.

12. Regulatory/Permitting Acceptability **Rating: Average**

There are no federal regulations on catalytic oxidation. However, California, New Jersey, and Texas regulate this technology. With the trend in regulations to limit emissions from vacuum extraction and air strippers, catalytic oxidation is likely to receive more attention.

13. Community Acceptability **Rating: Average**

BIOFILTRATION:

Vapor-phase organic contaminants are pumped through a soil bed and sorb to the soil surface where they are degraded by microorganisms in the soil. Specific strains of bacteria may be introduced into the filter and optimal conditions provided to preferentially degrade specific compounds. **Biofiltration is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- The size of the biofilter is constrained by the rate of influent air flow.
- Fugitive fungi may be a problem.

Biofiltration is used primarily to treat non-halogenated volatile organics and fuel hydrocarbons (3 and 5). Halogenated volatiles (1) also can be treated, but the process may be less effective.

1. Overall Cost **Rating: Better**

2. Capital (Cap) or O&M Intensive? **Neither**

3. Commercial Availability **Rating: Average**

Non-proprietary filters that require low air loading rates for organics (≥100 ppm) have been used successfully for more than 20 years. Proprietary designs that support higher air loadings also are available. Biofilters have been used extensively in Europe and Japan, but only recently have they received attention in the United States.

4. Typically Part of a Treatment Train? **Not Applicable**

The definition of this factor is not applicable to this technology. The technology, by design, is the final step in treatment processes.

5. Residuals Produced (Solid, Liquid, Vapor) **None**

6. Minimum Contaminant Concentration Achievable **Rating: Better**

As with other biological treatment processes, this is highly dependent upon the biodegradability of the contaminants. Under proper conditions, biofilters can remove virtually all selected contaminants.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? **Toxicity**

8. Long-Term Effectiveness/Permanence? **Yes**

Under proper conditions, biofilters can completely degrade selected contaminants to harmless products.

9. Time To Complete Cleanup

Rating: Not Applicable

10. System Reliability/Maintainability

Rating: Average

The primary maintenance concern is moisture control in the filter bed. Moisture levels, pH, and other filter conditions may have to be monitored to maintain high removal efficiencies. Filter flooding and plugging due to excessive biomass accumulation may require periodic mechanical cleaning of the filter.

11. Awareness of Remediation Consulting Community

Rating: Worse

Little use has been made of this technology in the United States. However, the technology has been used for about 20 years, mainly to remove odors from sewage, and more than 500 biofilters are being used in Europe and Japan.

12. Regulatory/Permitting Acceptability

Rating: Inadequate Information

13. Community Acceptability

Rating: Inadequate Information

THERMAL OXIDATION:

Organic contaminants are destroyed in a high temperature 1,832°F (1,000°C) combustor. **Thermal oxidation is a full-scale technology.**

The following factors may limit the applicability and effectiveness of the process:

- Potential problems exist when using the technology on waste streams containing chlorinated materials.

The target contaminant groups for thermal oxidation are non-halogenated volatile and semivolatile organic compounds and fuel hydrocarbons (3, 4, and 5). Only non-halogenated hydrocarbon systems were evaluated. If halogens are present, the system is then RCRA regulated as a hazardous waste incinerator.

1. Overall Cost — **Rating: Better**

2. Capital (Cap) or O&M Intensive? — **Neither**

3. Commercial Availability — **Rating: Better**

Commercial equipment is in operation, and there are at least five vendors promoting the technology.

4. Typically Part of a Treatment Train? — **Not Applicable**

The definition of this factor is not applicable to this technology. The technology, by design, is the final step in treatment processes.

5. Residuals Produced (Solid, Liquid, Vapor) — **None**

6. Minimum Contaminant Concentration Achievable — **Rating: Better**

The process normally begins with very low concentrations and the technology cleans the emissions to regulatory standards.

7. Addresses Toxicity (T), Mobility (M), or Volume (V)? — **Toxicity**

8. Long-Term Effectiveness/Permanence? — **Yes**

9. Time To Complete Cleanup — **Rating: Not Applicable**

Since thermal oxidation is a support technology used to treat off-gases produced by another remediation technology, the site cleanup time is wholly dependent upon the cleanup time associated with the primary technology.

10. System Reliability/Maintainability — **Rating: Better**

11. Awareness of Remediation Consulting Community **Rating: Better**

12. Regulatory/Permitting Acceptability **Rating: Better**

13. Community Acceptability **Rating: Average**

There is occasional resistance if the community focuses on the thermal oxidizer as an incinerator.

