United States Environmental Protection Agency | Office of Research and Development | Office of Solid Waste and Emergency Response | EPA/540/S-93/506 October 1993

EPA Engineering Issue

Technology Alternatives for the Remediation of PCB-Contaminated Soil and Sediment

B. Dávila[a], K.W. Whitford[b], and E.S. Saylor[c]

Because of the increased need for Superfund decision-makers to have a working knowledge of the remedial capabilities available to treat soil and sediment contaminated with polychlorinated biphenyls (PCBs), the Superfund Engineering Forum has identified remediation of PCB-contaminated soil and sediment at Superfund sites as a high priority. The Engineering Forum is a group of EPA professionals representing EPA's Regional Superfund Offices. The Forum is committed to the identification and resolution of engineering issues that impact the remediation of Superfund sites. The Forum advises and is supported by the Office of Solid Waste and Emergency Response (OSWER) Superfund Technical Support Project.

This document is intended to familiarize On-scene Coordinators (OSCs) and Remedial Project Managers (RPMs) with issues important to the successful selection of technology alternatives available for the remediation of soil and sediment contaminated with PCBs at Superfund sites. For further information on this paper, please contact Ms. Brunilda Dávila at the Risk Reduction Engineering Laboratory (RREL), (513) 569-7849.

INTRODUCTION

From 1929 to 1980, the cumulative world production of PCBs was approximately 2.4 billion pounds [1, p. 173]*. PCBs have not been manufactured in the United States since 1977. PCBs were used as dielectric fluids in electrical transformers and capacitors, and were often mixed with organic solvents such as chlorinated benzenes. Toxic metals, most commonly lead, are also present at many sites with PCB contamination. PCBs were also used in hydraulic, lubricating, and heat transfer fluids, as plasticizers in paint, and as dye carriers in carbonless copy paper [2, p. 4.1]. Due to their widespread use, large amounts of PCBs have been released into the environment. EPA has determined that PCBs may cause adverse reproductive effects, developmental toxicity, and cancer, and thus are dangerous to human health and wildlife [3].

The primary purpose of this report is to provide OSCs and RPMs with information on established, demonstrated, and emerging technology alternatives for remediating PCB-contaminated soil and sediment. This information includes process descriptions, site requirements, performance (including a pilot- or full-scale example for established and demonstrated technologies), process residuals, innovative systems, and EPA contacts. Estimated costs for basic technology operation and advantages and limitations of each technology are also presented. Information on current research and failed treatment technologies is also provided. The secondary purpose is to provide basic information on characteristics of PCBs, regulations governing PCB remediation, sampling and data collection methods applicable to PCB contamination, analytical methods and technologies used to quantify PCB contamination, treatability studies, and sources of further information. This Engineering Issue Paper condenses and updates the information presented in the EPA Superfund document entitled "Guidance on Remedial Actions for Superfund Sites with PCB Contamination," EPA/540/G-90/007, August 1990 [4]. The contents of this Issue Paper are based upon the assumption that the

a Chemical Engineer, Risk Reduction Engineering Laboratory, Cincinnati, OH
b Environmental Scientist, Science Applications International Corporation, Cincinnati, OH
c Civil /Environmental Engineer, Science Applications International Corporation, Cincinnati, OH

* [reference number, page number]

Superfund Technical Support Center for Engineering and Treatment

Risk Reduction Engineering Laboratory

Engineering Forum

Technology Innovation Office
Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC

Walter W. Kovalick, Jr., Ph.D.
Director

Printed on Recycled Paper

reader is already somewhat familiar with PCBs, remedial alternatives, and environmental regulations. The list of references at the end of the document will assist those who are less familiar with these topics.

CHARACTERISTICS OF PCBs

PCBs, also referred to by the trade names Aroclor*, Phenoclor, and Kanechlor [5, p.2], encompass a class of chlorinated compounds that includes up to 209 variations, or congeners, with different physical and chemical characteristics [6]. Most PCBs are oily liquids whose color darkens and viscosity increases with rising chlorine content. PCBs with fewer chlorine atoms are more soluble, more amenable to chemical and biological degradation, and less persistent in the environment than those PCBs with more chlorine atoms. PCBs are thermally stable and excellent electrical insulators [1, p.173].

PCBs are very persistent, hydrophobic, and generally do not migrate. However, there are some site characteristics that may have a bearing on the potential of PCBs to migrate. For example, PCBs in oil will be mobile if the oil itself is present in a volume large enough to physically move a significant distance from the source. Soil or sediment characteristics that affect the mobility of the PCBs include soil density, particle size distribution, moisture content, and permeability. Additionally, meteorological and chemical characteristics such as amount of precipitation, organic carbon content, and the presence of organic colloids also affect PCB mobility [4, p. 33]. Determination of these characteristics during the Remedial Investigation/Feasibility Study (RI/FS) activities will aid in estimating the mobility of PCBs at a site.

Because of the stability of PCBs, many exposure routes must be considered: dermal exposure; ingestion of PCB-contaminated soil, water, and food; and inhalation of ambient air contaminated with PCBs. PCBs have a high potential for bioaccumulation, which is an important factor to consider due to their ability to accumulate in aquatic environments such as lakes, rivers, and harbors [5, p. 1]. Although not very common, volatilization and other transport mechanisms may remove PCBs from the contaminated soil or sediment or entrain them into the air. Remedies involving excavation may create short-term exposures to workers and surrounding communities from inhalation of dust emissions.

Chronic exposure of animals to PCBs can lead to disrupted hormone balances, reproductive failure, teratomas, or carcinomas. Plants, however, do not appear to exhibit detectable toxicity responses to PCBs [4, p. 37]. A more significant health impact of PCBs may be caused by their incomplete combustion during thermal treatment processes. Incomplete oxidation of PCBs may form polychlorinated dibenzofuran (PCDF) emissions [7]. These are of a concern due to their toxicological and lethal effects on laboratory animals.

REGULATIONS GOVERNING PCB REMEDIATION

CERCLA

The National Contingency Plan, instituted by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, established a framework for identification and remediation of the nation's most contaminated and hazardous sites (Superfund sites). Section 121(d)(2)(A) of CERCLA requires adherence to other Federal and State laws through the identification of and compliance with applicable or relevant and appropriate requirements (ARARs). These ARARs must be complied with or waived for all Superfund remedial actions. Federal ARARs for PCB-contaminated sites are derived from the Toxic Substances Control Act (TSCA) and the Resource Conservation and Recovery Act (RCRA). Other requirements and regulations derived from the Clean Water Act (CWA) and the Clean Air Act (CAA) may be implemented when remediation of the site potentially affects water or air quality [4, p. 9]. Additionally, regulations of the Occupational Safety and Health Administration (OSHA) must be followed.

TSCA

TSCA as codified in 40 CFR 761 [8], establishes prohibitions of and requirements for the manufacture, processing, distribution in commerce, use, disposal, storage, and marking of PCBs and PCB items in the United States after January 1, 1978. TSCA regulations apply to concentrations of PCBs equal to or greater than 50 parts per million (ppm). PCBs that have been released into the environment after February 17, 1978 are regulated based upon the original concentration of the released material. This approach to regulating PCBs is found in 40 CFR 761.1(b) and states that "No provision specifying a PCB concentration may be avoided as a result of any dilution." This section is generally known as the "anti-dilution" provision of the PCB regulations. However, PCBs at Superfund sites are regulated based on the concentrations found at the site. During site characterization, EPA evaluates the form and concentration of PCB contamination at Superfund sites "as found" at the site, disposing of the contaminated medium as stated in 40 CFR 761.60 (a)(2) to 761.60(a)(5). Consequently, cleanup levels and remedial technologies at Superfund sites should not be selected based on the form and concentration of the original PCB material spilled or disposed of at the site prior to EPA's involvement (i.e., the anti-dilution provision of the PCB regulations should not be applied) [4, p. 11]. RPMs and OSCs should also be aware that remedial technologies that concentrate PCBs, such as thermal desorption, may produce a PCB residue that contains a concentration greater than 50 ppm. In such cases, TSCA regulations may not be an ARAR for treatment of PCB-contaminated soil or sediment, but may be an ARAR for the concentrated residues.

TSCA considers any person "whose act or process produces PCBs... or whose act first causes PCBs to become subject to the disposal requirements of Subpart D..." to be a generator [2, p. 4.9]. Persons generating soil, sediment, or treatment residuals contaminated with PCBs in concentrations equal to or greater than 50 ppm, must comply with TSCA generator requirements. These requirements include: notification to EPA of PCB-generating activities (if the generator owns or operates a PCB storage facility subject to the requirements of 40 CFR 761.65(b)), shipment of regulated wastes using the Uniform Hazardous Waste Manifest, and disposal at a TSCA-approved disposal facility.

The storage requirements of 40 CFR 761.65 are especially important, requiring disposal of TSCA-regulated PCB wastes within 1 year of being taken out of service for disposal and placed into storage. Where the final disposition of PCB wastes at a Superfund site is specified in that site's Record of Decision (ROD), a CERCLA waiver to allow storage to exceed 1 year may

* Mention of trade names, companies, or products does not constitute endorsement or recommendation for use.

be pursued [4, p.18]. Temporary storage of PCB-contaminated soil or sediment by the generator is allowed for up to 30 days with relatively minor requirements. Storage beyond this timeframe must be performed in an area meeting the siting, structural, labeling, and inspection requirements of 40 CFR 761.65 (b) [8].

Non-liquid PCBs in the form of soil, rags, or other debris, that contain PCBs in concentrations of 50 ppm or greater, may be disposed of in either an incinerator meeting the requirements of 40 CFR 761.70, or a chemical waste landfill meeting the requirements of 40 CFR 761.75. A third option is to employ a treatment method capable of achieving the same remedial results as incineration. Incineration is the demonstrated technology and the standard for PCB destruction. The performance standards for PCB incinerators are provided in the regulations at 40 CFR 761.70 (b)(l). Among the numerous requirements for PCB incinerators is that mass air emissions from the incinerator shall be no greater than 0.001 g PCB/kg of PCB introduced into the incinerator [8].

The regulations provide for approval of alternative technologies if they are demonstrated to be equivalent to incineration in ability to destroy PCBs. The EPA Regional Administrator may approve such disposal methods after submitting information required by 40 CFR 761.60(e) for both soil and sediment, or 40 CFR 761.60(a)(5) for sediment. 40 CFR 761.70(d)(5) contains provisions for waivers of the requirements which would otherwise be applicable to incinerators.

The TSCA PCB spill cleanup policy is found in 40 CFR 761.120 to 761.135. The policy takes into consideration how quickly the spill is reported, when cleanup is initiated, and the current use of the affected area. The remediation of spills reported within the timeframes identified in the regulations (24 to 48 hours after occurrence) is governed by the procedural and numerical requirements listed in this policy. Spills which are not reported within these timeframes are not covered by the policy and therefore, procedures and cleanup levels are determined on a case-by-case basis. Spills that occurred prior to May 4, 1987 also are not regulated by this policy. Although the TSCA PCB cleanup policy may not apply to a substantial number of Superfund sites, EPA generally uses the provisions of the policy to guide CERCLA cleanups.

RCRA

PCBs are not regulated as a hazardous waste under RCRA. However, if PCBs are mixed with hazardous wastes listed in 40 CFR 261.31 to 261.33 (e.g., spent trichloroethylene that was used to clean electrical equipment), the mixture is subject to the RCRA hazardous waste regulations. Similarly, if PCBs are mixed with other wastes, and the resulting mixture exhibits one or more of the hazardous characteristics discussed in 40 CFR 261.21 to 261.24 (i.e., ignitability, corrosivity, reactivity, or toxicity), the mixture must be managed as hazardous waste until the waste no longer exhibits the characteristic. PCB-contaminated soil or sediment that is also contaminated with listed waste or exhibits a hazardous characteristic, must be managed as hazardous waste until the contaminated media no longer contains the listed waste (a decision that can be made by EPA regional offices) or no longer exhibits the hazardous characteristic.

The 1984 Hazardous and Solid Waste Amendments to RCRA specified additional requirements for treatment and disposal of hazardous waste. Solid waste management units (SWMUs) at hazardous waste treatment, storage, and disposal (TSD) facilities became subject to more stringent corrective action requirements. Also, land disposal of hazardous waste without prior treatment by a specified technology, or to a specified constituent concentration, became prohibited under the land disposal restrictions (LDRs).

The California List of the LDRs states that liquid hazardous waste containing greater than 50 ppm of PCBs must either be incinerated in a TSCA incinerator or a high-efficiency boiler [9]. The California list also regulates the disposal of hazardous waste containing halogenated organic compounds (HOCs) when present in concentrations greater than 1,000 mg/kg. The HOC list includes seven specific Aroclors, as well as "PCBs not otherwise specified." Incineration is the specified remedial technology. The presence of other restricted hazardous waste in PCB-contaminated soil and sediment also subjects the media to the applicable LDRs.

Other Federal Regulations

Remediation of PCB-contaminated sediment may affect local and downstream water quality during activities such as dredging and dewatering. The Clean Water Act (CWA) establishes requirements and discharge limits for actions that affect surface water quality. Accordingly, the technical requirements of permits such as the National Pollutant Discharge Elimination System (NPDES) permit may have to be met.

Remedial technologies that have the potential to emit PCBs or other contaminants into the air may be required to employ control measures in accordance with the Clean Air Act (CAA). Regulated units could include baghouses, exhaust stacks, and pressure release devices on treatment tanks.

