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Agency

Solid Waste and
Emergency Response
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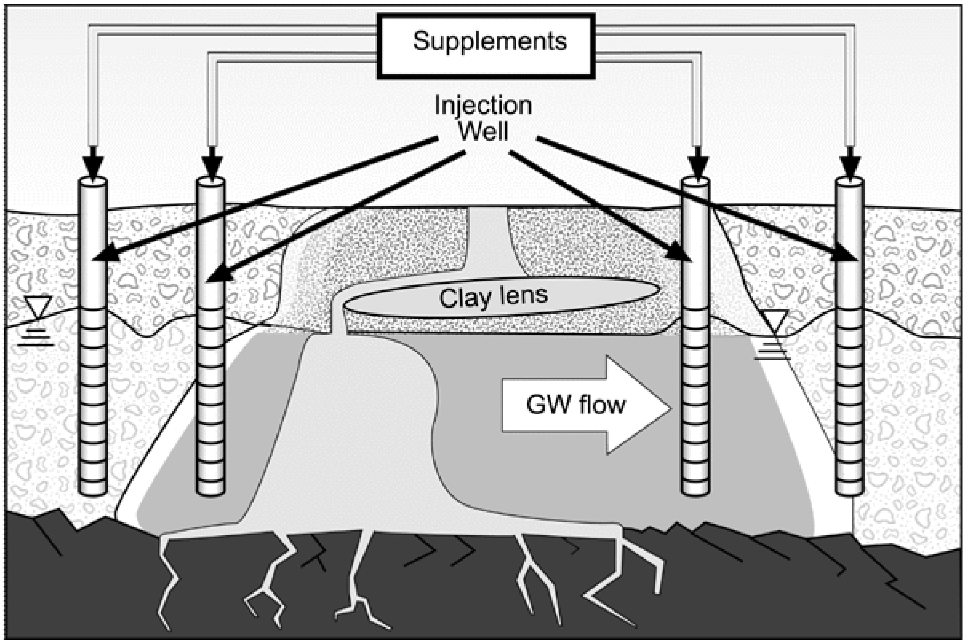
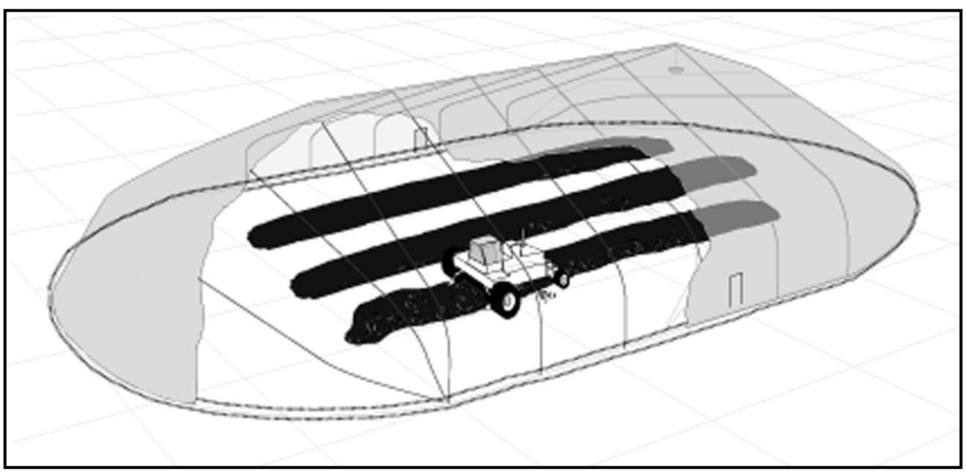
# Use of Bioremediation at Superfund Sites



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# Use of Bioremediation at Superfund Sites

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office
Washington, DC 20460

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## ACRONYMS

| | |
|---|---|
| AFB | Air Force Base |
| AFCEE | Air Force Center for Environmental Excellence |
| ASR | Annual Status Report |
| BHC | "-Benzene Hexachloride |
| BTEX | Benzene, Toluene, Ethylbenzene, and Xylenes |
| CA | Corrective Action |
| $CCl_4$ | Carbon Tetrachloride |
| $CO_2$ | Carbon Dioxide |
| $Cr^{+3}$ | Trivalent Chromium |
| $Cr^{+6}$ | Hexavalent Chromium |
| CVOC | Chlorinated Volatile Organic Compound |
| cy | Cubic Yard |
| DCE | Dichloroethene |
| DDD | Dichlorodiphenyldichloroethane |
| DDE | Dichlorodiphenyldichloroethene |
| DDT | Dichlorodiphenyltrichloroethane |
| DoD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOI | U.S. Department of the Interior |
| DS | Demonstration Scale |
| EPA REACH IT | EPA REmediation And CHaracterization Innovative Technologies |
| ESD | Explanation of Significant Differences |
| FRTR | Federal Remediation Technologies Roundtable |
| FS | Full Scale |
| FY | Fiscal Year |
| JOAAP | Joliet Army Ammunition Plant |
| mg/kg | Milligrams per Kilogram |
| NC | Not Calculated |
| NNEMS | National Network of Environmental Management Studies |
| NR | Not Reported |
| NSCEP | National Service Center for Environmental Publications |
| OU | Operable Unit |
| PAH | Polycyclic Aromatic Hydrocarbon |
| PCB | Polychlorinated Biphenyl |
| PCE | Tetrachloroethene |
| PCP | Pentachlorophenol |
| PHC | Petroleum Hydrocarbons |
| POL | Petroleum, Oil, and Lubricant |
| RCRA | Resource Conservation and Recovery Act |
| ROD | Record of Decision |

## ACRONYMS (continued)

| | |
|---|---|
| SVE | Soil Vapor Extraction |
| SVOC | Semivolatile Organic Compound |
| TCE | Trichloroethene |
| Tetryl | N-methyl-n,2,4,6-tetranitroaniline |
| TNT | Trinitrotoluene |
| TPH | Total Petroleum Hydrocarbon |
| UST | Underground Storage Tank |
| VC | Vinyl Chloride |
| VOCs | Volatile Organic Compounds |

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## 1.0 SUMMARY

Bioremediation is a technology that uses microorganisms to treat contaminants through natural biodegradation mechanisms (intrinsic bioremediation) or by enhancing natural biodegradation mechanisms through the addition of microbes, nutrients, electron donors, and/or electron acceptors (enhanced bioremediation). This technology, performed *in situ* (below ground or in place) or *ex situ* (above ground), is capable of degrading organic compounds to less toxic materials such as carbon dioxide ($CO_2$), methane, and water through aerobic or anaerobic processes. Bioremediation is being used with increasing frequency to remediate contaminated media at hazardous waste sites because, compared with other remediation technologies, it often is less expensive and more acceptable to the public.

This report focuses on the use of enhanced bioremediation technologies at 104 Superfund remedial action sites and other contaminated sites. It provides a snapshot of current applications of bioremediation and presents trends over time concerning selection and use of the technology, contaminants and site types treated by the technology, and cost and performance of the technology. This information will help inform site managers, technology users, developers, and other interested parties about the capabilities and current applications of bioremediation.

Highlights of this report are listed below:

- **Technology Types** - Since 1991, the percentage of bioremediation projects performed *ex situ* has decreased while the percentage of projects performed *in situ* has increased. In 1991, only 35 percent of the Superfund remedial action bioremediation projects were *in situ* versus 53 percent in 1999. Bioventing is the most commonly implemented *in situ* treatment technology for source treatment[1]. Land treatment is the most commonly used *ex situ* source treatment technology.

- **Site Types** - The most common type of Superfund remedial action site where bioremediation is used is wood preserving (31 percent), followed by petroleum sites (21 percent). The most common types of contaminants at these sites are polycyclic aromatic hydrocarbons (PAHs) (40 percent); benzene, toluene, ethylbenzene, and xylenes (BTEX) (37 percent); and pesticides and herbicides (27 percent).

- **Project Status** - Over half of bioremediation projects at Superfund remedial action sites (57 percent) are in the operational phase, while 26 percent are in the predesign, design, or installation phases, and 17 percent have been completed. Of the 18 completed projects, 14 are *ex situ* source treatment projects, and 4 are *in situ* projects for source treatment and groundwater treatment.

- **Trends in Use** - Few bioremediation Records of Decision (RODs) were signed in the early- to mid-1980s. Beginning in fiscal year (FY) 1988, the number of bioremediation RODs has increased. In general, 8 to 12 bioremediation RODs have been signed per year.

- **Performance** - Available performance data shows that bioremediation is capable of reducing contaminant concentrations in contaminated media. Bioremediation is being used to treat recalcitrant organic compounds, including chlorinated volatile organic compounds (VOCs), PAHs, pesticides and herbicides, and explosives. For ten projects treating chlorinated VOCs, concentrations of VOCs in treated groundwater ranged from below detect limit (<5 µg/L for tetrachloroethene [PCE], trichloroethene [TCE], and dichloroethene [DCE]) to 1,200 µg/L (for carbon tetrachloride).

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[1] The term source treatment includes treatment of soil, sludge, sediment, or other solid waste.

For seven projects treating PAHs, concentrations of PAHs in treated soil and sludges ranged from 3.3 mg/kg to 795 mg/kg, with some projects showing more than 90% removal. For four projects treating pesticides and herbicides, concentrations of specific pesticides and herbicides in treated soil were less than 10 mg/kg at two projects and less than 200 mg/kg at the other two projects, with some projects showing more than 90% removal. For six projects treating explosives, three showed removals of more than 75% and the others showed removals ranging from little or none to as much as 64%.

- **Cost** - Information about the cost of using bioremediation to treat contaminated media was available for 67 sites. Unit costs for bioventing projects ranged from approximately $2 per cubic yard (cy) to more than $300/cy, with most sites less than $40/cy. Unit costs for *ex situ* bioremediation of soil, such as land treatment or composting systems, ranged from $13/cy to more than $500/cy, with most projects costing less than $300/cy.

Information sources used for this report included Superfund RODs, ROD amendments, and Explanations of Significant Differences (ESDs) issued by EPA through fiscal year 1999 (EPA 2001); and cost and performance reports prepared by the Federal Remediation Technologies Roundtable (FRTR 2001). Specific references are identified at the end of this report.

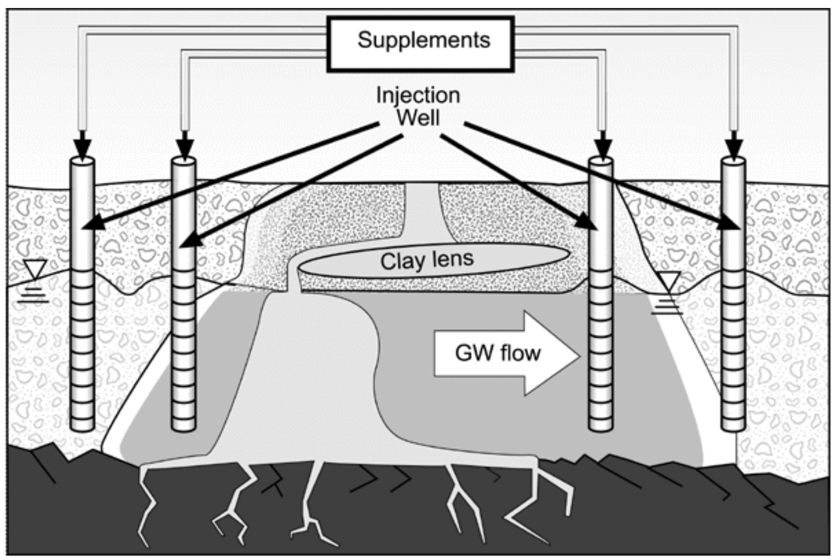
Section 2 of the report provides an overview of bioremediation technologies, including *in situ* and *ex situ* technologies, and provides examples of field use for three types of bioremediation technologies. The characteristics of bioremediation projects at Superfund and other sites are described in Section 3, including the types of bioremediation projects that have been conducted and the selection of bioremediation as a remedy. Section 4 provides a summary of the performance of bioremediation technologies, with a summary of bioremediation costs in Section 5. Information about vendors of bioremediation technologies is provided in Section 6. References used in preparation of this report are in Section 7, and additional information about selected information sources is in Section 8.

Appendix A to the report provides selected information about 104 bioremediation projects, including site name, location, ROD year, contaminants treated, project status, and contact name. Appendix B provides additional information related to the development of the cost curves for bioventing projects.

## 2.0 OVERVIEW OF BIOREMEDIATION TECHNOLOGIES

Bioremediation technologies use microorganisms to treat contaminants by degrading organic compounds to less toxic materials, such as $CO_2$, methane, water, and inorganic salts. These technologies include intrinsic or enhanced bioremediation, which is the focus of this report, and can be performed *in situ* or *ex situ* under aerobic or anaerobic conditions. During enhanced bioremediation, amendments are typically added to the media to supplement biodegradation processes.[2] Amendments include nutrients (such as nitrogen and phosphorus), electron donors (such as methanol or lactic acid for anaerobic processes), electron acceptors (such as oxygen for aerobic processes, ferric iron or nitrate for anaerobic processes), or microbes (bioaugmentation) (EPA 1994, EPA 2000).