APPENDIX A: INFORMATION RESOURCES

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APPENDIX B: CONTAMINANT GROUPS

Major contaminant groups used in the *Matrix* are:

(1) Halogenated volatiles
(2) Halogenated semivolatiles
(3) Non-halogenated volatiles
(4) Non-halogenated semivolatiles
(5) Fuel Hydrocarbons
(6) Pesticides
(7) Inorganics

These major groups include the contaminants listed below. These are not comprehensive lists, but they contain examples of contaminants encountered at many sites.

(1) Halogenated Volatiles

Bromodichloromethane
Bromoform
Bromomethane
Carbon tetrachloride
Chlorodibromomethane
Chloroethane
Chloroform
Chloromethane
Chloropropane
Cis-1,2-dichloroethylene
Cis-1,3-dichloropropene
Dibromomethane
1,1-Dichloroethane
1,2-Dichloroethane
1,2-Dichloroethene
1,1-Dichloroethylene
Dichloromethane
1,2-Dichloropopane
Ethylene dibromide
Fluorotrichloromethane (Freon 11)
Hexachloroethane
Monochlorobenzene
1,1,2,2-Tetrachloroethane
Tetrachloroethylene (Perchloroethylene)
1,2-Trans-dichloroethylene
Trans-1,3-dichloropropene
1,1,1-Trichloroethane
1,1,2-Trichloroethane
Trichloroethylene
1,1,2-Trichloro-1,2,2-trifluoroethane (Freon 113)
Vinyl chloride

(2) Halogenated Semivolatiles

Bis(2-chloroethoxy)ether
1,2-Bis(2-chloroethoxy)ethane
Bis(2-chloroethoxy)methane
Bis(2-chloroethoxy)phthalate
Bis(2-chloroethyl)ether
Bis(2-chloroisopropyl)ether
4-Bromophenyl phenyl ether
4-Chloroaniline
p-Chloro-m-cresol
2-Chloronapthalene
2-Chlorophenol
4-Chlorophenyl phenylether
1,2-Dichlorobenzene
1,3-Dichlorobenzene
1,4-Dichlorobenzene
3,3-Dichlorobenzidine

Halogentated Semivolatiles (Con'd.)

2,4-Dichlorophenol
Hexachlorobenzene
Hexachlorobutadiene
Hexachlorocyclopentadiene
Pentachlorophenol
Polychlorinated biphenyls (PCBs)
Tetrachlorophenol
1,2,4-Trichlorobenzene
2,4,5-Trichlorophenol
2,4,6-Trichlorophenol

(3) Non-Halogentated Volatiles

Acetone
Acrolein
Acrylonitrile
n-Butyl alcohol
Carbon disulfide
Cyclohexanone
Ethyl acetate
Ethyl ether
2-Hexanone
Isobutanol
Methanol
Methyl ethyl ketone
Methyl isobutyl ketone
4-Methyl-2-pentanone
Styrene
Tetrahydrofuran
Vinyl acetate

(4) Non-Halogentated Semivolatiles

Benzidine
Benzoic acid
Benzyl alcohol
Bis(2-ethylhexyl)phthalate
Bis phthalate
Butyl benzyl phthalate
Dibenzofuran
Di-n-butyl phthalate
Diethyl phthalate
Dimethyl phthalate
4,6-Dinitro-2-methylphenol
2,4-Dinitrophenol
2,4-Dinitrotoluene
2,6-Dinitrotoluene
Di-n-octyl phthalate
1,2-Diphenylhydrazine
Isophorone
2-Nitroaniline
3-Nitroaniline
4-Nitroaniline
2-Nitrophenol
4-Nitrophenol
n-Nitrosodimethylamine
n-Nitrosodiphenylamine
n-Nitrosodi-n-propylamine
Phenyl napthalene

(5) Fuel Hydrocarbons

Acenaphthene
Anthracene
Benz(a)anthracene
Benzene
Benzo(b)fluoranthene
Benzo(k)fluoranthene
Benzo(ghi)perylene
Benzo(a)pyrene
Chrysene
Cis-2-butene
Cresols
Cyclohexane
Cyclopentane
Dibenzo(a,h)anthracene
2,3-Dimethylbutane
3,3-Dimethyl-1-butene
Dimethylethylbenzene
2,2-Dimethylheptane
2,2-Dimethylhexane
2,2-Dimethylpentane
2,3-Dimethylpentane
2,4-Dimethylphenol
Ethylbenzene
3-Ethylpentane
Fluoranthene
Fluorene