State Regulations

At least 18 states currently regulate various aspects of PCB disposal [2, p. 4.22]. States also may regulate PCB treatment, and may have established cleanup levels. EPA, therefore, may also have to comply with state PCB requirements. Applicable state regulations must be included as ARARs or waived when appropriate.

DATA COLLECTION, SAMPLING, AND ANALYSIS

Data collection and sampling begin during project scoping. Sampling and data collection at Superfund sites should be designed to aid in selecting and implementing a remedial technology. Other reasons for such sampling and data collection at Superfund sites include: site characterization, health and safety monitoring during treatment, performance evaluation, and, if necessary, long-term monitoring. These activities also should be designed to support future enforcement actions. The end use of the data dictates the required quality of the information. This required quality is stated in the data quality objectives (DQOs) already established prior to any generation of data [10].

Before selection and implementation of a remedial technology, sampling to characterize site conditions must be performed. Samples chosen to document the concentration and distribution of contaminants throughout the area(s) of interest must be of sufficient number to be representative and of sufficient sample volume for all analytical, quality assurance, and quality

control operations. During sampling, it is also crucial to look for evidence of contaminant transport so that the proper sources are targeted for remediation. Many of the components of a successful sampling plan and associated sampling procedures are discussed in the handbook "Remediation of Contaminated Sediments" [11, pp.11-13]. Additional information is presented in Volume II of EPA's "Test Methods for Evaluating Solid Waste: Physical/Chemical Methods" (SW-846) [12]. The Methods Communication Exchange (MICE) Service provides answers to questions and takes comments over the telephone on technical issues regarding this manual. The MICE service telephone number is (703) 821-4789.

When sampling to identify potential remedial technology alternatives for treating contaminated soil and sediment, there are several soil, sediment, water, and contaminant data elements that need to be evaluated. The compiled data should permit prescreening of a group of potentially applicable remedial methods and the direct elimination of others. In the selection of a remedial technology, consideration of such information as the past history of the site, how and where wastes were disposed, topographic and hydrologic detail, and site stratigraphy will provide a more comprehensive assessment.

Physical and chemical characteristics of the PCB-contaminated soil or sediment also determine the types of remedial technologies potentially suitable for the site. The minimum set of soil and sediment measurements desirable for remedial technology prescreening is presented in Table 1 [13]. In addition to the physical characteristics of the PCB-contaminated media, OSCs and RPMs should be aware that the presence of other contaminants can impact the effectiveness of a remedial technology and PCB analyses. The ratings in Table 1 are relative values for the parameters of concern based upon expert opinion. The values are described as "higher" or "lower" in defining the tendency of these parameters to enhance or inhibit prescreening of a particular treatment process. For example, larger quantities of oil and grease would improve the performance of chemical dehalogenation (i.e., base-catalyzed decomposition); increased oil and grease content would decrease the performance of solidification/stabilization. Inclusion of a rating within the technology group, however, does not ensure that the rating will be applicable to each individual system within a technology group. *OSCs and RPMs are advised to contact the EPA experts listed later in this paper in order to discuss the importance and availability of quantitative values for specific characteristics.* This information also is generally applicable to the treatment of water produced as a residual from the remediation of PCB-contaminated soil or sediment. Additional information on site data requirements for the selection of remedial technologies may be found in other references [14][15].

During implementation of the chosen remedial technology, sampling is usually required to assess the effect of process emissions on site workers and the surrounding area. Remedial technologies that require excavation and movement of contaminated soil or sediment may generate PCB-contaminated dust. Thermal technologies produce offgases that may contain PCBs that have not been captured or destroyed by the process. Sampling of process emissions and surveillance of site conditions during waste treatment should be designed to evaluate all of the applicable concerns. Sampling and analytical methods designed to assess worker safety and health can be found in the "National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods" [16].

After implementation of the chosen remedial technology, the effectiveness of the system(s) must be evaluated through sampling and analysis. Depending on the technology, both short- and long-term performance needs to be assessed. Development of sampling plans to accomplish this objective is discussed in "Methods for Evaluating the Attainment of Cleanup Standards" [17].

Analytical methods for detection and quantification of PCBs in soil and sediment are primarily performed in the laboratory. Laboratory determination of Aroclors in these media generally costs $100 to $200 per sample and usually requires a minimum of 72 hours from sample collection to receipt of results [18]. The laboratory method 8080 (Organochlorine Pesticides and Polychlorinated Biphenyls by Gas Chromatography) in SW846 is the most commonly chosen procedure for the analysis of these PCB-contaminated media. The PCBs are first extracted from the soil or sediment, commonly using Method 3540 (Soxhlet

Table 1. Soil and Sediment Characteristics That Assist in Technology Alternative Prescreening

	REMEDIAL TECHNOLOGY							
	Established	Demonstrated				Emerging		
CHARACTERISTIC	Incineration	Thermal Desorption	Chemical Dehalogenation	Solvent Extraction	Soil Washing	Solidification/Stabilization	Bioremediation	Vitrification
Particle size	■	■	▼	■	■	■	▼	■
Bulk density	■	■		▼	▼			
Permeability				■	■		■	
Moisture content	□	□		▼	▼	□	■	□
pH and Eh	▼	▼	▼				▼	
Humic content	▼	▼	□	□	□	□	□	□
Total organic content (TOC)	■	■	▼			▼	□	▼
Biochemical oxygen demand (BOD)							□	
Chemical oxygen command (COD)			■				□	
Oil and grease			■	▼	▼	□		□
Volatile metals	□	□	□	■		■	□	□
Nonvolatile metals	□	□	□	■	■	■	□	■

Source: Vendor specific information and technology experts [adapted from 13]

■ = higher values support preselection of technology group.

□ = lower values support preselection of technology group.

▼ = effect is variable among systems within a technology group.

Where no symbol is shown, the effect of that characteristics considered inconsequential.

Extraction) or 3550 (Ultrasonic Extraction). The PCB extract is then concentrated and injected into a gas chromatograph equipped with an electron capture detector. The analyst identifies Aroclor residues by comparison of gas chromatographic peak profiles (peak retention times and relative intensities) produced by Aroclor standards with those produced by a sample extract [12]. Identification and quantification of PCBs can be hindered by interfering compounds, such as other halogenated organic compounds, which appear on the chromatogram in the same retention time region as PCBs.

Several lower cost field test kits, providing faster results, are currently available [18]. For example, one test kit, using colorimetric determination of PCBs, can provide semiquantitative results within 10 minutes for approximately $20 per sample [19]. Currently, another colorimetric test kit (the Dexsil Clor-N-Soil PCB Screening Kit™) is being tested through the Superfund Innovative Technology Evaluation (SITE) Monitoring and Measurement Technologies Program. Also being tested are an immunoassay kit (Enviroguard™ PCB Immunoassay Test Kit), and a chloride-specific electrode test kit (the Dexsil L 2000 PCB Chloride Analyzer™) [20, pp. 324-337].

Additional information on analytical methods for the analysis of PCB-contaminated soil and sediment is available in "Analytical Chemistry for PCBs, Second Edition" [21]. Technical questions regarding the analysis of PCB-contaminated soil and sediment should be directed to Ann Alford-Stevens (EMSL), at (513)569-7492.

TECHNOLOGIES FOR REMEDIATION OF PCBs IN SOIL AND SEDIMENT

This section discusses technologies that have been used to treat, destroy, or remove PCBs from PCB-contaminated soil and sediment. The technologies are classified under three headings: established, demonstrated, and emerging. Established technologies are those that have been employed at the full-scale level to successfully meet PCB cleanup goals at multiple sites; they are commercially available. Demonstrated technologies have been conducted at pilot- or full-scale at a limited number of sites. They have generated performance and cost data on the treatment of PCB-contaminated soil or sediment. Emerging technologies have not yet been shown to effectively or consistently treat PCB-contaminated soil or sediment at the pilot-scale level. They are in bench-scale studies or in pilot-scale testing stages and are designed to generate data on the treatment of PCB-contaminated soil or sediment. For each technology the following topics are discussed:

- Process description;
- Site requirements for technology implementation;
- Technology performance in treating PCBs in soil or sediment;
- Process residuals;
- Technology systems accepted in the SITE Demonstration and Emerging Programs [including the availability of Applications Analysis Reports (AARs) and Technology Evaluation Reports (TERs)]; and
- EPA contact for the technology.

Within the performance discussion for each remedial technology, the number of Superfund sites where the technology has been selected as either a stand-alone remedial alternative for a portion or all of the site, or as a component in a treatment train at the site is given. An example of application of the technology with available performance data is presented for established and demonstrated remedial technologies. Availability of certain additional performance data is limited due to legal conflicts, while other data are still being generated and analyzed prior to being reported. The reader is therefore referred to the contacts listed in the tables summarizing application of each technology for the most current information.

Estimated cost ranges for the basic operation of the technology, critical factors affecting cost ranges, and advantages and limitations of each alternative technology are presented at the end of this section in Figure 1 and Tables 12, 13, and 14 respectively. The information was compiled from EPA documents, including Engineering Bulletins, SITE Demonstration Reports, and EPA electronic databases. OSCs and RPMs are cautioned that the cost estimates generally do not include pretreatment, site preparation, regulatory compliance costs, costs for additional treatment of process residuals (e.g., stabilization of incinerator ash or disposal of PCBs concentrated by solvent extraction), or profit. Since the actual cost of employing a remedial technology at a specific site may be significantly higher than these estimates, the data are best used for order of magnitude cost evaluations.

TREATABILITY STUDIES FOR PCB-CONTAMINATED SOIL AND SEDIMENT

The presence of PCBs with other contaminants in soil or sediment often creates site-specific treatment problems. The varied structures and properties of PCBs also present site-specific concerns for remediation of Superfund sites. Therefore, prior to selecting PCB remedial technologies, site-specific treatability studies are necessary to evaluate the potential applicability and performance of a particular technology in remediation of PCB-contaminated soil or sediment. Treatability studies provide data to support remedial technology selection and remedy implementation. They should be performed as soon as it is evident that insufficient information is available to ensure the quality of the technology selection process. Conducting treatability studies early in the RI/FS process reduces uncertainties associated with selecting the remedy, provides a sound basis for the ROD, and minimizes the possibility of failure at full-scale implementation. EPA regional planning should factor in the time and resources required for these studies [22, p. 1].

Treatability studies conducted during the RI/FS activities indicate whether the technology can meet the cleanup goals for the site, whereas treatability studies conducted during the Remedial Design/Remedial Action (RD/RA) activities establish design and operating parameters for optimization of technology performance. Although the purpose and scope of these studies differ, they complement one another, since information obtained in support of remedy selection may also be used to support the remedy design [23].

The need for treatability testing is a management decision. The time and cost necessary to perform the testing are balanced against the improved confidence in the selection and design of alternatives. These decisions are based on the quantity and quality of data available and on other factors (e.g., state and community acceptance of the remedy, new site data, or experience with the technology). A useful document is EPA's "Guide for Conducting Treatability Studies Under CERCLA" [24].

Established Remedial Technologies

Incineration

Incineration treats organic contaminants in solids and liquids by subjecting them to temperatures typically greater than 1,000°F in the presence of oxygen, which causes volatilization, combustion, and destruction of these compounds. Many companies have built incinerators that are actively employed in the remediation of Superfund sites. Some of these are scaled-down, trailer-mounted versions of conventional rotary kiln or fluidized bed incinerators with thermal capacities of 10 to 20 million British thermal units per hour (Btu/hr). However, transportable units as large as 80 million Btu/hr are also available. At large sites where the cleanup will require several years, it may be feasible to actually construct an incinerator onsite. Economic reasons are often the key factor in determining whether mobile, transportable, fixed, or offsite commercial incineration will be used at a given site. Because onsite cleanups at Superfund sites can be conducted without having to meet the administrative requirements of Federal, State, or local permits, the time required for startup can usually be reduced [25, pp. 10-12].

The applicability of incineration to the remediation of PCB-contaminated soil or sediment may be limited by the types and concentrations of metals present in the medium. When soil or sediment containing metals is incinerated, the metals vaporize, react to form other metal species, or remain with the soil residuals. Metals in ash, scrubber sludge, or stack emissions, if improperly managed, can result in potential exposures and adverse health effects [26, p. 1]. Lead, a metal commonly found associated with PCB-contamination, volatilizes at most incinerator operating temperatures and must be captured before process offgases are released into the atmosphere. It is therefore important to adequately characterize the metal content of the soil or sediment when considering incineration systems for PCB treatment. For more information on the implications of incineration of soil containing metals refer to "Considerations for Evaluating the Impact of Metals Partitioning During the Incineration of Contaminated Soils from Superfund Sites" [26].

Process Description—

The primary stages in the incineration process are waste preparation, waste feed, combustion, and offgas treatment.

Waste preparation includes excavation and/or transporting the waste to the incinerator. Depending on the requirements of the incinerator, various classification equipment is used to remove oversized particles and obtain the necessary feed size for soil and sediment. Blending of the soil or sediment and size reduction are sometimes required to achieve a uniform feed size, moisture content, Btu value, and contaminant concentrations [27, p. 21].

The waste feed mechanism, which varies with the type of incinerator, introduces the waste into the combustion system. The feed mechanism sets the requirements for waste preparation. Bulk solids usually are shredded; contaminated media are usually ram or gravity fed [28, p. 10].