**Figure 1. Example Configuration for an *In Situ* Groundwater Bioremediation System**




Source: EPA 2000

As shown in Table 1, *in situ* bioremediation technologies include source treatment technologies such as bioventing and slurry-phase lagoon aeration, and groundwater technologies such as biosparging and *in situ* aerobic or anaerobic treatment. Amendments are added using direct injection and groundwater recirculation systems. For direct injection (illustrated in Figure 1), amendments are added to the contaminated media through injection points. With groundwater recirculation systems, contaminated groundwater is extracted, amendments are mixed with the groundwater *ex situ*, and the amended groundwater is re-injected into the subsurface, usually upgradient of the contaminated zone. One configuration for a recirculation system is to extract and re-inject groundwater in a single strata or at a common groundwater elevation. An alternative configuration for a groundwater recirculation system is extraction and re-injection at different elevations in a single treatment cell, creating vertical circulation.

As shown in Table 2, *ex situ* processes include land treatment, composting, biopiles, and slurry-phase treatment for source treatment.[3] Figure 2 presents an example configuration for a windrow composting system. Table 3 presents three examples of successful bioremediation projects: one *in situ* groundwater project, one *ex situ* source control project, and one *in situ* source control project.

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[2] During bioremediation, microorganisms also can affect the metal chemistry and bioavailability in the contaminated media; however, those effects are not addressed in this report.

[3] This report does not include *ex situ* groundwater bioremediation technologies.

**Table 1. Description of *In Situ* Bioremediation Technologies**

***In Situ*** **Source Treatment Processes**

- Bioventing - Oxygen is delivered to contaminated unsaturated soils by movement of forced air (either extraction or injection of air) to increase concentrations of oxygen and stimulate biodegradation.
- Slurry-Phase Lagoon Aeration - Air and soil are brought into contact with each other in a lagoon to promote biological degradation of the contaminants in the soil.

***In Situ*** **Groundwater Processes**

- Biosparging - Air is injected into groundwater to enhance biodegradation and volatilization of contaminants; biodegradation occurs aerobically.
- Aerobic - Air, oxygen, and/or nutrients are injected into groundwater to enhance biodegradation of contaminants. Systems include direct injections of oxygen release compound (ORC®) or hydrogen peroxide, or groundwater recirculation systems.
- Anaerobic - Carbon sources such as molasses, lactic acid, or hydrogen release compound (HRC®) are injected into groundwater to enhance biodegradation of contaminants using direct injection or groundwater recirculation systems.

Sources: EPA 2000, FRTR 2001a

**Table 2. Description of *Ex Situ* Bioremediation Technologies**

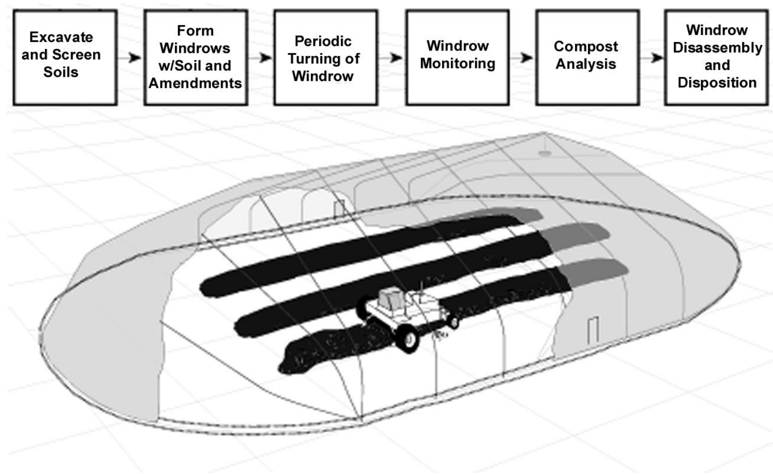
***Ex Situ*** **Source Treatment Processes**

- Land Treatment - Contaminated soil, sediment, or sludge is excavated, applied to lined beds, and periodically turned over or tilled to aerate the contaminated media. Amendments can be added to the contaminated media in the beds.
- Composting - Contaminated soil is excavated and mixed with bulking agents such as wood chips and organic amendments such as hay, manure, and vegetable wastes. The types of amendments used depends on the porosity of the soil and the balance of carbon and nitrogen needed to promote microbial activity.
- Biopiles - Excavated soils are mixed with soil amendments and placed in aboveground enclosures. The process occurs in an aerated static pile in which compost is formed into piles and aerated with blowers or vacuum pumps.
- Slurry-Phase Treatment - An aqueous slurry is created by combining soil, sediment, or sludge with water and other additives. The slurry is mixed to keep solids suspended and microorganisms in contact with the contaminants. Treatment usually occurs in a series of tanks.

Sources: EPA 2000, FRTR 2001a

Biodegradation occurs under aerobic and anaerobic conditions, with the majority of bioremediation systems designed to treat contaminants aerobically. Aerobic processes use oxidation to degrade organic compounds to less toxic compounds such as $CO_2$ and water. Anaerobic processes, used to treat contaminants such as chlorinated VOCs, include dechlorination where the chlorinated VOCs act as an electron acceptor, and are degraded to nonchlorinated compounds. During anaerobic degradation, persistent intermediate compounds may be produced. For example, anaerobic biodegradation of chlorinated aliphatic solvents can produce lower substituted chlorinated hydrocarbons, such as chloroethane or vinyl chloride (VC). Such compounds are not readily degraded under anaerobic conditions (these contaminants may be more readily degraded under aerobic conditions) and may be more toxic than the original contaminant.

**Figure 2. Typical Windrow Composting System**




Source: FRTR 2001a

Biodegradation of contaminants occurs as direct or cometabolic processes. For direct bioremediation processes, the microorganisms use the contaminants as a source of food or energy. When contaminants cannot be used as a food source, biodegradation may occur though cometabolism in which the contaminant is degraded by an enzyme or cofactor produced during microbial metabolism of another compound.

The types of contaminants that are amenable to bioremediation include petroleum hydrocarbons, such as gasoline and diesel fuel; nonchlorinated solvents, such as acetone and other ketones; wood-treating wastes, such as creosote and pentachlorophenol (PCP); some chlorinated aromatic compounds, such as chlorobenzenes and biphenyls having fewer than five chlorine atoms per molecule; and some chlorinated aliphatic compounds, such as trichloroethene (TCE).

**Table 3. Field Use of Three Types of Bioremediation Technologies**

***In Situ* Bioremediaton of Soil**

The Dover Air Force Base, Building 719 site in Dover, Delaware had groundwater contaminated with TCE, 1,1,1-trichloroethane (TCA), and cis-1,2-DCE. A field-scale cometabolic bioventing system was operated at the site between May 1998 and July 1999. The primary objectives of the project were to determine the efficiency of an *in situ* cometabolic bioventing process for chlorinated aliphatic hydrocarbons under field conditions. During the 4-month period immediately prior to system startup, small amounts of propane were added directly to the soil to drive the cometabolism of TCE and TCA. Concentrations of TCE, TCA, and DCE in the soil decreased to less than 0.25 mg/kg for each contaminant during the 14-month period of operation. Increased levels of chloride (a product of the biodegradation of chlorinated solvents) in the soil during this period showed that the reduced contaminant concentrations were a result of the cometabolic bioventing system. (FRTR 2001)

***In Situ* Bioremediation of Groundwater**

The Avco Lycoming Superfund site in Williamsport, Pennsylvania had groundwater contaminated with TCE, DCE, VC, hexavalent chromium ($Cr^{+6}$), and cadmium. Since January 1997, as part of a full-scale cleanup effort, molasses has been injected directly into the groundwater to reductively dechlorinate (cometabolic and direct) the chlorinated aliphatic hydrocarbons and to reduce the groundwater concentrations of the cadmium and $Cr^{+6}$ (the chromium is not degraded as a result of the molasses injection; rather, it is reduced from $Cr^{+6}$ to trivalent chromium ($Cr^{+3}$)). By July 1998, the use of molasses injection had created an anaerobic reactive zone, with concentrations of TCE, DCE, and $Cr^{+6}$ reduced to below their cleanup goals in many monitoring wells at the site (cleanup goals are 6.5 µg/L, 30 µg/L, and 32 µg/L, respectively). According to the technology vendor, ARCADIS Geraghty & Miller, this technology saved substantial resources when compared to pump and treat. (FRTR 2001)

***Ex Situ* Bioremediation of Soil and Sludge**

The Southeastern Wood Preserving Superfund site in Canton, Mississippi had soil and sludge contaminated with PAHs. During a full-scale cleanup effort, a slurry-phase bioremediation system was operated from July 1991 until 1994. The average total PAH concentration was reduced from 8,545 to 634 mg/kg (below the cleanup goal of 950 mg/kg). The average benzo(a)pyrene (B(a)P)-equivalent PAH concentration[4] was reduced from 467 to 152 mg/kg (below the cleanup goal of 180 mg/kg). The data indicate that the greatest reductions occurred during the first 10 days of treatment and that after 19 days of treatment, the cleanup goal for total PAHs was met for 12 of the 13 batches. The initial and final concentrations are for the soil and sludge in the slurry phase, after passing through the soil/sludge wash tank and the slurry mix tank. (FRTR 2001)

[4] For the Southeastern Wood Preserving site, EPA used published toxicity-equivalent factors to calculate the B(a)P-equivalent of the carcinogenic PAHs (Benzo(a)anthracene, Chrysene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Benzo(a)pyrene, Dibenzo(ah)anthracene, Indeno(1,2,3-cd)pyrene). In calculating B(a)P-equivalent concentrations, the concentration of each PAH is multiplied by a factor which is equal to its carcinogenicity relative to benzo(a)pyrene. The resulting weighted concentrations are summed to calculate the B(a)P-equivalent carcinogenic PAH value.

# 3.0 CHARACTERISTICS OF BIOREMEDIATION PROJECTS AT SUPERFUND AND OTHER SITES

This section presents detailed information about the use of bioremediation to treat contaminated media for 104 Superfund remedial action projects (referred to as Superfund projects in this report; does not include removal actions), along with summary information for other sites. The information presented includes the specific types of bioremediation projects, trends in implementation of bioremediation, and remedy changes under the Superfund remedial action program.

The 104 Superfund projects include bioremediation projects that have been completed or are operating, and projects that are planned (projects where bioremediation has been selected as the remedy in the ROD and are installed (but not operating) or in the predesign or design stage). Information about these projects was obtained primarily from EPA's *Treatment Technologies for Site Cleanup: Annual Status Report, Tenth Edition* (EPA 2001). Appendix A to this report presents site-specific information about the 104 Superfund projects (including site name, location, year in which the ROD was signed, contaminants treated, status of the project, and contact information) and is organized by type of remediation technology.

## 3.1 TYPES OF BIOREMEDIATION PROJECTS

This section summarizes information about the types of technologies, types of sites, contaminant groups, and status of bioremediation projects at Superfund projects and other sites. This analysis includes *in situ* and *ex situ* projects for source treatment and *in situ* projects for groundwater treatment.

### Technology Types

Figure 3 (source treatment) and Table 4 (groundwater treatment) compare the number of Superfund bioremediation projects with the number of Superfund projects using other treatment technologies. As shown in Figure 3, 49 of the 425 *ex situ* projects for source treatment (12%) use bioremediation. Figure 3 also shows that 35 of the 314 *in situ* projects for source treatment (11%) use bioremediation. Table 4 shows that 20 of the 80 *in situ* projects for groundwater treatment (25%) use bioremediation. Approximately 10% of sites treating groundwater are using *in situ* technologies, including bioremediation. In addition, some *ex situ* (pump and treat) projects used bioremediation in their above-ground treatment system. Information was not provided in the available sources about the number of *ex situ* groundwater bioremediation projects and they are not discussed further in this report.

As shown in Figure 4, of the 104 Superfund bioremediation projects, 55 (53 percent) are *in situ. In situ* projects include 35 for source treatment (24 for bioventing) and 20 for groundwater treatment (3 biosparging projects and 17 other projects, usually injection of amended groundwater).

Figure 4 also shows that 49 (47%) of the 104 Superfund bioremediation projects are for *ex situ* source treatment. Land treatment is the most common of these, with 33 projects. Other *ex situ* source treatment projects include composting, biopiles, and slurry-phase technologies.

As shown in Figure 5, between August 1991 and August 2000, the relative percentage of *in situ* bioremediation projects at Superfund sites increased, and *ex situ* projects decreased correspondingly.[5]

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[5] The number of bioremediation projects in each year is cumulative, and represents all bioremediation projects planned, implemented, or completed prior to that year.