Indeno(1,2,3-c,d)pyrene
Isobutane
Isopentane
2-Methyl-1,3-butadiene
3-Methyl-1,2-butadiene
2-Methyl-butene
2-Methyl-2-butene
3-Methyl-1-butene
Methylcyclohexane
Methylcyclopentane
2-Methylheptane
3-Methylheptane
3-Methylhexane
Methylnapthalene
2-Methylnapthalene
2-Methylpentane
3-Methylpentane
3-Methyl-1-pentene
2-Methylphenol
4-Methylphenol
Methylpropylbenzene
M-Xylene
Napthalene
N-Butane
N-Decane
N-Dodecane
N-Heptane
N-Hexane
N-Hexylbenzene
Nitrobenzene
N-Nonane
N-Octane
N-Pentane
N-Propylbenzene
N-Undecane
O-Xylene
1-Pentene
Phenanthrene
Phenol
Propane
P-Xylene
Pyrene
Pyridine
1,2,3,4-Tetramethylbenzene
1,2,4,5-Tetramethylbenzene
Toluene
1,2,4-Trimethylbenzene
1,3,5-Trimethylbenzene
1,2,4-Trimethyl-5-ethylbenzene
2,2,4-Trimethylheptane
2,3,4-Trimethylheptane
3,3,5-Trimethylheptane
2,4,4-Trimethylhexane
3,3,4-Trimethylhexane
2,2,4-Trimethylpentane
2,3,4-Trimethylpentane
Trans-2-butene
Trans-2-pentene

(6) Pesticides

Aldrin
Bhc-alpha
Bhc-beta
Bhc-delta
Bhc-gamma
Chlordane
4,4'-DDD
4,4'-DDE
4,4'-DDT
Dieldrin
Endosulfan I
Endosulfan II
Endosulfan sulfate
Endrin
Endrin aldehyde
Ethion
Ethyl parathion
Heptachlor
Heptachlor epoxide
Malathion
Methylparathion
Parathion
Toxaphene

(7) Inorganics

Aluminum
Antimony
Arsenic
Asbestos
Barium
Beryllium

Bismuth
Cadmium
Calcium
Chromium
Cobalt
Copper
Cyanide
Fluorine
Iron
Lead
Magnesium
Manganese
Mercury
Metallic cyanides
Nickel
Potassuim
Selenium
Sodium
Tin
Vanadium
Zinc

REMEDIATION TECHNOLOGIES SCREENING MATRIX

NOTE: There are factors that may limit the applicability and effectiveness of any of the technologies and processes listed below. These factors are discussed in the *Remediation Technologies Screening Matrix Reference Guide*. This Matrix should always be used in conjunction with the *Reference Guide*, which contains additional information that can be useful in identifying potentially applicable technologies.

