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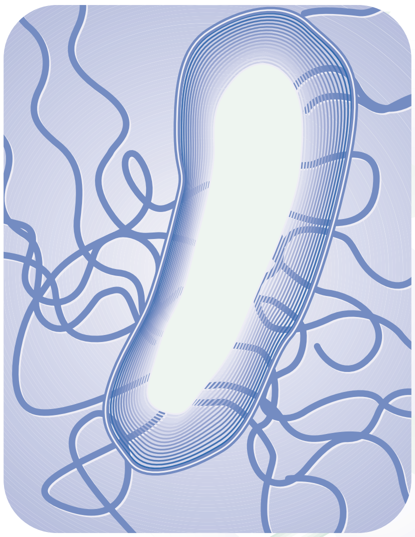
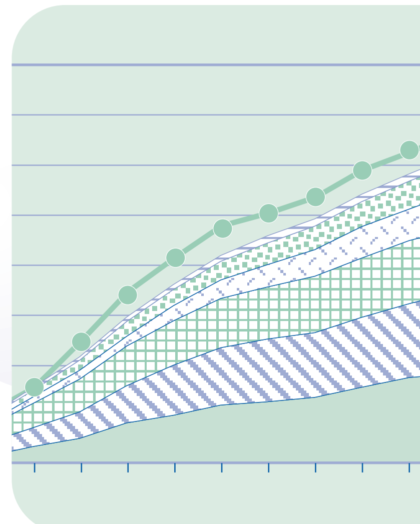
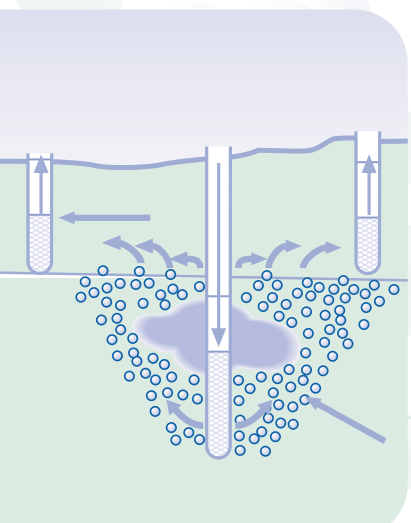
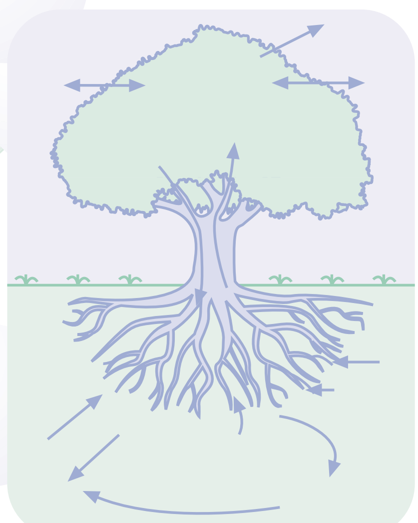
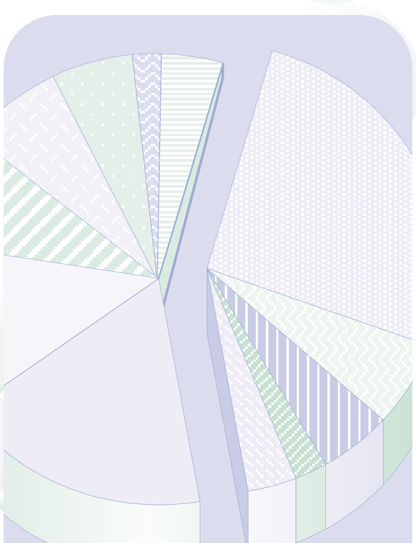
Treatment Technologies for Site Cleanup: Annual Status Report (Tenth Edition)











On The Cover

Top row from left to right:

Azospirillum brasilense, nitrogen-fixing soil bacterium.

Figure 10. Superfund Remedial Actions: Cumulative Trends for Most Common Technologies for Source Control (FY 1988 - FY 1999), page 14. See Section 2: Treatment Technologies for Source Control, Most Common Technologies for Source Control, for a discussion of this figure.

Middle row from left to right:

Model of an Air Sparging System. See page 5 for a description of air sparging.

Model of Phytoremediation. See page 4 for a description of phytoremediation.

Bottom row from left to right:

Figure 14. Superfund Remedial Actions: Percentage of Soil Treated by Technology Type (FY 1982 - FY 1999), page 22. See Section 2: Treatment Technologies for Source Control, Quantity of Soil Addressed for a discussion of this figure.

Halomonadaceae, bacteria believed to be capable of biodegrading the herbicide 2,4 - dichlorophenoxyacetic acid.

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List of Acronyms

ASR	Annual Status Report
BTEX	Benzene, toluene, ethylbenzene, and xylene
CERCLIS	Comprehensive Environmental Response, Compensation, and Liability Information System
CLU-IN	EPA's CLeanUp INformation system
Cr	Chromium
CROW™	Contained Recovery of Oily Waste
cy	Cubic yard
DRE	Destruction and removal efficiency
EOU	Excess, obsolete, or unserviceable
EPA	U.S. Environmental Protection Agency
ESD	Explanation of significant differences
FRTR	Federal Remediation Technologies Roundtable
FY	Fiscal year
HTTD	High temperature thermal desorption
LTTD	Low temperature thermal desorption
mg/L	Milligrams per liter
MNA	Monitored natural attenuation
NAPL	Nonaqueous phase liquids
NPL	National Priorities List
OB	Open burn
OB/OD	Open burn/open detonation
OD	Open detonation
OERR	Office of Emergency and Remedial Response
OSC	On-scene coordinator
OSWER	Office of Solid Waste and Emergency Response
OU	Operable unit
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
pCi/L	Pico curies per liter
PRB	Permeable reactive barrier
REACH IT	EPA's REmediation And CHaracterization Innovative Technologies on-line searchable database
ROD	Record of Decision
RPM	Remedial Project Manager
S/S	Solidification/stablilization
SARA	Superfund Amendments and Reauthorization Act
SVE	Soil vapor extraction
SVOC	Semivolatile organic compounds
TIO	Technology Innovation Office
ug/L	Micrograms per liter
VEB	Vertical engineered barrier
VOC	Volatile organic compounds

Notice

Preparation of this report has been funded wholly or in part by the U.S. Environmental Protection Agency (EPA) under contract numbers 68-W-99-003 and 68-W-99-020. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. A limited number of printed copies of Treatment Technologies for Site Cleanup: Annual Status Report (ASR), Tenth Edition is available free of charge by mail or by facsimile from:

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An HTML and a PDF version of the ASR are available for viewing or downloading from the Hazardous Waste Cleanup Information (CLU-IN) web site at *http://clu-in.org/asr*. Printed copies of the ASR can also be ordered through that web address, subject to availability.

The data for the ASR have been incorporated into EPA's REmediation And CHaracterization Innovative Technologies (EPA REACH IT) on-line searchable database at *http://www.epareachit.org*. EPA REACH IT, sponsored by EPA's Technology Innovation Office, is a system that lets environmental professionals use the power of the Internet to search, view, download, and print information about innovative remediation and characterization technologies. EPA REACH IT provides information about more than 750 service providers that offer almost 1,300 remediation technologies and more than 150 characterization technologies. EPA REACH IT fosters communication between technology vendors and users by providing information about the availability, performance, and cost associated with the application of treatment and characterization technologies.

Acknowledgment

This document was prepared for EPA's Technology Innovation Office under contract numbers 68-W-99-003 and 68-W-99-020.

Special acknowledgment is given to the federal and state staff and other remediation professionals for individual sites, for providing the detailed information presented in this document. Their cooperation and willingness to share their expertise on treatment technologies encourages the application of those technologies at other sites.

Executive Summary

This report documents the status, as of the summer of 2000, of treatment technology applications for soil, other solid wastes, and groundwater at Superfund sites. The data in this report were gathered from Superfund Records of Decision (RODs) from fiscal year (FY) 1982 through 1999 and project managers at Superfund remedial and removal sites. The report examines both source control technologies (addressing soil, sludge, sediment, and other solid-matrix wastes) and innovative groundwater treatment technologies. The principal technologies for the treatment of soil and other solid wastes that are discussed in the report are:

- on- and off-site incineration
- solidification/stabilization
- soil vapor extraction (SVE)
- thermal desorption
- bioremediation

The innovative groundwater treatment technologies included in this report are:

- air sparging
- in situ bioremediation
- in situ chemical treatment
- dual-phase extraction (for soil and groundwater)
- thermally enhanced recovery
- surfactant flushing
- permeable reactive barriers (also known as passive treatment walls).

In addition, one technology for groundwater containment, vertical engineered barriers (VEB), is addressed in this report.

This 10th edition provides a summary of the technology applications identified for Superfund remedial and removal actions. This report includes data on 934 treatment technology projects, 834 of which are being carried out under Superfund remedial actions. For the most frequently selected technologies in the Superfund remedial program, the report analyzes selection trends over time, contaminant groups treated, quantities of soil treated (for soil treatment technologies), and the status of project implementation.

The major findings of this report on the use of treatment at Superfund remedial action sites are:

- At over half (58 percent) of Superfund sites, the remedy already implemented or currently planned includes treatment of a source or groundwater (including groundwater pump-and-treat remedies).
- For treatment technologies (excluding groundwater pump-and-treat) at Superfund remedial action sites, a total of 353 projects (42 percent) have been completed and another 276 (33 percent) are operational.

For the use of treatment technologies for source control:

- The percentage of RODs selecting treatment as a method of managing sources of contamination increased from 40 percent in 1997 to 47 percent in 1999, while the percentage selecting containment has decreased from 46 percent in 1997 to 32 percent in 1999.
- More than half of all source control treatments at Superfund remedial action sites (58 percent) are ex situ.
- More than twice as much contaminated soil is undergoing remediation by in situ treatment (34 million cubic yards) than by ex situ treatment (14 million cubic yards).
- Approximately 47 percent of source control treatment projects have been completed.
- In situ SVE is the most frequently used source control treatment technology (26 percent of source control projects), followed by ex situ solidification/stabilization (19 percent) and off-site incineration (13 percent).
- Approximately 57 percent (27 million cubic yards) of the total volume of soil is being treated by SVE.

Results for contaminants treated at Superfund sites indicate that:

- More than 80 percent of the Superfund remedial projects in the report address organic contaminants.
- More than 20 percent of the remedial projects address metal contaminants.

Access to more detailed project information has been made easier by the incorporation of the site-specific data used as the basis for this report into EPA's REmediation And CHaracterization Innovative Technologies (EPA REACH IT) on-line searchable database at *http://www.epareachit.org*. Additionally, an HTML version of this report is available at EPA's hazardous waste CLeanUp INformation (CLU-IN) website at *http://clu-in.org*.

This report also includes a new appendix (Appendix F) that describes the classification of remedy types and RODs. Appendix F provides details on the methodology for analyzing RODs and the remedies they select and identifying specific remedy and ROD types. The procedures contained in Appendix F are intended to provide a standard methodology for identifying remedy and ROD types. Establishing consistent and reproducible remedy and ROD evaluation procedures will facilitate technology transfer and data collection and reporting.

Overview

Introduction

The Treatment Technologies for Site Cleanup: Annual Status Report (ASR), Tenth Edition was prepared by the Technology Innovation Office (TIO) of the U.S. Environmental Protection Agency's (EPA) Office of Solid Waste and Emergency Response (OSWER) to document the use of treatment technologies at hazardous waste sites. The report presents a list and an analysis of Superfund sites (both remedial and removal actions) at which treatment technologies are being used. Site managers can use this report to evaluate cleanup alternatives for similar sites, while technology vendors can use it to identify potential markets for their products. EPA also uses the information to track progress in the application of established and innovative treatment technologies.

The ASR usually is updated annually. The ninth edition of this report, published in April 1999, included data from Superfund Records of Decision (RODs) through fiscal year (FY) 1997. This tenth edition updates and expands information provided in the April 1999 report with the inclusion of data from FY 1998 and FY 1999 RODs. This document includes a list of sites and an analysis of 834 applications of treatment technologies under remedial actions and 100 applications under removal actions. Added to the update is information about 66 applications of treatment technologies selected by RODs in FY 1998 and 67 selected in FY 1999. A ROD is the decision document used to specify the way a site, or part of a site, will be remediated.

What Treatment Technologies are Addressed in This Report?

Most RODs for remedial actions address the source of contamination, such as soil, sludge, sediments, and solid-matrix wastes. Such "source control" RODs select "source control technologies." Groundwater remedial action "a non-source control action" may be a component of the "source control" ROD and the treatment technologies chosen for groundwater remediation are referred to as "groundwater technologies." Appendix F to this document is a detailed description of the methodology used to identify ROD types, including detailed definitions of "source control," "groundwater technologies," and other remedy types.

New in the Tenth Edition

- A presentation of the actual remedies being implemented at Superfund remedial action sites, on a site-specific basis, based on a historical review of RODs, ROD amendments, and Explanations of Significant Differences (ESDs).
- A more detailed look at two innovative treatment technologies, phytoremediation and permeable reactive barriers (PRB).
- A special analysis of vertical engineered barriers, one type of groundwater containment at Superfund remedial action sites.

The ASR documents and tracks the use of source control treatment, in situ groundwater treatment, and groundwater containment remedies at Superfund remedial and removal action sites. The ASR also contains some limited information on other remedies, including groundwater pump-and-treat, and groundwater monitored natural attenuation remedies.

The methodology used to determine ROD and remedy types has evolved over time. As new technologies are developed and innovative techniques for site remediation are implemented, the methodology for identifying ROD and remedy types has been expanded to accommodate them. Because the ROD and remedy type identification methodology has changed over time, the methodology and definitions described in Appendix F may not be applicable to all RODs issued before FY 1998 and the remedies they contain. However, the tenth edition of the ASR does use this methodology for FY 1998 and FY 1999 RODs and their remedies. The Appendix F methodology will be modified to account for the evolving nature of technologies.

The term "treatment technology" means any unit operation or series of unit operations that alters the composition of a hazardous substance or pollutant or contaminant through chemical, biological, or physical means so as to reduce toxicity, mobility, or volume of the contaminated materials being treated. Treatment technologies are an alternative to land disposal of hazardous wastes without treatment. (Federal Register,

Remedy Type Summary

Source Control Treatment

- Treatment of a contaminant source.
- Can include any of the source control treatment technologies described in this report.

Source Control Containment

- Containment of a contaminant source.
- Can include the use of caps, liners, covers, and landfilling both on and off site.

Source Control Other

- Other forms of remediation of a contaminant source.
- Can include institutional controls, monitoring, and population relocation.

Groundwater Remedy

- Remediation of a contaminated aquifer.
- Can include any of the in situ groundwater treatment technologies described in this report, groundwater containment using vertical engineered barriers, groundwater pump-and-treat, and other groundwater remedies such as institutional controls, monitoring, and alternate drinking water supply.

volume 55, page 8819, 40 CFR 300.5: Definitions).

Established treatment technologies are those for which cost and performance information is readily available. The most frequently used established technologies are on- and off-site incineration, solidification/stabilization, soil vapor extraction (SVE), thermal desorption, and pump-and-treat technologies for groundwater. Treatment of groundwater after it has been pumped to the surface usually involves traditional water treatment and consequently pump-and-treat groundwater remedies are considered established technologies.

Innovative treatment technologies are alternative treatment technologies whose limited number of applications result in a lack of data on cost and performance. In general, a treatment technology is considered innovative if it has had limited full-scale application. Often, these technologies are established in other fields, such as chemical manufacturing or hazardous waste treatment. In such cases, it is the application of a technology or process at a waste site (to soils, sediments, sludge, and solid-matrix waste [such as mining slag] or groundwater) that is innovative, not the technology itself. Innovative technologies are discussed in greater detail in Section 3.

Both innovative and established technologies are grouped as source control treatment or in situ groundwater treatment technologies on the basis of the type of application most commonly associated with the technology. Some technologies may be used for both source control and in situ groundwater treatment. These technologies and their respective groupings are listed in Appendix F.

Sources of Information for This Report

EPA initially used RODs to compile information about Superfund remedial actions and used on-scene coordinator (OSC) reports and the OSWER Removal Tracking System to compile data on removal actions. EPA then verified and updated the draft information through interviews with remedial project managers (RPMs), OSCs, and other contacts for each site. Project status data in the Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS 3), EPA's Superfund tracking system, provided more detailed information about the specific portion of the remedy involving a treatment technology. In addition, information about technologies and sites identified here may differ from information found in the CERCLIS 3 database. Such differences occur when changes are made in the remedy during the design phase of the project. The changes may not have required official documentation (that is, a ROD amendment or an explanation of significant differences [ESD]), and hence, would not be recorded in CERCLIS 3.

Definitions of Specific Treatment Technologies

This document reports on the use of the treatment technologies listed previously and one groundwater containment technology, VEB. This section provides brief definitions of the 20 types of source control (primarily soil) treatment technologies, five types of in situ groundwater treatment technologies, and one groundwater containment technology, as they are discussed in this document. The definitions are based on the Remediation Technologies Screening Matrix and Reference Guide, Version 3.0, which can be viewed at the Federal Remediation Technologies Roundtable (FRTR) web site at *http://www.frtr.gov*. Sketches for some of the newer innovative treatment technologies are provided.

Source Control Treatment Technologies

BIOREMEDIATION uses microorganisms to degrade organic contaminants in soil, sludge, and solids either excavated or in situ. The microorganisms break down contaminants by using them as a food source or cometabolizing them with a food source. Aerobic processes require an oxygen source, and the end products typically are carbon dioxide and water. Anaerobic processes are conducted in the absence of oxygen, and the end products can include methane, hydrogen gas, sulfide, elemental sulfur, and dinitrogen gas. Ex situ bioremediation includes slurry-phase bioremediation, in which the soils are mixed in water to form a slurry to keep solids suspended and microorganisms in contact with the soil contaminants, and solid-phase bioremediation, in which the soils are placed in a cell or building and tilled with added water and nutrients. Land farming, biopiles, and composting are examples of ex situ, solid-phase bioremediation. In situ bioremediation is bioremediation in place, rather than ex situ. In situ techniques stimulate and create a favorable environment for microorganisms to grow and use contaminants as a food and energy source. Generally, this means providing some combination of oxygen, nutrients, and moisture, and controlling the temperature and pH. Sometimes, microorganisms that have been adapted for degradation of specific contaminants are applied to enhance the process. Bioventing is a common form of in situ bioremediation. Bioventing uses extraction wells to circulate air through the ground, sometimes pumping air into the ground.

CHEMICAL TREATMENT, also known as chemical reduction/oxidation, typically involves reduction/oxidation (redox) reactions that chemically convert hazardous contaminants to nonhazardous or less toxic compounds that are more stable, less mobile, or inert. Redox reactions involve the transfer of electrons from one compound to another. Specifically, one reactant is oxidized (loses electrons) and one is reduced (gains electrons). The oxidizing agents most commonly used for treatment of hazardous contaminants in soil are ozone, hydrogen peroxide, hypochlorites, chlorine, chlorine dioxide, potassium permanganate, and Fentons reagent (hydrogen peroxide and iron). Cyanide oxidation and dechlorination are examples of chemical treatment. This method may be applied in situ or ex situ, to soils, sludges, sediments, and other solids, and may also be applied for the in situ treatment of groundwater.