**Figure 3. Superfund Source Treatment Projects (FY 1982 - FY 1999)**

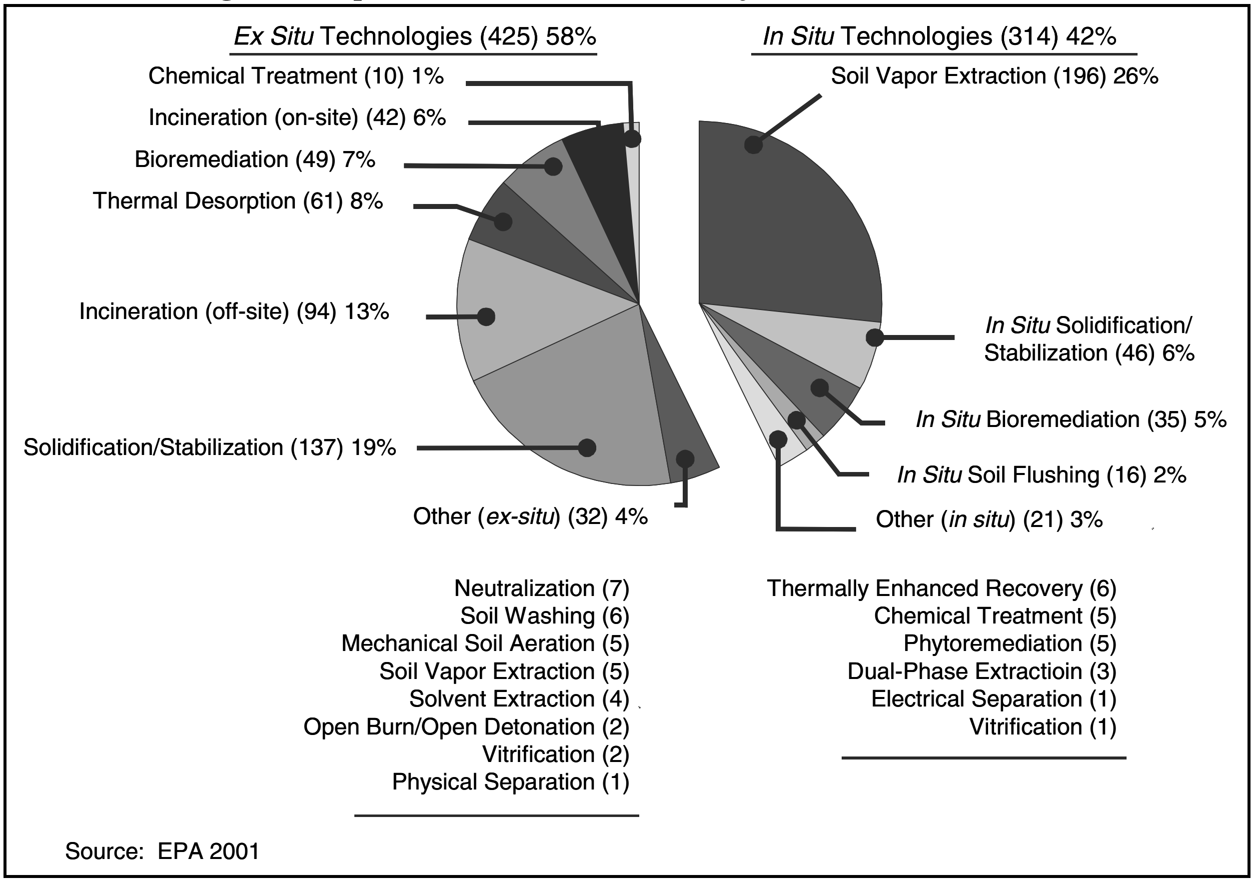



**Table 4. Superfund Groundwater Treatment Projects (FY 1982 - FY 1999)**

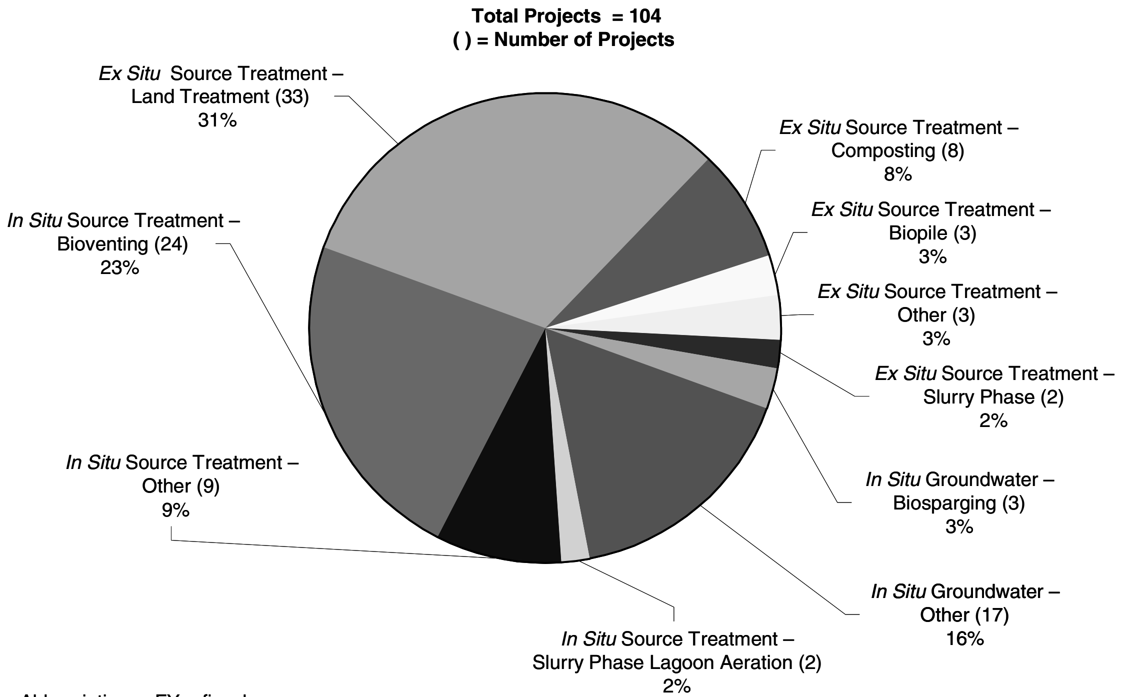
| Technology | Number of Sites |
|---|---|
| ***Ex Situ* Technologies** | |
| Pump and Treat | 638[1] |
| ***In Situ* Technologies[2]** | |
| Air Sparging | 48 |
| Bioremediation | 20 |
| Dual-Phase Extraction | 10 |
| Permeable Reactive Barrier | 8 |
| Phytoremediation | 4 |
| Chemical Treatment | 2 |
| In-Well Air Stripping | 2 |

Source: EPA 2001; EPA 2001b

[1] Number of Superfund remedial action sites that have signed RODs selecting a P&T remedy. Some sites may have more than one P&T system.

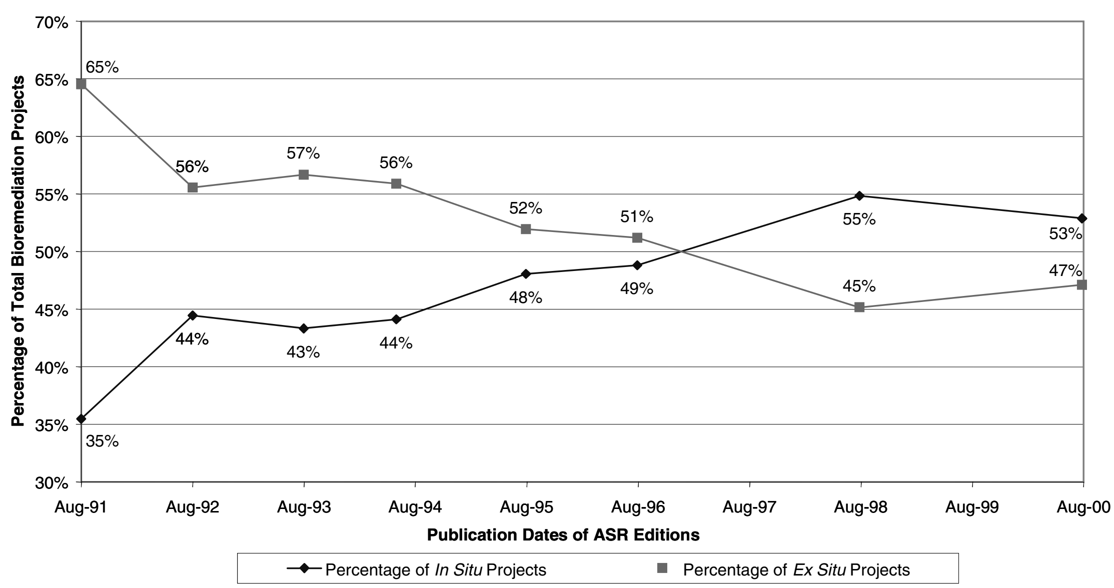
[2] Some sites use more than one *in situ* technology.

**Figure 4. Superfund Bioremediation Projects (FY 1982 - FY 1999)**




Abbreviations: FY = fiscal year
[1] Ex situ groundwater bioremediation treatments are not included in this figure.
[2] Some sites may have more than one project.
[3] Other in situ groundwater projects involved injection or recirculation of amended groundwater, and cover both aerobic and anaerobic environments.
Source: EPA 2001b

**Figure 5. Relative Number of In Situ and Ex Situ Superfund Bioremediation Projects[1]**



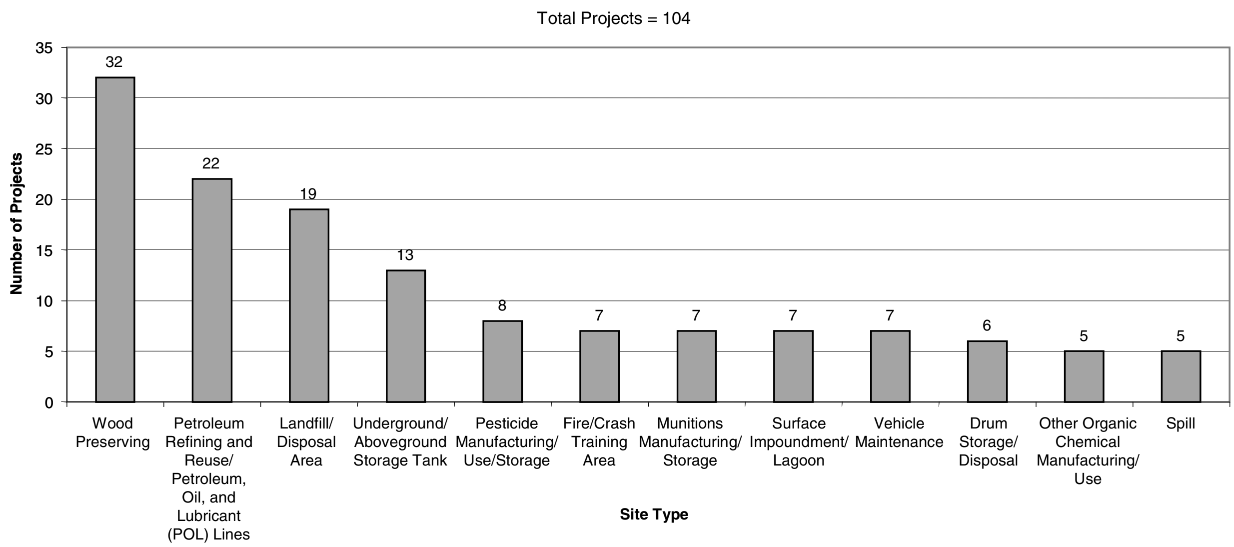

[1] Each edition of the ASR includes all of the bioremediation projects from previous editions that have not been cancelled, plus additional projects selected in RODs since the previous edition. Therefore, the number of bioremediation projects in each edition is cumulative, and represents all bioremediation projects planned, implemented, or completed prior to the publication of each edition.

Source: EPA 2001

### Site Types

Figure 6 summarizes the 104 Superfund bioremediation projects by the type of facility or operation that caused site contamination. The most common site types include wood-preserving (32 sites), followed by petroleum sites (22 sites). The latter includes petroleum refining and reuse/petroleum, oil, and lubricant (POL) lines.[6]

**Figure 6. Superfund Site types Most Commonly Treated by Bioremediation (FY 1982 - FY 1999)[1]**




[1] Some sites are described by more than one site type.

Abbreviations: FY = fiscal year

Source: EPA 2001b

### Contaminant Groups

Figure 7 presents data about the types of contaminant groups treated by bioremediation. The figure shows that bioremediation is used most frequently to treat nonchlorinated compounds at Superfund projects, including non-chlorinated SVOCs and VOCs. Bioremediation was used less often to treat chlorinated compounds, which are typically more difficult to biodegrade. Figure 8 presents the 14 most common contaminants treated by bioremediation. As shown in Figure 8, benzene (32 projects), pentachlorophenol (25 projects), and toluene (21 projects) are the most common contaminants treated by bioremediation. Appendix A presents the site-specific contaminants at each of the 104 Superfund bioremediation projects.

Table 5 presents data about the types of contaminant groups treated by a specific type of bioremediation technology. Almost all the contaminant groups have been treated both *in situ* and *ex situ* by both source treatment and groundwater remediation technologies.

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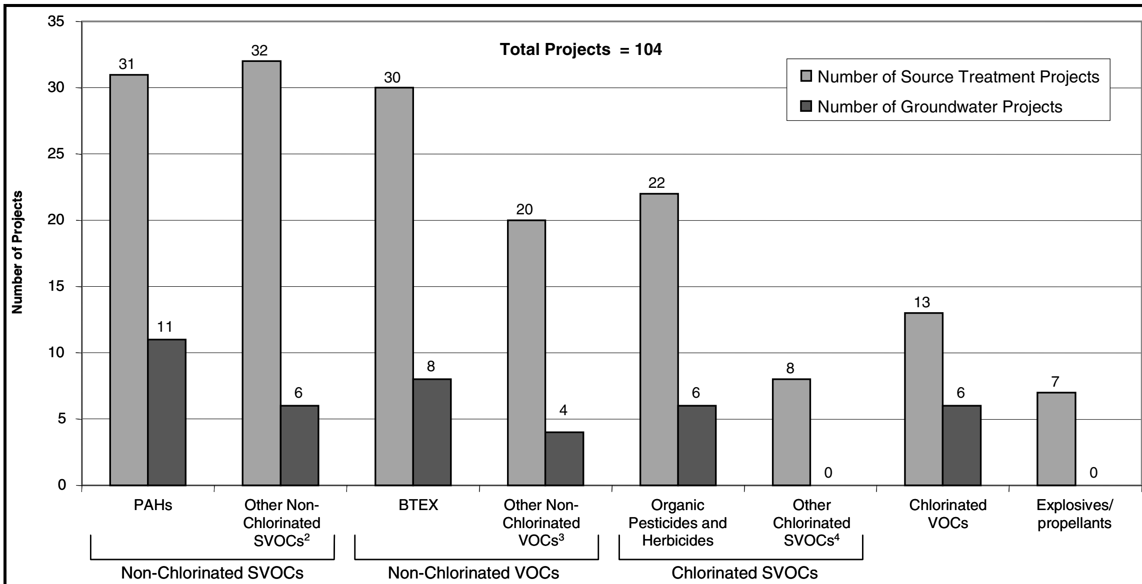
[6] Sites cannot be listed on the NPL solely as a result of petroleum contaminants. These sites likely were listed because they contain other hazardous contaminants.