In the combustion stage, the three major systems are rotary kiln, infrared, and circulating fluidized bed. The primary factors affecting the design and performance of the system are the temperature at which the furnace is operated, the time during which the combustible material is subjected to that temperature (residence time), and the turbulence required to expose the combustible material to oxygen to obtain complete combustion.

Offgases from the incinerator are treated by air pollution control (APC) equipment to remove particulates and capture and neutralize acid gases. APC equipment includes cyclones, venturi scrubbers, wet electrostatic precipitators, baghouses, and packed scrubbers. Rotary kilns and infrared processing systems may require both external particulate control and acid gas scrubbing systems. Circulating fluidized beds do not require scrubbing systems because limestone can be added directly into the combustor loop; however, they may require a system to remove particulates [28, p. 29].

Site Requirements—

The site should be accessible by truck or rail, and a graded or gravel area is required for setup of onsite mobile systems. Concrete pads may be required for some equipment (e.g., rotary kiln). For a typical commercial-scale unit, 2 to 5 acres are required for the overall system site including ancillary support [27, p. 25]. Standard 440V, three-phase electrical service is generally needed. A continuous water supply must be available at the site. Auxiliary fuel for feed Btu improvement may also be required.

Various ancillary equipment may be required, such as liquid or sludge transfer and feed pumps, ash collection and solids handling equipment, personnel and maintenance facilities, and process-generated waste treatment equipment. In addition, a feed-materials staging area, decontamination trailer, ash handling area, water treatment facilities, and a parking area may be required [27, p. 24]. A site safety plan covering all onsite activities should be developed. An emergency shut down plan also should be prepared. Special handling measures should be provided to hold any process residual streams until they have been tested to determine their acceptability for disposal or release. Depending on the site, a method to store waste that has been prepared for treatment may also be necessary. Storage capacity will depend on waste volume and equipment feed rates.

Performance—

As of September 1991, incineration technologies had been selected as the remedial action at 65 Superfund sites with PCB-contaminated soil or sediment [29][30]. Incinerator performance is most often measured by comparing initial PCB concentrations in feed materials with both final concentrations in ash (i.e., removal efficiency) and concentrations present in offgas emissions. Incinerators burning non-liquid PCB wastes must meet the performance and monitoring requirements specified in 40 CFR 761.70 [8].

In November 1989, a pilot-scale incineration unit was tested as part of the SITE program at the Demode Road Superfund Site. Soil contaminated with PCBs having initial concentrations ranging from 290 to 3,000 ppm was present at the site. Prior to entering the system, the feed material was screened to remove aggregate and debris greater than 1 inch in diameter. The system consisted of a primary combustion chamber, where electric infrared heating rods were used to heat the waste, and a secondary chamber where a propane-fired flame was used to destroy any remaining hydrocarbons in the exhaust from the first chamber. A venturi scrubber and horizontal packed tower were also used for particulate and acid gas removal before exhausting the gas to the atmosphere [31, pp. 1-11.].

The test indicated that the system would remove and destroy PCBs from the waste. Final PCB concentration ranged from 0.003 to 3.396 ppm in the ash [31, p. 12]. However, there was no evidence that the process reduced the mobility of heavy metals that were present in the furnace ash as compared to the feed. This was to be expected since metals are not destroyed by combustion and will be present in the ash or released into the flue gas. Stack gas, primary combustion chamber (PCC) offgas, HCl, and particulate emissions all were well below the maximum amount allowed under RCRA standards. DREs in excess of the 99.99 percent required for RCRA applications were achieved. Performance with respect to the TSCA requirement of 99.9999 percent DRE for PCBs could not be ascertained because of the low concentration of PCBs in the incinerator feed [31, pp. 10-19]. Information on the application of incineration for the treatment of PCB-contaminated soil and sediment at other sites is presented in Table 2 [30][32]. For further site-specific information contact the EPA individual listed or obtain the reference indicated.

Process Residuals—

Three major waste streams generated by incineration are: solids from the incinerator and APC system, water from the APC system, and emissions from the incinerator. Ash is commonly either air-cooled or quenched with water after discharge from the combustion chamber. Dewatering or solidification/stabilization of the ash may also have to be applied since the ash could contain leachable metals at concentrations above regulatory limits. The alkalinity of the matrix may influence the leachability of the ash [33, p. 63]. The flue gases from the incinerator are treated by APC systems such as electrostatic precipitators or venturi scrubbers before discharge through a stack. A high-pH liquid waste may be generated by the APC system. This waste may contain high concentrations of chlorides, volatile metals, trace organics, metal particulates, and other inorganic particulates. Wastewater requiring treatment may be subjected to neutralization, chemical precipitation, reverse osmosis, settling, evaporation, filtration, or carbon adsorption before discharge [15, p. 127].

SITE Demonstration and Emerging Projects—

As of November 1992, the SITE Program included two demonstrated incineration systems reportedly capable of treating PCBs in soil and sediment. The technology developer, system name, status of the technology, and EPA contact for these systems are presented in Table 3 [20].

Contact—

Technology-specific questions regarding incineration may be directed to Donald A. Oberacker (RREL) at (513) 569-7510.

Demonstrated Remedial Technologies

Thermal Desorption

Thermal desorption is an ex situ means to physically separate volatile and semivolatile contaminants from soil, sediment, sludge, and filter cake by heating them at temperatures high enough to volatilize the organic contaminants. It is generally cost-effective to implement thermal desorption on wastes containing up to 10 percent organics and a minimum of 20 percent solids [34, p. 2].

Table 2. Application of Incineration at Selected Superfund Sites with PCB-Contaminated Soil or Sediment

Site	Type of Medium	Status	Lead	Contact
Florida Steel, FL [30][32]	Soil	Process residuals management in predesign.	Federal lead/ Fund financed	Randy Bryant (404) 347-2643
Twin City Army Ammunition Plant, MN [30][32]	Soil	Pilot-scale tests completed 1989.	PRP lead U.S. Army/ Federal oversight	Larry LeVeque (312) 886-4359
Rose Township, MI [30][32]	Soil	Full-scale remediation started. Completion expected summer 1993.	PRP lead/ Federal oversight	Kevin Adler (312) 886-7078
LaSalle Electric Utilities, IL [30][32]	Soil	Completion expected summer 1993.	State lead	Dave Seeley (312) 886-7058
New Bedford Harbor, MA [32]	Sediment	Remediation ongoing	Federal lead/ Fund financed	Gail Garman (617) 223-5522
Douglassville, PA [32]	Sediment	Full-scale design completed. Remediation to begin winter 1993.	PRP lead/ Federal oversight	Victor Janosik (215) 597-8996

Table 3. Innovative Incineration Systems Currently Accepted Into the SITE Program [20]

Developer	System Name	Status	EPA Contact
Gruppo Italimpresse	Infrared Thermal Destruction [a]	Two SITE demonstrations were conducted in 1987 (AARs and TERs available). Used in full-scale remediation.	Laurel Staley (513) 569-7863
Ogden Environmental Services	Circulating Bed Combustor [a]	SITE demonstration was conducted in 1988 (TER available).	Douglas Grosse (513) 569-7844

[a] Demonstration Program

Process Description—

Thermal desorption is a process that uses either an indirect or direct heat exchange to heat organic contaminants to a temperature high enough to volatilize and separate them from a contaminated solid medium. Air, combustion gas, or an inert gas is used to transfer vaporized contaminants from the medium. The bed temperatures achieved (usually between 300°F and 1,000°F) and residence times used by thermal desorption systems will volatilize selected contaminants and drive off water, but typically not oxidize nor destroy organic compounds [34, p. 1].

The primary stages of a thermal desorption system are materials handling, desorption, particulate removal, and offgas treatment. Materials handling requires excavation of the contaminated soil or sediment. Typically, objects larger than one to two inches in diameter are screened, crushed or shredded and, if still too large, rejected. The medium is then delivered by gravity to the desorber inlet or conveyed by augers to a feed hopper, rotary airlock, or other equipment [35].

As the contaminants are desorbed, they volatilize and are transferred to the gas stream. An inert gas, such as nitrogen, may be injected as a sweep stream to prevent contaminant combustion and to aid in volatilizing and removing the contaminants [36][37]. Other systems simply direct the hot gas stream from the desorption unit to the offgas treatment system [38]. Offgas from desorption is typically processed to remove particulates that remain in the gas-contaminated stream after the desorption step. Organics in the offgas may be treated onsite, collected on activated carbon, or recovered in condensation equipment. The selection of the gas treatment system will depend on the concentrations and types of contaminants, air emission standards, and the economics of the offgas treatment system(s) employed. Methods commonly used to remove the particulates from the gas stream are cyclones, wet scrubbers, and baghouses.

Site Requirements—

Thermal desorption systems are typically transported on modified flatbed semitrailers. Since most systems consist of three components (desorber, particulate control, and gas treatment), space requirements onsite are typically less than 150 by 150 feet, exclusive of materials handling and decontamination areas. Standard 440V, three-phase electrical service is generally needed. Water must be available at the site. The quantity of water needed is equipment- and site-specific.

A site safety plan covering all onsite activities should be developed. An emergency shut down plan also should be prepared. Special handling measures should be provided to hold any process residual streams until they have been tested to determine their acceptability for disposal or release. Depending on the site, a method to store waste that has been prepared for treatment may also be necessary. Storage capacity will depend on waste volume and equipment feed rates.

Performance—

As of October 1992, thermal desorption technologies had been selected as the remedial action at seven Superfund sites with PCB-contaminated soil or sediment [39]. Performance objectives must consider the existing site contaminant levels and relative cleanup goals for soil and sediment at the site. System performance is typically measured by the comparison of untreated solid contaminant levels with those of the processed solids. The actual bed temperature and residence time are primary factors affecting performance in thermal desorption. These factors are controlled in the desorption unit by using a series of increasing temperature zones [36], multiple passes of the medium through the desorber where the operating temperature is sequentially increased, separate compartments where the heat transfer fluid temperature is higher, or sequential processing into higher temperature zones [40][41].

In June 1991, an EPA SITE demonstration was performed at the Outboard Marine Corporation Superfund site in Waukegan Harbor, Illinois. The site was primarily contaminated with PCBs, along with VOCs, SVOCs, and metals. The technology vendor's system used a combination of thermal desorption and chemical dehalogenation. Approximately 253 tons of contaminated soil were treated. The average PCB concentration in the feed soil was 9,173 mg/kg; the average final concentration was 2 mg/kg, which is a 99.98 percent removal efficiency. The concentration of PCBs in the stack gas was 0.834 µg/dscm (a 99.9999 percent removal efficiency). The pH of the soil rose from 8.59 in the contaminated soil to 11.35 in the treated soil. This was likely due to the addition of sodium bicarbonate used to reduce PCB emissions [42, pp. 3, C-1 through C-31]. Informa-

tion on the application of thermal desorption for the treatment of PCB-contaminated soil and sediment at other sites is presented in Table 4 [32][39].

Process Residuals—

Operation of thermal desorption systems may create up to eight process residual streams: treated medium, oversized medium and debris rejects, condensed contaminants, water, particulate control system dust, clean offgas, spent carbon, and aqueous phase activated carbon. Treated medium, debris, and oversized rejects may be suitable for replacement onsite, or may require offsite disposal.

The vaporized organic contaminants can be captured by condensation or passing the offgas through a carbon adsorption bed or other treatment system. Condensed contaminants would then have to be destroyed by another technology. Organic compounds may also be destroyed by using an offgas combustion chamber or a catalytic oxidation unit integrated into the thermal desorption system [22, p. 5].

When offgas is condensed, the resulting water stream may contain significant contamination, depending on the boiling points and solubilities of the contaminants, and may require further treatment (i.e., carbon adsorption). If the condensed water is relatively clean, it may be used to suppress the dust from the treated medium. If carbon adsorption is used to remove contaminants from the offgas or condensed water, spent carbon will be generated, which is either returned to the supplier for reactivation or incineration, or regenerated onsite [22, p. 5].

Offgas from a thermal desorption unit will contain entrained particulates from the medium, vaporized organic contaminants, and water vapor. Particulates are removed by conventional equipment such as cyclones, fabric filters, or wet scrubbers.

When offgas is destroyed by a combustion process, compliance with incineration emission standards may be required; therefore, obtaining the necessary permits and demonstrating compliance prior to beginning the remediation may be advantageous. This approach is also advantageous since it would not leave residuals requiring further treatment [22, p. 5].

SITE Demonstration and Emerging Projects—

As of November 1992, the SITE Program listed six demonstrated thermal desorption systems capable of treating PCBs in soil and sediment. Two of these systems are no longer active in the Program. The Program also listed one emerging system with potential capability. The technology vendor, system name, status of the technology, and EPA contact for these systems are presented in Table 5 [20].

Contact—

Technology-specific questions regarding thermal desorption may be directed to Paul dePercin (RREL) at (513) 569-7797.

Chemical Dehalogenation

Chemical dehalogenation includes technologies such as base-catalyzed decomposition (BCD), alkaline metal hydroxide/polyethylene glycol (APEG), and potassium metal hydroxide/polyethylene glycol (KPEG™). These technologies all employ chemical reactions to remove halogen atoms (chlorine atoms for PCBs) from organic molecules. Due to performance concerns described below, very little research on APEG is performed anymore; thus, it will be briefly discussed in this document. KPEG™ is no longer in use and will not be discussed in this document.