ELECTRICAL SEPARATION relies upon application of a low-intensity direct current through the soil between ceramic electrodes that are divided into a cathode array and an anode array. This mobilizes charged species, causing ions and water to move toward the electrodes. Metal ions, ammonium ions, and positively charged organic compounds move toward the cathode. Anions such as chloride, cyanide, fluoride, nitrate, and negatively charged organic compounds move toward the anode. Removal of contaminants at the electrode may be accomplished by several means, among which are: electroplating at the electrode; precipitation or co-precipitation at the electrode; pumping of water near the electrode; or complexing with ion exchange resins.

For IN SITU SOIL FLUSHING, large volumes of water, at times supplemented with surfactants, cosolvents, or treatment compounds, are applied to the soil or injected into the groundwater to raise the water table into the contaminated soil zone. Injected water and treatment agents are isolated within the underlying aquifer and recovered together with flushed contaminants.

Both on-site and off-site INCINERATION use high temperatures, 870 to 1,200°C (1,600 to 2,200°F), to volatilize and combust (in the presence of oxygen) halogenated and other refractory organics in hazardous wastes. Often, auxiliary fuels are employed to initiate and sustain combustion. The destruction and removal efficiency (DRE) for properly operated incinerators exceeds the 99.99 percent requirement for hazardous waste and can be operated to meet the 99.9999 percent requirement for polychlorinated biphenyls (PCBs) and dioxins. Off-gases and combustion residuals generally require treatment. On-site incineration typically uses a transportable unit; for off-site incineration, waste is transported to a central facility.

MECHANICAL SOIL AERATION agitates contaminated soil, using tilling or other means to volatilize contaminants.

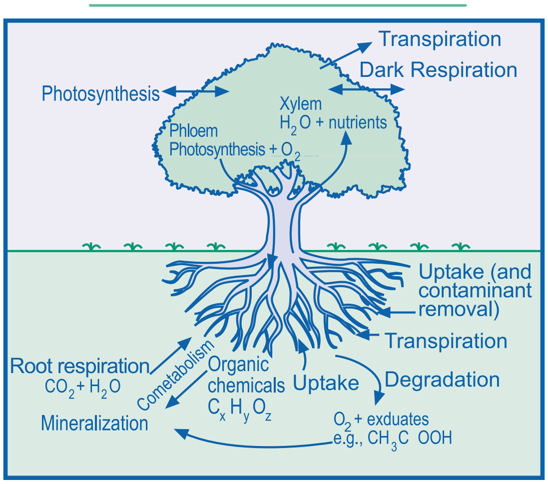
NEUTRALIZATION is a chemical reaction between an acid and a base. The reaction involves acidic or caustic wastes that are neutralized (pH is adjusted toward 7.0), using caustic or acid additives.

OPEN BURN (OB) and OPEN DETONATION (OD) operations are conducted to destroy excess, obsolete, or unserviceable (EOU) munitions and energetic materials. In OB operations, energetics or munitions are destroyed by self-sustained combustion, which is ignited by an external source, such as a flame, heat, or a detonation wave. In OD operations, explosives and munitions are destroyed by detonation, which generally is initiated by an energetic charge.

PHYSICAL SEPARATION processes use different size sieves and screens to concentrate contaminants into smaller volumes. Most organic and inorganic contaminants tend to bind, either chemically or physically, to the fine fraction of the soil. Fine clay and silt particles are separated from the coarse sand and gravel soil particles to concentrate the contaminants into a smaller volume of soil. The smaller volume then can be treated further or disposed.

PHYTOREMEDIATION is a process that uses plants to remove, transfer, stabilize, or destroy contaminants in soil, sediment, and groundwater. The mechanisms of phytoremediation include enhanced rhizosphere biodegradation (takes place in soil or groundwater immediately surrounding plant roots), phytoextraction (also known as phytoaccumulation, the uptake of contaminants by plant roots and the translocation/accumulation of contaminants into plant shoots and leaves), phytodegradation (metabolism of contaminants within plant tissues), and phytostabilization (production of chemical compounds by plants to immobilize contaminants at the interface of roots and soil). Phytoremediation applies to all biological, chemical, and physical processes that are influenced by plants (including the rhizosphere) and that aid in cleanup of the contaminated substances. Plants can be used in site remediation, both through the mineralization of toxic organic compounds and through the accumulation and concentration of heavy metals and other inorganic compounds from soil into aboveground shoots. Phytoremediation may be applied in situ or ex situ, to soils, sludges, sediments, other solids, or groundwater.

Model of Phytoremediation



SOIL VAPOR EXTRACTION (SVE) is used to remediate unsaturated (vadose) zone soil. A vacuum is applied to the soil to induce the controlled flow of air and remove volatile and some semivolatile organic contaminants from the soil. SVE usually is performed in situ; however, in some cases, it can be used as an ex situ technology.

For SOIL WASHING, contaminants sorbed onto fine soil particles are separated from bulk soil in a water-based system on the basis of particle size. The wash water may be augmented with a basic leaching agent, surfactant, or chelating agent or by adjustment of pH to help remove organics and heavy metals. Soils and wash water are mixed ex situ in a tank or other treatment unit. The wash water and various soil fractions are usually separated using gravity settling.

SOLIDIFICATION/STABILIZATION (S/S) reduces the mobility of hazardous substances and contaminants in the environment through both physical and chemical means. The S/S process physically binds or encloses contaminants within a stabilized mass. S/S is performed both ex situ and in situ. Ex situ S/S requires excavation of the material to be treated, and the resultant material must be disposed. In situ S/S uses auger/caisson systems and injector head systems to add binders to the contaminated soil or waste without excavation, and the resultant material is left in place.

SOLVENT EXTRACTION uses an organic solvent as an extractant to separate organic and metal contaminants from soil. The organic solvent is mixed with contaminated soil in an extraction unit. The extracted solution then is passed through a separator, where the contaminants and extractant are separated from the soil. Organically bound metals may be extracted along with the target organic contaminants.

For THERMAL DESORPTION, wastes are heated so that organic contaminants and water volatilize. Typically, a carrier gas or vacuum system transports the volatilized water and organics to a gas treatment system. Based on the operating temperature of the desorber, thermal desorption processes can be categorized into two groups: high temperature thermal desorption (HTTD) (320 to 560°C or 600 to 1000°F) and low temperature thermal desorption (LTTD) (90 to 320°C or 200 to 600°F). Thermal desorption is an ex situ treatment process. In situ thermal desorption processes are discussed below as thermally enhanced recovery.

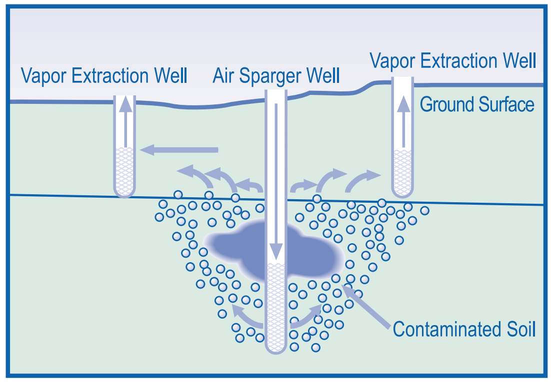
THERMALLY ENHANCED RECOVERY is an in situ treatment process that uses heat to increase the volatilization rate of organics and facilitate extraction. Volatilized contaminants are typically removed from the vadose zone using soil vapor extraction. Specific types of thermally enhanced recovery techniques include Contained Recovery of Oily Waste (CROW™), radio frequency heating, conductive heating, steam heating, in situ steam stripping, hot air injection, dynamic underground stripping, in situ thermal desorption, and electrical resistance heating. Thermally enhanced recovery is usually applied to contaminated soil but may also be applied to groundwater.

VITRIFICATION uses an electric current to melt contaminated soil at elevated temperatures (1,600 to 2,000°C or 2,900 to 3,650°F). Upon cooling, the vitrification product is a chemically stable, leach-resistant, glass and crystalline material similar to obsidian or basalt rock. The high temperature component of the process destroys or removes organic materials. Radionuclides and heavy metals are retained within the vitrified product. Vitrification may be conducted in situ or ex situ.

In Situ Groundwater Treatment Technologies

AIR SPARGING involves the injection of air or oxygen through a contaminated aquifer. Injected air traverses horizontally and vertically in channels through the soil column, creating an underground

Model of an Air Sparging System



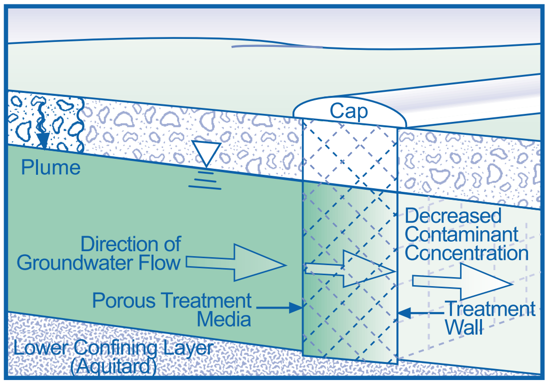
stripper that removes volatile and semivolatile organic contaminants by volatilization. The injected air helps to flush the contaminants into the unsaturated zone. SVE usually is implemented in conjunction with air sparging to remove the generated vapor-phase contamination from the vadose zone. Oxygen added to the contaminated groundwater and vadose-zone soils also can enhance biodegradation of contaminants below and above the water table.

With IN SITU GROUNDWATER BIOREMEDIATION, substrates, nutrients, or an oxygen source (for aerobic processes), are pumped into an aquifer through wells to enhance biodegradation of contaminants in groundwater. Specific types of enhanced in situ groundwater bioremediation include biosparging and bioslurping.

DUAL-PHASE EXTRACTION, also known as multi-phase extraction, uses a vacuum system to remove various combinations of contaminated groundwater, separate-phase petroleum product, and vapors from the subsurface. The system lowers the water table around the well, exposing more of the formation. Contaminants in the newly exposed vadose zone are then accessible to vapor extraction. Once above ground, the extracted vapors or liquid-phase organics and ground water are separated and treated.

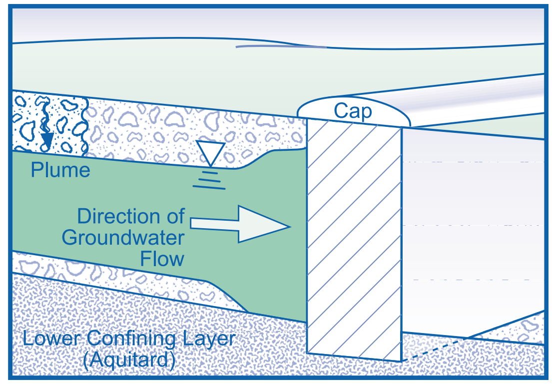
For IN-WELL AIR STRIPPING, air is injected into a double-screened well, causing the volatile organic compounds in the contaminated groundwater to transfer from the dissolved phase to the vapor phase in air bubbles. As the air bubbles rise to the surface of the water, the vapors are drawn off and treated by a SVE system.

Model of a Permeable Reactive Barrier



PERMEABLE REACTIVE BARRIERS (PRBs) also known as passive treatment walls, are installed across the flow path of a contaminated groundwater plume, allowing the water portion of the plume to flow through the wall. These barriers allow the passage of water while prohibiting the movement of contaminants by employing agents within the wall such as zero-valent metals, chelators, sorbents, and microbes. The contaminants are either degraded or retained in a concentrated form by the barrier material, which may need to be replaced periodically.

Model of a Vertical Engineered Barrier



In Situ Groundwater Containment Technology

VERTICAL ENGINEERED BARRIERS (VEBs) are subsurface barriers made of an impermeable material designed to contain or divert groundwater. VEBs can be used to contain contaminated groundwater, divert uncontaminated groundwater from a contaminated area, or divert contaminated groundwater from a drinking water intake or other protected resource.

Section 1: Overview of RODs

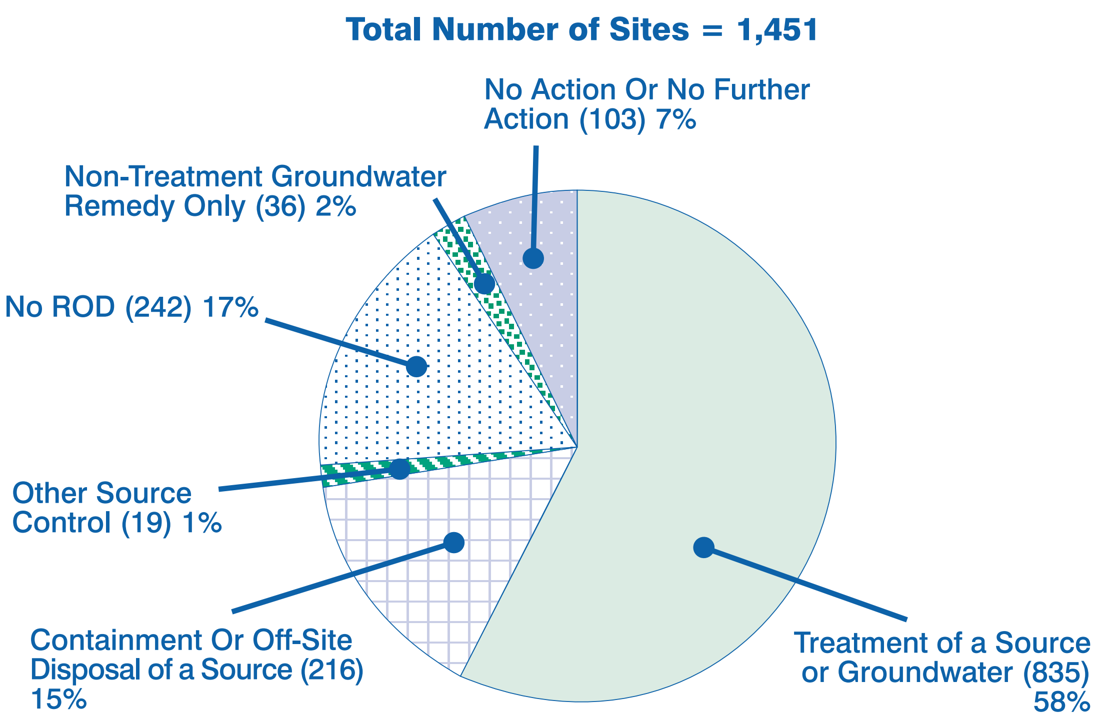
As of August 2000, 1,234 sites were on the National Priorities List (NPL); 217 sites had been removed from the NPL. Therefore, 1,451 sites are or have been listed. An additional 59 sites are proposed for the NPL. Some sites may cover a large area, include several types of contaminated media, or include areas in which the types of contamination differ. To facilitate the establishment of remedies at a complex site, the site may be divided into operable units, with separate remedies for each. Remedies for NPL sites are documented in Records of Decision (RODs). A separate ROD may be developed for each operable unit. In addition, each operable unit may require a number of RODs to address different media within that operable unit or to revise the selected remedy. Therefore, each site may have multiple RODs.

Through fiscal year (FY) 1999, approximately 2,292 RODs (including ROD amendments) had been signed. Of them, 1,561 RODs for remedial actions address the source of contamination, such as soil, sludge, sediments, nonaqueous phase liquids (NAPL), leacheate, and solid-matrix wastes; they are referred to as "source control" RODs. Appendix F to this report provides the definitions of the various ROD types and the methodology used to assign a type to each ROD. A type was assigned to each ROD based on the remedies in the ROD. A type was then assigned to each site based on the types of RODs issued for that site. For sites for which a number of RODs have been signed, the hierarchy presented in Appendix F was used to assign a site type.

At over half of NPL sites (58 percent), source control or groundwater treatment has been implemented or is planned as a remedy for some portion of the site. For another 15 percent of sites, the remedy does not include source control or groundwater treatment but does include source containment or off-site disposal of the source. For 17 percent of sites, no ROD has been issued. Figure 1 summarizes the number of NPL sites for each type of remedy.

Previous editions of the ASR quantified the remedy types at Superfund sites based on the remedies selected in RODs. However, the remedies selected in RODs may not be the remedies actually implemented at a site. For example, a treatment technology that was selected in a ROD based on bench-scale treatability testing may prove to be ineffective in pilot-scale tests conducted during the design phase; in such a case, a different remedy

Figure 1. Superfund Remedial Actions: Actual Remedy Types At Sites On The National Priorities List (FY 1982 - FY 1999)



Sources: 1, 2, 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.
Note: Appendix F describes the methodology used to indentify remedy types for each site.

may be substituted. Additional contamination at the site may be discovered during the implementation of a remedy; a remedy change might then be necessary. Further, a particular remedy may have been included in a ROD only as a contingent remedy, with future site investigations revealing that implementation of that contingent remedy was not warranted. When remedies are changed, the changes usually are documented in a ROD amendment or Explanation of Significant Difference (ESD). However, some remedy changes are not documented in that manner.

The information used to develop Figure 1 reflects not only the remedies selected in RODs, but also the remedies actually implemented or currently planned at those sites. Sources for the information include the RODs, ROD amendments, and ESDs published for each site, and contacts with remedial project managers (RPM) to identify the most current remedy selected for each site. Figure 1 therefore reflects the current status of remedial actions at NPL sites, rather than only the documented historical decisions.

The HTML version of the tenth edition of the ASR includes a downloadable spreadsheet to help site managers, the regulated community, and remediation professionals identify sites at which particular remedy types are being implemented. The spreadsheet contains information for each NPL site where a ROD has been issued, including the site name, location, and site type. The HTML version of the ASR can be found at *http://clu-in.org/asr.*

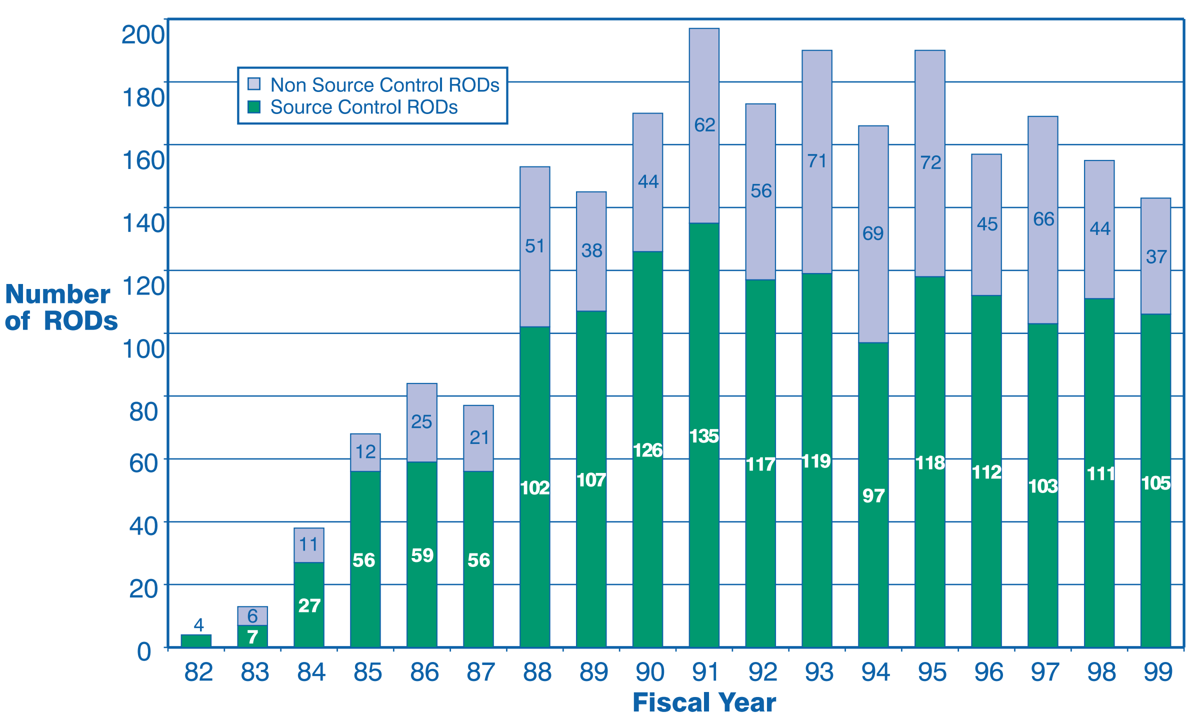
RODs Signed by Fiscal Year

Data from FY 1998 and FY 1999 RODs are included in this tenth edition of the ASR. Since 1988, the total number of RODs signed in each FY has fluctuated between 142 and 197. Figure 2 shows the number of source control RODs, compared with the total number of RODs for each FY since FY 1982. Non source control RODs are those selecting groundwater remedies, no action, or no further action without selecting any source control remedies. Those RODs that select both a source control remedy and a groundwater remedy are considered source control RODs.