## Figure 7. Contaminant Groups Treated by Bioremediation at Superfund Sites (FY 1982 - FY 1999)[1]

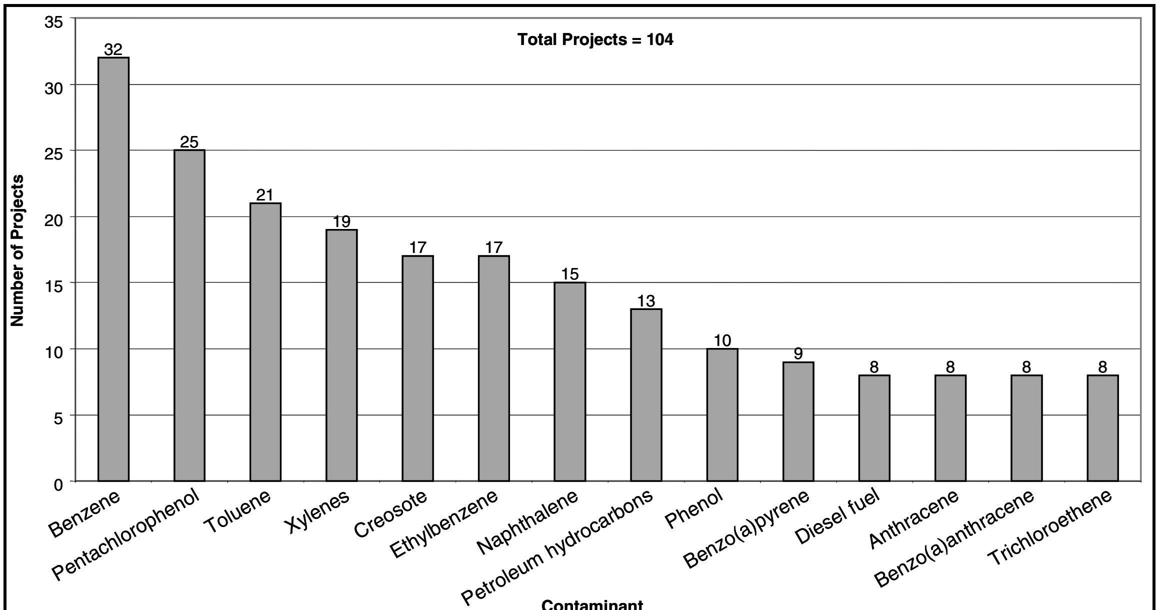



Abbreviations: BTEX = benzene, toluene, ethylbenzene, and xylenes; FY = fiscal year; PAH = Polycyclic aromatic hydrocarbon; SVOC = semivolatile organic compound; VOC = volatile organic compound

[1] Some projects address more than one contaminant group. Technology effectiveness not considered.

Source: EPA 2001b

## Figure 8. Contaminants Most Frequently Treated by Bioremediation at Superfund Sites (FY 1982 - FY 1999)[1]




[1] Some projects address more than one contaminant group. Technology effectiveness not considered.

Source: EPA 2001b

**Table 5. Contaminant Groups Treated by Bioremediation Technologies at Superfund Sites (FY 1982 - FY 1999)**

| Technology | Total Number of Projects | PAHs | Other Non-Chlorinated SVOCs[1] | BTEX | Other Non-Chlorinated VOCs[2] | Pesticides and Herbicides | Other Chlorinated SVOCs[3] | Chlorinated VOCs | Explosives/Propellants[4] |
|---|---|---|---|---|---|---|---|---|---|
| ***Ex Situ* Source Treatment Technologies** | | | | | | | | | |
| Land Treatment | 33 | Ž | Ž | Ž | Ž | Ž | Ž | Ž | Ž |
| Composting | 8 | Ž | Ž | Ž | Ž | Ž | Ž | Ž | Ž |
| Biopile | 3 | | | Ž | Ž | Ž | | Ž | |
| Slurry Phase | 2 | Ž | Ž | Ž | | Ž | | | |
| Other | 3 | | | Ž | | | | Ž | |
| ***In Situ* Source Treatment Technologies** | | | | | | | | | |
| Bioventing | 24 | Ž | Ž | Ž | Ž | Ž | Ž | Ž | |
| Slurry-Phase Lagoon Aeration | 2 | Ž | | | Ž | Ž | Ž | Ž | |
| Other | 9 | Ž | Ž | Ž | | Ž | | Ž | |
| ***In Situ* Groundwater Technologies** | | | | | | | | | |
| Biosparging | 3 | Ž | Ž | Ž | Ž | | | Ž | |
| Direct Injection or Recirculation | 17 | Ž | Ž | Ž | Ž | Ž | | Ž | |

Source: EPA 2001b
Abbreviations: FY = fiscal year; PAH = polycyclic aromatic hydrocarbon; SVOC = semivolatile organic compound; BTEX = benzene, toluene, ethylbenzene, and xylenes; VOC = volatile organic compound
[1] Does not include PAHs.
[2] Does not include BTEX.
[3] Does not include organic pesticides and herbicides.
[4] *In situ* treatment of propellents has been implemented in several projects. However, the sites are not Superfund remedial actions sites; therefore, they are not discussed in more detail in this figure.
ž - Contaminant was reported present at one or more sites treated using the technology shown; does not consider effectiveness of technology.

### Status

Table 6 presents a summary of the status of the Superfund bioremediation projects. The 104 Superfund projects include completed and operating bioremediation projects, as well as projects in pre-design, design, or installation stages. Most projects (57 percent) are operational, 26 percent are planned (predesign/design and installed), and 17 percent are completed. Of the 18 completed projects, 14 are *ex situ* projects compared to four *in situ* (source treatment and groundwater).

**Table 6. Project Status of Bioremediation Technologies at Superfund Sites (FY 1982 - FY 1999)**

| Type of Bioremediation Technology | Number of Projects (Percentage of Projects) | | | |
|---|---|---|---|---|
| | Predesign/ Design | Design Complete/ Being Installed | Operational | Completed |
| *Ex Situ* Source Treatment | 10 (20%) | 1 (2%) | 24 (49%) | 14 (29%) |
| *In Situ* Source Treatment | 9 (26%) | 3 (9%) | 20 (57%) | 3 (9%) |
| *In Situ* Groundwater | 4 (20%) | 0 (0%) | 15 (75%) | 1 (5%) |
| **Total** | **23 (22%)** | **4 (4%)** | **59 (57%)** | **18 (17%)** |

Source: EPA 2001b

### Other Bioremediation Projects

Bioremediation also is being used at sites other than Superfund remedial action sites:

- At Superfund removal action sites, information was available about 42 bioremediation projects. Removal actions are short-term immediate actions taken to address releases of hazardous substances that require expedited response. Thirty-nine of the projects are operational (20 projects) or have been completed (19 projects). (EPA 2001)

- Under the RCRA corrective action program and other federal programs, information was available for 29 bioremediation projects. (EPA 2001, EPA 2001b)

- Under a U.S. Air Force initiative, information was available about bioventing at 45 Air Force sites throughout the country. (Air Force 1996)

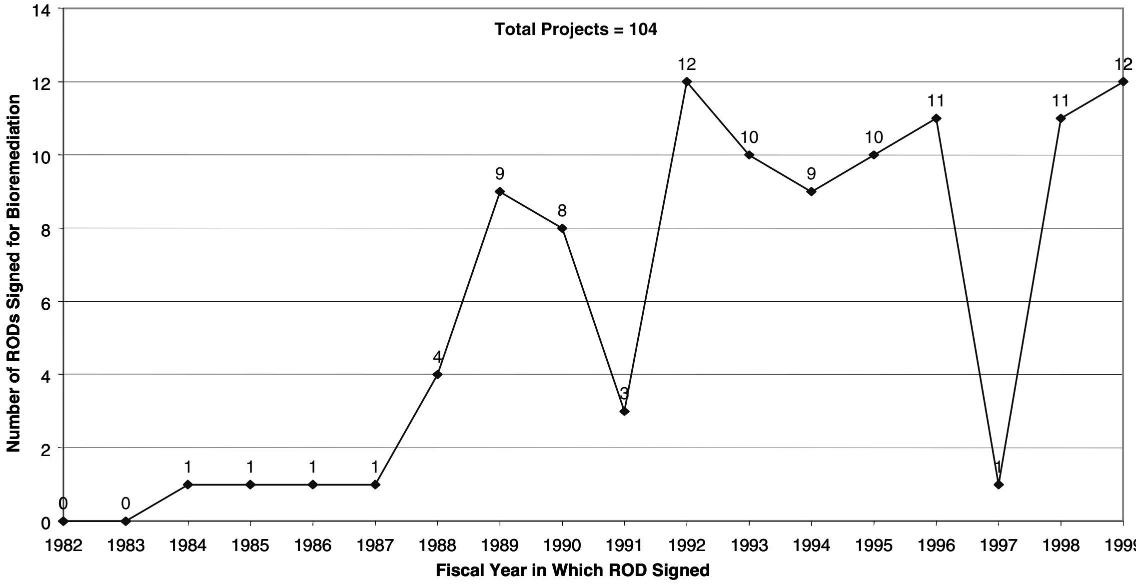
- Under EPA's Underground Storage Tanks (UST) program, states estimated that bioremediation was used at more than approximately 4,600 leaking underground storage tank (UST) sites, as of FY 1997. (Tulis 1998)

## 3.2 REMEDY SELECTION

Information about remedy selection is based on planned, ongoing, and completed bioremediation projects. (Cancelled bioremediation projects have been excluded from this analysis.) As shown in Figure 9, few bioremediation RODs were signed in the early- to mid-1980s. The number of bioremediation RODs increased beginning in FY 1988, except for two years (FY 1991 and FY 1997). In general, 8 to 12 bioremediation RODs have been signed per year.

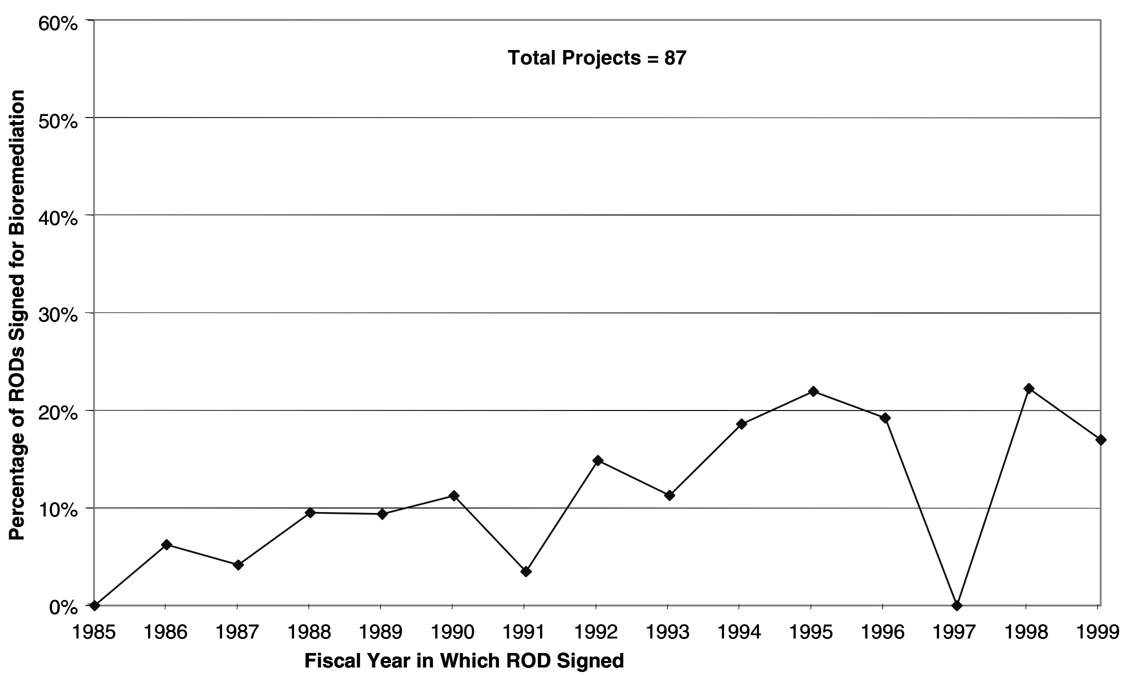
Figure 10 shows that bioremediation RODs as a percentage of source control RODs has generally increased between FY 1985 and FY 1999. Only two source control RODs were signed in FY 1984, with bioremediation implemented at one.

**Figure 9. Number of RODs Signed for Planned or Implemented Bioremediation Projects at Superfund Sites (FY 1982 - FY 1999)**




Source: EPA 2001b

**Figure 10. Bioremediation as a Percentage of Total Source Treatment RODs (FY 1982 - FY 1999)[1]**




[1] FY 1982 – FY 1984 not shown because of small number of source treatment RODs.
Source: EPA 2001b

Possible reasons for the increase in bioremediation as a selected remedy in RODs include:

- An increase in the amount of data on full-scale bioremediation projects, including information about cost and performance. Data on full-scale projects has increased in recent years. Six to ten years ago, available information was limited primarily to research papers.