Process Description—

The BCD process was developed by RREL in Cincinnati, Ohio. This process, which does not use polyethylene glycol (PEG) as a primary reagent, has been used to remediate soil and sediment contaminated with chlorinated organic compounds. BCD is an efficient, relatively inexpensive treatment process for

Table 4. Application of Thermal Desorption at Selected Sites with PCB-Contaminated Soil or Sediment [32][39]

Site	Type of Medium	Status	Lead	Contact
Re-Solve, MA	Soil and Sediment	Construction in progress.	PRP lead/ Federal oversight	Rick Cavagnera (617) 573-5731
Wide Beach, NY*	Soil and Sediment	Remediation completed in 1992.	PRP lead/ Federal oversight	Herb King (212) 264-1129
Martin Marietta (Denver Aerospace), CO	Soil	Predesign completed in 1992. Implementation plan under review.	State lead under RCRA	George Dancik (303) 293-1506
Carter Industries, MI	Soil	30% design review completed.	PRP lead/ Federal oversight	John Peterson (312) 886-4439
Solvent Savers, NY	Soil	Predesign completion planned summer 1994.	PRP lead/Federal oversight	Lisa Wong (212) 264-9348

* Combined thermal desorption-chemical dehalogenation system.

Table 5. Innovative Thermal Desorption Systems Currently Accepted Into the SITE Program [20]

Developer	System Name	Status	EPA Contact
Chemical Waste Management	X*TRAX™ [a]	Full-scale system remediating soil and conducting a SITE demonstration at a Superfund site (reports in preparation).	Paul dePercin (513) 569-7797
Recycling Sciences International, Inc.	Desorption and Vapor Extraction System (DAVES) [a]	System no longer active in Program..	Laurel Staley (513) 569-7863
Clean Berkshires (formerly Retech)	High Temperature Thermal Processor [a]	Commercial-scale system in operation. SITE demonstration proposed for fall 1993.	Ronald Lewis (513) 569-7856
SoilTech ATP Systems, Inc.	Anaerobic Thermal Processor [a]	Two SITE demonstrations were conducted during May 1991 and June 1992 (reports in preparation).	Paul dePercin (513) 569-7797
Texarome, Inc.	Solid Waste Desorption [a]	System no longer active in Program.	John Martin (513) 569-7758
Eco Logic Intl.	Thermal Gas Phase Reduction Process [a]	SITE demonstration conducted in 1992. (Bulletin available, reports in preparation.)	Gordon Evans (513) 569-7684
IT Corporation	Mixed Waste Treatment Process [b]	Pilot-scale testing under the Program planned for spring 1994.	Douglas Grosse (513) 569-7844

[a] Demonstration Program
[b] Emerging Program

PCBs. The process can be employed using either sodium hydroxide, sodium bicarbonate, or aliphatic hydrocarbons as hydrogen donors [43]. The U.S. Navy and EPA have developed a BCD unit typifying the process. The contaminated soil is first screened, processed with a crusher and pug mill, and stockpiled. This stockpile is mixed with sodium bicarbonate ($NaHCO_3$) in the amount of 10 percent of the weight of the stockpile and is heated for about 1 hour at 630°F in a rotary reactor. PCBs are completely dechlorinated and partially volatilized in this step. The PCBs in the vapor condensate, residual dust, spent carbon, and filter cake are dechlorinated after about 2 hours at 662°F in a stirred-tank slurry (i.e., liquid phase) reactor (STR) utilizing a high boiling point hydrocarbon oil, catalyst, and sodium hydroxide (NaOH) [44, p. 1].

The APEG chemical dehalogenation system is applicable to aromatic halogenated compounds, including PCBs [45]. APEG partially dehalogenates the pollutant to form a glycol ether or a hydroxylated compound and an alkali metal salt, which are water-soluble by-products. The disadvantages of the APEG process are that it often takes numerous cycles of the process to achieve the desired results, the process only effects partial dehalogenation, and the formation of dioxins and furans often occurs when the process is implemented [43].

Site Requirements—

Access roads capable of supporting semitrailers are required to transport the BCD components to the site. A BCD unit with the capacity to treat 1 ton per hour requires 0.75 to 1 acre of space when fully assembled. Diesel fuel or natural gas must be available to heat the primary reactor. Standard 440V, three-phase electrical service is required for downstream processing and operation of the secondary reactor. Water for cooling and washing must be accessible, and provisions for onsite or offsite wastewater disposal must be established [44, p. 4].

A site safety plan covering all onsite activities should be developed. An emergency shut down plan also should be prepared. Special handling measures should be provided to hold any process residual streams until they have been tested to determine their acceptability for disposal or release. Depending on the site, a method to store waste that has been prepared for treatment may also be necessary. Storage capacity will depend on waste volume and equipment feed rates.

Performance—

As of October 1992, chemical dehalogenation technologies had been selected as the remedial action at three Superfund sites with PCB-contaminated soil or sediment [39]. Performance is

primarily measured by comparing the PCB concentration in the soil or sediment before and after treatment. The presence of metals in the PCB-contaminated media affects performance by scavenging the hydrogen ions, requiring increased amounts of the hydrogen donating reagent.

Depending on the process used, BCD is capable of treating PCBs at virtually any concentration [43]. In 1991 and 1992, 40,000 cubic yards of PCB-contaminated soil with initial concentrations of 100 to 600 ppm were treated at a Superfund Site in Brandt, New York by the BCD process [20, p. 141]. In 1992, the BCD technology achieved a 99.999 percent destruction efficiency at the Waukegan Harbor Superfund Site. BCD was used as part of a treatment train along with thermal desorption in the remediation of the site [20, p. 141].

Laboratory research has shown that BCD treatment of PCBs does not produce chlorinated dioxins (CDDs) and furans (CDFs). In fact, the process has been shown to destroy these classes of compounds, reducing 455 ppb of tetra-CDD and 869 ppb of tetra-CDF to 1.42 ppb and 0.73 ppb, respectively [46].

Process Residuals—

Whereas APEG residuals contain partially dechlorinated compounds with chlorine and hydroxyl groups (which make them water soluble and slightly toxic), the BCD process produces only biphenyl and low-boiling olefinics (which are not water soluble and much less toxic) and sodium chloride. The treated water and condensate from the treatment process can generally be discharged to a publicly-owned treatment works (POTW) after being pumped through activated carbon. Depending on regulatory status and co-contaminants, the treated soil may be suitable for replacement onsite. The decontaminated sludge from the STR can generally be disposed of in the same way as municipal sewage sludge. Before final disposition, however, both the treated soil and sludge must be analyzed to ensure conformance with regulatory requirements.

SITE Demonstration and Emerging Projects—

Other than the RREL-sponsored BCD process, one emerging chemical treatment process is funded for the next fiscal year. This chemical oxidation research utilizes photocatalytic degradation for PCB-contaminated sediment and waters. The developer is the State University of New York at Oswego. The EPA contact is Hector Moreno who can be contacted at (513) 569-7882

Contact—

Technology-specific questions regarding chemical dehalogenation may be directed to Fred Kawahara or Harold Sparks (treatability tests) at (513) 569-7313 or (513) 569-7516.

Solvent Extraction

Solvent extraction does not destroy wastes but is a physical means of separating hazardous contaminants from soil and sediment, thereby reducing the volume of the hazardous waste that must be treated. It is generally applicable to organic wastes, using an organic chemical as a solvent in which to collect and concentrate the contaminant(s) of concern [47, p. 30].

Process Description—

The primary stages of the solvent extraction technology are media preparation, contaminant extraction, solvent/media separation, contaminant collection, and solvent recycling. Waste preparation includes excavation or moving the waste material to the process where it is normally screened to remove debris and large objects. Depending upon the process vendor and whether the process is semi-batch or continuous, the waste may need to be made pumpable by the addition of solvent or water.

In the extractor, the soil or sediment and solvent mix, and the organic contaminant dissolves into the solvent. The extraction behavior exhibited by this technology is typical of a mass-transfer-controlled process, although equilibrium considerations often become limiting factors. It is important to have a competent source conduct a laboratory-scale treatability test to determine whether mass transfer or equilibrium will be controlling. The controlling factor is critical to the design of the unit and to the determination of whether the technology is appropriate for the waste.

The extracted organics are removed from the extractor with the solvent and go to the separator, where the pressure or temperature is changed, causing the organic contaminants to separate from the solvent [48, p. 4-2]. The solvent is recycled to the extractor and the concentrated contaminants are removed from the separator [49, p. 1].

Site Requirements—

Typical commercial-scale units (50 to 70 tons per day) may require a setup area of 10,000 square feet. Standard 440V, three-phase electrical service is generally needed. Water must be available at the site.

A site safety plan covering all onsite activities should be developed. An emergency shut down plan also should be prepared. Special handling measures should be provided to hold any process residual streams until they have been tested to determine their acceptability for disposal or release. Depending on the site, a method to store waste that has been prepared for treatment may also be necessary. Storage capacity will depend on waste volume and equipment feed rates.

Performance—

As of October 1992, solvent extraction technologies had been selected as the remedial action for PCB-contaminated soil or sediment at four Superfund sites [39]. The performance of solvent extraction systems is usually determined by comparing initial and final PCB concentrations in the contaminated media. The number of times the medium must be recycled through the system (the number of passes) in order to meet the treatment goal is another measure of system performance.

An EPA SITE demonstration using the solvent extraction technology was conducted during July 1992. The material tested consisted of bottom sediment from the Grand Calumet River in Gary, Indiana. Initial PCB concentrations averaged between 12 mg/kg and 430 mg/kg. The process removed greater than 99 percent of the PCB contaminants from the sediment [50, pp. 1-2]. Information on the application of solvent extraction for the treatment of PCB-contaminated soil and sediment at other sites is presented in Table 6 [32][39].

Process Residuals—

There are three main process streams generated by this technology: the extract containing concentrated contaminants, the treated soil or sludge, and the separated water. The extract

contains contaminants concentrated into a smaller volume, which requires further treatment such as incineration or dehalogenation.

The treated solids may need to be dewatered, forming a dry solid and a separate water stream. The volume of product water depends on the inherent dewatering capability of the liquid-solid separation process, the specific water requirement for feed slurrying, and initial soil or sediment water content. The water should be analyzed to determine if treatment is necessary before discharge. Since the solvent is an organic material, some residue may remain in the soil matrix. This can be mitigated by solvent selection, and if necessary, an additional separation stage.

SITE Demonstration and Emerging Projects--

As of November 1992, the SITE Program listed five innovative solvent extraction system reportedly capable of treating PCBs in soil and sediment. The Program also listed one emerging system with this capability. Information on these systems is presented in Table 7 [20].

Contact—

Technology-specific questions regarding solvent extraction may be directed to Mark Meckes (RREL) at (513) 569-7348.

Soil Washing

Soil washing is an ex situ water-based remedial technology that mechanically mixes, washes, and rinses soil to remove contaminants. The process removes contaminants from soil in one of two ways: by dissolving or suspending them in the wash solution (which is later treated by conventional wastewater treatment methods), or by concentrating them into a smaller volume of soil through simple particle size separation techniques.

The process of reducing soil contamination through the use of particle size separation is effective because contaminants that chemically or physically bind to soil or sediment often preferentially adhere to the clay or silt fractions. Contaminants in media containing a high percentage (greater than 40 percent) of silt- and clay-sized particles, typically are strongly adsorbed and difficult to remove [51, p. 3]. Washing processes that separate the fine clay and silt particles from the coarser sand and gravel particles separate and concentrate the contaminants into a smaller volume of soil that can be further treated or disposed of. The clean, larger fraction can be returned to the site for continued use.

Process Description—

The primary stages in the soil washing process are soil preparation, washing, soil and water separation, wastewater treatment, and vapor treatment when required. Soil preparation includes the excavation or moving of contaminated soil to the process, where it is normally screened to remove debris and large objects. Depending upon the technology and whether the process is semi-batch or continuous, the soil may be made pumpable by the addition of water.