Since 1988, the total number of source control RODs has varied between 97 and 135. Source control RODs represented between 58 percent and 74 percent of all RODs signed in each of these years. In FY 1999, source control RODs represented 74 percent of all RODs signed in that year. Appendix F presents the definitions of the various ROD types and the methodology used to assign a type to each ROD.

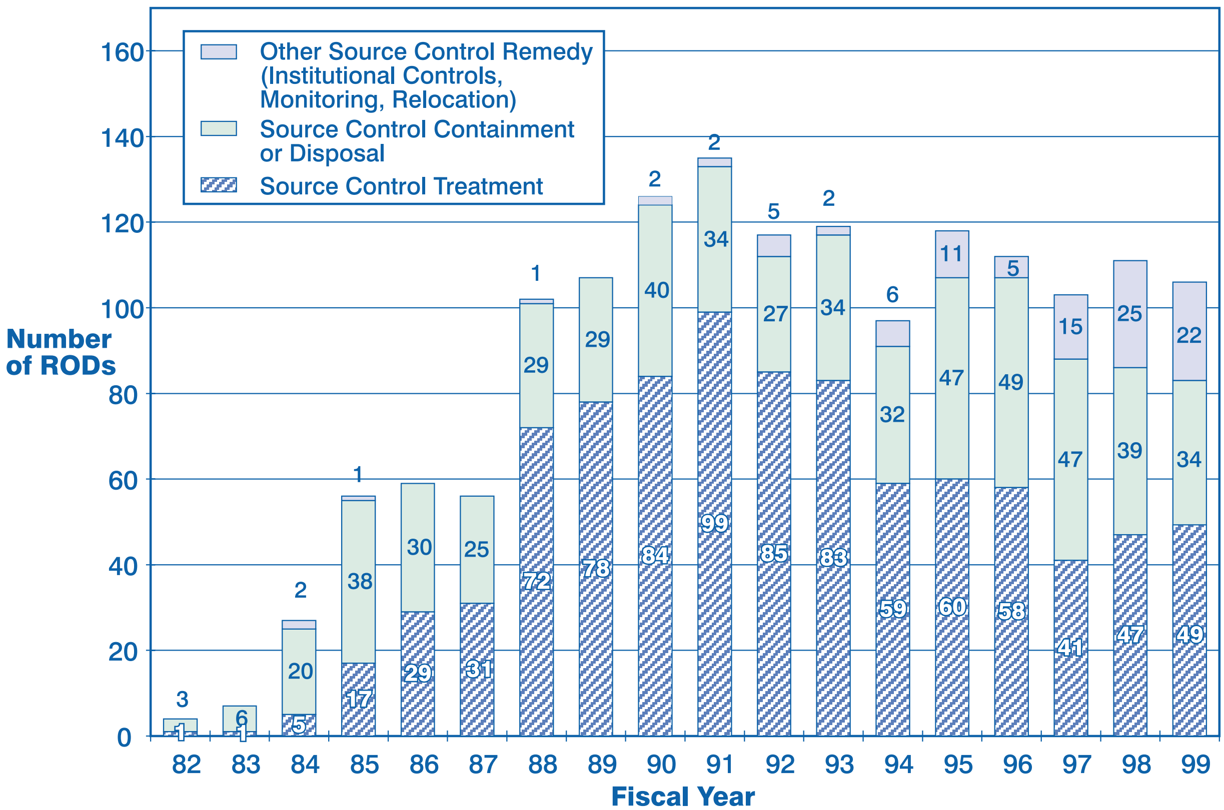
As Figure 2 shows, from FY 1996 to FY 1999 there was little change in the total number of RODs and the percentage of RODs that specified a source control remedy.

Figure 2. Superfund Remedial Actions: RODs Signed by Fiscal Year (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Figure 3. Superfund Remedial Actions: Source Control RODs (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Source Control RODs

Source control RODs can be delineated further by the general type of remedy selected: (1) RODs specifying treatment, (2) RODs specifying on-site containment or off-site disposal only, and (3) RODs specifying institutional controls or other actions (such as monitoring or relocation of the affected community). Appendix F describes in detail how remedy and ROD types are identified.

Shown in Figure 3 is the number of source control RODs of each type. RODs that select treatment may also include containment of treatment residues or waste at another part of the site. In FY 1998 and 1999, the number of source control treatment RODs was 47 and 49, respectively, which is an increase from the 41 source control treatment RODs issued in 1997. In all years from FY 1988 through FY 1999, the number of source control treatment RODs was greater than 41. Figure 3 also shows that, since FY 1991, the number of RODs specifying other remedies, such as institutional controls, monitoring, relocation, or other nontreatment remedies, has increased. In FY 1998 and FY 1999, the highest number of RODs specifying other remedies occurred, with 25 such RODs in FY 1988 and 22 in FY 1999. Cumulatively, 899 source control RODs are of the type "treatment", 563 "containment or disposal only", and 99 "other".

Section 2: Treatment Technologies for Source Control

Source control treatment technologies are designed to treat soil, sediment, sludge, or solid-matrix wastes (in other words, the source of contamination) and are not designed to treat groundwater. In this section, source control RODs are discussed first; however, most of the information in this section focuses on technologies, rather than RODs. It is important to note that in each ROD that specified treatment, more than one technology may have been selected. Groundwater technologies are discussed in Section 4. Some of the figures presented in this section include information on in situ groundwater treatment to facilitate comparison of source control treatment to in situ groundwater treatment.

Source Control RODs

The Superfund Amendments and Reauthorization Act of 1986 (SARA) expressed a preference for permanent remedies (that is, treatment) over containment or disposal in the remediation of Superfund sites. From FY 1988 through FY 1993, approximately 70 percent of source control RODs contained provisions for treatment of wastes. As shown in Figure 4, the percentage of RODs that specify source control treatment has decreased from a high of 73 percent (FY 1989, 1991, and 1992) to the current level of 47 percent (FY 1999). However, the percentage of source control treatment RODs each year has exceeded the percentage of source control containment RODs for the past 13 years, with the exception of FY 1997.

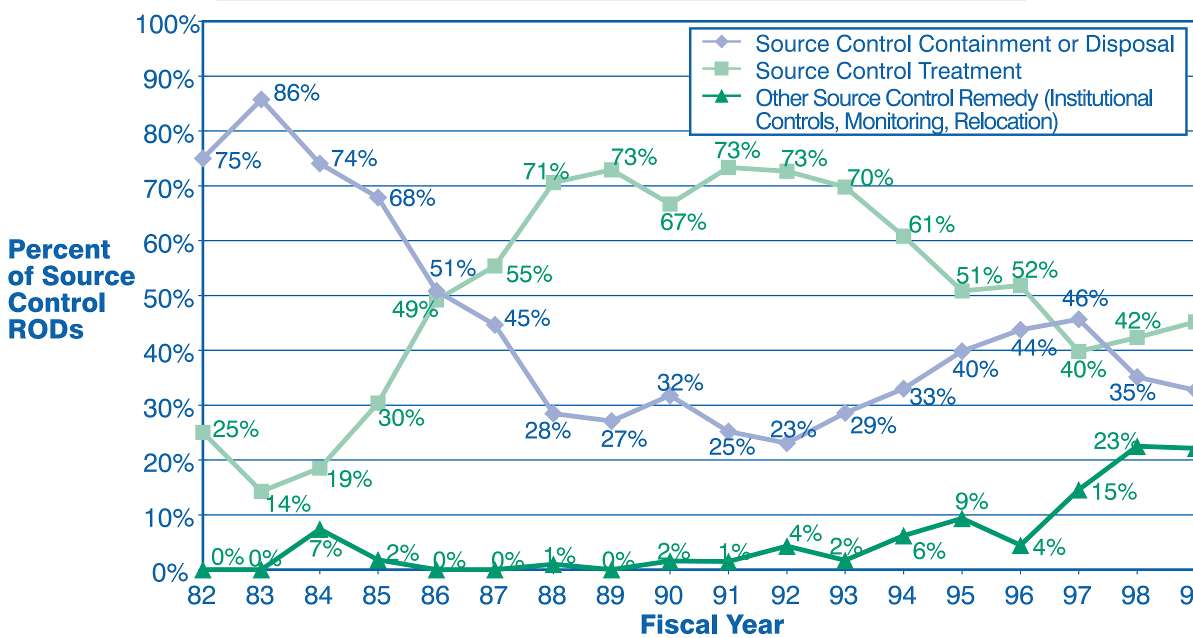
One notable observation is the increase in source control RODs that select "other" remedies, such as institutional controls, monitoring, and relocation of affected populations. Such "other" remedies represented less than 10 percent of source control RODs from FY 1982 through FY 1996, but that figure has increased to about 20 percent of all source control RODs in FY 1999. Cumulatively, 57 percent of source control RODs are of the type "treatment", 36 percent "containment or disposal", and 6 percent "other source remedy".

In Situ Versus Ex Situ Technologies

In situ technologies for source control are those applications in which the contaminated medium is treated or the contaminant is removed from the contaminated medium without excavating, pumping, or otherwise moving the contaminated medium to the surface. Implementation of ex situ technologies requires excavation, dredging, or other processes to remove the contaminated medium before treatment either on site or off site.

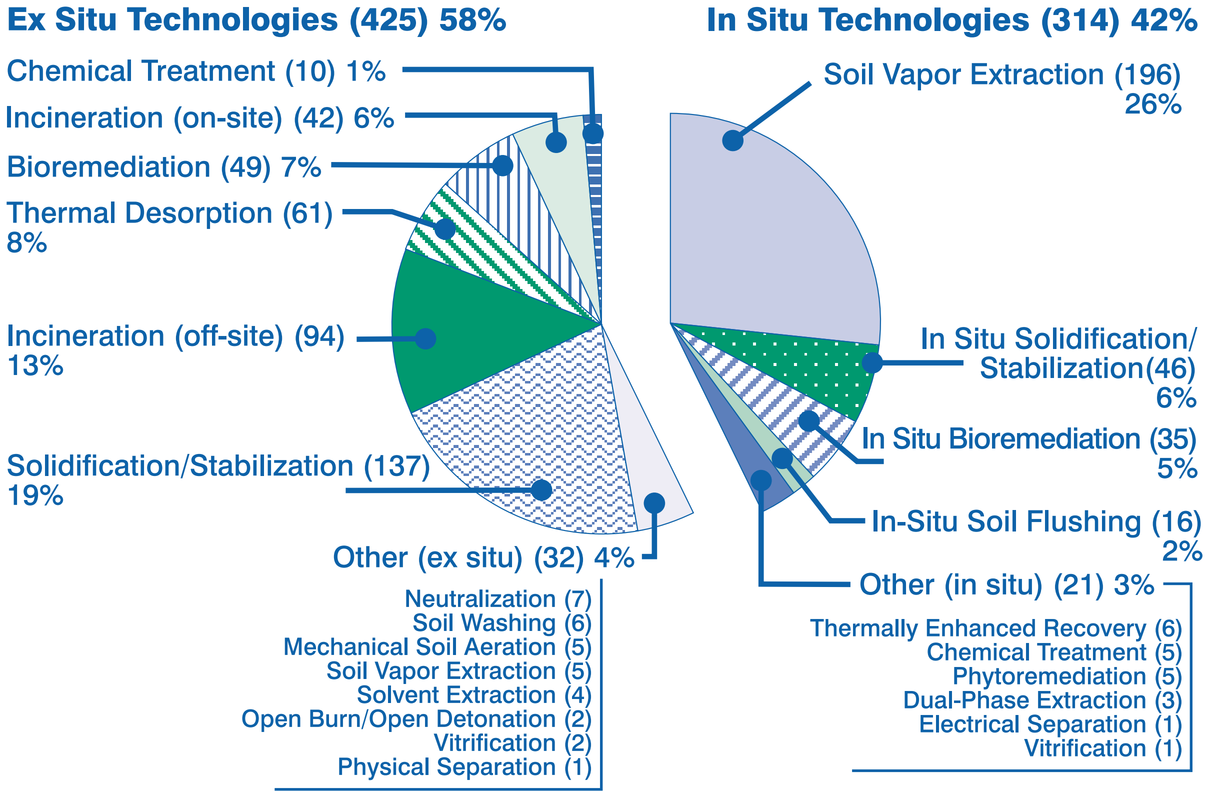
Through FY 1999, 739 treatment technologies have been, are currently being, or are planned to

Figure 4. Superfund Remedial Actions: Trends in Types of Source Control RODs (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Figure 5. Superfund Remedial Actions: Summary of Source Control Treatment Technologies (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

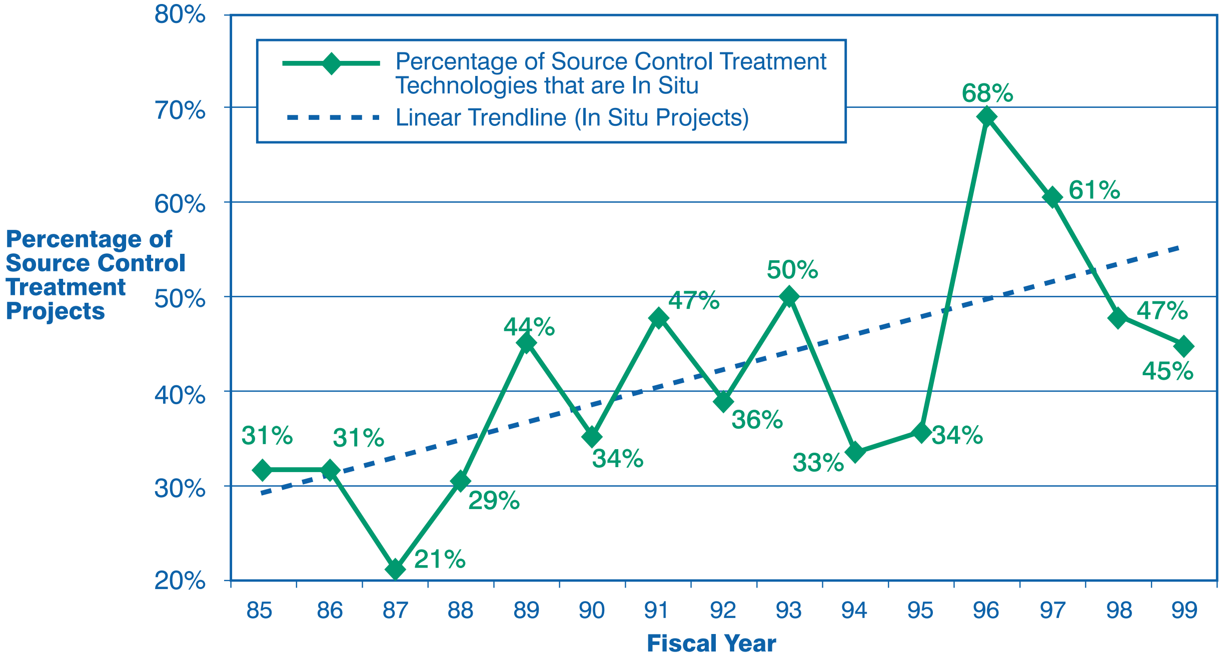
be implemented for source control. Figure 5 provides a cumulative overview of in situ and ex situ treatment technologies selected for source control. The cumulative number of source control treatment RODs exceeds the total number of treatment technologies because the remedy at some sites was changed from one that included a source control treatment technology to one that does not. Therefore, the remedies described in RODs do not always represent what is actually occurring at a site.

As Figure 5 indicates, SVE (196 projects, 26 percent), solidification/stabilization (46 projects, 6 percent), and bioremediation (35 projects, 5 percent) are the most common in situ technologies. The most common ex situ technologies are solidification/stabilization (137 projects, 19 percent); incineration (136 projects, 19 percent), both off-site (94 projects, 13 percent) and on-site (42 projects, 6 percent); thermal desorption (61 projects, 8 percent); and bioremediation (49 projects, 7 percent). Some 42 percent of all treatments selected for source control at Superfund remedial action sites were in situ technologies.

The HTML version of the tenth edition of the ASR includes a downloadable spreadsheet to help site managers, the regulated community, and remediation professionals identify sites at which particular in situ and ex situ treatment technologies are being employed. The spreadsheet contains information for each source control treatment project tracked in the ASR, including the site name, location, treatment technology, and whether the treatment is in situ or ex situ. The spreadsheet can be used by RPMs, OSCs, and remediation professionals to identify the sites using technologies similar to their own, and assist in technology transfer between those sites. The HTML version of the ASR can be found at *http:\\clu-in.org\asr*.

In situ treatment technologies increased as a percentage of all treatment technology projects between FY 1985 and FY 1996. While the percentage of in situ treatment projects decreased from a peak of 68 percent in FY 1996 to 45 percent in FY 1999, on average they remain at 42 percent (see Figure 5) of all source control treatment technologies from FY 1982 through FY 1999. Figure 6 presents the number of in situ technologies as a percentage of all treatment technologies for source control by fiscal year. Over time, use of in situ technologies has been

Figure 6. Superfund Remedial Actions: In Situ Technologies for Source Control (FY 1985 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

increasing, as the trendline in Figure 6 shows. A five-year moving average of the percentage of in situ treatment technologies shows a generally steady increase from 28 percent (FY 1985 - 1988) to 51 percent (FY 1995 - 1999).

Several factors may play a role in the upward trend in the use of in situ treatment technologies. Because in situ technologies require no excavation, risk from exposure to contaminated media is reduced, compared with levels of risk associated with technologies that do require excavation. Further, for large sites where excavation and materials-handling for ex situ technologies can be expensive, in situ technologies are often more cost-effective.