- More bioremediation research and field demonstrations have been performed.

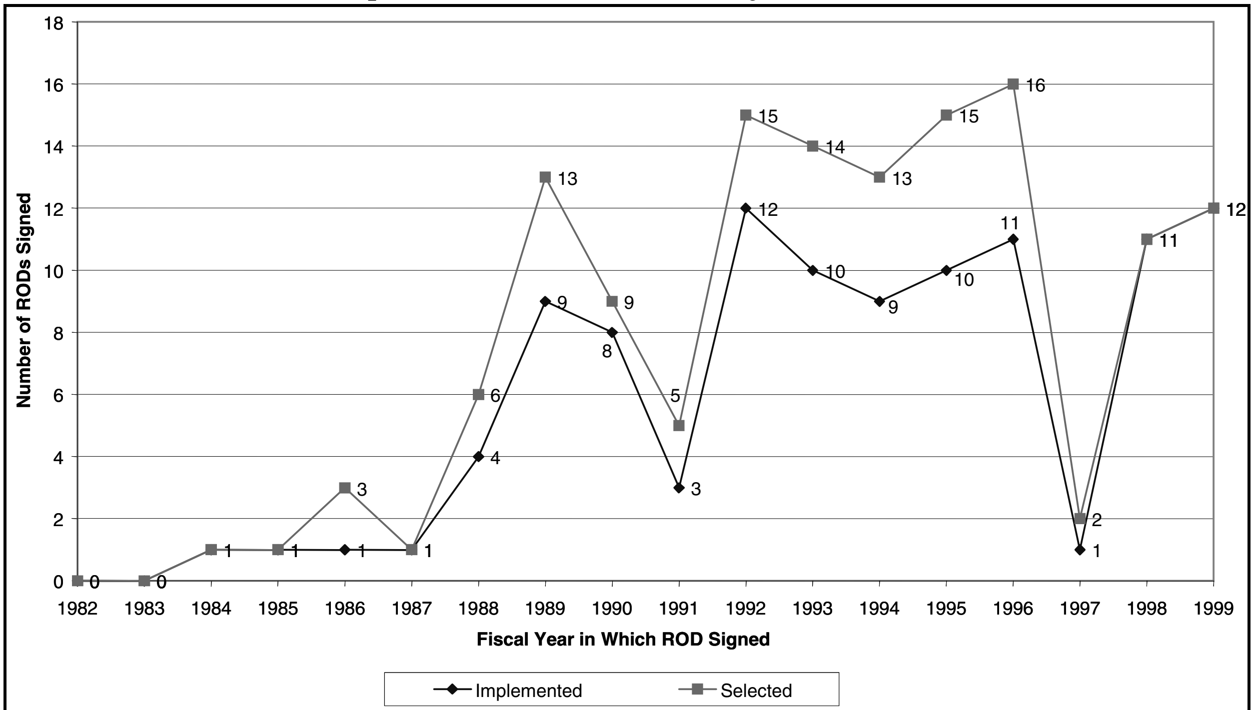
- Widespread use of bioremediation in programs other than Superfund. As discussed earlier, the Air Force has undertaken a bioventing initiative, and bioremediation is being used extensively at leaking UST sites throughout the country. Use outside of Superfund provide additional data and increases familiarity and expertise with bioremediation.

**Remedy Changes**

A remedy may change during the predesign or design phase of a project when new information about characteristics of the site are discovered or when treatability studies for the selected technologies are performed. The change can be documented through a second ROD, a ROD amendment, or an Explanation of Significant Difference (ESD). In some cases, no decision document is necessary to implement a change.

Figure 11 compares the number of bioremediation RODs originally signed with the number still planned or already implemented, taking into account any remedy changes.

**Figure 11. Superfund Remedial Actions: Comparison of the Number of RODs for Selected Versus Planned or Implemented Bioremediation Projects (FY 1982 - FY 1999)**




Source: EPA 2000, EPA 2001b

Between FY 1982 and 1995, some RODs changed to bioremediation from another remedy. However, in most years, more RODs changed from bioremediation to another remedy than from another remedy to bioremediation. The most frequent reasons cited by project managers for changing the bioremediation remedy include (EPA 2001):

- The volume of contaminated material was less than originally anticipated, and other alternatives are more cost-effective.
- Further characterization or investigation of the site after the ROD has been signed revealed that site conditions have changed and bioremediation is no longer a suitable remedy.
- A treatability study revealed that bioremediation is not capable of meeting the cleanup goals for the site.

Table 7 presents two example projects in which the selected remedy was changed from another treatment technology to bioremediation.

**Table 7. Examples of Remedy Changes to Bioremediation**

The Gulf Coast Vacuum Services site in Louisiana handled waste primarily associated from oil and gas exploration until 1984, when the owners filed for bankruptcy. The soils and sludges at the site are contaminated with benzene, toluene, mercury, lead, chromium, arsenic, barium, and numerous organic compounds. EPA first selected on-site incineration as the remedy (September 1992). After determining that on-site incineration was not cost-effective, an amended ROD was signed for the site on May 5, 1995 and included on-site land treatment of sludges and soils contaminated with organic compounds and stabilization of soils contaminated with inorganic compounds.

The Petro-Chemical Systems, Inc. (Turtle Bayou) site in Texas is a former petrochemical facility that operated until the late 1970s. While the facility was in operation, waste oils were dumped into unlined waste pits at the site. The principal contaminant in the soil and groundwater is benzene. The original ROD for the site, signed on September 6, 1991, established air sparging and soil vapor extraction as the selected remedies at the site. A 1998 ROD amendment for the site added *in situ* bioremediation of the aquifer, bioventing, and slurry-phase soil bioremediation, as well as other non-bioremediation technologies (thermally-enhanced soil vapor extraction, soil cap, pump and treat, and monitored natural attenuation), as selected remedies for soil and groundwater. Over time, the air sparging and soil vapor extraction systems had become less effective in removing contamination, and other technologies were needed to meet cleanup goals.

## 4.0 PERFORMANCE OF BIOREMEDIATION TECHNOLOGIES

For sites contaminated with total petroleum hydrocarbons (TPH) and BTEX, bioremediation of soil and groundwater is generally considered to be a well-established technology compared to sites contaminated with PAHs, chlorinated VOCs, pesticides and herbicides, and explosives, which are more recalcitrant organic compounds. This section focuses on available performance information from projects where bioremediation has been used to treat the less biodegradable compounds.

For these recalcitrant compounds, the contaminant reductions observed may not be attributed entirely to bioremediation of the contaminant; instead, the reduction may be attributed in part to mixing of soils with high contaminant concentrations with soils with lower concentrations.

### PAHs

As shown in Figure 6, wood preserving sites are one of the most common site types treated by bioremediation. Contaminants typically found at wood preserving sites include PAHs and PCP. Consequently, a significant amount of data about treatment of PAHs using bioremediation is available, specifically on treatment of 2-ring PAHs such as naphthalene, acenaphthylene, and acenaphthene; 3-ring PAHs such as fluorene, phenanthrene, and anthracene; and 4- and 5-ring PAHs such as fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, benzo(ghi)perylene, dibenz(a,h)anthracene, and indeno(1,2,3-cd)pyrene.

Table 8 shows performance data that are available for bioremediation of PAHs at 7 *ex situ* source treatment projects: 4 land treatment projects, 2 slurry-phase bioremediation projects, and 1 composting project. Bioremediation reduced concentrations of PAHs from soil and sludges at all 7 projects. Cleanup goals for PAHs were met for 3 of the 4 land treatment projects, where the goals ranged from 100 mg/kg to 8,632 mg/kg for total PAHs. At one project, the Burlington Northern Superfund site in Brainerd/Baxter, Minnesota, the concentrations of total PAHs were reduced from as high as 70,633 mg/kg to less than 800 mg/kg (nearly 99% reduction). The one land treatment project that did not meet cleanup goals was a demonstration project at the Bonneville Power Administration Ross Complex, Operable Unit A, Wood Pole Storage Area in Vancouver, Washington, where concentrations of high molecular weight PAHs were reduced by nearly 90%, but did not meet the goal of 1 mg/kg.

For the one composting project, the cleanup goal of 50 mg/kg was met for total PAHs, with concentrations reduced from as high as 367 mg/kg to less than 50 mg/kg (87%). Cleanup goals also were met for the two slurry-phase projects, with one of the projects, Southeastern Wood Preserving, in Canton, Mississippi, meeting cleanup goals of 950 mg/kg for total PAHs and 180 mg/kg for carcinogenic PAHs.

### Chlorinated VOCs

Table 9 presents performance data for 13 bioremediation projects at sites contaminated with chlorinated VOCs, such as TCE, PCE, DCE, VC, dichlorobenzene, and carbon tetrachloride. The 13 projects include 10 *in situ* groundwater projects, 1 *in situ* source treatment project, and 2 *ex situ* source treatment projects. Bioremediation was successful in reducing concentrations of chlorinated VOCs or in meeting site cleanup goals for groundwater, soil, sediments, and sludges at all 13 projects.

Most of the *in situ* groundwater projects were field demonstration and numerical cleanup goals were not established. Two of the 10 *in situ* groundwater projects had numerical cleanup goals: the U.S. DOE Savannah River Site, M Area, in South Carolina and the Avco Lycoming Superfund Site in Williamsport, Pennsylvania. At the Savannah River Site, cleanup goals were met for PCE and TCE, with PCE concentrations reduced from 124 micrograms per liter (µg/L) to less than 5 µg/L, and TCE concentrations reduced from 1,031 µg/L to less than 5 µg/L. At the Avco Lycoming Superfund site, the concentration of TCE was reduced from 67 µg/L to 6.7 µg/L (90%), but did not meet cleanup goal (5 µg/L) in all wells.

**Table 8. Performance Data for Bioremediation of PAHs**

| Site Name | Media Treated | Technology | Additives | Contaminants Treated | Initial Contaminant Concentrations | Final Contaminant Concentrations | Comments |
|---|---|---|---|---|---|---|---|
| **Land Treatment** | | | | | | | |
| Burlington Northern Superfund Site, Brainerd/Baxter, MN | Soil and sludge | Land treatment | Lime, cow manure | Total PAHs | 33,982 - 70,633 mg/kg | 608-795 mg/kg | Full-scale cleanup; cleanup goal of 8,632 mg/kg for total PAHs met. |
| | | | | Other SVOCs | Not reported | Not reported | Full-scale cleanup; cleanup goal for other SVOCs not met. |
| Scott Lumber Company Superfund Site, Alton, MO | Soil | Land treatment (two lifts of soil) | Nutrients | Total PAHs | First lift: 560 mg/kg | First lift: 130 mg/kg | Full-scale cleanup; cleanup goal of 500 mg/kg for total PAHs met. |
| | | | | | Second lift: 700 mg/kg | Second lift: 155 mg/kg | |
| | | | | Benzo(a)pyrene | First lift: 16 mg/kg | First lift: 8 mg/kg | Full-scale cleanup; cleanup goal of 14 mg/kg for benzo(a)pyrene met. |
| | | | | | Second lift: 23 mg/kg | Second lift: 10 mg/kg | |
| Brown Wood Preserving Superfund Site, Live Oak, FL | Soil | Land treatment (three lifts of soil) | Not reported | Total carcinogenic PAHs | 100 - 208 mg/kg | < 100 mg/kg | Full-scale cleanup; cleanup goal of 100 mg/kg for total carcinogenic PAHs met. |
| Bonneville Power Administration Ross Complex, Operable Unit A, Wood Pole Storage Area, Vancouver, WA | Soil | Land treatment (and UV oxidation) (demonstration project) | Peroxide, ethanol | High molecular weight PAHs | 150 mg/kg | 6.76-21.83 mg/kg | Full-scale cleanup; cleanup goals of 1 mg/kg for high molecular weight PAHs and 8 mg/kg for PCP not met for all soil. |
| | | | | PCP | 62 mg/kg | 6.8 - 20.7 mg/kg | |

**Table 8. Performance Data for Bioremediation of PAHs (continued)**

| Site Name | Media Treated | Technology | Additives | Contaminants Treated | Initial Contaminant Concentrations | Final Contaminant Concentrations | Comments |
|---|---|---|---|---|---|---|---|
| **Composting** | | | | | | | |
| Dubose Oil Products Co. Superfund Site, Cantonment, FL | Soil | Composting | Not reported | VOCs | 0.022-38.27 mg/kg | Not reported | Full-scale cleanup; each batch of soil treated to concentrations that met the cleanup goals (includes total PAHs at 50 mg/kg) within 14 to 30 days. |
| | | | | Total PAHs | 0.578-367 mg/kg | 3.3-49.9 mg/kg | |
| | | | | PCP | 0.058-51 mg/kg | Not reported | |
| **Slurry-Phase Bioremediation** | | | | | | | |
| French Limited Superfund Site, Crosby, TX | Soil and sludge | Slurry-phase bioremediation | Not reported | VOCs | 400 mg/kg | Not reported | Full-scale cleanup; all cleanup goals met. Cleanup goals established for vinyl chloride (43 mg/kg), benzene (14 mg/kg), benzo(a)pyrene (9 mg/kg), total PCBs (23 mg/kg), and arsenic (7 mg/kg). Benzo(a)pyrene reduced to 6.0 and 6.8 mg/kg in two treatment cells. |
| | | | | PCP | 750 mg/kg | Not reported | |
| | | | | SVOCs (including PAHs) | 5,000 mg/kg (for an individual contaminant) | Not reported | |
| | | | | Metals | 5,000 mg/kg (for an individual contaminant) | < 23 mg/kg | |
| | | | | PCBs | 616 mg/kg | < 23 mg/kg (cleanup goal for total PCBs) | |
| Southeastern Wood Preserving Superfund Site, Canton, MS | Soil and sludge | Slurry-phase bioremediation | Not reported | Total PAHs | 8,545 mg/kg | 634 mg/kg | Full-scale cleanup; all cleanup goals met, including total PAHs of 950 mg/kg and carcinogenic PAHs of 180 mg/kg. |
| | | | | Carcinogenic PAHs | 467 mg/kg | 152 mg/kg | |