The contaminated soil is mixed with washwater and possibly surfactants (also chelating agents for metals) to remove contaminants from soil and transfer them to the extraction fluid. The soil and washwater are then separated, and the soil is rinsed with clean water. Clean soil is then removed from the process as product. Suspended soil particles are recovered, as

Table 6. Application of Solvent Extraction at Selected Superfund Sites with PCB-Contaminated Soil or Sediment [32][39]

Site	Type of Media	Status	Lead	Contact
New Bedford Harbor, MA	Sediment	Pilot-scale demonstration completed. Full-scale application not planned.	Federal lead/ Fund financed	Gail Garman (617) 223-5522
O'Conner, ME	Soil and Sediment	Beginning design.	PRP lead/ Federal oversight	Ross Gilleland (617) 573-5766
General Refining, GA	Sludge Solids Soil	Remediation completed 1987.	Federal lead/ Fund financed	Shane Hitchcock (404) 347-3931
Carolina Transformer, NC	Soil	In design; completion expected December 1993.	Federal lead/ Fund financed	Michael Townsend (404) 347-7791
Norwood PCBs, MA	Soil	In design.	Federal lead/ Fund financed	Bob Cianciarulo (617) 573-5778
Pinette's Salvage Yard, ME	Soil	Technology performed inadequately. ROD amended to land disposal.	Federal lead/ Fund financed	Ross Gilleland (617) 573-5766

Table 7. Innovative Solvent Extraction Systems Currently Accepted Into the SITE Program [20]

Developer	System Name	Status	EPA Contact
Sanexen - Sanivan Group	Extrasol TM[a]	Several pilot-scale tests have been conducted. Demonstration was cancelled by the developer.	Mark Meckes (513) 569-7348
CF Systems Corporation	Solvent Extraction [a]	SITE demonstration completed in 1988 (AAR and TER available). Completed one commercial treatment operation.	Laurel Staley (513) 569-7863
Dehydro-Tech Corporation	Carver-Greenfield process for Extraction of Oily Wastes [a]	SITE demonstration completed in 1991 (AAR and TER available).	Laurel Staley (513) 569-7863
Resources Conservation Company (RCC)	B.E.S.T.®Solvent Extraction [a]	SITE demonstration completed in 1992 (AAR and TER available).	Mark Meckes (513) 569-7348
Terra-Klean Corp. (Formerly Sevenson Extraction Technology, Inc.)	Soil Restoration Unit [a]	Used for full-scale remediation at two Superfund sites. SITE demonstration is planned for 1993.	Mark Meckes (513) 569-7348
ART International, Inc.	Low-Energy Solvent Extraction Process [b]	Pilot plant tests are ongoing.	S. Jackson Hubbard (513) 569-7507

[a] Demonstration Program
[b] Emerging Program

sludge, directly from the spent washwater using gravity separation and, when necessary, flocculation with a polymer or other chemical. Sand particles larger than 50 to 80 µm can be easily separated because of their relatively high settling velocity; equipment such as settling chambers are often used. Coarse soil particles are generally separated with a trommel or vibrating screen device. The separated smaller particles will most likely be of less quantity but carry higher levels of contamination than the original soil and, therefore, should be targeted for either further treatment or secure disposal. Water used in the soil washing process is treated by conventional wastewater treatment processes to enable it to be recycled for further use. Residual solids such as spent ion exchange resin and carbon, and sludges from biological treatment, may require post-treatment to ensure safe disposal or release. Vapor treatment may be needed to control air emissions from excavation, feed preparation, and extraction processes; these emissions are collected and treated, normally by carbon adsorption or incineration, before being released to the atmosphere [51, p. 5].

Site Requirements—

Access roads are required for transport of vehicles to and from the site. Typically, mobile soil washing systems are located onsite and may occupy up to 4 acres for a 20 ton-per-hour unit; the exact area will depend on the vendor system selected, the amount of soil storage space required, and the number of tanks or ponds needed for washwater preparation and wastewater treatment.

Typical utilities required are water, electricity, steam, and compressed air. An estimate of the net (consumed) quantity of local water required for soil washing, including water cleanup and recirculation, is 130 to 800 gallons per cubic yard of soil (approximately 0.05 to 0.3 gallons per pound of soil) [51, p. 5].

A site safety plan covering all onsite activities should be developed. An emergency shut down plan also should be prepared. Special handling measures should be provided to hold any process residual streams until they have been tested to determine their acceptability for disposal or release. Depending on the site, a method to store waste that has been prepared for treatment may also be necessary. Storage capacity will depend on waste volume and equipment feed rates.

Performance—

The performance of soil washing systems is usually evaluated by comparing initial PCB concentrations in the contaminated feed with the concentrations in the recovered (clean) soil fraction, fine soil fraction, wastewater treatment sludge, and the washwater. The number of times the medium must be recycled through the system in order to meet the treatment goal is another measure of system performance.

In 1992, an EPA SITE Program Demonstration was conducted at the U.S. Army Corps of Engineers Confined Disposal Facility in the Saginaw Bay of Lake Huron. The sediment at the site was comprised mostly of sand. The process successfully separated the less than 45-micron grain fraction from the input soil or sediment, concentrating this fraction into the output fines, and producing two other output streams, a humic fraction and a

washed coarse fraction. The overall average initial concentration of PCBs was approximately 1.35 mg/kg. During Test 1, the average concentrations of the PCBs in the output streams were as follows: humic fraction- 10.4 mg/kg; washed coarse fraction- 0.194 mg/kg; and clarifier underflow or fines- 4.61 mg/kg. During Test 2, the average concentrations were: humic fraction- 13.4 mg/kg; washed coarse fraction- 0.189 mg/kg; and clarifier underflow- 3.68 mg/kg. An 86 percent removal efficiency was obtained when comparing the initial feed concentration to the final washed coarse fraction [52, pp. 6-11].

Process Residuals—

There are four main waste streams generated during soil washing: contaminated fines and humics from the soil washing unit, wastewater, wastewater treatment sludges and residuals, and air emissions.

Contaminated clay fines and humics resulting from the process may require further treatment using acceptable remedial technologies in order to permit disposal in an environmentally safe manner [53]. Most will remain suspended in the washwater supernatant after treatment and ultimately settle out to form the wastewater treatment sludge. Discharge water may need treatment to meet appropriate discharge standards prior to release to a local, publicly owned wastewater treatment works or receiving stream. To the maximum extent practical, this water should be recovered and reused in the washing process. The wastewater treatment process residual solids, such as spent carbon and spent ion exchange resin, must be appropriately treated before disposal. Any air emissions from the waste preparation area or the washing unit should be collected and treated to meet applicable regulatory standards.

SITE Demonstration and Emerging Projects—

As of November 1992, the EPA SITE Program listed five demonstrated soil washing systems reportedly capable of treating PCBs in soil and sediment. One of these systems is no longer active in the Program. The Program also listed two emerging systems with this capability. Information on these systems is presented in Table 8 [20].

Contact—

Technology-specific questions regarding soil washing may be directed to Mary K. Stinson (RREL) at (908) 321-6683.

Table 8. Innovative Soil Washing Systems Currently Accepted Into the SITE Program [20]

Developer	System Name	Status	EPA Contact
Bergmann USA	Soil and Sediment Washing [a]	Two SITE demonstrations were conducted in 1992 (reports in preparation).	S. Jackson Hubbard (513) 569-7507
BioGenesis Enterprises, Inc.	Soil Washing Process [a]	SITE demonstration conducted in 1992 (reports available). Full commercial operation began in 1992.	Annette Gatchett (513) 569-7697
Biotrol, Inc.	Soil Washing System [a]	SITE demonstration conducted in 1989 (AAR and TER available).	Mary Stinson (908) 321-6683
Excalibur Enterprises, Inc.	Soil Washing and Catalytic Ozone Oxidation [a]	System no longer active in Program.	Norma Lewis (513) 569-7665
Risk Reduction Engineering Laboratory	Volume Reduction Unit [a]	SITE demonstration conducted in 1992 (reports in preparation).	Teri Richardson (513) 569-7949
New Jersey Institute of Technology	GHEA Associates Process [b]	Tests have been conducted and the final report is available.	Annette Gatchett (513) 569-7697
Williams Environmental Services, Inc.	Soil Washing [b]	Developer completed first year of research and elected to leave the SITE Emerging Technology Program. Project summary available in 1993.	S. Jackson Hubbard (513) 569-7507

[a] Demonstration Program
[b] Emerging Program

Emerging Remedial Technologies

Solidification/Stabilization

Waste stabilization involves the addition of a binder, such as Portland cement, cement kiln dust, or fly ash to a waste to convert contaminants into a less soluble, mobile, or toxic form. Waste solidification involves the addition of a binding agent, such as Portland cement or asphalt, to the waste encapsulating the contaminants in solid material. Solidifying waste improves its materials handling characteristics and reduces permeability to leaching agents by reducing waste porosity and exposed surface area. Solidification/stabilization (S/S) processes utilize one or both of these techniques and are fundamentally different from other PCB remedial technologies in that they reduce the mobility of PCBs, but do not concentrate or destroy them [54].

Process Description—

Ex situ S/S processes involve (1) soil or sediment excavation, (2) classification to remove oversized debris, (3) mixing and pouring and, (4) offgas treatment, if necessary. In situ processes generally have only two steps: (1) mixing and (2) offgas treatment, if necessary. Both approaches require that the soil or sediment be mixed with the binding agents and water in a batch or continuous system. In ex situ applications, the resultant slurry can be (1) poured into containers (e.g., 55-gallon drums) or molds for curing and then disposed of onsite or offsite, (2) disposed of in onsite waste management cells or trenches, (3) injected into the subsurface environment, or (4) reused as construction material with the appropriate regulatory approvals. In in situ applications, the S/S agents are injected into the subsurface environment in the proper proportions and mixed with the soil or sediment using backhoes for surface mixing or augers for deep mixing [54].

Site Requirements—

The site must be prepared for the construction, operation, maintenance, decontamination, and ultimately decommissioning of the equipment. An area must be cleared for heavy equipment access roads, automobile and truck parking lots, material transfer stations, the S/S process equipment, setup areas, decontamination areas, the electrical generator, equipment sheds, storage tanks, sanitary and process wastewater collection and treatment systems, workers' quarters, and approved disposal facilities (if required). The size of the area required for the process equipment depends on several factors, including the type of S/S process involved, the required treatment capacity of the system, and site characteristics, especially soil topography and load-bearing capacity. A small mobile ex situ unit could occupy a space as small as that taken up by two standard flatbed trailers. An in situ system may require a larger area to accommodate drilling rigs and equipment decontamination areas [54].

A site safety plan covering all onsite activities should be developed. An emergency shut down plan also should be prepared. Special handling measures should be provided to hold any process residual streams until they have been tested to determine their acceptability for disposal or release. Depending on the site, a method to store waste that has been prepared for treatment may also be necessary. Storage capacity will depend on waste volume and equipment feed rates.

Performance—

Evaluation of the effectiveness of S/S as a technology for the remediation of PCBs in soil and sediment often provides inconclusive results. The effectiveness of S/S technologies is most often measured using leachability tests. Due to the hydrophobic properties of PCBs, test results typically do not show significant differences between the leachability of PCBs in the untreated and treated medium. A portion of the PCBs may volatilize during heating and mixing with the S/S agents; the remaining PCBs appear to stay in the solidified mass. High concentrations of PCBs and other organics may in fact impede the setting of cement, pozzolan, or organic-polymer S/S materials. High organic concentrations also may decrease long-term durability and allow escape of volatiles during mixing.

Process Residuals—

Under normal operating conditions neither ex situ nor in situ S/S technologies generate significant quantities of contaminated liquid or solid waste. Certain S/S projects require treatment of the offgas. Prescreening collects debris and materials too large for subsequent treatment; this material may have to be further treated. Treated media that cannot be returned to the original location may have to be disposed offsite [54].

SITE Demonstration and Emerging Projects--

As of November 1992, the SITE Program listed four demonstrated S/S systems reportedly capable of treating PCBs in soil and sediment. Table 9 provides information on these systems. No applicable emerging S/S systems were included in the program [20].

Contact—

Technology-specific questions regarding S/S may be directed to Patricia M. Erickson (RREL) at (513) 569-7884.

Bioremediation

Biodegradation refers to the breakdown of organic compounds by microorganisms. Making use of indigenous or exogenous bacteria, bioremediation techniques attempt to optimize the microorganisms' ability to reduce complex organic compounds to simpler ones, and completely mineralize others. Bioremediation of contaminated soil and sediment can be performed, at a higher rate, in the presence of oxygen (aerobically), or more slowly under near oxygen-free conditions (anaerobically).

Process Description—

Solid-phase, slurry-phase, soil-heaping, and composting technologies are commonly employed ex situ bioremediation systems. Solid-phase bioremediation (sometimes referred to as land treatment or land farming) is a process that treats soil in above-grade systems. Slurry-phase bioremediation typically uses onsite stirred-tank reactors to combine PCB-contaminated soil or sediment with water. Soil heaping involves piling contaminated soil in heaps with aeration being accomplished by pulling a vacuum through the heap. Composting is a thermophilic process that involves the co-storage of contaminated soil with bulking agents, such as chopped hay or wood chips [55, pp. 3-7].

In situ technologies encourage contaminant biodegradation by

Table 9. Innovative Solidification/Stabilization Systems Currently Accepted Into the SITE Program [20]

Developer	System Name	Status	EPA Contact
Funderburk & Associates	Dechlorination and Immobilization [a]	SITE demonstration conducted in 1987 (AAR and TER available). Used to remediate one Superfund site.	Paul dePercin (513) 569-7797
International Waste Technologies/GeoCon, Inc.	In Situ Solidification and Stabilization Process [a]	SITE demonstration conducted in 1988 (AAR and TER available).	Mary Stinson (908) 321-6683
S.M.W. Seiko, Inc.	In Situ Solidification and Stabilization [a]	Demonstration site being selected.	S. Jackson Hubbard (513) 569-7507
Soliditech, Inc.	Ex Situ Solidfication and Stabilization [a]	SITE demonstration conducted in 1988 (AAR and TER available).	S. Jackson Hubbard (513) 569-7507

[a] Demonstration Program

enhancing site conditions (e.g., nutrient concentrations, pH, etc.) without substantially disturbing the impacted media. These technologies often employ systems to increase the availability of water, nutrients, electron acceptors, and microorganisms (if microbial addition is employed). Oxygen concentrations may also be increased through systems such as bioventing.

PCBs may be degraded aerobically, anaerobically, or through a combination of the two. Laboratory and field studies indicate that PCB compounds with fewer chlorine atoms are amenable to complete mineralization by way of oxidative degradation [56]. PCB compounds with higher chlorine content are generally resistant to oxidative degradation. However, these highly chlorinated molecules may be partially degraded through reductive dechlorination, which is an anaerobic process that removes chlorine while leaving the biphenyl rings intact. The byproducts of reductive dechlorination may then be amenable to aerobic degradation [57, p. 179].