	Reference Guide Page Number	Status — (F)ull-scale or (P)ilot-scale	Contaminants/Pollutants Treated [a]		Overall Cost	Capital (Cap) or O&M Intensive?	Commercial Availability	Typically Part of a Treatment Train? (excludes off-gas treatment)	Residuals Produced — (S)olid, (L)iquid, or (V)apor?	Minimum Contaminant Concentration Achievable	Addresses (T)oxicity, (M)obility, or (V)olume?	Long-Term Effectiveness/ Permanence?	Time to Complete Cleanup	System Reliability/ Maintainability	Awareness of Remediation Consulting Community	Regulatory/Permitting Acceptability	Community Acceptability
	SOIL, SEDIMENT AND SLUDGE																
	***In Situ* Biological Processes**																
Biodegradation	21	F	**3,4,5**	1,2,6	○	O&M	■	No	None	○	T	Yes	△	△	○	△	■
Bioventing	23	F	**3,4,5**	1,2,6	■	Neither	■	No	None	■	T	Yes	○	■	○	○	■
	***In Situ* Physical/Chemical Processes**																
Soil Vapor Extraction (SVE)	25	F	**1,3,5**		■	O&M	■	No	L	○	V	Yes	○	■	■	■	■
Soil Flushing	27	P	**1,3,7**	2,4-6	I	O&M	■	No	L	△	V	Yes	△	○	○	△	○
* **Solidification/Stabilization**	29	F	**7**	2,4,6	■	Cap	■	No	S	NA	M	I	■	■	○	○	○
Pneumatic Fracturing (enhancement)	31	P		1-7	■	Neither	△	Yes	None	NA	M	Yes	NA	■	△	I	I
	***In Situ* Thermal Processes**																
Vitrification	33	P	**7**	1-6	△	Both	△	No	L	NA	M	Yes	■	△	○	△	△
Thermally Enhanced SVE	35	F	**2,4,6**	1,3,5	○	Both	○	No	L	○	V	Yes	■	○	○	○	○
	***Ex Situ* Biological Processes (assuming excavation)**																
Slurry Phase Biological Treatment	37	F	**3,5**	1,2,4,6	○	Both	○	No	None	○	T	Yes	○	○	○	■	○
Controlled Solid Phase Bio. Treatment	39	F	**3,5**	1,2,4,6	■	Neither	■	No	None	○	T	Yes	○	■	■	■	○
* **Landfarming**	41	F	**3,5**	1,2,4,6	■	Neither	■	No	None	○	T	Yes	△	■	■	○	○
	***Ex Situ* Physical/Chemical Processes (assuming excavation)**																
Soil Washing	43	F	**2,4,5,7**	1,3,6	○	Both	○	Yes	S,L	○	V	Yes	■	○	○	○	■
* **Solidification/Stabilization**	45	F	**7**	2,4,6	■	Cap	■	No	S	NA	M	I	■	■	■	○	○
Dehalogenation (Glycolate)	47	F	**2,6**	1	△	Both	○	No	L	■	T	Yes	△	△	○	○	○
Dehalogenation (BCD)	49	F	**2,6**	1	I	I	△	No	V	I	T	Yes	I	I	△	I	I
Solvent Extraction (chemical extraction)	51	F	**2,4,6**	1,3,5	△	Both	○	Yes	L	○	V	Yes	△	○	○	○	○
Chemical Reduction/Oxidation	53	F	**7**	3-6	○	Neither	■	Yes	S	NA	T,M	I	■	■	○	○	○
Soil Vapor Extraction (SVE)	55	F	**1,3**		■	Neither	■	No	L	○	V	Yes	○	■	■	○	○
	***Ex Situ* Thermal Processes (assuming excavation)**																
Low Temperature Thermal Desorption	57	F	**1,3,5**	2,4,6	■	Both	■	Yes	L	■	V	Yes	■	○	■	○	○
High Temperature Thermal Desorption	59	F	**2,4,6**	1,3,5	○	Both	■	Yes	L	■	V	Yes	■	○	○	○	○
Vitrification	61	F	**7**	1-6	△	Both	○	No	L	NA	M	Yes	○	○	○	△	△
* **Incineration**	63	F	**2,4,6**	1,3,5	△	Both	■	No		■	T		■	○	■	○	△