Abbreviations: PAH = polycyclic aromatic hydrocarbon, PCP = pentachlorophenol, SVOC = semivolatile organic compound, VOC = volatile organic compound
Source: FRTR 2001

**Table 9. Performance Data for Bioremediation of Chlorinated VOCs**

| Site Name | Media Treated | Technology | Additives | Contaminants Treated | Initial Contaminant Concentrations | Final Contaminant Concentrations or Percent Removal | Comments |
|---|---|---|---|---|---|---|---|
| ***In Situ* Groundwater** | | | | | | | |
| Moffett Naval Air Station, Mountain View, CA | Groundwater | Recirculating cell (aerobic conditions) | Methane | TCE | Not reported | 19% removal | Field demonstration; numeric remedial goals not established. |
| | | | | 1,1-DCE | Not reported | Not evaluated | |
| | | | | cis-DCE | Not reported | 43% removal | |
| | | | | trans-DCE | Not reported | 90% removal | |
| | | | | VC | Not reported | 95% removal | |
| | Groundwater | Recirculating cell (aerobic conditions) | Phenol | TCE | Not reported | 94% removal | |
| | | | | 1,1-DCE | Not reported | 54% removal | |
| | | | | cis-DCE | Not reported | 92% removal | |
| | | | | trans-DCE | Not reported | 73% removal | |
| | | | | VC | Not reported | >98% removal | |
| | Groundwater | Recirculating cell (aerobic conditions) | Toluene | TCE | Not reported | 93% removal | |
| | | | | 1,1-DCE | Not reported | Not evaluated | |
| | | | | cis-DCE | Not reported | >98% removal | |
| | | | | trans-DCE | Not reported | 75% removal | |
| | | | | VC | Not reported | Not evaluated | |
| Edwards Air Force Base, Site 19, CA | Groundwater | Recirculating cell (aerobic conditions) | Toluene, dissolved oxygen, hydrogen peroxide | TCE | 1,000 µg/L | 18-24 µg/L | Field demonstration; numeric remedial goals not established. Final toluene concentration at site was 1.1 µg/L. |
| Hanford 200 West Area Site, Richland, WA | Groundwater | Recirculating cell | Acetate and nitrate | $CCl_4$ | 2,000 µg/L | 1,200 µg/L | Field demonstration; numeric remedial goals not established. |

**Table 9. Performance Data for Bioremediation of Chlorinated VOCs (continued)**

| Site Name | Media Treated | Technology | Additives | Contaminants Treated | Initial Contaminant Concentrations | Final Contaminant Concentrations or Percent Removal | Comments |
|---|---|---|---|---|---|---|---|
| Watertown, MA | Groundwater | Recirculating cell (anaerobic conditions for eight months, then aerobic conditions) | Anaerobic - lactic acid Aerobic - ORC and methane | TCE | 12,000 µg/L | < 1,000 µg/L | Field demonstration; numeric remedial goals not established. |
| | | | | PCE | Not reported | Not reported | |
| Texas Gulf Coast Site, Houston, TX | Groundwater | Recirculating cell | Methanol | TCE | 50,000 µg/L | 5 µg/L | Pilot- and full-scale; numeric remedial goals not established. |
| | | | | $Cr^{+6}$ | Not reported | Not reported | |
| Abandoned Manufacturing Facility, Emeryville, CA | Groundwater | Direct injection | Molasses | TCE | 3,040 µg/L (average) | 4 µg/L (average) | Pilot- and full-scale; numeric remedial goals not established. |
| | | | | $Cr^{+6}$ | Not reported | 99% removal | |
| Dover Air Force Base, Area 6, Dover, DE | Groundwater | Recirculating cell (anaerobic conditions) | Sodium lactate, ammonia, and phosphate, bioaugment-ation | PCE | 46 µg/L | Not reported | Field demonstration; numeric remedial goals not established. |
| | | | | TCE | 7,500 µg/L | Less than the detection limit | |
| | | | | cis-DCE | 2,000 µg/L | Less than the detection limit | |
| | | | | VC | 34 µg/L | Not reported | |

**Table 9. Performance Data for Bioremediation of Chlorinated VOCs (continued)**

| Site Name | Media Treated | Technology | Additives | Contaminants Treated | Initial Contaminant Concentrations | Final Contaminant Concentrations or Percent Removal | Comments |
|---|---|---|---|---|---|---|---|
| Avco Lycoming Superfund Site, Williamsport, PA | Groundwater | Direct injection (anaerobic conditions) | Molasses | TCE | 67 µg/L | 6.7 µg/L (treatment ongoing) | Pilot- and full-scale; concentrations of TCE reduced by 90%, but did not meet cleanup goal (5 µg/L) in all wells; cleanup goal for $Cr^{+6}$ (32 µg/L) and cadmium (3 µg/L) met in some wells |
| | | | | Cr+6 | 1,950 µg/L | 10 µg/L (treatment ongoing) | |
| | | | | Cadmium | 800 µg/L | Not reported | |
| U.S. DOE, Pinellas Northeast Site, Largo, FL | Groundwater | Recirculating cell (anaerobic conditions) | Benzoate, lactate, and methanol | TCE | Not reported | Not reported | Demonstration; VOC concentrations reduced 60% - 91% within four to eight weeks after nutrient addition. |
| | | | | Methylene chloride | Not reported | Not reported | |
| | | | | DCE | Not reported | Not reported | |
| | | | | VC | Not reported | Not reported | |
| U.S. DOE, Savannah River Site, M Area, SC | Groundwater | Recirculating cell | Nitrogen, phosphorus, methane | TCE | 10 to 1,031 µg/L | < 5 µg/L | Field demonstration; all cleanup goals at the site met. |
| | | | | PCE | 3 to 124 µg/L | < 5 µg/L | |
| ***In Situ* Source Treatment** | | | | | | | |
| U.S. DOE, Savannah River Site, M Area, SC | Soil and sediment | Recirculating cell | Nitrogen, phosphorus, methane | TCE | 0.67 to 6.29 mg/kg | Not detected | Field demonstration; all cleanup goals at the site met. |
| | | | | PCE | 0.44 to 1.05 mg/kg | Not detected | |

**Table 9. Performance Data for Bioremediation of Chlorinated VOCs (continued)**

| Site Name | Media Treated | Technology | Additives | Contaminants Treated | Initial Contaminant Concentrations | Final Contaminant Concentrations or Percent Removal | Comments |
|---|---|---|---|---|---|---|---|
| | | | | ***Ex Situ* Source Treatment** | | | |
| Dubose Oil Products Co. Superfund Site, Cantonment, FL | Soil | Composting | NA | VOCs (including chlorinated VOCs) | 0.022 to 38.27 mg/kg | Not reported | Full-scale cleanup; each batch of soil treated to concentrations that met cleanup goals within 14 to 30 days. |
| | | | | PAHs | 0.578 to 367 mg/kg | 3.3 to 49.9 mg/kg | |
| | | | | PCP | 0.058 to 51 mg/kg | Not reported | |
| French Limited Superfund Site, Crosby, TX | Soil and sludge | Slurry-phase bioremediation | NA | VOCs (including chlorinated VOCs) | 400 mg/kg | Not reported | Full-scale cleanup; all cleanup goals at the site met. Cleanup goals established for vinyl chloride (43 mg/kg), benzene (14 mg/kg), benzo(a)pyrene (9 mg/kg), total PCBs (23 mg/kg), and arsenic (7 mg/kg). |
| | | | | PCP | 750 mg/kg | Not reported | |
| | | | | SVOCs | 5,000 mg/kg | Not reported | |
| | | | | Metals | 5,000 mg/kg | < 23 mg/kg | |
| | | | | PCBs | 616 mg/kg | < 23 mg/kg (cleanup goal for total PCBs) | |

Abbreviations: $CCl_4$ = carbon tetrachloride, $Cr^{+6}$ = hexavalent chromium, DCE = dichloroethene, PAH = polycyclic aromatic hydrocarbon, PCB = polychlorinated biphenyl, PCE = tetrachloroethene, PCP = pentachlorophenol, SVOC = semivolatile organic compound, TCE = trichloroethene, VC = vinyl chloride, VOC = volatile organic compound

Sources: EPA 2000; FRTR 2001; McCarty and others, 1998.

Cleanup goals were met for the three source treatment bioremediation projects: the Savannah River Site, M Area, in South Carolina; the Dubose Oil Products Company Superfund Site in Florida, and the French Limited Superfund Site in Texas, with final concentrations of TCE and PCE reduced to non-detectable levels at the Savannah River Site.

**Pesticides and Herbicides**

Table 10 presents performance data for four sites at which bioremediation was used to treat media contaminated with pesticides and herbicides. At the Novartis site in Ontario, Canada, the concentration of metolachlor was reduced by nearly 99% using a composting process. At the Navajo Indian Reservation Superfund Removal site in Window Rock, Arizona, a slurry-phase process reduced the concentration of toxaphene from 4,000 mg/kg to 180 mg/kg (95%). At the Stauffer Chemical Company site in Tampa, Florida, soil contaminated with seven pesticides was treated using a registered composting process. Cleanup goals were met for four of the seven contaminants, with concentrations reduced to less than 9 mg/kg for DDE and DDT, and to less than 1 mg/kg for dieldrin and molinate. The concentrations of DDD and toxaphene were reduced by 90% but they did not meet their cleanup goals of 12.6 mg/kg and 2.75 mg/kg, respectively. Chlordane was reduced by nearly 90% but also did not meet its cleanup goal of 2.3 mg/kg. At the Creotox Chemical Products Superfund Removal site in Tennessee, contaminant concentrations in the soil for aldrin, BHC, and lindane did not decrease as a result of bioremediation (as reported in the source), although no numerical data were provided about final concentrations for these compounds. The waste subsequently was sent off site for disposal.

**Table 10. Performance Data for Bioremediation of Soil Contaminated with Pesticides and Herbicides**

| Site Name | Technology | Contaminant | Initial Concentration | Final Concentration |
|---|---|---|---|---|
| Novartis Site, Ontario Canada | Daramend$^{TM}$, a composting process developed by the W.R. Grace Company | Metolachlor | 84 mg/kg | 1 mg/kg |
| Navajo Indian Reservation Superfund Removal Site, Window Rock, Arizona | Anaerobic slurry-phase bioremediation | Toxaphene | 4,000 mg/kg | 180 mg/kg |

**Table 10. Performance Data for Bioremediation of Soil Contaminated with Pesticides and Herbicides (continued)**

| Site Name | Technology | Contaminant | Initial Concentration | Final Concentration |
|---|---|---|---|---|
| Stauffer Chemical Company Site, Tampa, Florida | Xenorem™, a composting process registered by Stauffer Management Company | Chlordane<br>DDD<br>DDE<br>DDT<br>Dieldrin<br>Molinate<br>Toxaphene | Chlordane - 47.5 mg/kg<br>DDD - 162.5 mg/kg<br>DDE - 11.3 mg/kg<br>DDT - 88.4 mg/kg<br>Dieldrin - 3.1 mg/kg<br>Molinate - 10.2 mg/kg<br>Toxaphene - 469 mg/kg | Cleanup goals met for DDE - 8.91 mg/kg; DDT - 8.91 mg/kg; dieldrin - 0.19 mg/kg; and molinate - 0.74 mg/kg; DDD and toxaphene concentrations reduced by 90% but did not meet cleanup goals - 12.6 and 2.75 mg/kg, respectively; chlordane reduced by nearly 90% but did not meet cleanup goal - 2.3 mg/kg<br>(at end of 64 day demonstration) |
| Creotox Chemical Products Superfund Removal Site, Tennessee | Not reported | Chlordane<br>Aldrin<br>BHC<br>Lindane | 596 mg/kg<br>Not reported<br>Not reported<br>Not reported | 77.3 mg/kg<br>No decrease<br>No decrease<br>No decrease |

Abbreviations: DDT = dichlorodiphenyltrichloroethane, DDD = dichlorodiphenyldichloroethane, DDE = dichlorodiphenyldichloroethene, BHC = "-benzene hexachloride

Source: Frazar 2000, FRTR 2001

Research efforts are underway to improve the effectiveness of bioremediation of soils and groundwater contaminated with pesticides and herbicides, including research into techniques to minimize or eliminate harmful by-products that sometime occur (for example, DDD and DDE by-products of DDT biodegradation), and into ways to shorten the treatment time. A pilot test at 9 sites used white-rot fungus treatment and cycling between aerobic and anaerobic phases to treat organochlorine pesticides in soil gas (the same class of pesticides that were not treated successfully at the Creotox Chemical Products Superfund removal site). Organophosphate pesticides, such as malathion and parathion, can be treated successfully by composting, land treatment, and use of aerobic bioreactors. (Frazer 2000)

**Explosives**

Bioremediation has been used to treat soils and groundwater contaminated with explosives, with varying degrees of success. At Umatilla Army Depot in Oregon, composting was used successfully at full scale to treat explosives in soil. Initial concentrations of trinitrotoluene (TNT) and 1,3,5-trinitro-1,3,5-triazine (RDX) were 88,000 mg/kg (5,250 mg/kg in the blended soil prior to treatment) and 1,900 mg/kg, respectively. Concentrations of both contaminants after treatment were less than 30 mg/kg.