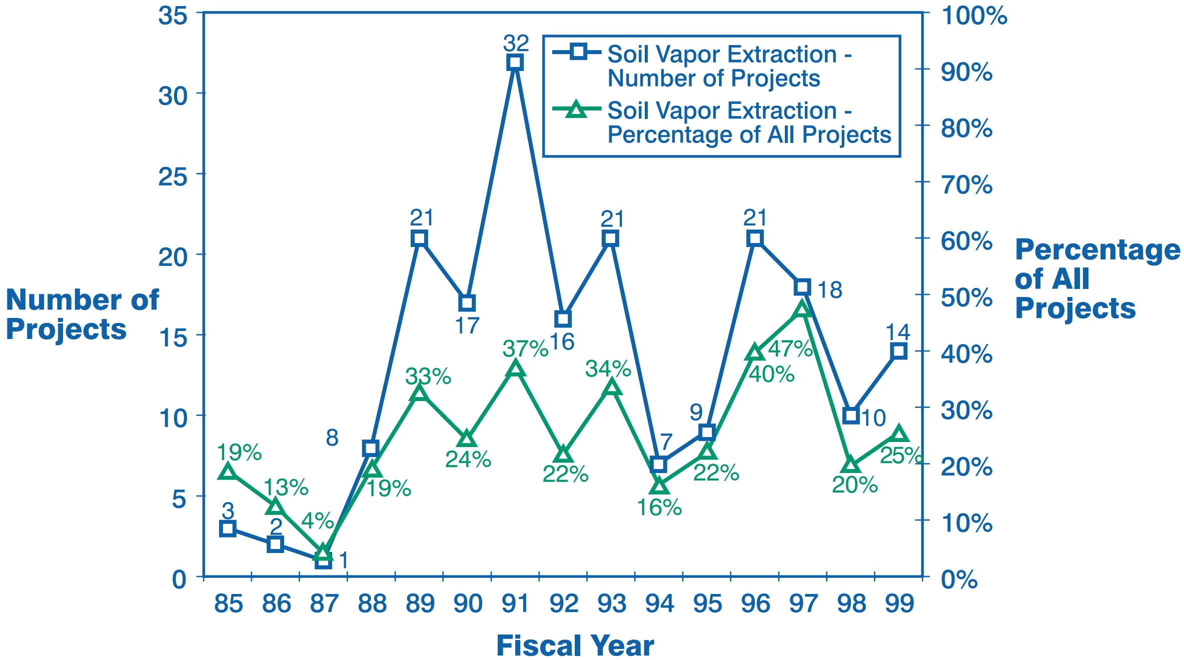
Another factor in the more widespread use of in situ technologies is their greater acceptance as a reliable technology by site managers and other remediation professionals. In situ treatment traditionally has been considered an innovative approach. However, as technologies are used more often, site managers deciding on a treatment technology can rely on a greater base of experience to determine whether the technology will remediate a given site successfully. For example, SVE and thermal desorption were considered innovative technologies in the eighth edition of the ASR. After widespread use (26 percent of all source control treatment projects are in situ SVE and 8 percent are thermal desorption), site managers now have better performance information and have more confidence in their effectiveness. A significant body of documentation on the performance of these technologies already exists. For example, the FRTR website at *http://www.frtr.gov* contains 31 and 17 cost and performance reports on projects employing soil vapor extraction and thermal desorption, respectively.

Each previous edition of the ASR included an appendix that listed treatment technology projects for source control at remedial sites by EPA region. The printed version of this tenth edition of the ASR does not include that appendix. However, the HTML version of the tenth edition, which can be accessed at *http://clu-in.org/asr*, does include the appendix. (The appendix also lists in situ groundwater projects and Superfund removal actions that will be discussed in later sections of this report.) The U.S. Environmental Protection Agency's (EPA) REmediation And CHaracterization Innovative Technologies (REACH IT) on-line searchable database (see Notice on page iii) provides detailed information about treatment technologies and projects sumarized in this report.

Most Common Technologies For Source Control

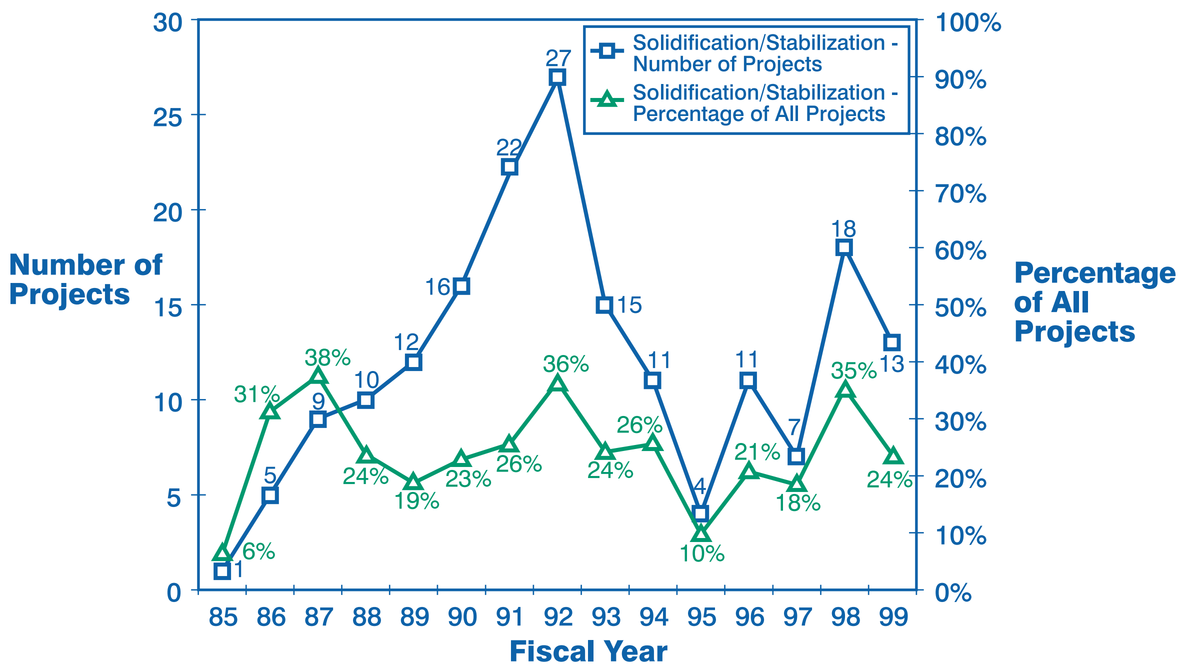
For each fiscal year, Figures 7, 8, and 9 graphically depict the frequency of selection and the percentage of all projects for the three most frequently selected treatment technologies for source control: SVE, solidification/stabilization, and incineration (both on-site and off-site). For each fiscal year from 1988 through 1999, Figure 10 shows the cumulative

Figure 7. Superfund Remedial Actions: Trends for Soil Vapor Extraction for Source Control (FY 1985 - FY 1999)



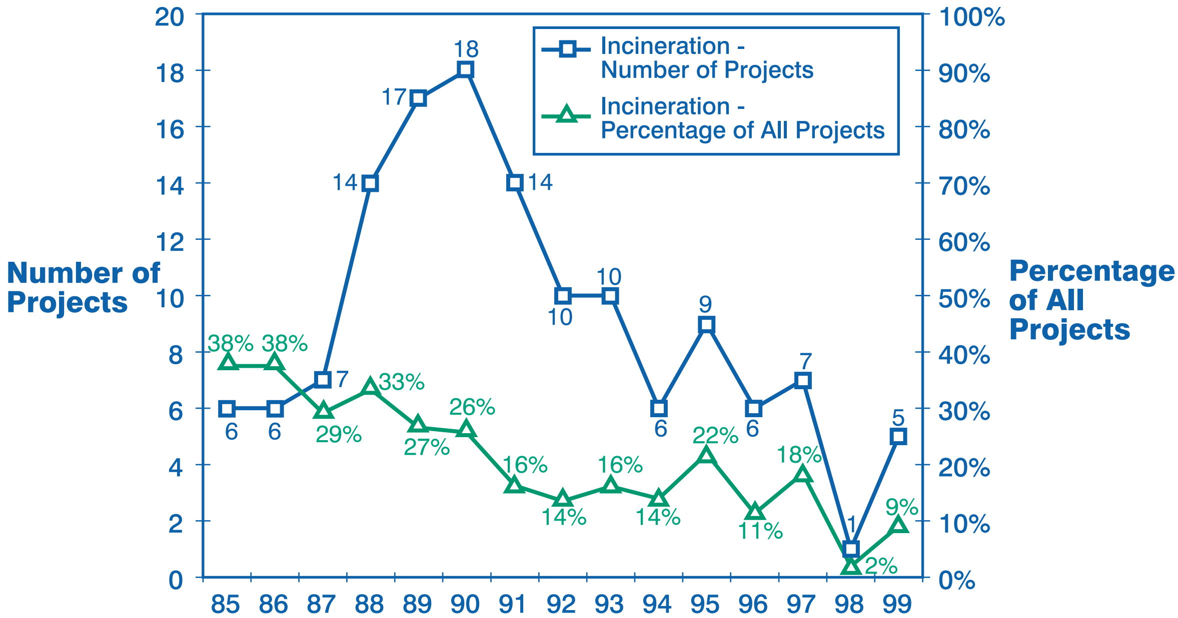
Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Figure 8. Superfund Remedial Actions: Trends for Solidification/ Stabilization for Source Control (FY 1985 - FY 1999)



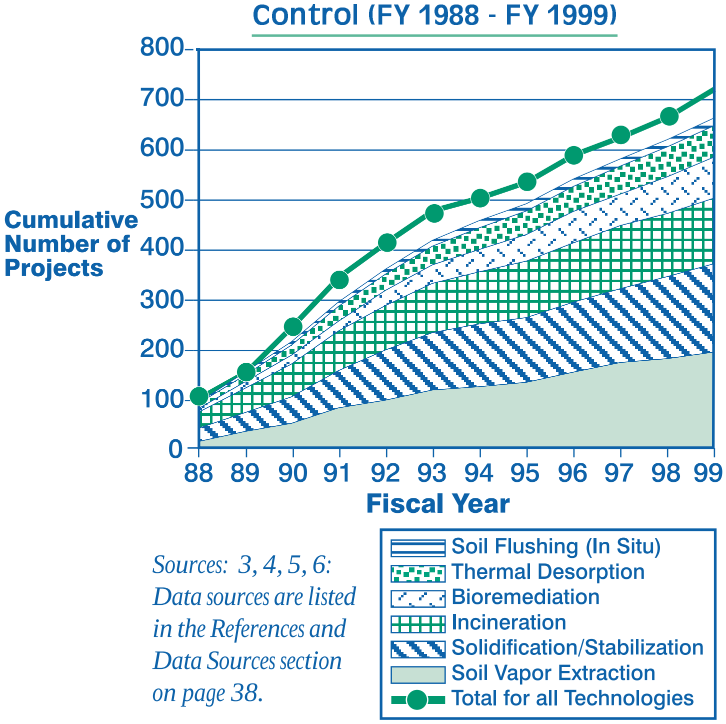
Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Figure 9. Superfund Remedial Actions: Trends for Incineration for Source Control (FY 1985 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Figure 10. Superfund Remedial Actions: Cumulative Trends for Most Common Technologies for Source Control (FY 1988 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

number of applications for source control. As the figure shows, SVE, solidification/stabilization, incineration, bioremediation, thermal desorption, and in situ soil flushing continue to represent most of the applications of source control treatment remedies at remedial action sites.

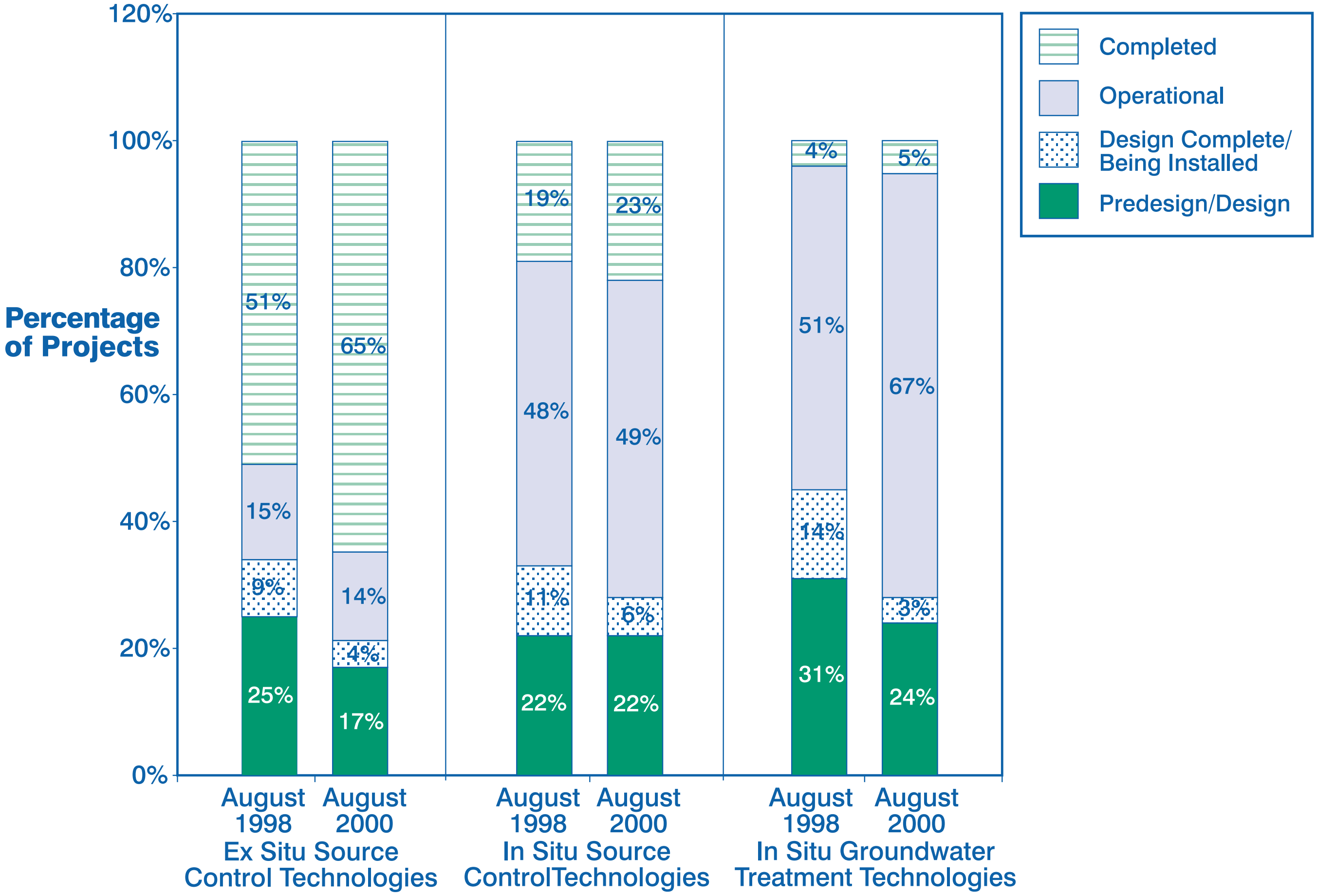
Implementation Status of Treatment Technology Projects

For in situ, ex situ, and groundwater treatment technologies, Figure 11 shows how the status of projects has changed since the publication of the ninth edition of the ASR. Published in April 1999, the ninth edition included data from FY 1982 through FY 1997 RODs, updated by RPMs through August 1998. This tenth edition of the ASR includes data from FY 1982 through FY 1999 RODs, updated by RPMs through August 2000. Completed projects are those where the treatment has been performed and is no longer ongoing. Projects that are completed may not have met all cleanup goals.

Some observations on the status of treatment selected in FY 1998 and FY 1999 at Superfund remedial action sites are:

- 106 additional treatment technology projects for source control and 27 projects for in situ groundwater treatment were selected.
- Six projects selected in the period have been completed, including three ex situ solidification/stabilization projects, two off-site incineration projects, and one thermal desorption project. The completed projects used established technologies that generally require relatively short treatment times.
- An additional 40 projects became operational.
- An additional 15 projects have progressed

Figure 11. Superfund Remedial Actions: Treatment Technologies Status by Technology Type



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

beyond the design phase, and the remedies are being installed.

Some observations based on the data in Figure 11 are:

- In August 1998, 51 percent of ex situ source control projects were completed, and 25 percent were in the design phase. As of August 2000, the percentage of ex situ source control projects that were completed increased to 65 percent, and the percentage in the design phase decreased to 17 percent.
- The percentage of completed in situ source control projects increased from 19 percent in August 1998 to 23 percent in August 2000.
- The percentage of completed groundwater projects increased from 4 percent in August 1998 to 5 percent in August 2000.

For each technology type, Table 1 provides a summary of project status. Among ex situ technologies, bioremediation represents the largest number of projects (24) that are operational, even though it is only the fourth most common ex situ technology (see Figure 5). That high percentage is most likely the result of the length of time required for bioremediation, compared with other ex situ technologies. For bioremediation, which enhances the ability of microorganisms to degrade contaminants, the time required to reach cleanup goals often is limited by the natural degradation process. The rate of degradation also varies depending on the contaminant. Other factors such as temperature and moisture, which are influenced by the weather, play a large role in determining the degradation rate for bioremediation. Because of those considerations, treatment by bioremediation typically requires a longer period of time than other ex situ technologies, such as incineration, thermal desorption, or solidification/ stabilization, for which the treatment rate is limited primarily by the capacity and throughput of the equipment used.

Among in situ technologies, SVE represents the largest number of projects. About 80 percent of the SVE projects are in the operational or completed phase. Among in situ groundwater treatment projects, air sparging is the most frequently selected technology.

Table 1. Superfund Remedial Actions: Project Status of Treatment Technologies (FY 1982 - FY 1999)

Technology	Predesign/ Design	Design Complete/ Being Installed	Operational	Completed	Total
Ex Situ Source Control					
Solidification/Stabilization	31	7	13	86	137
Incineration (off-site)	6	2	7	79	94
Thermal Desorption	12	4	5	40	61
Bioremediation	10	1	24	14	49
Incineration (on-site)	1	0	1	40	42
Chemical Treatment	4	0	2	4	10
Neutralization	0	0	3	4	7
Soil Washing	2	1	1	2	6
Mechanical Soil Aeration	0	1	0	4	5
Soil Vapor Extraction	1	1	2	1	5
Solvent Extraction	2	1	0	1	4
Open Burn/Open Detonation	0	0	1	1	2
Vitrification	2	0	0	0	2
Physical Separation	0	0	0	1	1
Total	71	18	59	277	425
Percentage of Ex Situ Technologies	17%	4%	14%	65%	—
Percentage of All Source Control Technologies	10%	2%	8%	37%	58%
Percentage of All Treatment Technologies	9%	2%	7%	33%	51%
In Situ Source Control					
Soil Vapor Extraction	31	10	114	41	196
Solidification/Stabilization	15	3	5	23	46
Bioremediation	9	3	20	3	35
Soil Flushing	6	0	9	1	16
Thermally Enhanced Recovery	3	0	2	1	6
Chemical Treatment	3	1	0	1	5
Phytoremediation	2	1	2	0	5
Dual-Phase Extraction	0	2	1	0	3
Electrical Separation	0	1	0	0	1
Vitrification	0	0	0	1	1
Total	69	21	153	71	314
Percentage of In Situ Technologies	22%	6%	49%	23%	—
Percentage of All Source Control Technologies	9%	3%	21%	10%	42%
Percentage of All Treatment Technologies	8%	3%	18%	9%	38%
In Situ Groundwater					
Air Sparging	12	1	32	3	48
Bioremediation	4	0	16	1	21
Dual-Phase Extraction	0	0	9	1	10
Permeable Reactive Barrier	2	2	4	0	8
Phytoremediation	3	0	1	0	4
Chemical Treatment	1	0	1	0	2
In-Well Air Stripping	1	0	1	0	2
Total	23	3	64	5	95
Percentage of Groundwater Technologies	24%	3%	67%	5%	—
Percentage of All Technologies	3%	0%	8%	1%	11%
TOTAL FOR ALL TREATMENTS	**163**	**42**	**276**	**353**	**834**
PERCENTAGE OF TOTAL FOR ALL TREATMENTS	**20%**	**5%**	**33%**	**42%**	**—**

Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

The HTML version of the tenth edition of the ASR includes a downloadable spreadsheet to help site managers, the regulated community, and remediation professionals identify sites at which particular treatment technologies are being employed and the status of those projects. The spreadsheet contains information for each site tracked in the ASR, including the site name, location, treatment technology, and treatment status. The spreadsheets can be used by RPMs, OSCs, remediation professionals, and the public to identify the sites using a particular technology and obtain current implementation status for those sites. One potential benefit will be to allow RPMs, OSCs, and remediation professionals to identify sites similar to their own that are in a similar implementation phase, and assist in technology transfer between those sites. The HTML version of the ASR can be found at *http:\\clu-in.org\asr*.