Site Requirements—

Normally, access roads are required during either in situ or ex situ treatment. These roads must be capable of supporting the movement of heavy equipment both on and off the site. During ex situ applications, access roads are needed to transport commercial treatment (i.e., reactor tanks) and support systems (i.e., pre- and post-treatment equipment). During in situ treatment, adequate access roads are needed to transport heavy equipment (i.e., well-drilling rigs and backhoes) used to install wells or infiltration trenches. The soil bearing capacity and traction onsite can also affect vehicular traffic.

Space requirements depend on the specific technology employed. In general, during in situ applications the area required to set up mixing equipment is insignificant. Installation of infiltration galleries and wells to circulate amendment-laden water, however, will require from several hundred to several thousand square feet of clear surface area. During ex situ applications more open space will typically be required for equipment setup (e.g., 0.5 to 1 acre per million gallons of reactor volume during slurry treatment). Electrical requirements will depend on the type of technology required. Standard 440V three-phase electrical service may be needed during larger ex situ applications. However, during most in situ applications, standard 220V, three-phase electrical service will adequately power most pumps and mixing equipment [58, p. 3].

Water is used for a variety of purposes during biological treatment. A readily available water supply is therefore needed at most sites. City water or clean groundwater may be used. Contaminated groundwater may be used if permitted by the appropriate regulatory agency. The quantity of water needed is site- and process-specific.

Climate can influence site requirements by necessitating covers to protect against heavy rainfall or cold for the extended time periods necessary for bioremediation [58, p. 3]. Waste storage is not normally required for in situ biodegradation.

A site safety plan covering all onsite activities should be developed. An emergency shut down plan also should be prepared. Special handling measures should be provided to hold any process residual streams until they have been tested to determine their acceptability for disposal or release. Depending on the site, a method to store waste that has been prepared for treatment may also be necessary. Storage capacity will depend on waste volume and equipment feed rates.

Performance—

Historically, PCBs have been considered resistant to biodegradation. However, the results of laboratory studies on PCB biodegradability and the results from environmental monitoring studies indicate that PCBs do biodegrade in the environment, but at a very slow rate. This is true of PCBs with any level of chlorination. However, to date, there is not a process demonstrated to EPA's satisfaction that can accelerate PCB biodegradation to rates necessary to make such a process commercially viable for use in site cleanups. EPA requires evidence that PCB molecules have been biologically degraded, not attenuated by nonbiological processes (bulking agents in composting can sorb PCBs, making them non-extractable by standard EPA methods and consequently leading to false conclusions on the effectiveness of biodegradation). More research on the bioremediation of PCB-contaminated soil and

sediment is needed to provide data of known quality with which to properly evaluate the performance of the technology before it can be used for site remediation. To date, all of the permits issued by EPA for the bioremediation of PCBs have been for research and development; none have been issued for commercial projects.

Process Residuals—

In situ systems generally do not have discrete process residuals. Depending on the type of ex situ system employed, residuals may include contaminated water and possibly offgases. A portion of the PCBs typically adsorbed to the soil or sediment particles will not be available for biodegradation during active bioremediation treatment. Biodegradation of contaminants that does not completely mineralize the compounds will produce substances that may be of environmental concern [57, p. 151].

SITE Demonstration and Emerging Projects—

As of November 1992, the SITE Program listed two demonstrated bioremediation systems reportedly capable of treating PCBs in soil and sediment. However, no technology currently exists that is capable of biodegrading PCBs on a scale large enough to be used for site remediation. There were three emerging technologies for the treatment of PCB-contaminated soil or sediment [20]. Table 10 presents information on these systems.

Contact—

Technology-specific questions regarding bioremediation may be directed to Edward Opatken (RREL) at (513) 569-7855.

Vitrification

Vitrification can be used to treat soil and sediment containing organic, inorganic, and radioactive contaminants. All existing vitrification technologies use heat to melt the contaminated soil or sediment, which forms a rigid, glassy product when it cools. The volume of this vitrified product is typically 20 to 45 percent less than the volume of the untreated soil or sediment [59].

Organic contaminants, including PCBs, are destroyed by the high temperatures used during vitrification. The destruction mechanism is either pyrolysis (in an oxygen-poor environment) or oxidation (in an oxygen-rich environment) [59].

Vitrification can either be performed in situ or ex situ. At this time, there is only one vendor of commercially available in situ vitrification systems.

Process Description—

In situ vitrification (ISV) typically uses a square array of four electrodes up to 18 feet apart. The electrodes are inserted or gravity fed into the ground to the desired treatment depth. The gravity feed approach is being used at the Parsons, MI site (a non-PCB site). An electric current flows through the electrodes and generates heat, melting first a starter path and then the soil, which typically melts at 1,100°C to 1,400°C [60]. The molten mass continues to grow downward and outward until the melt zone reaches the desired depth and width. The process can typically produce individual melts of up to 1,000 tons, which solidify into vitrified monoliths upon cooling [61]. Multiple melts can be combined for the remediation of an entire site. Offgas collection systems such as tents or hoods are generally necessary.

Table 10. Innovative Bioremediation Systems Currently Accepted Into the SITE Program [20]

Developer	System Name	Status	EPA Contact
In-Situ Fixation Company	Deep In Situ Bioremediation Process [a]	Demonstration site selected.	Edward Opatken (513) 569-7855
International Environmental Technology	Geolock and Biodrain Treatment Platform [a]	Demonstration site being selected.	Randy Parker (513) 569-7271
Institute of Gas Technology	Chemical and Biological Treatment (CBT) [b]	Accepted into the SITE Emerging Technology Program 1991.	Naomi Barkely (513) 569-7854
Institute of Gas Technology	Fluid Extraction-Biological Degradation Process (FEBD) [b]	Second year of testing completed (reports in preparation).	Annette Gatchett (513) 569-7697
IT Corporation	Photolytic and Biological Soil Detoxification [b]	Project completed (reports in preparation).	Randy Parker (513) 569-7271

[a] Demonstration Program
[b] Emerging Program

There are a number of ex situ vitrification systems commercially available that can be distinguished from one another primarily by the heating method employed. Ex situ processes typically heat the contaminated media at temperatures between 1,000 and 2,000°C. In thermal heating, the heat for the vitrification of the contaminated material is generated by the combustion of an external fuel source. In the other heating methods, the heat is generated electrically. Ex situ joule heating utilizes an electric current that flows through the contaminated material, producing resistance and thereby producing heat. Ex situ vitrification by plasma heating relies on the conversion of a gas into a plasma by applying energy to it using an electrical arc. In microwave heating, the contaminated material is heated by electromagnetic radiation. Miscellaneous other electrical processes such as resistance heating, induction heating, and electric arc heating have also been used for ex situ vitrification [61].

Site Requirements—

There are very few site requirements for offsite ex situ vitrification, since the only onsite activity is excavation. Access to the site must be available for the excavation equipment, and a site safety plan must be developed.

For ISV systems, areas must be cleared for heavy equipment access roads, automobile and truck parking lots, the ISV equipment, setup areas, equipment sheds, and workers' quarters [59]. The ISV system also requires electricity, typically between 800 kilowatt-hours/ton (kWh/ton) and 1,000 kWh/ton for the full-scale system. The electricity can be supplied by a utility distribution system or generated onsite by a diesel generator [61].

A site safety plan covering all onsite ISV activities should be developed. An emergency shut down plan also should be prepared. Special handling measures should be provided to hold any process residual streams (i.e., offgas treatment residues) until they have been tested to determine their acceptability for disposal or release.

Performance—

The effectiveness of vitrification for the treatment of PCB-contaminated soil or sediment is difficult to assess. Sampling and analysis of the glass matrix produced by vitrification is difficult, since current EPA leachability and total digestion methods are not designed for a glass matrix.

In April 1991, a fire involving the full-scale collection ISV hooding occurred at the Geosafe Hanford, Washington test site. The vendor was testing a new, lighter hooding material. The hooding caught fire during the test when a spattering of the melt occurred. For a period of time after the incident, Geosafe suspended full-scale field operations. A new offgas collection hood was then designed, composed entirely of metal rather than the high-temperature fabric that was previously used. The new design is heavier than the fabric hood, but is capable of being transported by the same equipment [59].

Process Residuals—

The main residuals produced during operation of the vitrification technology are the vitrified mass of soil or sediment and scrubber water. When vitrification is conducted in situ, the vitrified product can be left in place after treatment. The vitrified product from ex situ vitrification should also be acceptable for onsite or offsite disposal [59].

The scrubber water, filters, and activated carbon used to treat offgases from vitrification systems may require further treatment or disposal. Typical scrubber water treatment consists of passing the water through diatomaceous earth and activated carbon, followed by reuse or discharge to a sanitary sewer. Contaminated activated carbon or diatomaceous earth can be treated by the vitrification system [59].

SITE Demonstration and Emerging Projects—

As of November 1992, the SITE Program listed one demonstrated vitrification system reportedly capable of treating PCBs in soil and sediment. The program also listed one emerging system with this capability. Table 11 provides information on these systems [20].

Contact—

Technology-specific questions regarding ISV may be directed to Teri Richardson at (513) 569-7949.

Current Research

White Rot Fungus

White rot fungus is currently undergoing research in order to assess its ability to treat PCB-contaminated soil and sediment. White rot fungus treatment uses fungi to treat soil in situ. The

Table 11. Innovative Vitrification Systems Currently Accepted Into the SITE Program [20]

Developer	System Name	Status	EPA Contact
Geosafe Corporation	In Situ Vitrification (ISV) [a]	Large-scale tests have been conducted. SITE demonstration conducted fall 1993.	Teri Richardson (513) 569-7949
Vortec Corporation	Oxidation and Vitrification Process [b]	Additional test to be conducted in conjunction with DOE.	Teri Richardson (513) 569-7949

[a] Demonstration Program
[b] Emerging Program

fungus is cultivated in a reactor and allowed to grow for 2 to 4 days. Once enough of the fungus has grown, the reactor conditions are altered to force the fungus into a secondary metabolic state. In this state, the fungus excretes enzymes capable of degrading organic compounds through catalyzed oxidation reactions [2, p. 4.32].

Organic materials inoculated with the fungi are then mechanically mixed into the contaminated soil. Because this technology uses a living organism (the fungi), the greatest degree of success occurs with optimal growing conditions. Additives that enhance growing conditions may be required for successful treatment. Moisture control is necessary, and temperature control may be utilized [20, pp. 148-149].

Failed Technologies

Quicklime

The performance of the stabilization agent quicklime (calcium oxide, or CaO) as a chemical dehalogenation compound was investigated after observing large reductions in PCB concentrations at Superfund sites when cement kiln dust was added to PCB-contaminated wastes. Low PCB recoveries in open-vessel quicklime application tests indicated the possibility that significant PCB destruction had occurred. Subsequent studies, however, confirmed that the primary mechanism for PCB removal is volatilization and stripping (resulting from the exothermic reaction associated with lime slaking), and that only a small percentage of the initial PCB content was decomposed by partial dechlorination and hydroxyl substitution [62, p. 6-3]. It was also determined that improper laboratory procedures failed to completely extract the PCBs from the matrices and led to the conclusion that quicklime was decomposing PCBs [63, pp. 34-40]. Therefore, it was concluded that quicklime treatment of PCB-contaminated soil or sediment did not result in significant chemical dehalogenation.

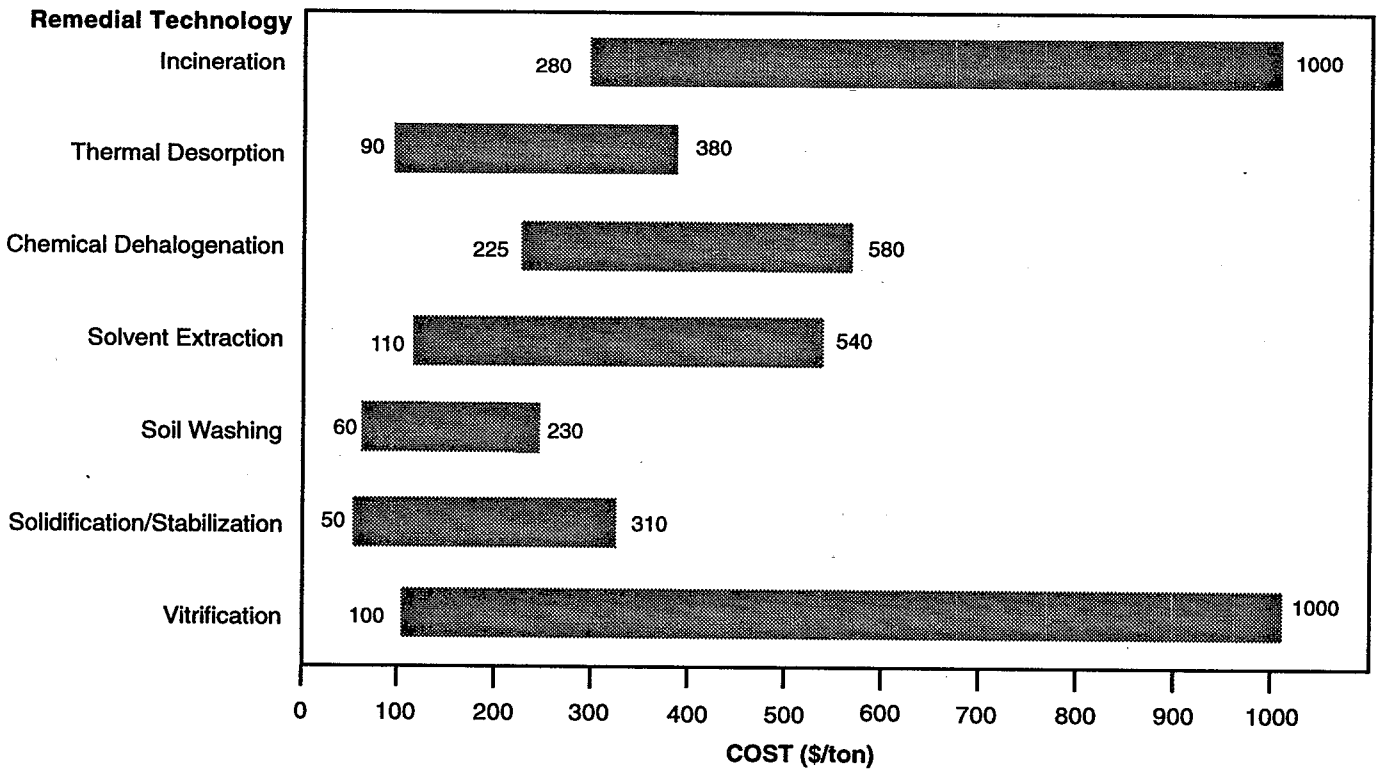
Use of Treatment Trains

Because of the presence of additional contaminants in PCB-contaminated soil and sediment, or due to the need for further treatment of process residuals, remedial technologies may have to be employed sequentially. These treatment trains increase both the effectiveness and cost of remediation. When selecting remedial alternatives for a site, OSCs and RPMs should factor in the performance and cost parameters associated with the use of treatment trains.