Soil Washing	43	F	**2,4,5,7**	1,3,6	○	Both	○	Yes	S,L	○	V	Yes	■	○	○	○	■
* **Solidification/Stabilization**	45	F	**7**	2,4,6	■	Cap	■	No	S	NA	M	I	■	■	■	○	○
Dehalogenation (Glycolate)	47	F	**2,6**	1	△	Both	○	No	L	■	T	Yes	△	△	○	○	○
Dehalogenation (BCD)	49	F	**2,6**	1	I	I	△	No	V	I	T	Yes	I	I	△	I	I
Solvent Extraction (chemical extraction)	51	F	**2,4,6**	1,3,5	△	Both	○	Yes	L	○	V	Yes	△	○	○	○	○
Chemical Reduction/Oxidation	53	F	**7**	3-6	○	Neither	■	Yes	S	NA	T,M	I	■	■	○	○	○
Soil Vapor Extraction (SVE)	55	F	**1,3**		■	Neither	■	No	L	○	V	Yes	○	■	■	○	○
***Ex Situ* Thermal Processes (assuming excavation)**																	
Low Temperature Thermal Desorption	57	F	**1,3,5**	2,4,6	■	Both	■	Yes	L	■	V	Yes	■	○	■	○	○
High Temperature Thermal Desorption	59	F	**2,4,6**	1,3,5	○	Both	■	Yes	L	■	V	Yes	■	○	○	○	○
Vitrification	61	F	**7**	1-6	△	Both	○	No	L	NA	M	Yes	○	○	○	△	△
* **Incineration**	63	F	**2,4,6**	1,3,5	△	Both	■	No	L,S	■	T	Yes	■	○	■	○	△
Pyrolysis	65	P	**2,4,6**	1,3,5	△	Both	△	No	L,S	■	T	Yes	■	I	△	○	△
Other Processes																	
* **Natural Attenuation**	67	NA	**3,4,5**	1,2,6	■	Neither	■	No	None	I	T	Yes	△	■	○	△	△
Excavation and Off-Site Disposal	71	NA		1-7	△	Neither	■	No	NA	NA	M	No	■	■	■	△	■
GROUNDWATER																	
***In Situ* Biological Processes**																	
Oxygen Enhancement with H_2O_2	73	F	**3,4,5**	1,2,6	○	O&M	■	No	None	■	T	Yes	○	△	■	○	■
Co-metabolic Processes	75	P	**1,2**	3-6	○	O&M	△	No	None	■	T	Yes	○	△	△	I	I
Nitrate Enhancement	77	P	**3,4,5**	1,2,6	■	Neither	△	No	None	■	T	Yes	○	○	△	△	○
Oxygen Enhancement with Air Sparging	79	F	**3,4,5**	1,2,6	■	Neither	■	No	None	■	T	Yes	○	■	○	○	■
***In Situ* Physical/Chemical Processes**																	
* **Slurry Walls (containment only)**	81	F		1-7	■	Cap	■	NA	NA	NA	M	I	■	■	■	△	○
Passive Treatment Walls	83	P	**1,2,7**	3,4,5	I	Cap	△	No	S	I	T	I	△	I	△	I	I
Hot Water or Steam Flushing/Stripping	85	P	**2,4,5**	1,3	○	Cap	○	Yes	L,V	○	V	Yes	■	△	△	○	○
Hydrofracturing (enhancement)	87	P		1-7	○	Neither	I	Yes	None	NA	M	Yes	■	■	△	■	○
Air Sparging	89	F	**1,3,5**		■	Neither	■	Yes	V	○	V	Yes	■	■	○	■	■
Directional Wells (enhancement)	91	F		1-7	I	Neither	△	Yes	L,S	NA	NA	Yes	■	○	○	■	■
Dual Phase Extraction	93	F	**1,3,5**		○	O&M	■	Yes	L,V	○	V	Yes	○	○	■	○	■
Vacuum Vapor Extraction	95	P	**1,2,5**	3,4,6,7	○	Cap	△	No	L,V	■	V	Yes	○	■	△	○	■
* **Free Product Recovery**	97	F	**4,5**		■	Neither	■	No	L	NA	V	Yes	■	○	■	■	■
***Ex Situ* Biological Processes (assuming pumping)**																	
Bioreactors	99	F	**3,4,5**	1,2,6	■	Cap	■	No	S	○	T	Yes	NA	○	○	■	○
***Ex Situ* Physical/Chemical Processes (assuming pumping)**																	
* **Air Stripping**	101	F	**1,3**	2,4,5	■	O&M	■	No	L,V	■	V	Yes	NA	○	■	△	○
* **Carbon Adsorption (liquid phase)**	103	F	**2,4**	1,5-7	△	O&M	■	No	S	■	V	Yes	NA	■	■	■	■
UV Oxidation	105	F	**1,2,6**	3,5	○	Cap	■	No	None	■	T	Yes	NA	△	○	○	○
Other Processes																	
* **Natural Attenuation**	107	NA	**3,4,5**	1,2,6	■	Neither	■	No	None	I	T	Yes	△	■	○	△	△
AIR EMISSIONS/OFF-GAS TREATMENT																	
* **Carbon Adsorption (vapor phase)**	111	F	**1-6**		■	Neither	■	NA[b]	S	■	V	Yes	NA	■	■	○	■
* **Catalytic Oxidation (non-halogenated)**	113	F	**3,4,5**		■	Neither	■		None	■	T	Yes	NA	■	■	■	■
Catalytic Oxidation (halogenated)	115	F	**1,2**		■	Neither	○		None	■	T	Yes	NA	○	△	○	○
Biofiltration	117	F	**3,5**	1	■	Neither	○		None	■	T	Yes	NA	○	△	I	I
* **Thermal Oxidation**	119	F	**3,4,5**		■	Neither	■		None	■	T	Yes	NA	■	■	■	○

[a] The listing of contaminant groups is intended as a general reference only. A technology may treat only selected compounds within the contaminant groups listed. Further investigation is necessary to determine applicability to specific contaminants.

[b] The definition of this factor is not applicable to these technologies. They are, by design, the final step in treatment processes.

* Conventional technologies/processes

Contaminant Codes

1 - Halogenated volatile organics
2 - Halogenated semivolatile organics
3 - Non-halogenated volatile organics
4 - Non-halogenated semivolatile organics
5 - Fuel hydrocarbons
6 - Pesticides
7 - Inorganics

Target contaminants are listed first and in bold type

Rating Codes

■	Better
○	Average
△	Worse
I	Inadequate information
NA	Not applicable