Contaminants Addressed

The data collected for this report form the basis for an analysis of the classes of contaminants treated by each technology type at remedial action sites. Table 2 provides that information, by technology, for nine major groups of contaminants.

For this report, compounds are categorized as halogenated VOCs, SVOCs, or PAHs according to the lists provided in EPA's SW-846 test methods

Table 2. Superfund Remedial Actions: Contaminants Treated by Technology Type (FY 1982 - FY 1999)

Technology	Halogenated Volatile Organic Compounds	Benzene, Toluene, Ethylbenzene and Xylene	Metals	Halogenated Semivolatile Organic Compounds (a)	Non-Halogenated Semivolatile Organic Compounds (b)	Non-Halogenated Volatile Organic Compounds (c)	Polycyclic Aromatic Hydrocarbons	Organic Pesticides and Herbicides	Polychlorinated Biphenyls
Air Sparging	36	20	0	1	4	3	3	1	0
Bioremediation	19	38	2 (d)	8	39	25	42	28	1
Chemical Treatment	3	1	8 (e)	4	0	2	1	3	3
Dual-Phase Extraction	11	6	0	3	2	2	1	1	0
Electrical Separation	1	0	0	0	0	0	0	0	0
Incineration	48	29	2 (f)	63	37	23	22	32	38
Mechanical Soil Aeration	4	1	0	1	0	0	0	0	0
Open Burn/Open Detonation	0	0	0	0	1	0	0	0	0
Permeable Reactive Barrier	4	0	3	0	0	0	0	0	0
Physical Separation	0	0	0	0	0	0	0	1	0
Phytoremediation	3	2	1	0	0	0	0	1	0
Soil Flushing (In Situ)	8	6	4	4	5	5	3	1	0
Soil Vapor Extraction	171	91	0	24	25	31	12	2	2
Soil Washing	0	0	3	1	1	0	1	1	1
Solidification/Stabilization	15	7	155	35	13	11	11	12	30
Solvent Extraction	2	0	0	3	1	1	1	0	3
Thermal Desorption	29	20	0	20	13	12	14	9	12
Thermally Enhanced Recovery (in situ)	2	2	0	0	0	0	4	2	0
Vitrification	2	1	0	2	0	0	0	0	1
In-Well Air Stripping	2	1	0	0	0	1	0	0	0
TOTAL PROJECTS	360	225	166	169	141	116	115	94	91

(a) Does not include halogenated semivolatile pesticides and herbicides.
(b) Does not include polycyclic aromatic hydrocarbons.
(c) Does not include benzene, toluene, ethylbenzene, and xylene.
(d) Bioremediation of hexavalent chromium. Biological activity resulted in an environment which reduced hexavalent chromium to a trivalent state.
(e) Chemical reduction of hexavalent chromium to a trivalent state.
(f) Incineration of organics with high tempertaure metals recovery of lead or mercury.
Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

8010, 8270, and 8310, with the exceptions noted above. Overall, approximately 80 percent of the Superfund remedial projects address organics, with slightly more than 20 percent of projects addressing metals. The number of projects in Table 2 exceeds the total number of projects in Table 1 because some projects involve more than one type of contaminant. Such projects are therefore listed in Table 2 a number of times, once for each contaminant type.

The selection of a treatment technology for a site often depends on the physical and chemical properties of the contaminants at the site. For example, VOCs are amenable to treatment by certain technologies, such as SVE, because of their volatility. In other cases, metals, which are not volatile and do not degrade, are not amenable to treatment by SVE, thermal desorption, or bioremediation. However, because metals form insoluble compounds when combined with appropriate additives, such as Portland cement, solidification/stabilization is most often used for treatment of those contaminants.

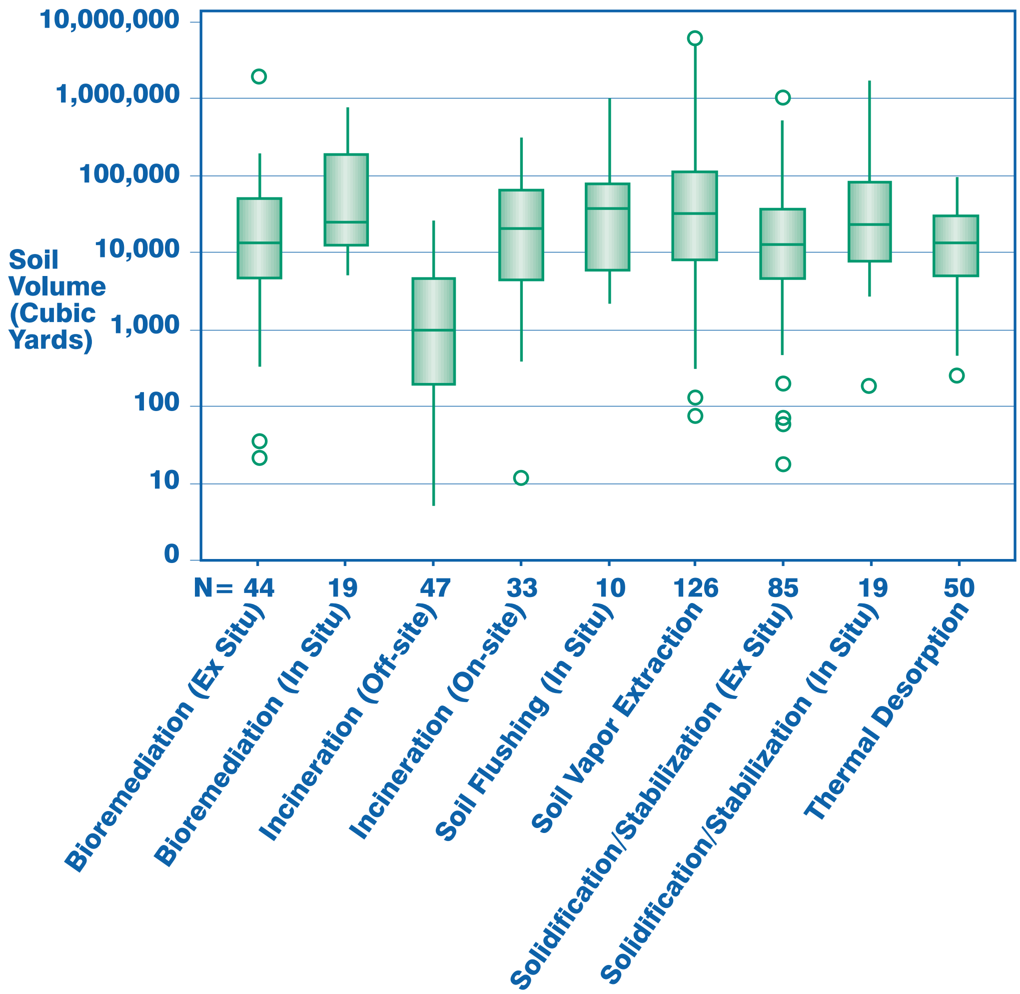
As Table 2 shows, halogenated VOCs, BTEX, and non-halogenated VOCs are being treated most often by SVE. Non-halogenated SVOCs and PAHs are being treated most often by bioremediation. PCBs and halogenated SVOCs are being treated most often by incineration. Metals are being treated almost exclusively by solidification/stabilization.

Table 3. Superfund Remedial Actions: Estimated Quantities of Soil Treated by Source Control Technologies (FY 1982 - FY 1999)

Technology	Total Number of Projects	Number of Projects with Data	Quantity (cubic yards)[a] Minimum	Median[a]	Average	Maximum	Total Quantity
Ex Situ							
Bioremediation	49	44	21	14,000	77,000	1,900,000	3,400,000
Chemical Treatment	10	6	13,000	18,000	19,000	30,000	120,000
Incineration (off-site)	94	47	5	1,000	4,600	27,000	220,000
Incineration (on-site)	42	33	12	21,000	53,000	330,000	1,800,000
Mechanical Soil Aeration	5	2	2,100	NC	NC	12,000	14,000
Neutralization	7	1	3,500,000	NC	NC	3,500,000	3,500,000
Open Burn/Open Detonation	2	0	NC	NC	NC	NC	NC
Physical Separation	1	1	8,000	NC	NC	8,000	8,000
Soil Vapor Extraction	5	5	540	2,300	3,500	10,000	17,000
Soil Washing	6	6	6,400	13,000	41,000	180,000	250,000
Solidification/Stabilization	137	85	18	13,000	45,000	1,000,000	3,900,000
Solvent Extraction	4	4	7,000	NC	NC	20,000	49,000
Thermal Desorption	61	50	250	14,000	22,000	100,000	1,100,000
Vitrification	2	1	9,300	NC	NC	9,300	9,300
AVERAGE	—	—	273,000	12,000	33,000	550,000	1,100,000
TOTAL	425	285	—	—	—	—	14,000,000
In Situ							
Bioremediation	35	19	5,000	25,000	120,000	800,000	2,200,000
Chemical Treatment	5	3	2,600	NC	NC	41,000	55,000
Dual-Phase Extraction	3	1	100,000	NC	NC	100,000	100,000
Electrical Separation	1	1	1,000	NC	NC	1,000	1,000
Phytoremediation	5	2	11,000	NC	NC	60,000	71,000
Soil Flushing	16	10	2,000	37,000	140,000	1,000,000	1,400,000
Soil Vapor Extraction	196	126	75	32,000	220,000	6,100,000	27,000,000
Solidification/Stabilization	46	19	180	24,000	300,000	1,900,000	2,800,000
Thermally Enhanced Recovery	6	3	200	NC	NC	1,000	1,500
Vitrification	1	1	4,600	NC	NC	4,600	4,600
AVERAGE	—	—	13,000	30,000	200,000	1,000,000	3,400,000
TOTAL	313	185	—	—	—	—	34,000,000
AVERAGE FOR ALL TECHNOLOGIES			**160,000**	**18,000**	**87,000**	**740,000**	**2,100,000**
TOTAL FOR ALL TECHNOLOGIES	**738**	**470**					**48,000,000**

Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.
NC = Not calculated
(a) The median and average values were not calculated for technologies for which data on soil treatment volumes are available for fewer than five projects.

Figure 12. Superfund Remedial Actions: Box-and-Whiskers Plot of Cubic Yards of Soil Treated (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Quantity of Soil Addressed

EPA analyzed the quantity of soil addressed by the various treatment technologies, and the results of this analysis are shown in Table 3. Data on the quantity treated are available for 185 in situ projects and 285 ex situ projects for which source control treatment technologies were selected to treat soil. Typically, in situ technologies are used to address larger quantities of soil, while ex situ technologies are used to treat smaller quantities. Because quantities for in situ projects often cannot be determined accurately and many projects have not been completed, the quantities in Table 3 should be considered estimates.

For ex situ technologies, the median volume of soil treated per project ranged from approximately 1,000 cubic yards (cy) for off-site incineration to 21,000 cy for on-site incineration. After on-site incineration, chemical treatment had the next highest median (18,000 cy), followed by bioremediation and thermal desorption (both with 14,000 cy). For in situ technologies, the median volume of soil treated per project ranged from 24,000 cy (solidification/stabilization) to 37,000 cy (in situ soil flushing).

The volume of soil treated by the nine technologies for which data on soil volume were available for at least 10 projects were plotted for comparison purposes. Figure 12 presents a box-and-whiskers plot of the volume of soil treated by technology type. Because of the wide range in volumes of soil treated, the soil volumes are plotted on a logarithmic scale.

Presentation of data in the box-and-whiskers format is useful because it shows how the data are distributed by displaying the median, 25th, and 75th percentiles, as well as the largest and smallest nonoutlier values. In a box plot, the 25th and 75th percentiles are shown as the ends of the box. The largest and smallest nonoutlier values are shown by the lines that extend from the ends of the box, which are known as the "whiskers." Outliers represent values that are between one-and-one-half and three box lengths from the top or bottom of the box. Extreme values are more than three box lengths from the top or bottom of the box. Outliers and extreme values are depicted on Figure 12 by circles.

With the exception of off-site incineration, the median volume of soil treated for all technologies falls between 10,000 and 100,000 cy. The range of values, as shown by the length of the box and whiskers, was much greater for SVE than for all other technologies. The 75th percentile value for SVE, bioremediation (in situ), and solidification/stabilization (in situ) is about 100,000 cy, indicating that the volume being treated by these technologies was about 100,000 cy for 25 percent of the projects for which data were available. That finding indicates that those technologies are applicable to sites at which very large volumes of soil require treatment.

By comparing similar technologies that can be conducted both in and ex situ, the box plot reaffirms that in situ technologies are typically used to treat larger volumes of soil. As Figure 12 shows, the median and range of volumes of soil per project for in situ bioremediation were greater than those for ex situ bioremediation. The range of soil volumes for in situ bioremediation also appeared to indicate that it may be more applicable to projects for which large volumes of soil require treatment.

Similarly, the median and range for volume of soil per project for in situ solidification/stabilization were a little greater than those for ex situ solidification/stabilization. However, the range of soil volumes treated for in situ solidification/stabilization appeared to be limited to large projects, while ex situ solidification/stabilization treatments were applied to a wider range of soil volumes.

Volumes of Soil Treated in Trains

In some cases, two or more innovative and established technologies may be used together in treatment trains, which are either integrated processes or a series of treatments that are combined in sequence to provide the necessary treatment. Some treatment trains are employed when no single technology is capable of treating all the contaminants in a particular medium. For example, soil contaminated with organics and metals may be treated first by bioremediation to remove organics and then by solidification/stabilization to reduce the leachability of metals. In other cases, a treatment train might be used to render a medium more easily treatable by a subsequent technology, reduce the amount of waste that requires further treatment by a subsequent and more expensive technology, or minimize the overall cost of the treatment.

The sites at which treatment trains were used and for which data are available on the volume of soil treated by each technology in the treatment train are shown in Figure 13. The figure does not display data for trains where data are available for only one technology in the train. At nine sites where treatment trains were used, the volume of soil treated by each technology in the train remained the same.

At two sites, the volume of soil subjected to subsequent treatment steps decreased by 20 and 50 percent. The initial technologies used in those treatment trains were solvent extraction and physical separation, respectively. The data indicate that the use of solvent extraction in a treatment train may reduce the volumes of soil that require treatment in subsequent unit operations of the train. In this project, solvent extraction was applied to remove PCB's and solidification/stabilization was applied to treat metals. The purpose of the physical separation treatment technology is to concentrate contaminants into smaller volumes.

At the Petro-Chemical Systems site, thermally enhanced recovery is being used to treat 330 cy of soil followed by SVE of 300,000 cy of soil. At this site, the thermally enhanced recovery unit is treating areas contaminated with NAPL and areas with high contaminant concentrations. The thermally enhanced recovery is expected to treat these areas more quickly and effectively than SVE.

A detailed discussion of the use of treatment trains that include innovative technologies is contained in Section 3: Innovative Applications, Treatment Trains, on page 30.

Cumulative Soil Treatment Volumes

For each technology type, Figure 14 shows the percentage of soil volume being treated. As Figure 14 shows, a majority of the soil volume is treated by SVE. As Figure 5 shows, SVE is also the most frequently selected technology. Figure 12 shows that SVE is the selected technology for projects for which the largest volumes of soil require treatment. Those factors explain the large fraction of soil being treated by this technology. Figure 14 is based on the 63 percent of source control treatments at Superfund remedial action sites where soil treatment data are available.

Binders Used for Solidification/Stabilization

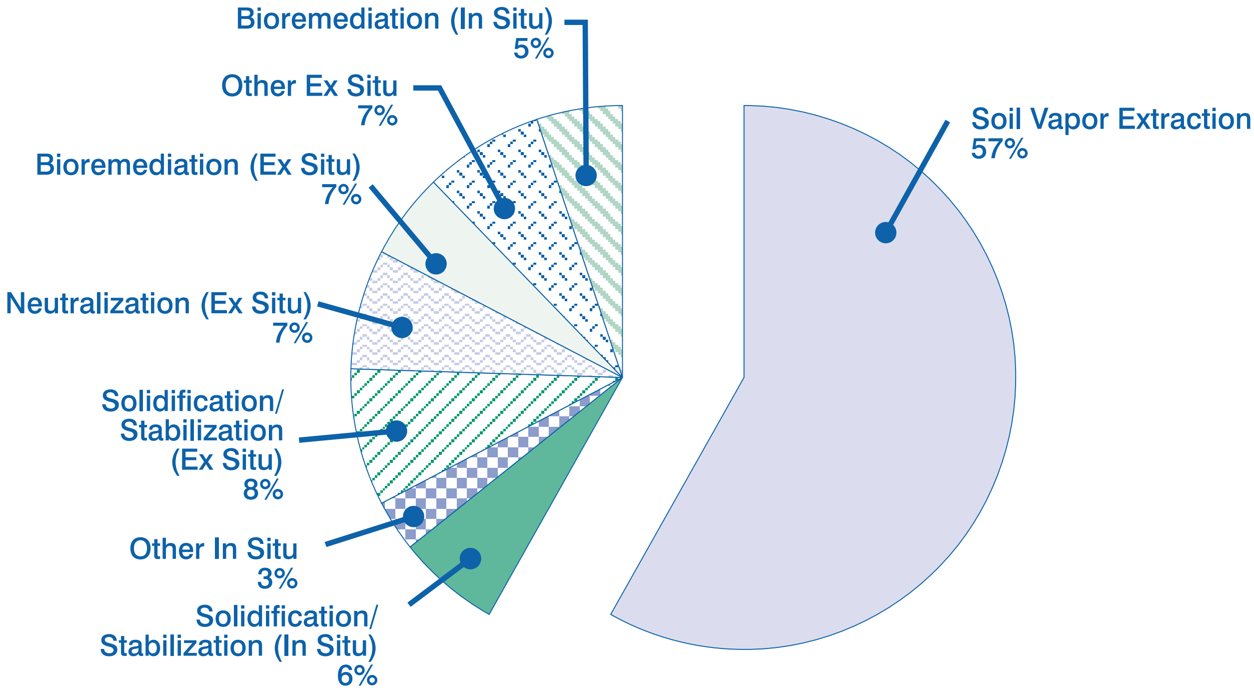
The term "solidification/stabilization" is generic and is applied to a wide range of discrete technologies that are closely related in that both use chemical and physical processes to treat a wide

Figure 13. Superfund Remedial Actions: Cubic Yards of Soil Treated by Treatment Trains (FY 1982 - FY 1999)

	First Treatment Technology		Second Treatment Technology		Third Treatment Technology
Myers Property	Soil Washing 26,000	and	Thermal Desorption 26,000	and	Chemical Treatment 26,000
Smith's Farm	Thermal Desorption 21,000	and	Chemical Treatment 21,000		
Gulf Coast Vacuum Services	Bioremediation (ex situ) 21,000	and	Solidification/Stabilization 21,000		
Macgillis and Gibbs/Bell Lumber and Pole	Chemical Treatment 14,000	and	Bioremediation (ex situ) - Biopile 14,000		
Arctic Surplus	Solvent Extraction 13,000	and	Solidification/Stabilization 10,000		
FCX - Statesville	Thermal Desorption 14,000	and	Chemical Treatment 14,000		
Arkwoodl, Inc.	Physical Separation 8,000	and	Incineration (off-site) 3,500		
Petro-Chemical Systems, Inc. - OU 2	Thermally Enhanced Recovery 330	and	Soil Vapor Extraction 300,000		
Idaho National Engineering Laboratory	Solvent Extraction 9,300	and	Vitrification 9,300		
Jadco-Hughes Facility	Soil Vapor Extraction 7,400	and	Soil Flushing (In Situ) 7,400		
Cabot/Koppers - Koppers OU	Soil Washing 6,400	and	Bioremediation (Ex Situ) - Bioslurry 6,400		
Palmetto Wood Preserving	Chemical Treatment 13,000	and	Solidification/Stabilization 13,000		

Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Figure 14. Superfund Remedial Actions: Percentage of Soil Treated by Technology Type (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

variety of wastes, both solid and liquid. Solidification refers to techniques that encapsulate the waste, forming a solid material, and does not necessarily involve a chemical interaction between the contaminants and the solidifying additives. Stabilization refers to techniques that chemically reduce the hazard potential of a waste by converting the contaminants into less soluble, mobile, or toxic forms. Stabilization usually involves mixing a contaminated medium, such as soil or sludge, with agents such as Portland cement, lime, fly ash, cement kiln dust, or polymers to create a slurry, paste, or other semiliquid state. The mixture then is allowed time to cure into a solid form. The solidification process also may include the addition of iron salts, silicates, clays, or pH adjustment agents to enhance the setting or curing time, increase the compressive strength of the solidified waste, or reduce the leachability of contaminants.