Comparison of Remedial Technologies

Costs

Figure 1 presents cost ranges for the technologies discussed in this paper. These ranges can aid OSCs and RPMs in selecting a remedial technology for a site with PCB-contaminated soil and sediment. The reader is cautioned that these data may not include the cost of many site-specific factors and necessary modifications, including disposal costs for those technologies that concentrate and separate PCBs. These data are derived from conversations with various EPA RPMs, technology experts, and from vendor databases, and may not reflect the final cost incurred after implementation is completed [64]. The



Note: Current cost information on bioremediation is very limited and not included in this chart.
Source: Derived from EPA RPMs, technology experts, and vendor databases.

Figure 1. Estimated Cost Ranges of PCB Remediation Technologies.

Table 12. Critical Factors Affecting Cost Ranges for Technology Alternatives for Remediating PCB-Contaminated Soil and Sediment

COST FACTORS	Incineration (Established)	Thermal Desorption (Demonstrated)	Chemical Dehalogenation (Demonstrated)	Solvent Extraction (Demonstrated)	Soil Washing (Demonstrated)	Solidification/Stabilization (Emerging)	Bioremediation (Emerging)	Vitrification (Emerging)
Particle size heterogeneity		★	★	★	★	★	★	
High moisture content	★	★	★	★		★		★
PCB concentration		★	★	★	★	★	★	
Regulatory compliance	★	★						★
Residuals/offgases requiring treatment	★	★	★		★	★		★
Excavation	★	★	★	★	★	●	●	●
Site preparation	★	★	★	★	★	★	★	★
Undersized treatment unit capacity	★	★	★	★	★		★	★
Long-term monitoring						★	★	★
High clay content		★	★	★	★	★	★	
Required chemicals			★	★		★	★	
Water usage			★		★			
Fuel/electricity usage	★	★	★	★	★			★

Note: Technologies for which a cost factor is identified by "★" generally incur increased cost due to this factor. If a factor increases cost only for the ex situ subgroup of a technology the technology will show an "●".

Source: Derived from technology experts and EPA Engineering Bulletins.

financial feasibility of using any of these technologies for the treatment of PCB-contaminated soil or sediment at a particular site should not be determined by using this chart alone. Also, due to extremely limited cost information on the application of bioremediation to the cleanup of PCB-contaminated soil and sediment, cost ranges for this technology are not presented.

Table 12 presents critical factors affecting the cost ranges presented in Figure 1. This table is designed for intertechnology comparison, and the reader is cautioned that critical cost factors for individual systems may vary. Several factors, such as site preparation and treatment capacity, are critical to all listed technologies. Others, including water usage and long-term monitoring, are critical to only a few groups.

Table 13. Advantages for Technology Alternatives for Remediating PCB-Contaminated Soil and Sediment

ADVANTAGES	Incineration (Established)	Thermal Desorption (Demonstrated)	Chemical Dehalogenation (Demonstrated)	Solvent Extraction (Demonstrated)	Soil Washing (Demonstrated)	Solidification/Stabilization (Emerging)	Bioremediation (Emerging)	Vitrification (Emerging)
Proven ability to reduce high concentrations to cleanup goals	◆	◆		◆				
Destroys PCBs	◆		◆			◆	◆	◆
Can be implemented in situ						◆	◆	◆
Concentrates PCBs, reducing disposal costs		◆		◆	◆			
Effective across wide range of soil/sediment characterisitics	◆							◆
Effective on inorganic co-contaminants					◆	◆		◆

Notes: - Technologies for which a specific advantage is applicable are identified by a "◆".

Source: Derived from technology experts and EPA Engineering Bulletins.

Advantages and Limitations

Table 13 lists the advantages inherent in the remedial technologies described in this paper. Table 14 presents limitations potentially encountered when implementing these technologies for the treatment of PCB-contaminated soil and sediment. This information is generally applicable for intertechnology comparisons. The reader is cautioned, however, that individual systems within a technology group may have different advantages and limitations, or varying degrees of a listed advantage or limitation.

LONG-TERM MANAGEMENT CONTROLS

After treatment of PCB-contaminated soil or sediment is completed, residual concentrations of PCBs may remain in the treated medium. If the chosen technology treated the soil or sediment in situ, or if the treated media is to be reused onsite, long-term management controls may be required. Table 15 presents a general framework of recommended controls for PCB-contaminated soil or sediment remaining onsite, and

Table 14. Limitations for Technology Alternatives For Remediating PCB-Contaminated Soil and Sediment

LIMITATIONS	Incineration (Established)	Thermal Desorption (Demonstrated)	Chemical Dehalogenation (Demonstrated)	Solvent Extraction (Demonstrated)	Soil Washing (Demonstrated)	Solidification/Stabilization (Emerging)	Bioremediation (Emerging)	Vitrification (Emerging)
High moisture content adversely effects treatment	▼	▼	▼			▼		▼
PCBs must be destroyed by another technology		▼		▼	▼			
Produces other residuals that must be treated and/or disposed	▼		▼	▼	▼			●
Sensitive to media particle size, clay content, and/or pH		▼	▼	▼	▼	▼	▼	
Not proven to treat all PCB congeners			▼			▼	▼	
Sensitive to co-contaminants	▼		▼			▼	▼	
Offgases must be treated prior to release	▼	▼	▼					▼
Often subject to negative public opinion	▼	▼						▼
Volume and/or characteristic changes to treated media					▼	▼		▼
Potentially affected by ambient temperature extremes					▼	●	▼	
Difficult to measure effectiveness of treatment						▼	▼	▼
Long-term monitoring required for onsite treatment						▼	▼	

Notes: - Technologies for which a specific limitation is applicable are identified by a "▼". Limitations that only apply to the ex situ subgroup of a technology are identified by a "●".

chemical landfill requirements for disposal of PCB-contaminated media under TSCA regulations. If disposal of PCBs regulated by TSCA (i.e., PCB concentrations equal to or greater than 50 ppm) occurred after 1978, the landfill requirements must be addressed for soil or sediment that was not incinerated or treated by an equivalent method. In certain situations, TSCA waivers of specific chemical waste landfill requirements may be possible. If disposal occurred before 1978, RCRA closure requirements instead of TSCA chemical waste landfill requirements would usually be the ARAR [4, p. 47].

SOURCES OF ADDITIONAL INFORMATION

The following EPA hotlines, databases, and reports offer additional information on the remediation of PCB-contaminated soil and sediment. The reader is also encouraged to review sources referenced in this paper.

TSCA Assistance Hotline. Washington, D.C., (202) 554-1404.

RCRA/Superfund Assistance Hotline. Washington, D.C., (800) 424-9346.

Risk Reduction Engineering Laboratory (RREL) Treatability Database. Available on disk and through the ATTIC database. Contact Glenn Shaul -(513) 569-7408 or Tom Holdsworth (513) 569-7675.

Alternative Treatment Technology Information Center (ATTIC) database. U.S. EPA Assistance - (908) 906-6828. Online database searching - (301) 670-3808.

Vendor Information System for Innovative Treatment Technologies (VISITT) database. Available on disk - (800) 245-4505 or (703) 883-8448.

Records of Decision System (RODS) database. Systems Information, Jalania Ellis-(703) 603-8884

The Clean-Up Information Bulletin Board (CLU-IN). System Operator -(301) 589-8368. Online communication - (301) 589-8366.

Office of Research and Development (ORD) Bulletin Board. Assistance - (513) 569-7272, Online Communication - (513) 569-7610 or (800) 258-9605.

Federal Remediation Technologies Roundtable. Federal Publications on Alternative and Innovative Treatment Technologies for Corrective Action and Site Remediation, Second Edition. EPA/542/B-92/001, August 1992.

Innovative Treatment Technologies: Overview and Guide to Information Sources. EPA/540/9-91/002, October 1991.

Table 16 lists EPA Regional Superfund Engineering Forum contacts and other sources of assistance in remediation of PCB-contaminated soil and sediment.

Table 15. Selection of Long-term Management Controls to be Considered for PCB-Contaminated Sites [4]

PCB - CONCENTRATION (ppm)	APPROXIMATE DEPTH TO GROUND WATER	ACCESS	RCRA COROLLARY	LONG-TERM MANAGEMENT CONTROLS RECOMMENDED: Cover System 1	Leachate Collection	Leak Detection	Bottom Liner	Ground Water Monitoring	Surface Water Monitoring	Surface Water Management	CHEMICAL WASTE LANDFILL REQUIREMENTS: Bottom Liner	Depth to ground Water	Ground Water Monitoring	Leachate Collection	Surface Water Monitoring	Fence	POTENTIAL BASIS FOR TSCA WAIVER (761.75(C)(4)) OF INDICATED CHEMICAL WASTE LANDFILL REQUIREMENT(S)
≤1	All Depths	• Nonrestricted Access	Clean Closure														No waiver required; clean closure
1-10	All Depths	• Nonrestricted Access	Hybrid Closure	2							x	3	x	x	x	x	Low PCB concentration Design and installation of a protective cover system Evaluation of PCB migration to GW and SW
10-25	All Depths	• Limited Access • Deed Notice	Hybrid Closure	2							x	3	x	x	x	x	Low PCB concentration Design and installation of a protective cover system Evaluation of PCB migration to GW and SW
25-100	All Depths	• Restricted Access • Fence • Deed Notice	Landfill Closure	x				x		4	x	3		x	x		Relatively low PCB concentration Implementation of a GW monitoring program Evaluation of PCB migration to GW and SW Design and installation of a protective cover system
100-500	3-50 Feet	• Restricted Access • Fence • Deed Notice	Landfill Closure	x				x	x	4	x	x		x			Implementation of GW monitoring program Design and installation of a protective cover system Evaluation of PCB migration to GW and SW
	>50 Feet	• Restricted Access • Fence • Deed Notice	Landfill Closure	x				5	x	4	x		x	x			Design and installation of a protective cover system Demonstrate sufficient depth to GW to protect human health and the enviroment Evaluation of PCB migration to GW and SW
>500	3-50 Feet	• Restricted Access • Fence • Deed Notice	Landfill Closure Minimum Technology	x	x	x	x	x	x	4		x					Demonstrate other long-term management controls will provide adequate protection of GW
	>50 Feet	• Restricted Access • Fence • Deed Notice	Landfill Closure Minimum Technology	x	x	x	x	x	x	4	x			x			Demonstrate sufficent depth to GW and long-term management controls to protect human health and the environment Implementation of GW monitoring program Evaluation of PCB migration to GW and SW

GW=ground water; SW=surface water

1 = Cover system may range from 12" soil cap for low concentrations to a full RCRA cap for concentrations exceeding 55 ppm.

2 = The need for a cover system will depend on the land use (i.e., residential or industrial).

3 = 40 CFR 761.75(b)(3) requires that landfills be located at least 50 feet above the high-water table.

4 = In accordance with 49 CFR 761.75(b)(4) if the site is located below the 100-year floodwater elevation, diversion dikes shall be constructed around the perimeter of the landfill site with a minimum height equal to 2 feet above the 100-year floodwater elevation. Flood protection for landfills above the 100-year floodwater elevation is not applicable to closed landfill units.

5 = When the site is located in a permeable formation, incorporation of this long-term management control should be evaluated.