At Superfund sites, solidification/stabilization has been implemented, or currently is planned for use, 183 times, 137 times as an ex situ treatment and 46 times as an in situ treatment. Solidification/stabilization is the most frequently occurring ex situ treatment technology (see Table 1).

Data on the binders used at solidification/stabilization sites is available for 49 percent of the 183 solidification/stabilization projects. Table 4 shows the types of binders and reagents used.

Table 4. Superfund Remedial Actions: Binders and Reagents Used for 90 Solidification/Stabilization Projects (FY 1982 - FY 1999)

Binder or Reagent	Number of Projects
Cement	50
Proprietary Additives	22
Other Inorganic	20
Phosphate	14
pH Buffering Agents(a)	11
Lime	10
Other Organic	6
Asphalt	4
Sulfur	4
TOTAL	141

(a) pH buffering and adjustment agents, such as sodium hydroxide, are sometimes added during stabilization processes to decrease post-treatment contaminant leachability.

Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

They include cement, phosphate, lime, pH buffering agents, asphalt, sulfur, other inorganic components, proprietary additives, other organic components, and other inorganic components. Other organics and other inorganics are binders and reagents that do not fall under the other groupings, such as polymers, iron salts, silicates, and clays. Proprietary additives are those that are considered trade secrets and were not identified further. The most commonly used binder or reagent was cement, followed by proprietary additives, other inorganics, and phosphate. Each solidification/stabilization project may use more than one reagent.

Solidification/stabilization is used most commonly to treat media contaminated with metals (see Table 2). Cement, other inorganics, phosphates, and lime are probably the most commonly used solidification/stabilization additives because they often are used in the solidification/stabilization of metals.

Additional information on the application of solidification/stabilization can be found on the CLU-IN website at *http://www.clu-in.org*. In addition to HTML and PDF versions of this document, the CLU-IN website contains the following recently published documents on solidification/stabilization:

- Solidification/Stabilization Resource Guide. U.S. EPA: Office of Solid Waste and Emergency Response. EPA 542-B-99-0032. 1999.
- Solidification/Stabilization Use at Superfund Sites. U.S. EPA: Office of Solid Waste and Emergency Response. EPA-542-R-00-010. 2000.

Remedy Changes

As indicated in Section 1, remedies selected for Superfund remedial actions are documented through a ROD. When a remedy is changed, the change can be documented through another ROD, a ROD amendment, or an ESD. A ROD amendment also can be used to add a new remedy. In some cases, a decision document is not necessary to document a change if the new remedy was included in the original ROD as a contingency. Remedy changes often occur during the pre-design or design phase of a project when new information about site characteristics is discovered or treatability studies for the selected technologies are completed.

Many of the treatment remedies that were modified involved a change from a source control treatment remedy to a remedy that is not a source control treatment remedy. Source control treatment remedies have been changed to non-treatment remedies at over 100 Superfund remedial action sites. These remedies are often changed to source control containment, groundwater pump-and-treat, monitored natural attenuation, or institutional controls. The most commonly cited reason for changing a source control remedy to another type of remedy was that further site investigation revealed that the concentration or extent of contamination was less than expected. Other frequently cited reasons included rising groundwater levels making soil treatment impracticable, community concerns about on-site remedies, and high costs. The Superfund program allows EPA and state environmental regulators the flexibility to modify remedies as site conditions change. The frequency of remedy changes suggest that regulatory officials are using that flexibility.

In 81 instances, one source control or in situ groundwater treatment technology was replaced with another treatment technology. Table 5 provides information about the most frequently changed treatment technologies, and the technologies that replaced them, as indicated by cumulative data from FY 1982 through FY 1999.

The technologies that were most frequently changed to another technology were incineration, bioremediation (both in-situ and ex-situ bioremediation), and thermal desorption. Those technologies are the third, fourth, and fifth most frequently selected treatment technologies (see Figure 5). Table 5 shows the technologies that replaced 26 incineration treatments, 13 bioremediation treatments, and 12 thermal desorption treatments. Incineration was replaced by other commonly selected treatment technologies, including thermal desorption (9

Table 5. Superfund Remedial Actions: Number of Most Commonly Changed Technologies (FY 1982 - FY 1999)

New Treatment Technology	Technology Initially Selected: Incineration	Bioremediation	Thermal Desorption
Thermal Desorption	9	4	–
Solidification/ Stabilization	6	1	0
Bioremediation	5	–	0
Soil Vapor Extraction	5	2	5
Solvent Extraction	1	0	0
Incineration	–	5	5
Air Sparging	0	1	0
Chemical Treatment	0	0	1
Soil Washing	0	0	1
TOTAL NUMBER OF REMEDY REVISIONS	26	13	12

Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

projects), solidification/stabilization (6 projects), bioremediation (5 projects), and SVE (5 projects). Bioremediation also was replaced by other commonly selected treatment technologies, including incineration (5 projects) and thermal desorption (4 projects). Thermal desorption was replaced by other commonly selected treatment technologies, including incineration (5 projects) and SVE (5 projects).

Previous editions of the ASR included an appendix that listed all the technology changes, additions, and deletions made since the previous edition of the ASR. The printed version of the tenth edition of the ASR no longer includes that appendix. However, the on-line version, which can be accessed at *http://clu-in.org/asr*, includes a revised version of that appendix.

Section 3: Innovative Applications

This section discusses innovative treatment technologies for source control. In the Overview, innovative technologies were defined as alternative treatment technologies whose limited number of applications result in a lack of data on cost and performance. In general, a treatment technology is considered innovative if it has had limited full-scale application. Innovative technologies are used for a variety of reasons, and have the potential for providing more cost-effective and reliable alternatives for cleanup of contaminated soils and groundwater.

In some cases, it may be difficult to treat a particular waste or medium using an established technology. For example, soil containing a high percentage of large particle sizes, such as cobbles, boulders, and large debris, may be difficult to treat using ex situ thermal desorption because many thermal desorption units have limitations on the size of materials that can pass through them. However, in situ bioremediation may effectively treat the soil regardless of its particle size distribution. In other cases, an innovative technology may be less expensive than an established technology. It may be expensive to treat soils deep below the ground surface by incineration because of the amount of excavation required to reach the soil. However, a thermally enhanced recovery process may work effectively at that depth, resulting in a lower cost. Other reasons for selecting innovative technologies can include reduction in the exposure of workers to contaminated media; reduction in costs for excavation and materials handling (in situ technologies); and community concern about off-site releases of contaminants, noise, or smell.

In the ninth edition of the ASR, SVE and thermal desorption, formerly defined as innovative, were categorized as established because of the large number of applications of those technologies. In addition, several reports and case studies were published documenting their cost and performance. In the tenth edition, no changes in technology classifications are made.

The Federal Remediation Technologies Roundtable (FRTR) has published more than 200 case studies covering a wide range of treatment technologies that are available for viewing online or downloading from the FRTR web site at *http://www.frtr.gov*. Of those case studies, 27 discuss SVE and 12 discuss thermal desorption. The case studies were developed by EPA, DoD, and DOE. The case studies and abstracts present available cost and performance information for full-scale remediation efforts and several large-scale demonstration projects. They provide information about site background and setting, contaminants and media treated, technology, cost and performance, and points of contact for the technology application. The levels of detail provided in the studies vary, reflecting differences in the availability of data and information.

The FRTR website also contains the North American Site Demonstrations Database and Reports. This resource contains information on demonstrations of site remediation treatment technologies in North America, and can be accessed at *http://www.frtr.gov/northa/scrguide.htm*.

Although SVE and thermal desorption are no longer included in the innovative category, there are several innovative enhancements or adaptations of those technologies. For example, SVE can be enhanced by pneumatic fracturing or a variety of thermal methods. Additional information about enhancements for SVE systems is presented in EPA's *Soil Vapor Extraction (SVE) Enhancement Technology Resource Guide* (EPA-542-B-95-003) and EPA's *Analysis of Selected Enhancement for Soil Vapor Extraction* (EPA-542-R-97-007), available at *http://clu-in.org*.

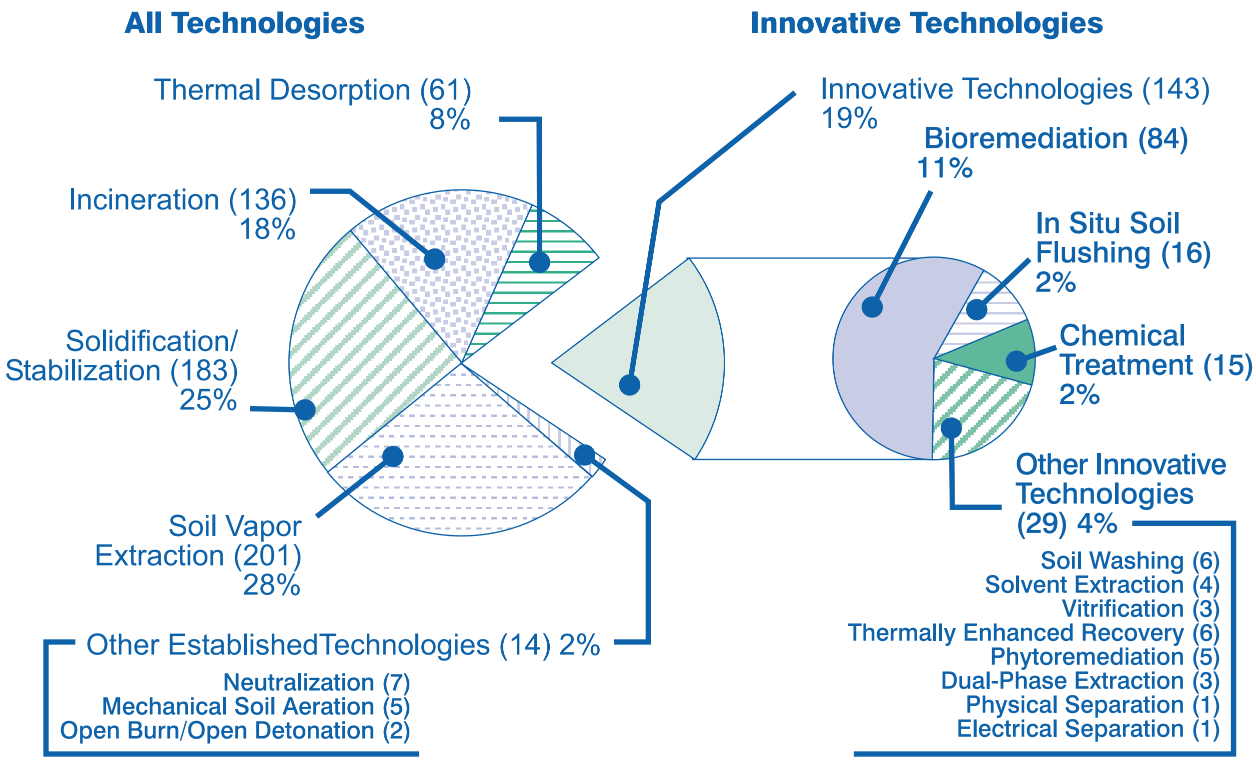
For source control treatment, Figure 15 depicts the number and types of innovative and established technologies used. As shown, innovative treatment technologies represent approximately 20 percent of all technologies used for source control. Bioremediation represents most of the innovative applications (84). Soil flushing (in situ) and chemical treatment are the second and third most frequently selected innovative technologies. Innovative technologies being used for fewer than nine projects at Superfund sites are listed under the other innovative technology category, a total of 8 technologies and 29 applicaitons.

The remainder of this section discusses two innovative treatment technologies in depth, bioremediation and phytoremediation, and describes current experiences in jointly applying several treatment technologies, i.e., treatment trains. Bioremediation is the most frequently applied innovative technology. Phytoremediation is a technology for which there are relatively few, but a rapidly increasing number, of applications. The use of a treatment train can render sites with multiple contaminants or media that are difficult to treat more amenable to treatment.

Bioremediation

Bioremediation uses indigenous or inoculated microorganisms (that is, fungi, bacteria, or other

Figure 15. Superfund Remedial Actions: Innovative Applications of Source Control Treatment Technologies (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

microbes) to degrade (metabolize) organic contaminants found in soil or groundwater. Frequently, bioremediation techniques enhance the activity of the microorganisms and subsequent contaminant degradation through the use of nutrients or, in aerobic bioremediation, oxygen, or by controlling temperature and pH.

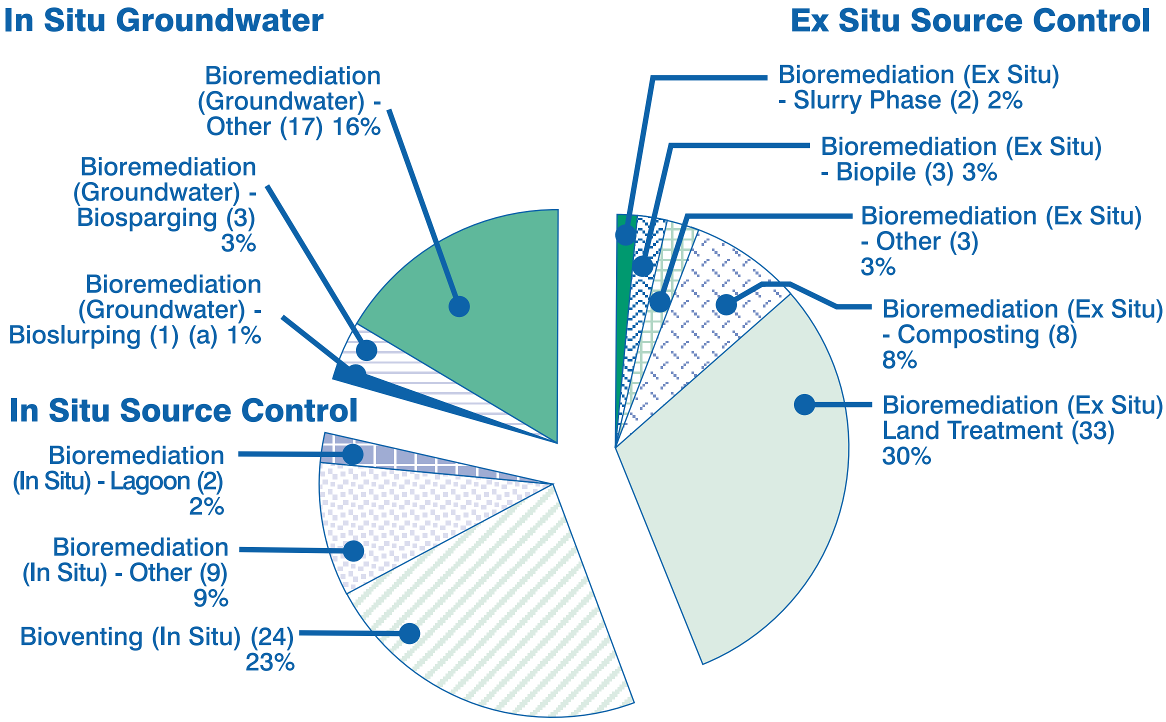
Bioremediation may occur through either aerobic or anaerobic processes. The former involves the conversion of contaminants, in the presence of sufficient oxygen, to carbon dioxide, water, and microbial cell mass. The latter involves the metabolism of contaminants, in the absence of oxygen, to methane, limited amounts of carbon dioxide, and trace amounts of hydrogen gas. Under sulfate-reducing conditions, sulfate may be converted to sulfide or elemental sulfur. Under nitrate-reducing conditions, dinitrogen gas ultimately is produced.

Bioremediation can be conducted in situ or ex situ. The information about bioremediation presented here includes its use on soil, sediment, sludge, or other solid media, both in situ and ex situ, as well as on groundwater in situ. Examples of in situ processes include bioventing and in situ groundwater bioremediation. Bioventing systems deliver air from the atmosphere into the soil above the water table through injection wells placed in contaminated areas, while in situ groundwater bioremediation involves engineering of subsurface conditions to induce or accelerate biodegradation of contaminants in an aquifer.

Examples of ex situ processes include slurry-phase treatment and composting. Slurry-phase treatment combines contaminated soil, water, and other additives under controlled conditions in "bioreactors," to create an optimum environment for microbial degradation. Composting involves mixing contaminant-laden waste with a bulking agent, such as straw or hay, to facilitate the delivery of optimum levels of air and water to the microorganisms.

Currently, 105 bioremediation projects have been, are currently being, or are planned to be implemented for source control and in situ groundwater treatment. Figure 16 shows the types of bioremediation for source control and in situ groundwater treatment. More than half (54 percent) of the bioremediation projects conducted at Superfund sites are in situ projects, and 34 percent are in situ source control projects. Bioventing is the most common type of bioremediation applied for in situ source control, with 24 remedies. Land treatment is the most common form of ex situ bioremediation, with 33 projects, followed by composting (8 projects).

Figure 16. Superfund Remedial Actions: Bioremediation Methods For Source Control and In Situ Groundwater Treatment (FY 1982 - FY 1999)



(a) Bioslurping can be used to treat both soil and groundwater. Reported data indicate that the one bioslurping project implemented at a Superfund remedial action site treated only groundwater.

Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

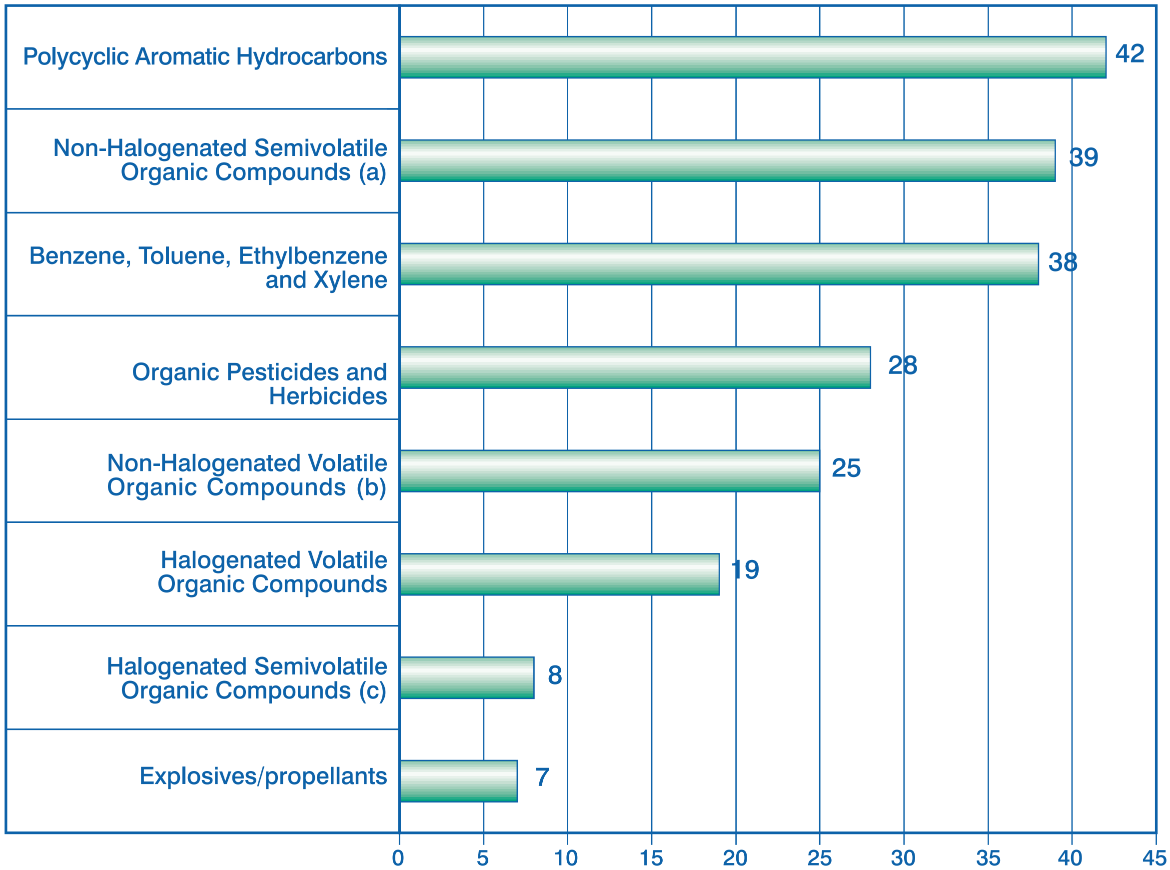
Contaminant groups treated by bioremediation are shown in Figure 17, which lists the number of projects at Superfund remedial action sites addressing each of eight groups of contaminants through bioremediation. At some sites, more than one contaminant group is addressed. Where contaminants may fall into more than one group, the groups have been limited to ensure that contaminants are not double counted in Figure 17. For example, some organic pesticides and herbicides are also non-halogenated SVOCs. However, the group "non-halogenated SVOCs" in Figure 17 does not include any chemicals that are in the "organic pesticides and herbicides" group.

The contaminant groups treated most often are PAHs, non-halogenated SVOCs (not including PAHs), and BTEX. The types of Superfund sites most commonly treated by bioremediation have been contaminated through processes or wastes associated with wood preserving and petroleum refining and reuse. Wood preserving commonly employs creosote, which has a high concentration of PAHs and other non-halogenated SVOCs. Similarly, petroleum refining and reuse processes frequently involve BTEX.

Because the two contaminant groups most commonly treated using bioremediation are SVOCs (PAHs and other non-halogenated SVOCs), it may be difficult to treat them using technologies that rely on volatility, such as SVE. In addition, bioremediation treatment often does not require heating, requires relatively inexpensive inputs, such as nutrients, and usually does not generate residuals requiring additional treatment or disposal. Also, when conducted in situ, it does not require excavation of contaminated media. Compared with other technologies, such as thermal desorption and incineration (which require excavation and heating), thermally enhanced recovery (which requires heating), chemical treatment (which may require relatively expensive chemical reagents), and in situ soil flushing (which may require further management of the flushing water), bioremediation may enjoy a cost advantage in the treatment of nonhalogenated SVOCs. Lower energy inputs are reflected in longer remmediation times, as discussed on page 15 and reflected in Table 1.

Additional information on the application of bioremediation can be found on the CLU-IN website at *http://www.clu-in.org*. In addition to HTML and PDF versions of this document, the CLU-IN website contains the following recently published documents on bioremediation:

Figure 17. Superfund Remedial Actions: Contaminant Groups Treated by Bioremediation (FY 1982 - FY 1999)



(a) Does not include polycyclic aromatic hydrocarbons.
(b) Does not include benzene, ethylbenzene, toluene, and xylene.
(c) Does not include organic pesticides and herbicides.
Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

- Engineered Approaches to In Situ Bioremediation of Chlorinated Solvents: Fundamentals and Field Applications. U.S. EPA: Office of Solid Waste and Emergency Response. EPA 542-R-00-008. 2000.
- The Bioremediation and Phytoremediation of Pesticide-contaminated Sites. Chris Frazar. National Network of Environmental Management Studies (NNEMS) Fellow. 2000.

Phytoremediation

Phytoremediation is the use of certain features of plants, such as their biological processes or physical characteristics, to remediate contaminated media. It encompasses a number of methods that can address a variety of contaminants and media.

Phytoremediation can be used either to contain, remove, extract, or destroy contaminants. Containment is achieved through phytostabilization, which immobilizes contaminants in soil. Removal and extraction techniques may include phytovolatilization, which is uptake and volatilization of the contaminant, or rhizofiltration, which is a process by which contaminants are adsorbed onto the roots of the plants. Destruction of the contaminant may be achieved through phytodegradation or rhizodegradation, the former being uptake and metabolism within the plant, and the latter being enhancement of biodegradation in the root zone.

For optimum effectiveness, the various forms of phytoremediation require different characteristics in the plants used. In general, terrestrial plants are more likely to be effective for phytoremediation than aquatic plants because their root systems are larger. Poplar and cottonwood trees commonly are used because they are fast-growing and have a wide geographic distribution. Examples of other types of vegetation used in phytoremediation include sunflower, Indian mustard, and grasses (such as ryegrass and prairie grasses).

Phytoremediation is a relatively new technology, for which there are only a few applications at Superfund sites. Table 6 lists nine Superfund

Table 6. Superfund Remedial Actions: Phytoremediation Projects (FY 1982 - FY 1999)

Site Name (Operable Unit)	Contaminants (Target Cleanup Levels)	Media Type (a)	Remediating Flora	Status
Aberdeen Pesticide Dumps (OU5)	Benzenehexachloride (NR) Dieldrin (NR) Hexachlorohexane (NR)	Groundwater	Hybrid Poplar Trees	Pre-design
Aberdeen Proving Grounds (Edewood Area, J-Field Soil OU)	1,1,2,2-Tetrachloroethene (NR) Trichloroethane (NR)	Soil and Groundwater	Hybrid Poplar Trees Magnolia Trees Silver Maple Trees	Operational
Boarhead Farm	Cadmium (5 ug/L, Groundwater) Nickle (100 ug/L, Groundwater) Benzene (0.5 mg/kg, Soil) Trichloroethene (0.4 mg/kg, Soil)	Soil and Groundwater	NR	Design
Bofors Nobel (OU1)	Benzene (NR)	Soil, Sludge, and Groundwater	NR	Pre-design
Calhoun Park Area (OU1)	Benzene (NR) Toluene(NR) Ethylbenzene (NR) Xylene (NR)	Groundwater	Hybrid Poplar Tress	Operational
Idaho National Engineering Laboratory (USDOE, OU 21)	Chromium (NR) Cesium-137 (NR) Mercury (NR) Selenium (NR) Silver (NR) Zinc (NR)	Soil	Prairie Cascade Willows Kochia Scoparia	Operational
Naval Surface Warfare Center, Dahlgren, Site 17	Mercury (<0.14 ug/L)	Soil and Groundwater	Hybrid Poplar Trees Evergreen Trees	Pre-design
Naval Undersea Warfare Station (4 Areas, OU1)	1,1,1-Trichloroethane (NR)	Groundwater	Poplar Trees	Operational
Tibbetts Road	Trichloroethene (NR)	Groundwater	Poplar Trees	Pre-design

NR - Not Reported
(a) Treatments including both soil and groundwater are classified as source control treatments in this report.
Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

remedial action projects for which data on phytoremediation are available. The technology is being applied to a variety of contaminants, including halogenated VOCs, BTEX, chlorinated pesticides, radionuclides, and metals. The most commonly used flora in phytoremediation projects are poplar trees, primarily because the trees are fast- growing and can survive in a broad range of climates. In addition, poplar trees can draw large amounts of water (relative to other plant species) as it passes through soil or directly from an aquifer. This may draw greater amounts of dissolved pollutants from contaminated media and reduce the amount of water that may pass through soil or an aquifer, thereby reducing the amount of contaminant flushed though or out of the soil or aquifer. In many cases, phytoremediation may have a cost advantage over other treatment technologies because it relies on the use of the natural growth processes of plants and often requires a relatively small investment in both capital and maintenance costs.

Additional information on the application of phytoremediation can be found on the CLU-IN website at *http://www.clu-in.org*. In addition to HTML and PDF versions of this document, the CLU-IN website contains four recently published documents on phytoremediation:

- An Overview of Phytoremediation of Lead and Mercury. Jeanna R. Henry. National Network of Environmental Management Studies (NNEMS) Fellow. 2000.
- Introduction to Phytoremediation. U.S. EPA: National Risk Management Research Laboratories. Office of Research and

Development. EPA 600-R-99-107. 2000.

- Phytoremediation Resource Guide. U.S. EPA: Office of Solid Waste and Emergency Response. EPA 542-B-99-003. 1999.
- The Bioremediation and Phytoremediation of Pesticide-contaminated Sites. Chris Frazar. National Network of Environmental Management Studies (NNEMS) Fellow. 2000.
- The Use of Plants for the Removal of Toxic Metals from Contaminated Soil. Mitch M. Lasat. American Association for the Advancement of Science; Environmental Science and Engineering Fellow. 2000.

Innovative Technology Treatment Trains

In some cases, more than one innovative or established technology may be used together in a treatment train, which is either an integrated process or a series of treatments that are combined in sequence to provide the necessary treatment. A more detailed description of treatment trains is presented in Section 2. Treatment trains that include one or more innovative technologies are the selected source control remedy at 28 Superfund sites. Figure 18 identifies specific treatment trains used in remedial actions.

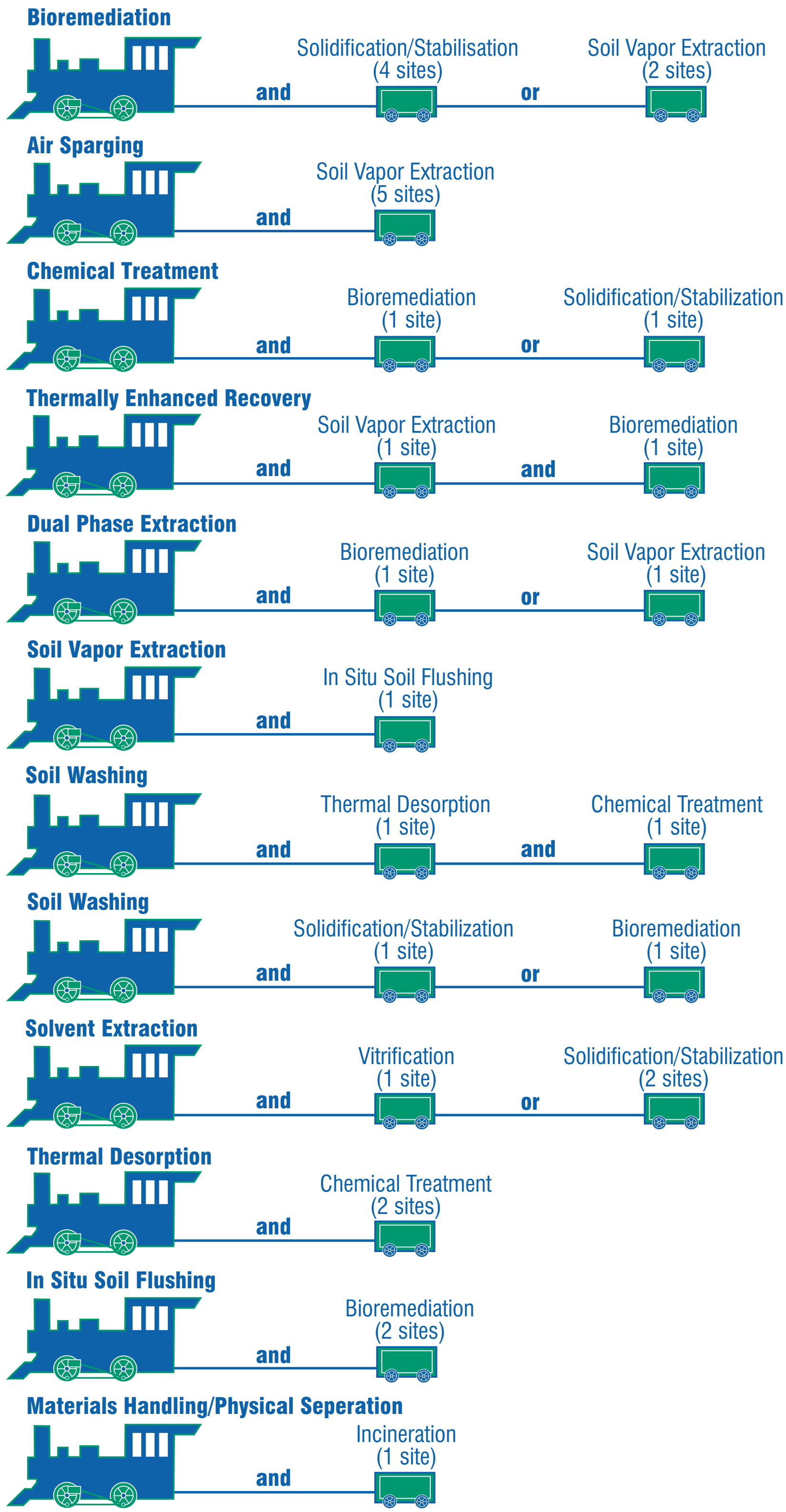
Innovative treatment technologies may be used with established technologies or with other innovative technologies. The most common treatment trains are air sparging used in conjunction with SVE and bioremediation followed by solidification/stabilization. Technologies may be combined to reduce the volume of material that requires further treatment, prevent the emission of volatile contaminants during excavation and mixing, or treat several contaminants in a single medium. In the case of air sparging used with SVE, the air sparging is used to remove contaminants from groundwater in situ, while the SVE captures the contaminants removed from the groundwater and removes contaminants from the soil above the groundwater (the vadose zone).

The treatment train of bioremediation followed by solidification/stabilization is used at Superfund sites for media contaminated by both organics and metals. The organic contaminants are remediated by bioremediation, while the leachability of the metals is reduced through solidification/stabilization.

This report documents 28 treatment trains that include innovative technologies. The ninth edition of the ASR documented 17 treatment trains. The increase is largely the result of classifying air sparging or bioslurping used in conjunction with SVE as a treatment train, as well as changes in or cancellations of some selected technologies. In previous editions, when air sparging or bioslurping was used in conjunction with SVE, only one technology was identified for the site. However, they are distinct technologies, are not always used together, and are applicable to different media (air sparging and bioslurping are applicable primarily to groundwater, while SVE is applicable primarily to soil).

A detailed discussion of the volumes of soil treated through treatment trains at Superfund remedial action sites is contained in Section 2: Treatment Technologies for Source Control, Volumes of Soil Treated in Treatment Trains on page 20.

Figure 18. Superfund Remedial Actions: Treatment Trains with Innovative Treatment Technologies (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Section 4: Groundwater Remedies

This section focuses on three groups of groundwater treatment remedies: conventional pump-and-treat systems, monitored natural attenuation (MNA), and in situ treatment. At least one of those groundwater remedies has been selected for 749 sites. Pump-and-treat systems alone were selected for 521 sites, MNA alone for 92 sites, and in situ groundwater treatment alone for 16 sites. When several types of groundwater remedies were used at the same site, a pump-and-treat approach was used most frequently with MNA (55 sites). Next in frequency was a pump-and-treat system with in situ treatment (48). In addition this section highlights more detailed information on the use of vertical engineered barriers (VEB) and permeable reactive barriers (PRB) at Superfund remedial action sites. VEBs are highlighted becuase of new developments in their applications. PRBs are highlighted because of their innovative use in the treatment of groundwater in situ.

The data in Figure 19 are presented on a site basis. At some sites, several applications of the same type of groundwater remedy may have occurred. At sites at which several types of groundwater remediation, such as a pump-and-treat system and in situ remediation were used, the remediation may not have occurred in the same aquifer or groundwater plume. Information about Superfund sites at which pump-and-treat and MNA remedies are in use was compiled from a variety of sources, including EPA's CERCLIS 3 database and RODs, ROD amendments, and ROD abstracts.

In Situ Groundwater Treatment

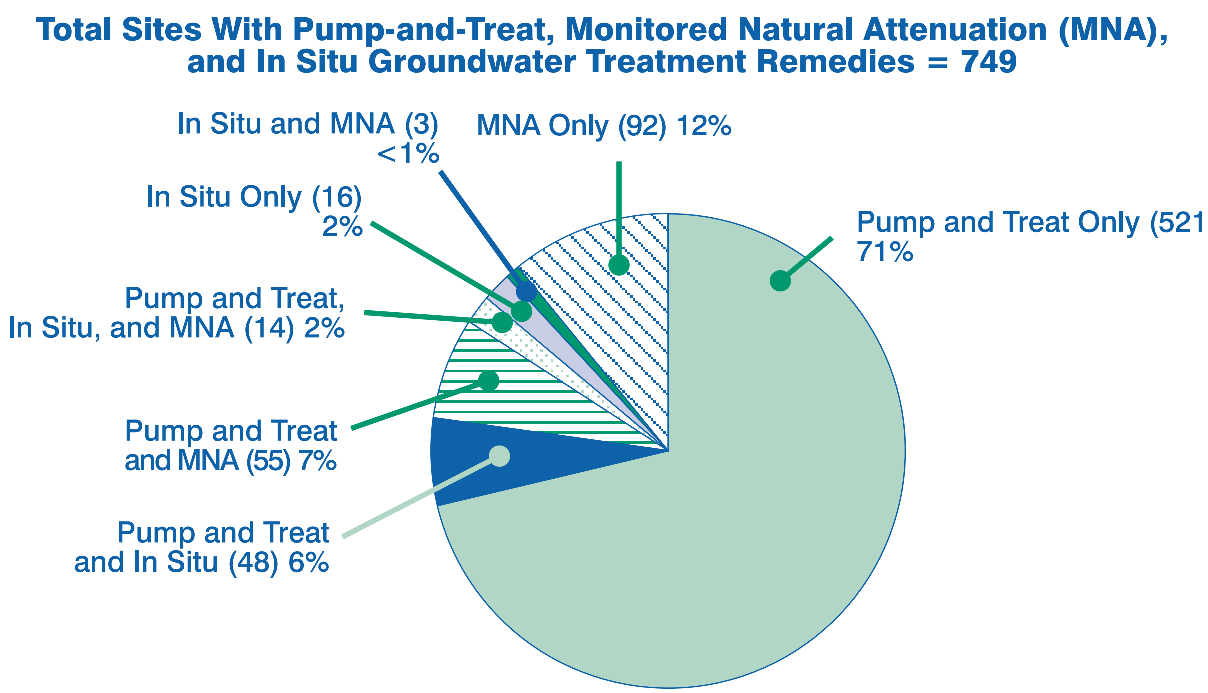
The specific types of in situ treatment remedies for groundwater selected at Superfund sites are listed in Table 7. EPA has selected in situ treatment of groundwater 95 times at 81 Superfund sites. Air sparging is the most frequently selected in situ groundwater treatment remedy, with 48 projects, followed by bioremediation with 21 projects.