Table 16. Engineering Forum and PCB Remediation Contacts

EPA Regional Superfund Engineering Forum Contacts		
Region 1	Lynne Jenings	(617) 565-9834
Region 2	Richard Ho	(212) 264-9543
Region 3	Paul Leonard	(215) 597-3163
Region 4	Jon Bornholm	(404) 347-7791
Region 5	Anthony H. Holoska	(312) 886-7603
Region 6	Deborah Griswold	(214) 655-8520
Region 7	Steve Kinser	(913) 551-7728
Region 8	Desiree Golub	(303) 293-1838
Region 9	Ken Erickson	(415) 744-2324
Region 10	Bob Stamnes	(206) 553-1512
Superfund Innovative Technology Evaluation (SITE) Program		
Program Management	Robert Olexsey	(513) 569-7871
SITE MailingList/ Solicitation (RFPs)	William Frietsch	(513) 569-7659
Demonstration Program	John Martin	(513) 569-7658
Emerging Technologies Program	Norma Lewis	(513) 569-7665
Other Contacts		
Superfund Technical Support Program	Ben Blaney	(513) 569-7406
Technology Innovative Office	Walter Kovalick	(202) 382-4363
Engineering Forum-Headquarters	Richard Steimle	(703) 308-8846
TSCA Regulatory Assistance	Winston Lue	(202) 260-3962

ACKNOWLEDGMENTS

This Issue Paper was prepared by the U.S. Environmental Protection Agency, Office of Research and Development (ORD), Risk Reduction Engineering Laboratory (RREL), Cincinnati, Ohio, with the assistance of Science Applications International Corporation (SAIC) under Contract No. 68-C8-0048 (WA 0-41). Ms. Brunilda Dávila served as the EPA Technical Project Manager. Mr. Kurt Whitford was SAIC's Work Assignment Manager. This document was written by Ms. Dávila (RREL), Mr. Whitford, and Mr. Eric Saylor (SAIC). The paper was extensively reviewed by Steve Kinser and Paul Leonard as well as other members of the EPA Regional Superfund Engineering Forum. The authors are especially grateful to Ms. Akiko Frietsch and other SAIC personnel who contributed significantly to the production of this document.

The following other personnel have contributed their time and comments by participating in peer reviews of the document: Ben Blaney, Donald Oberacker, Patricia Erickson, Paul de Percin, Charles Rogers, Mark C. Meckes, Mary Stinson, Teri Richardson, and Edward Opatken of EPA-RREL, and Tom Simmons of EPA-Operations Branch. The following personnel provided outside peer review of the document: Seth Frisbee of ENSR; Frank Darmiento of Darmiento Environmental Management; Toni Allen of Piper and Marbury; and Lori Traweek of the American Gas Association. The following SAIC personnel participated in peer review of the document: Clyde Dial, Jim Rawe, and Robert Hartley.

REFERENCES

1. Amend, L. and P. Lederman. "Critical Evaluation of PCB Remediation Technologies." Environmental Progress, Volume 11. August 1992. pp. 173-177.

2. "Polychlorinated Biphenyls (PCBs)-Regulations and Treatment Technologies." The Hazardous Waste Consultant. May/June 1992. pp. 4.1-4.37.

3. Sittig, Marshall. Handbook of Toxic and Hazardous Chemical and Carcinogens, Third Edition. Noyes Publications. 1991.

4. Guidance on Remedial Actions for Superfund Sites with PCB Contamination. EPA/540/G-90/007, U.S. Environmental Protection Agency. August 1990.

5. Development of Advisory Levels for Polychlorinated Biphenyl (PCBs) Cleanup. Project Summary. EPA/600/S6-86/002, U.S. Environmental Protection Agency. June 1987.

6. A Guide on Remedial Actions at Superfund Sites with PCB Contamination. Quick Reference Fact Sheet. U.S. Environmental Protection Agency. August 1990.

7. Federal Register. Polychlorinated Biphenyls; Exclusions, Exemptions, and Use Authorizations; Proposed Rule 52 FR 25849-50. Office of the Federal Register, Washington, D.C. July 8, 1987.

8. 40 CFR 761. Polychlorinated Biphenyls (PCBs) Manufacturing, Processing, Distribution in Commerce, and Use Prohibitions. Office of the Federal Register, Washington, D.C. July 1992.

9. 40 CFR 268.42. Land Disposal Restrictions, Subpart D-Treatment Standards. Office of the Federal Register, Washington, D.C. July 1992.

10. Data Quality Objectives for Remedial Response Activities. EPA/540/G-87/003, U.S. Environmental Protection Agency. March 1987.

11. Remediation of Contaminated Sediments. Handbook. EPA/625/6-91/028, U.S. Environmental Protection Agency. April 1991.

12. Test Methods for Evaluating Solid Waste, Volume II, Third Edition, SW-846. U.S. Environmental Protection Agency. December 1987.

13. Technology Preselection Data Requirements. Engineering Bulletin. EPA/540/S-92/009, U.S. Environmental Protection Agency. October 1992.

14. Summary of Treatment Technology Effectiveness for Contaminated Soil. EPA/540/2-89/053, U.S. Environmental Protection Agency. June 1990.

15. Technology Screening Guide for Treatment of CERCLA Soils and Sludges. EPA/540/2-88/004, U.S. Environmental Protection Agency. September 1988.

16. NIOSH Manual of Analytical Methods, Third Edition. NIOSH 84-100. National Institute for Occupational Safety and Health, Washington, D.C. June 1988.

17. Methods for Evaluating the Attainment of Cleanup Standards, Volume 1: Soil and Solid Media. EPA/230/02-89-042, U.S. Environmental Protection Agency. February 1989.

18. Conversations between Dr. Seth Frisbie of ENSR and SAIC personnel. May 1993.

19. Fast, Low-Cost Water and Soil Analysis for Aromatics and Petroleum Hydrocarbons. Hnu-Hanby Environmental Field Test Kits. HNU Systems, Inc. Marketing Brochure. 1993.

20. The Superfund Innovative Technology Evaluation Program: Technology Profiles, Fifth Edition. EPA/540/R-92/077, U.S. Environmental Protection Agency. November 1992.

21. Erickson, M. Analytical Chemistry for PCBs, Second Edition. McGraw and Hill. 1992. pp. 63-89.

22. Guide for Conducting Treatability Studies under CERCLA: Thermal Desorption Remedy Selection, Interim Guidance. EPA/540/R-92/074a, U.S. Environmental Protection Agency. September 1992.

23. Treatability Studies Under CERCLA: An Overview. OSWER Directive 9380.3-02FS, U.S. Environmental Protection Agency. 1987.

24. Guide for Conducting Treatability Studies Under CERCLA: Final. EPA/540/R-92/071a, U.S. Environmental Protection Agency. October 1992.

25. Issues Affecting the Applicability and Success of Remedial/Removal Incineration Projects. Superfund/Engineering Issue. EPA/540/2-91/004, U.S. Environmental Protection Agency. February 1991.

26. Considerations for Evaluating the Impact of Metals Partitioning During the Incineration of Contaminated Soils from Superfund Sites. Superfund Engineering Issue. EPA/540/5-92/014, U.S. Environmental Protection Agency. September 1992.

27. Shirco Infrared Incineration System, Applications Analysis Report. EPA/540/A5-89/010, U.S. Environmental Protection Agency. June 1989.

28. Gupta, G., A. Sherman, and A. Gangadharan. Hazardous Waste Incineration: The Process and the Regulatory/Institutional Hurdles. Foster Wheeler Enviresponse, Inc., Livingston, NJ. (undated).

29. Record Of Decision database. Print out of Abstracts for PCBs in Soil and Sediment in FY90 and 91. U.S. Environmental Protection Agency. 1993.

30. ROD Annual Report FY1990. EPA/540/8-91/067, U.S. Environmental Protection Agency. July 1991.

31. Technology Evaluation Report: SITE Program Demonstration Test, Shirco Pilot-Scale Infrared Incineration System at the Rose Township Demode Road Superfund Site, Volume I. EPA/540/5-89/007a, U.S. Environmental Protection Agency. April 1989.

32. Conversations between SAIC and EPA personnel. June 1993.

33. Technology Evaluation Report SITE Program Demonstration Test, Shirco Infrared Incineration System, Peak Oil, Brandon, Florida. EPA/540/5-88/002a, U.S. Environmental Protection Agency. September 1988.

34. Thermal Desorption Treatment. Engineering Bulletin. EPA/540/2-91/008, U.S. Environmental Protection Agency. May 1991.

35. Abrishamian, R. Thermal Treatment of Refinery Sludges and Contaminated Soils. Presented at American Petroleum Institute Meetings. Orlando, Florida. 1990.

36. T.D.I. Services, Marketing Brochures. Circa 1990.

37. Swanstrom, C., and C. Palmer. X*TRAX™ Transportable Thermal Separator for Organic Contaminated Solids. Presented at Second Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International. Philadelphia, Pennsylvania. May 1990.

38. Canonie Environmental Services Corp., Low Temperature Thermal Aeration (LTTA®)Marketing Brochures. Circa 1990.

39. Innovative Treatment Technologies. Semi-Annual Status Report (Fourth Edition). EPA/542/R-92/011, U.S. Environmental Protection Agency. October 1992.

40. Soil Tech, Inc., AOSTRA - Taciuk Processor Marketing Brochure. Circa 1990.

41. Ritcey, R., and F. Schwartz. Anaerobic Pyrolysis of Waste Solids and Sludges - The AOSTRA Taciuk Process System. Presented at Environmental Hazards Conference and Exposition. Seattle, Washington. May 1990.

42. Applications Analysis Report Wide Beach Development Site and Outboard Marine Corporation Site. Anaerobic Thermal Processor. Soil Tech ATP Systems, Inc. U.S. Environmental Protection Agency, (Final Draft). 1993. Paul dePercin, EPA Technical Project Manager, (513) 569-7797.

43. Rogers, C. U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH. Personnal communication of June 28, 1993.

44. Base-Catalyzed Decomposition Process (BCDP). Technical Data Sheet. U.S. Naval Civil Engineering Laboratory, Port Hueneme, CA, undated.

45. Chemical Dehalogenation Treatment: APEG Treatment. Engineering Bulletin. EPA/540/2-90/015, U.S. Environmental Protection Agency. September 1990.

46. Kornel, A. Memorandum to C. Rogers. U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH. November 3, 1992.

47. Raghavan, R., D. Dietz, and E. Coles. Cleaning Excavated Soil Using Extraction Agents: A State-of-the-art Review. EPA/600/2-89/034, U.S. Environmental Protection Agency. Edison, NJ. December 1988.

48. Rowe, G. Evaluation of Treatment Technologies for Listed Petroleum Refinery Wastes, Chapter 4. API Waste Technologies Task Force, Washington, D.C. December 1987.

49. Applications Analysis Report, CF Systems Organics Extraction Process, New Bedford Harbor, MA. EPA/540/A5-90/002, U.S. Environmental Protection Agency. August 1990.

50. Applications Analysis Report. Resources Conservation Company, Inc. B.E.S.T.® Solvent Extraction Technology. EPA/540/AR-92/079. U.S. Environmental Protection Agency. June 1993.

51. Soil Washing Treatment. Engineering Bulletin. EPA/540/2-90/017, U.S. Environmental Protection Agency. September 1990.

52. Applications Analysis Report Bergmann USA. Soil/Sediment Washing Technology. U.S. Environmental Protection Agency. (Preliminary Draft). January 1993. S. Jackson Hubbard, EPA Technical Project Manager, (513) 569-7507.

53. Superfund LDR Guide #6A: Obtaining a Soil and Debris Treatability Variance for Remedial Actions. OSWER Directive 9347.3-06FS, U.S. Environmental Protection Agency. July 1989.

54. Solidification/Stabilization of Organics and Inorganics. Engineering Bulletin. EPA/540/S-92/015, U.S. Environmental Protection Agency. February 1993.

55. Guide for Conducting Treatability Studies under CERCLA: Aerobic Biodegradation Remedy Screening, Interim Guidance. EPA/540/2-91/013A, U.S. Environmental Protection Agency. July 1991.

56. Microbial Decomposition of Chlorinated Aromatic Compounds. EPA/600/2-86/090, U.S. Environmental Protection Agency. September 1986.

57. Abromowicz, et al. 1991 In Situ Hudson River Research Study: A Field Study on Biodegradation of PCBs in Hudson River Sediments - Final Report. General Electric Company. February 1992.

58. Slurry Biodegradation Engineering Bulletin. EPA/540/2-90/016, U.S. Environmental Protection Agency. September 1990.

59. In Situ Vitrification Treatment. Engineering Bulletin (Draft). U.S. Environmental Protection Agency. 1993. Eugene Harris, EPA Technical Project Monitor, (513) 569-7862.

60. Fitzpatrick, V., C. Timmerman, and J. Buetl. In Situ Vitrification: An Innovative Thermal Treatment Technology. In: Proceedings of the Second International Conference on New Frontiers for Hazardous Waste Management. EPA/600/9-87/018F, U.S. Environmental Protection Agency. 1987. pp. 305-322.

61. Handbook: Vitrification Technologies for Treatment of Hazardous and Radioactive Waste. EPA/625/R-92/002, U.S. Environmental Protection Agency. May 1992.

62. Solidification/Stabilization and Its Application to Waste Materials. Technical Resource Document. EPA/530/R-93/012, U.S. Environmental Protection Agency. June 1993.

63. Fate of Polychlorinated Biphenyls (PCBs) in Soil Following Stabilization with Quicklime. EPA/600/2-91/052, U.S. Environmental Protection Agency. September 1991.

64. VISITT Database, U.S. Environmental Protection Agency. 1993.

☆U.S. GOVERNMENT PRINTING OFFICE. 1994-0-551-448

United States
Environmental Protection Agency
Center for Environmental Research Information
Cincinnati, OH 45268

Official Business
Penalty for Private Use
$300

EPA/540/S-93/506

Please make all necessary changes on the below label, detach or copy, and return to the address in the upper left-hand corner.

If you do not wish to receive these reports CHECK HERE ☐; detach, or copy this cover, and return to the address in the upper left-hand corner.

BULK RATE
POSTAGE & FEES PAID
EPA
PERMIT No. G-35