Information on the status of in situ groundwater treatment projects is presented in Figure 11 and Table 1. Table 2 presents information on the types of contaminants addressed by in situ groundwater treatment remedies. Figure 16 presents information on the use of bioremediation for in situ groundwater treatment.

Vertical Engineered Barriers

A groundwater containment remedy, vertical engineered barriers (VEB), was selected at 51 Superfund remedial action sites. In the past, the ASR has not included information about

Figure 19. Superfund Remedial Actions: Groundwater Remedies (FY 1982 - FY 1999)



Sources: 1, 2, 3, 4, 5, 6, 8: Data sources are listed in the References and Data Sources section on page 38.

Table 7. Superfund Remedial Actions: In Situ Groundwater Treatment Technologies at 81 Sites Selecting These Technologies (FY 1982 - FY 1999)

Technology	Number of Projects Selected
Air Sparging	48
Bioremediation	21
Dual-Phase Extraction	10
Permeable Reactive Barrier	8
Phytoremediation	4
Chemical Treatment	2
In-Well Air Stripping	2
TOTAL	95

Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

VEBs because a VEB is not a treatment technology. However, it has been used to contain groundwater, and some innovative methods of constructing VEBs, such as deep soil mixing, and geosynthetic walls have been undertaken. Table 8 indicates the number of each type of VEB. The types of barriers are:

- Slurry wall - Consists of a vertical trench that is filled with a bentonite slurry to support the trench and is subsequently backfilled with a low-permeability material.
- Geosynthetic wall - Constructed by placing a geosynthetic liner into a trench.
- Grout - Constructed by grouting or jet-grouting soils to create a vertical grout curtain.
- Deep soil mixing - Overlapping columns created by a series of large-diameter, counter-rotating augers that mix in situ soils with an additive, usually bentonite, cement, or grout, which is injected through the augers.
- Sheet pile - Series of overlapping sheets of impermeable material, such as metal.

Table 8. Superfund Remedial Actions: Types of Vertical Engineered Barriers at 51 Sites Selecting This Technology (FY 1982 - FY 1999)

Vertical Engineered Barrier Type	Number of Barriers
Slurry Wall	44
Geosynthetic Wall	3
Grout	3
Deep Soil Mixing	2
Sheet Pile	2
Other - VEB	1
TOTAL	55

Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Definitions of barrier types are from *Evaluation of Subsurface Engineered Barriers at Waste Sites*, EPA OSWER, 542-R-98-005, August 1998, available on the internet at *http://clu-in.org*.

Overwhelmingly, slurry walls are the most frequently used type of barrier, with 44 applications. For each of the other types of VEBs, there are fewer than five applications at Superfund remedial action sites. The total number of barrier types (55) exceeds the total number of projects (51) because some projects use more than one type of barrier.

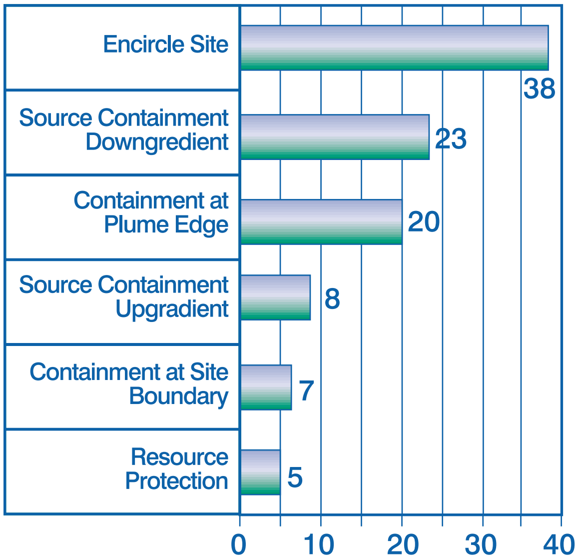
VEBs may be used for a variety of purposes, including:

- Preventing uncontaminated groundwater from flowing into a contaminated area (source containment upgradient)
- Stopping the migration of a contaminated groundwater plume at the edge of the plume (containment at plume edge)
- Completely encircling a site or subsurface contaminated area (encirclement of site)
- Preventing contaminated groundwater from flowing out of a contaminated area (source containment downgradient)
- Preventing a contaminated plume from migrating off site (containment at the boundary of the site)
- Protecting an environmentally sensitive feature, such as surface water or a drinking- water well, from a contaminated groundwater plume (resource protection)

Some VEBs can be used for multiple reasons (for example, a VEB that encircles a site and reaches an impermeable bed [that is, the aquitard] serves a number of the purposes listed above). In addition, at some sites, several VEBs are used; each may have one or more of those purposes. Figure 20 shows the number of VEB projects that were constructed for each of the reasons listed above. The most common purposes for which VEBs are used include encirclement of a site, as a source containment downgradient, and for containment at a plume edge.

Additional information on the application of VEBs can be found on the CLU-IN website at *http://www.clu-in.org*. In addition to HTML and PDF versions of this document, the CLU-IN website contains the following recently published document on VEBs: Subsurface Containment and Monitoring Systems: Barriers and Beyond. Leslie Pearlman. National Network of Environmental Management Studies (NNEMS) Fellow. 1999.

Figure 20. Superfund Remedial Actions: Purpose For Vertical Engineered Barriers (FY 1982 - FY 1999)



Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

Permeable Reactive Barriers

Permeable reactive barriers (PRBs) are installed across the path of a contaminated groundwater plume, allowing the plume to move passively through the barrier while contaminants are precipitated or degraded. PRBs may contain metal-based catalysts for degrading organics; chelators for immobilizing metals; or other reagents for degrading contaminants into less toxic compounds, precipitating contaminants, or otherwise rendering them less mobile.

PRBs may be constructed by excavating a trench of the appropriate width and backfilling it with a reactive medium. In some cases, the trench may be shored up with an appropriate slurry or steel sheet piling to keep the trench open during construction and to contain the reactive medium during operation. The sheet piling or slurry is not intended to present a barrier to groundwater flow, because the purpose of a PRB is to treat contaminants as the groundwater passes through the barrier.

Unlike VEBs, for which a soil-bentonite or cement-based slurry typically is used, it may be necessary to use a biodegradable polymer in installing a PRB to avoid the problem of plugging the barrier with residual slurry. PRBs also may be used in conjunction with VEBs, where VEBs guide groundwater flow into the PRB. That type of system is referred to as a funnel-and-gate system.

At superfund remedial action sites, PRBs are being used to treat metals, chlorinated VOCs, and cyanide. The most commonly used reactants include reducing agents such as zero-valent iron and strong bases such as calcium hydroxide, magnesium hydroxide, and crushed agricultural limestone. Through reductive reactions, zero-valent iron can dechlorinate organics and precipitate anions and oxyanions. Strongly basic reagents may reduce the solubility of metals or cause them to precipitate as metal hydroxides, such as converting chromium (Cr) +6 to insoluble Cr +3 hydroxides. Table 9 lists all eight Superfund remedial action sites at which PRBs are being implemented to treat groundwater.

Additional information on the application of PRBs can be found on the CLU-IN website at *http://www.clu-in.org*. In addition to HTML and PDF versions of this document, the CLU-IN website contains the following recently published documents on PRBs:

- Field Applications of Remediation Technologies: Permeable Reactive Barriers. U.S. EPA: Office of Solid Waste and Emergency Response. EPA 542-R-99-002. 2000.
- Permeable Reactive Barriers for Chlorinated Solvent, Inorganic, and Radionuclide Contamination. U.S. EPA: Office of Research and Development. U.S. EPA: Technology Innovation Office. 2000.
- Permeable Reactive Barriers for Inorganics. Nichole Ott. National Network of Environmental Management Studies (NNEMS) Fellow. 2000.

Monitored Natural Attenuation

Monitored natural attenuation (MNA) is the reliance on natural attenuation processes (within the context of a carefully controlled and monitored approach to site cleanup) to achieve site-specific remediation objectives within a time frame that is reasonable compared with that offered by more active methods. The "natural attenuation processes" that are at work in such a remediation approach include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. The in situ processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants.

EPA does not view MNA to be a "no action" approach, but rather considers it to be an alternative means of achieving remediation objectives that may

Table 9. Superfund Remedial Actions: Permeable Reactive Barrier Projects (FY 1982 - FY 1999)

Site Name (Operable unit)	Contaminants (Target Cleanup Levels)	Construction	Wall Material	Status
Arrowhead Associates/ Scovill Corporation	Chromium (NR) Cyanide (NR)	Trench	Zero-Valent Iron	Design
Brown's Battery Breaking Site	Beryllium ($1.9x10^{-4}$ mg/L) Cadmium ($8.8x10^{-4}$ mg/L) Lead (<0.003 mg/L) Manganese (0.05 mg/L) Nickle (0.0029 mg/L) Sulfate (0.027 mg/L)	Trench	Calcium Hydroxide Magnesium Hydroxide	Design
F.E. Wareen Air Force Base - OU2	Trichloroethene	NR	NR	Operational
Lake City Army Ammunition Plant (NW Lagoon) - OU3	1,1-Dichloroethene (0.007 mg/L)[a] Trichloroethene (0.005 mg/L)[a] Vinyl Chloride (0.002 mg/L)[a]	Funnel and Gate	Zero-Valent Iron	Operational
Monticello Mill Tailings (USDOE) - OU3	Arsenic (0.05 mg/L)[a] Molybdenum (0.183 mg/L)[b] Radium 226 (5 pCi/L)[a] Selenium (0.05 mg/L)[a] Uranium (1.1 mg/L)[b]	Funnel and Gate	Zero-Valent Iron	Operational
Rocky Flats Plant (USDOE) - Buffer Zone	Carbon Tetrachloride (NR) Tetrachloroethene (NR) Trichloroethene (NR)	Funnel and Gate	Zero-Valent Iron	Operational
Somersworth Sanitary Landfill	Trichlorethene (0.005 mg/L) Vinyl Chloride (0.005 mg/L)	Funnel and Gate	Zero-Valent Iron	Operational
Tonolli Corporation	Lead (NR) Cadmium (NR) Arsenic (NR) Zinc (NR) Copper (NR)	Trench	Limestone	Operational

NR - Not Reported
(a) - U.S. Federal Drinking Water Standards: Maximum Containment Levels, www.epa.gov/safewater/regs/cfr141.pdf
(b) - Residential Risk-Based Groundwater Cleanup Levels. Developed based on EPA Human Health Evaluation Manual, Part B: Development of Risk Based Preliminary Remediation Goals, *OSWER Directive 9285.7-01B, December 13, 1991.*
Sources: 3, 4, 5, 6: Data sources are listed in the References and Data Sources section on page 38.

be appropriate for specific, well-documented site circumstances where its use meets the applicable statutory and regulatory requirements. As with any other remedial alternative, MNA should be selected only where it meets all relevant remedy selection criteria, and where it will meet site remediation objectives within a time frame that is reasonable compared to that offered by other methods. MNA is commonly selected as part of an overall site remedy that includes remediation of groundwater contamination sources.

In recent years, an increasing number of RODs have specified MNA as a remedy for groundwater contamination. Figure 21 shows the number of RODs at which MNA was selected for groundwater remediation at Superfund remedial action sites. As the figure shows, selection of MNA increased steadily from FY 1985 through FY 1998. In FY 1998, MNA was selected as a remedy for 39 sites, but in FY 1999, the number of sites for which MNA was selected as a remedy decreased to 18.

EPA's Office of Emergency and Remedial Response (OERR) analyzed FY 1982 through FY 1997 RODs in which MNA was selected. Data on MNA for FY 1998 and FY 1999 were obtained from an analysis of RODs issued during those years.

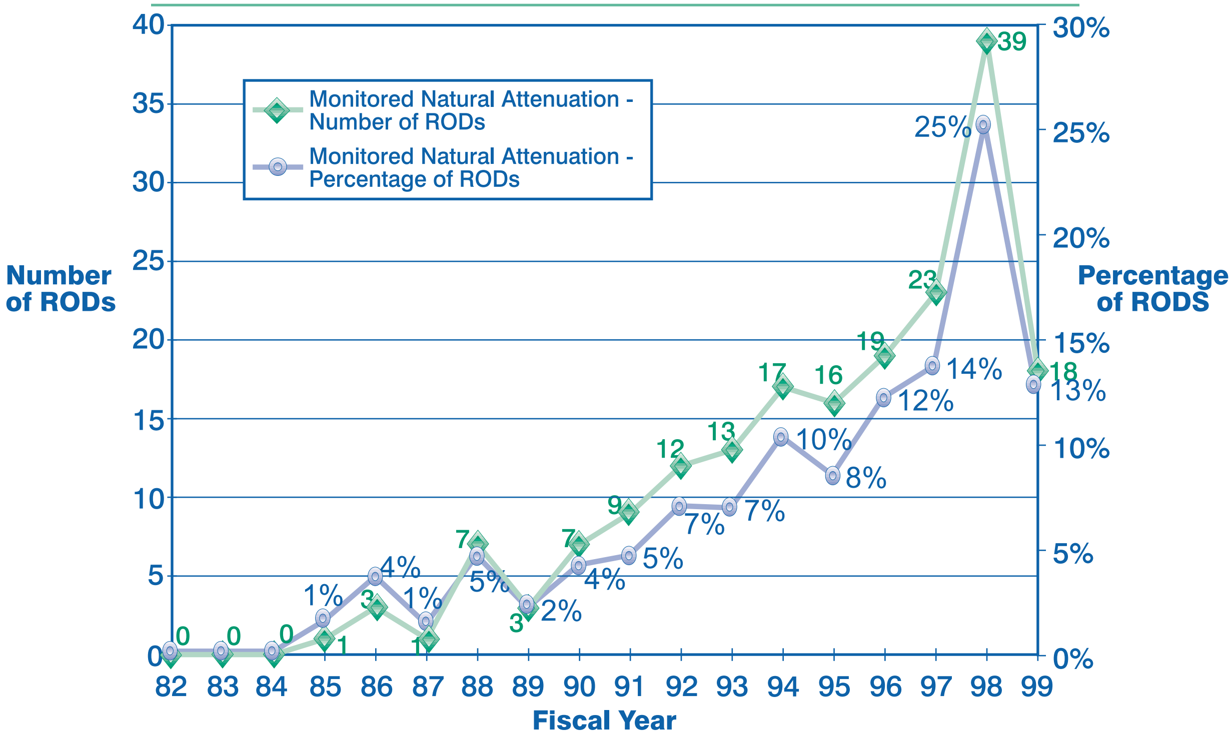
The analysis revealed that the most common reason cited for selecting MNA was low or decreasing concentrations of contaminants at the site. The analysis also indicated that the contaminant most frequently present at such sites was VOCs (including both chlorinated and non-chlorinated). Appendix E lists the RODs selecting natural attenuation.

EPA guidelines on the use of MNA to remediate groundwater can be found in *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites*, OSWER Directive Number 9200.4-17, which can be obtained by telephoning 800-424-9346 or 703-412-9810 or accessed on the Internet at *http://www.epa.gov/swerust1/directiv/d9200417.htm*.

Additional information on the application of MNA can be found on the CLU-IN website at *http://www.clu-in.org*. In addition to HTML and PDF versions of this document, the CLU-IN website contains the following recently published documents on MNA:

- Ground Water Issue Paper: Microbial Processes Affecting Monitored Natural Attenuation of Contaminants in the Subsurface. Ann Azadpour-Keeley, Hugh H. Russell, and Guy W. Sewell. EPA 540-S-99-001. 1999.
- Natural Attenuation of MTBE in the Subsurface under Methanogenic Conditions. U.S. EPA: Office of Research and Development. EPA 600-R-00-006. 2000.

Figure 21. Superfund Remedial Actions: RODs Specifying Monitored Natural Attenuation for Groundwater (FY 1982 - FY 1999)



Sources: 1, 2, 3, 4, 5, 6, 8: Data sources are listed in the References and Data Sources section on page 38.

Section 5: Superfund Removal Actions

Removal actions usually are conducted in response to a threat caused by a release of hazardous substances that is more immediate than threats addressed by remedial actions. Approximately 5,500 removal actions have been undertaken to address these more immediate threats. To date, innovative treatment technologies have been used in relatively few removal actions. The treatment technologies addressed in this report have been used 100 times in 54 removal actions (Table 10). The ninth edition of the ASR documented 97 removal actions for which innovative technologies were used.

The percentage of removal action projects that involve treatment technologies and have been completed, as shown in Table 10, is 55 percent.

Since removal actions are responses to an immediate threat and often involve smaller quantities of hazardous wastes than those addressed by remedial activities, implementation of a technology may be completed more quickly at a removal site than at a remedial site.

Because removal actions involve immediate threats, quick action to alleviate the hazard is necessary. Often, such activities do not lend themselves to on-site treatment or innovative technologies. In addition, SARA does not establish the same preference for innovative treatment for removal actions as it specifies for remedial actions.

Additional information on Superfund removal actions can be found in EPA's REmediation And CHaracterization Innovative Technologies (EPA REACH IT) on-line searchable database at *http://www.epareachit.org*.

Table 10. Superfund Removal Actions: Project Status of Treatment Technologies (FY 1982 - FY 1999)

Technology	Predesign/ Design	Design Completed/ Being Installed	Operational	Completed	Total
Ex Situ Source Control					
Bioremediation	1	0	0	14	15
Chemical Treatment	1	0	0	4	5
Incineration (off-site)	1	0	0	4	5
Soil Vapor Extraction	0	0	1	2	3
Soil Washing	0	0	0	3	3
Solidification/Stabilization	0	0	1	0	1
Solvent Extraction	0	0	0	2	2
Thermal Desorption	0	0	0	6	6
Total	**3**	**0**	**2**	**35**	**40**
Percent of Total	**8%**	**0%**	**5%**	**88%**	
In Situ Source Control					
Bioremediation	0	0	17	5	22
Chemical Treatment	0	0	0	3	3
Soil Vapor Extraction	0	1	15	10	26
Vitrification	0	0	0	1	1
Total	**0**	**1**	**32**	**19**	**52**
Percent of Total	**0%**	**2%**	**62%**	**37%**	
In Situ Groundwater					
Air Sparging	0	1	2	1	4
Bioremediation	0	0	3	0	3
In-Well Air Stripping	0	0	1	0	1
Total	**0**	**1**	**6**	**1**	**8**
Percent of Total	**0%**	**13%**	**75%**	**13%**	

Sources: 9: Data sources are listed in the References and Data Sources section on page 38.

Section 6: References and Data Sources

1. List of NPL sites. *www.epa.gov/superfund/sites/query/queryhtm/nplfina.txt* (9/2000).
2. List of Superfund National Priority List (NPL) sites that have been deleted. *www.epa.gov/superfund/sites/query/ queryhtm/npldela.txt* (9/2000).
3. Compilation of Record of Decision (ROD) abstracts, site summaries, and fact sheets for fiscal years (FY) 1982 through 1997. *www.epa.gov/superfund/sites/query/advquery.htm* (1/20/2000).
4. Records of Decision (RODs), ROD amendments, Explanations of Significant Difference, and ROD abstracts from FY 1982 through FY 1999.
5. Contacts with remedial project managers, FY 1992 through FY 1999.
6. ROD Annual Reports, EPA Office of Emergency and Remedial Response(OERR), 1998 through 1992.
7. Innovative Treatment Technologies: Annual Status Report (ASR) Eighth Edition (EPA-542-R-99-001). EPA. Office of Solid Waste and Emergency Response. April 1999.
8. Personal communication from Ken Lovelace, OERR, to Tom Sinksi of Tetra Tech EM Inc., April, 1998.
9. Contacts with EPA Superfund Removal Branch Chiefs and On-Scene Coordinators.

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