The U.S. Army recently completed a demonstration and evaluation of 5 innovative bioremediation technologies on soils contaminated with explosive compounds. Soils excavated from Joliet Army Ammunition Plant (JOAAP) were contaminated with TNT and N-methyl-n,2,4,6-tetranitroaniline (tetryl). The initial average concentrations of TNT and tetryl in the soil were approximately 3,000 mg/kg and 7,500 mg/kg, respectively. Table 11 provides a description of the technologies used and the results of the pilot-scale demonstrations. Results ranged from little or no removal of contaminants to almost complete removal. For example, the pilot-scale project performed by Midwest Microbial achieved only a 31% reduction of TNT and a 3% reduction of tetryl. In contrast, the pilot-scale project performed by GRACE Bioremediation Technologies achieved a 97% reduction of TNT and an almost 100% reduction of tetryl.

**Table 11. Performance Data for Bioremediation of Soil Contaminated with Explosives**

| Technology Vendor | Technology Description | Contaminant | Initial Concentration | Final Concentration (Percent Removed) |
|---|---|---|---|---|
| Midwest Microbial | Soil was compacted and mixed with potato waste. A blend of aerobic and anaerobic bacteria and microbial nutrients was sprayed onto the soil every two weeks. | TNT | 3,000 mg/kg | 2,070 mg/kg (31%) |
| | | Tetryl | 7,500 mg/kg | 7,275 mg/kg (3%) |
| Bioremediation Technology Services | Soil was mixed with BTS®, a patented humic substance that contains large numbers and varieties of microorganisms. | TNT | 3,000 mg/kg | 3,000 mg/kg (0%) |
| | | Tetryl | 7,500 mg/kg | 2,700 mg/kg (64%) |
| Institute of Gas Technology | Under anaerobic conditions, nutrient sources were added to enhance the degrading abilities of the indigenous microbes. Biological treatment was followed by treatment with chemical oxidation using Fenton's Reagent (hydrogen peroxide and iron salt). | TNT | 3,000 mg/kg | 480 mg/kg (84%) (includes chemical oxidation performance) |
| | | Tetryl | 7,500 mg/kg | 1,875 mg/kg (75%) (includes chemical oxidation performance) |
| GRACE Bioremediation Technologies | Powdered iron and DARAMEND®, an organic amendment that alters the physical and chemical properties of the waste to enhance biological activity, were mixed with the soil. Conditions cycled between anoxic and oxic conditions during remediation. | TNT | 3,000 mg/kg | 90 mg/kg (97%) |
| | | Tetryl | 7,500 mg/kg | Not detected (100%) |
| EarthFax Engineering | Substrate inoculated with white-rot fungus was mixed with soil at a ratio of 4:1 by volume. | TNT | 3,000 mg/kg | 1,170 mg/kg (61%) |
| | | Tetryl | 7,500 mg/kg | 3,525 mg/kg (53%) |

Abbreviations: mg/kg = milligrams per kilogram, Tetryl = N-methyl-n,2,4,6-tetranitroaniline, TNT = trinitrotoluene

Source: U.S. Army 2000

## 5.0 COST OF BIOREMEDIATION TECHNOLOGIES

Cost data for bioremediation projects at Superfund and other sites is limited. This section summarizes available cost data for 22 bioremediation projects involving *in situ* and *ex situ* soil and *in situ* groundwater, and for 45 bioventing projects from the *Remediation Technology Cost Compendium – Year 2000 (EPA 2001a)*.

**Cost Data for 22 Projects Using *In Situ* Bioremediation (Soil and/or Groundwater) and *Ex Situ* Bioremediation (Soil)**

Table 12 summarizes the available cost data for the 22 bioremediation projects with fully-defined cost data.[7] The table includes information about project status, contaminants treated, start date, volume treated, total cost, and unit cost. Thirteen of the projects (59 percent) are *ex situ* source treatment projects, primarily land treatment. The remaining projects are *in situ* source treatment projects (14 percent) and *in situ* groundwater projects (27 percent).

Total technology costs for the 22 bioremediation projects range from $48,700 for a project mainly consisting of plowing and tilling 1,786 cy of soil at the Havre Air Force Station to $26,810,000 for slurry-phase bioremediation of 300,000 cubic yards of soil and sludge at the French Limited Superfund site. Unit costs ranged from $12.50/cy for a project mainly involving tilling 4,800 cy of soil at Glasgow Air Force Base to $1,220/cy for extensive technology demonstration activities on 1,048 cy of soil at the Bonneville Power Administration Superfund site. Projects where bioremediation was used to treat soil in an *ex situ* treatment system, such as land treatment or composting systems, had unit costs ranging from $13/cy to more than $500/cy, with most sites less than $300/cy.

**Cost Data for 45 Bioventing Projects**

Table 13 summarizes the available cost data for the 45 bioventing projects performed at multiple sites by AFCEE, including total cost, volume treated, and unit cost. As Table 13 shows, total costs for the 45 AFCEE bioventing projects ranged from $37,500 at Randolph Air Force Base, TX, to treat 4,700 cubic yards of soil, to $622,000 at McClellan Air Force Base, CA, to treat 53,200 cubic yards of soil. Unit costs ranged from $1.36/cy at Davis Monthan, AZ, to treat 311,500 cubic yards of soil, to $333/cy at AFP 4, TX, to treat 1,800 cubic yards of soil.

Cost data for the bioventing projects were sufficient to perform a quantitative analysis of unit cost versus quantity of soil treated (Figure 12). A reverse-exponential linear fit with a 68% confidence interval was calculated and plotted on decimal and logarithmic scales. Economies of scale in unit cost were observed for relatively large volumes of soil treated. Appendix B provides additional information about the statistical analyses used to develop the cost curves.

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[7] "Fully-defined" cost data refers to projects where the costs directly related to the technology application were distinct from the total cost for the remediation project and where data about quantity treated was available.

**Table 12. Selected Information for 22 Bioremediation Projects with Fully-Defined Cost Data**

| Site Name | State | Cleanup Program | Status | Contaminants | Start Year | Area Cost Factor | Technology Cost ($)[1] (Source) | Volume Treated (cy) | Unit Cost ($/cy) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Ex situ* Bioremediation (Soil) - Land Treatment** | | | | | | | | | | |
| Brown Wood Preserving Superfund Site | FL | Superfund | FS Complete | PAHs | 1989 | 0.87 | 635,000 | 8,100 | 78.4 | Constructed lined treatment system; moderate initial contaminant concentrations |
| Dubose Oil Products Co. Superfund Site | FL | Superfund | FS Complete | BTEX, cVOCs, Other SVOCs, Other VOCs | 1993 | 0.87 | 4,990,000 | 13,137 | 380 | Composting treatment system constructed in building, including leachate collection, inoculant generation, vacuum extractions, and wastewater treatment |
| Fort Greely UST Soil Piles | AK | Other | FS Complete | BTEX, PHC | 1994 | 1.60 | 749,000 | 9,800 | 76.4 | O&M only in summer months; no liner |
| Fort Wainwright, North Post Site Soil Remediation | AK | Other | FS Complete | BTEX | 1993 | 1.60 | 433,000 | 4,240 | 102 | Activities included liner construction, drainage, tilling, and addition of nutrients |
| Glasgow Air Force Base UST Removal | MT | Other | FS Complete | PHC | 1994 | 1.14 | 60,000 | 4,800 | 12.5 | Application mainly consisted of soil tilling |
| Havre Air Force Station, Remove Abandoned USTs | MT | Other | FS Complete | BTEX | 1992 | 1.14 | 48,700 | 1,786 | 27.3 | Application mainly consisted of soil plowing and tilling |
| Lowry AFB | CO | Other | FS Ongoing | BTEX, PHC | 1992 | 1.03 | 130,000 | 5,400 | 24.1 | Conducted on plastic sheeting, nutrients added once and aerated; interim costs |
| Matagora Island Air Force Base | TX | Other | FS Complete | BTEX | 1992 | 0.82 | 77,600 | 500 | 155 | Cost of entire project including excavation, treatment, and monitoring |
| Scott Lumber Company Superfund Site | MO | Superfund | FS Complete | PAHs | 1990 | 0.96 | 6,580,000 | 10,641 | 618 | Constructed lined treatment area, irrigation and drainage system, and addition of nutrient and culture |
| Umatilla Army Depot Activity (FS) | OR | Other | FS Complete | Other SVOCs | 1994 | 1.15 | 5,260,000 | 10,969 | 479 | Composting conducted in building; one of first biotreatments for soil contaminated with explosives; maintained high moisture content |

**Table 12. Selected Information for 22 Bioremediation Projects with Fully-Defined Cost Data (continued)**

| Site Name | State | Cleanup Program | Status | Contaminants | Start Year | Area Cost Factor | Technology Cost ($)[1] (Source) | Volume Treated (cy) | Unit Cost ($/cy) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Ex situ* Bioremediation (Soil) - Slurry-Phase** | | | | | | | | | | |
| French Limited Superfund Site | TX | Superfund | FS Complete | cVOCs, Other SVOCs, Other VOCs, PAHs, PCBs | 1992 | 0.82 | 26,810,000 | 300,000 | 89.4 | Extremely large volume |
| Southeastern Wood Preserving Superfund Site, OU 1 | MS | Superfund | FS Complete | PAHs | 1991 | 0.87 | 2,550,000 | 10,500 | 243 | Slurry-phase bioreactor system constructed; high initial contaminant concentrations; extensive pretreatment |
| ***Ex situ* Bioremediation (Soil) - Solid-Phase** | | | | | | | | | | |
| Bonneville Power Administration Superfund Site | WA | Superfund | FS Complete | PAHs, Other SVOCs | 1995 | 1.07 | 1,280,000 | 1,048 | 1,220 | Included extensive technology demonstration activities |
| ***In Situ* Bioremediation (Soil) - Bioventing** | | | | | | | | | | |
| Dover AFB, Area 6 | DE | Superfund | DS Complete | cVOCs, Heavy metals | 1996 | 1.02 | 551,000 | 1,667 | 331 | Direct injection of air and propane; cometabolic aerobic; pilot test |
| Hill AFB, Site 280 | UT | Not Specified | FS Ongoing | BTEX, PHC | 1990 | 1.03 | 271,000 | NR | NC | Interim costs |
| Hill AFB, Site 914 | UT | Other | FS Complete | BTEX, PHC | 1989 | 1.03 | 863,000 | 5,000 | 173 | Early bioventing application; combined with SVE |
| Lowry AFB (*in situ*) | CO | Other | FS Complete | BTEX, PHC | 1992 | 1.03 | 75,300 | NR | NC | Interim costs; high initial contaminant concentrations; used horizontal trenches |
| ***In Situ* Bioremediation (Groundwater)** | | | | | | | | | | |
| Avco Lycoming Superfund Site | PA | Superfund | FS Ongoing | cVOCs, Heavy metals | 1997 | 1.03 | 455,000 | NR | NC | Direct injection of molasses; anaerobic; air sparging, with SVE |
| Edwards AFB | CA | Superfund | DS Complete | cVOCs | 1995 | 1.15 | 445,000 | 1,517[2] | 293 | Recirculation between two aquifer systems; aerobic |
| Pinellas Northeast Site, Anaerobic Bioremediation | FL | RCRA CA | DS Complete | cVOCs | 1997 | 0.87 | 359,000 | 1,238[2] | 290 | Recirculation with addition of benzoate, lactate, and methanol; anaerobic; intended to supplement active pump-and-treat system |

## Table 12. Selected Information for 22 Bioremediation Projects with Fully-Defined Cost Data (continued)

| Site Name | State | Cleanup Program | Status | Contaminants | Start Year | Area Cost Factor | Technology Cost ($)[1] (Source) | Volume Treated (cy) | Unit Cost ($/cy) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| Texas Gulf Coast Site | TX | Other | FS Complete | cVOCs | 1995 | 0.82 | 630,000 | NR | NC | Recirculation with addition of methanol; anaerobic; intended as a precursor to monitored natural attenuation |
| Department of Energy, Savannah River Site, M Area Process Sewer/Integrated Demonstration Site | SC | Superfund | DS Complete | cVOCs | 1992 | 0.87 | 729,000 | NR | NC | Direct injection of cometabolites; aerobic; SVE employing horizontal wells |

Notes and Cost Sources:

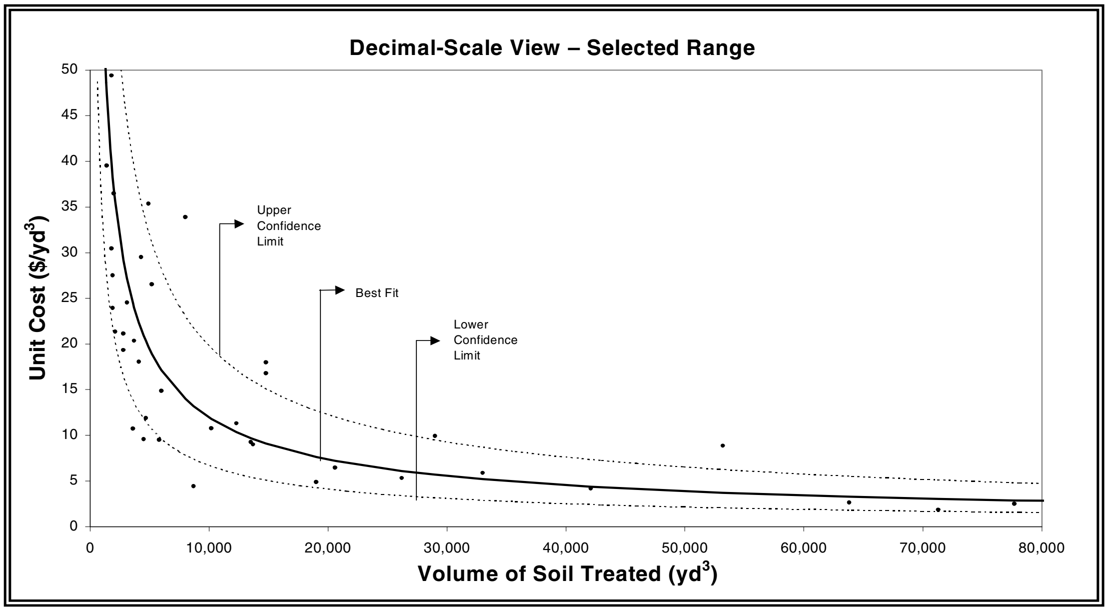
1 Technology costs for the selected sites were adjusted for the location of the site (location adjustment) and for the years in which costs were incurred (inflation adjustment). Costs were adjusted for location by multiplying the costs provided for each site by an Area Cost Factor (ACF) Index published by the U.S. Army Corps of Engineers in PAX Newsletter No. 3.2.1, dated March 31, 1999 and available on the web at <*http://www.hq.usace.army.mil/cemp/e/es/pax/paxtoc.htm*>. The inflation factor used for this analysis was based on the Construction Cost Index published by Engineering News Record. The most current year that had an annual average inflation adjustment factor available at the time of preparing this report was 1999. Costs were adjusted to 1999 dollars by multiplying the costs provided for each site by an inflation adjustment factor for the year in which the costs were incurred. For capital cost time adjustment, the inflation adjustment factor for the actual year the costs were incurred was used. For annual operating cost time adjustment, the inflation adjustment factor for the median year of all years over which the costs were incurred was used. The Cost Construction Index is available at *http://www.enr.com/cost/costcci.asp*.

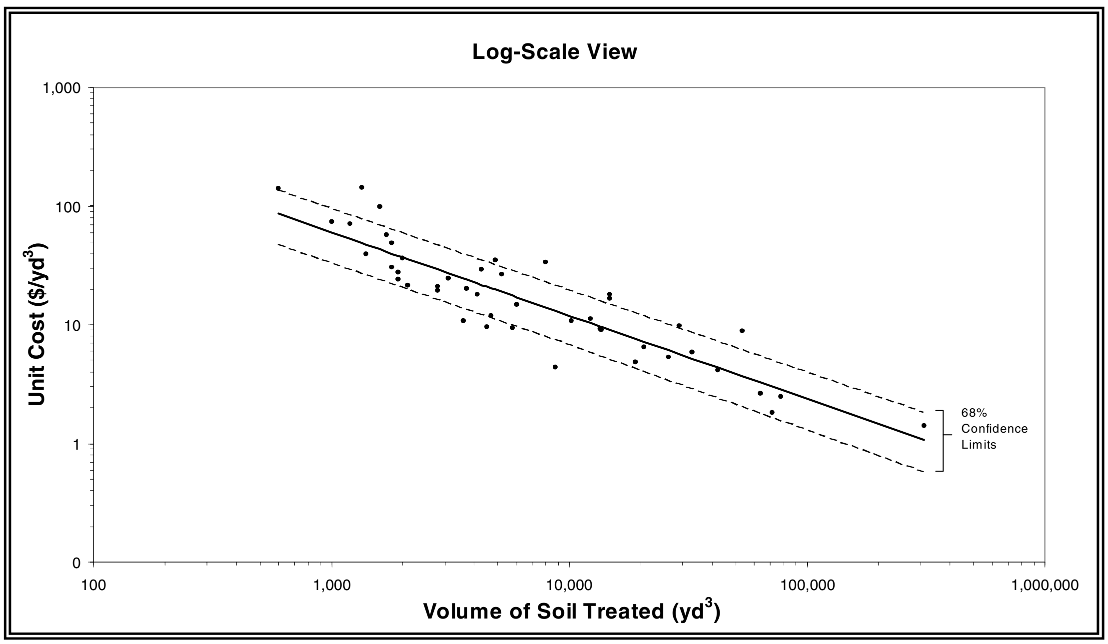
2 For *in situ* bioremediation (groundwater) applications, volume treated is the volume of aquifer material reported treated.

AFB Air Force Base
BTEX Benzene, Toluene, Ethylbenzene, and Xylenes
CA Corrective Action
cVOCs Chlorinated Volatile Organic Compounds
DS Demonstration scale
FS Full scale
NC Not calculated
NR Not reported
Other VOCs Other Volatile Organic Compounds (for example, ketones)
OU Operable Unit
PAHs Polycyclic Aromatic Hydrocarbons
PCBs Polychlorinated Biphenyls
PHC Petroleum Hydrocarbons
RCRA Resource Conservation and Recovery Act
UST Underground Storage Tank
SVE Soil Vapor Extraction
SVOCs Semivolatile Organic Compounds
cy Cubic yards

Source: EPA 2001a

## Figure 12. U.S. Air Force Bioventing Applications: Unit Cost Versus Volume Treated (68% Confidence Interval)




Notes:

[1] The line of best fit (solid line) and 68-percent confidence limits (dashed lines) for individual predicted points for 45 bioventing projects are shown in the plots above. The line of best fit and confidence limits were calculated using linear regression of the natural-log transformed data. The upper plot was prepared by back transformation of the log-transformed data to show the line of best fit and confidence limits in original units. (The upper plot shows projects under which less than 80,000 cubic yards of soil were treated and the unit cost was less than $50 per cubic yard.)

[2] All reported costs were adjusted for site locations, as described in the text.

[3] The coefficient of determination ($r^2$) for the linear fit to the data is 80 percent.

[4] Appendix B presents the methodology and other statistical information related to the plots above.

Source: EPA 2001a

## Table 13. U.S. Air Force Bioventing Projects

| Site Name | Site Location | Treatment Volume (cy) | Total Cost[1] ($) | Unit Cost ($/cy) |
|---|---|---|---|---|
| McClellan AFB | California | 53,200 | 622,000 | 11.7 |
| AFP 4 | Texas | 1,800 | 599,000 | 333 |
| Davis-Monthan | Arizona | 311,500 | 423,000 | 1.36 |
| Vandenberg AFB | California | 29,000 | 380,000 | 13.1 |
| Fairchild AFB | Washington | 8,000 | 310,000 | 38.8 |
| Pease AFB | New Hampshire | 14,800 | 293,000 | 19.8 |
| Hickam AFB | Hawaii | 13,700 | 270,000 | 19.7 |
| Plattsburgh AFB | New York | 63,800 | 255,000 | 4.00 |
| Elmendorf AFB | Alaska | 19,000 | 237,000 | 12.5 |
| Beale AFB | California | 42,100 | 232,000 | 5.51 |
| Offutt AFB | Nebraska | 14,800 | 219,000 | 14.8 |
| Hill AFB | Utah | 77,700 | 207,000 | 2.70 |
| Nellis AFB | Nevada | 26,200 | 181,000 | 6.91 |
| K.I. Sawyer AFB | Michigan | 71,300 | 179,000 | 2.50 |
| LA AFB | California | 20,600 | 176,000 | 8.54 |
| Edwards AFB | California | 4,300 | 168,000 | 39.1 |
| Patrick AFB | Florida | 1,350 | 146,000 | 108 |
| Cape Canaveral AFB | Florida | 4,900 | 131,000 | 26.7 |
| Kelly AFB | Texas | 33,000 | 130,000 | 3.94 |
| Cannon AFB | New Mexico | 13,500 | 128,000 | 9.48 |
| Charleston AFB | South Carolina | 1,600 | 120,000 | 75.0 |
| March AFB | California | 1,200 | 113,000 | 94.2 |
| Travis AFB | California | 600 | 112,000 | 187 |
| USCG Supp. Cen. Kodiak | Alaska | 4,500 | 110,000 | 24.4 |
| Eglin AFB | Florida | 12,300 | 105,000 | 8.54 |
| Shaw AFB | South Carolina | 5,200 | 104,000 | 20.0 |
| Bolling AFB | Washington DC | 10,200 | 99,000 | 9.71 |
| Camp Pendeleton | California | 4,100 | 97,900 | 23.9 |
| Grissom AFB | Indiana | 6,000 | 87,400 | 14.6 |
| McGuire AFB | New Jersey | 2,800 | 82,400 | 29.4 |
| Kirtland AFB | New Mexico | 3,100 | 77,500 | 25.0 |
| Malmstrom AFB | Montana | 1,400 | 71,900 | 51.4 |
| Pope AFB | North Carolina | 1,700 | 69,600 | 40.9 |
| Westover AFB | Massachusetts | 5,800 | 69,200 | 11.9 |
| Ft. Drum | New York | 1,900 | 68,800 | 36.2 |
| Ellsworth AFB | South Dakota | 3,700 | 68,000 | 18.4 |
| Mt. Hope AFB | Idaho | 1,900 | 58,700 | 30.9 |
| Little Rock AFB | Arkansas | 1,000 | 55,500 | 55.5 |
| Battle Creek ANGB | Michigan | 8,700 | 53,600 | 6.16 |
| FE Warren AFB | Wyoming | 2,800 | 53,000 | 18.9 |
| Dyess AFB | Texas | 2,000 | 49,000 | 24.5 |
| Hanscom AFB | Massachusetts | 3,600 | 48,500 | 13.5 |
| AFP PJKS | Colorado | 2,100 | 47,600 | 22.7 |
| Tinker AFB | Oklahoma | 1,800 | 41,500 | 23.1 |
| Randolph AFB | Texas | 4,700 | 37,500 | 7.98 |

[1] All reported costs were adjusted for site location, as described in the text.
Source: U.S. Air Force 1996

## 6.0 VENDORS OF BIOREMEDIATION

Information about vendors of bioremediation technologies is available in the EPA REACH IT database. As of August 2001, 175 vendors offered 344 types of bioremediation technologies, of which 294 were full scale, 15 were pilot scale, and 12 were bench scale. Of the vendors identified, 17 were classified as large businesses. The vendors provided information about 559 specific applications of their technologies, of which 514 were full scale.

The number of bioremediation vendors submitting information to EPA has increased significantly over the past 9 years. In 1992, EPA VISITT, the predecessor to EPA REACH IT, contained information about 30 bioremediation vendors. The larger number of bioremediation vendors in EPA REACHIT probably results primarily from an increase in service providers, along with increased awareness of the REACHIT database.

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## 8.0 ADDITIONAL INFORMATION ABOUT INFORMATION SOURCES

Additional information about selected sources of information about bioremediation are presented below:

- **Treatment Technologies for Site Cleanup: Annual Status Report (ASR) (Tenth Edition)** - This report documents the status of remediation technologies for soil, other solid wastes, and groundwater at sites in the Superfund program. Information in the ASR is collected annually from EPA and state project managers by EPA's Technology Innovation Office. The tenth edition of the ASR, which includes data collected through Summer 2000, was published in 2001 at <*http://clu-in.org/asr*>.

- **EPA's REmediation And CHaracterization Innovative Technologies (EPA REACH IT) online database <*http://www.epareachit.org*>** - EPA REACH IT contains site-specific technology data from the ASR, and vendor-supplied information about innovative treatment and characterization technologies. Information includes technology descriptions, performance, and cost. The database is searchable by key words.

- **Federal Remediation Technologies Roundtable (FRTR) cost and performance reports** - The FRTR has prepared over 270 cost and performance reports that present available information for full-scale remediation efforts and large-scale demonstration projects. They describe a wide variety of above-ground and *in situ* cleanup technologies, along with a variety of contaminants treated. The reports describe actual clean up projects, and contain project information on site background and setting, waste source, contaminants and media treated, technology design and operation, performance, cost, regulatory requirements, points of contact, and lessons learned.

- **Engineered Approaches to *In Situ* Bioremediation of Chlorinated Solvents: Fundamentals and Field Applications** - This report provides an overview of the fundamentals and field applications of *in situ* bioremediation to remediate chlorinated solvents in contaminated soil and groundwater and 9 case studies of chlorinated solvent cleanup. This report is available at <*http://clu-in.org*>.

- **Multiple Biotechnology Demonstrations of Explosives-Contaminated Soils -** This document presents the cost and performance results of five innovative laboratory- and pilot-scale bioremediation projects performed on explosives-contaminated soils at Joliet Army Ammunition Plant (JOAAP). The document is available on the United States Army web site at <*http://aec.army.mil/prod/usaec/et/restor/ecsoils.htm*>.

- **The Bioremediation and Phytoremediation of Pesticide-Contaminated Sites** - This report was prepared for EPA by Chris Frazar, a National Network of Environmental Studies (NNEMS) Fellow. The report provides a summary of bioremediation and phytoremediation technologies for treatment of pesticide-contaminated media. This report is available at <*http://clu-in.org*>.

- **Remediation Technology Cost Compendium – Year 2000** - This report wasprepared by EPA to provide information about costs of the following remediation technologies: bioremediation, thermal desorption, soil vapor extraction, on-site incineration, groundwater pump and treat, and permeable reactive barriers. It is available at <*http://clu-in.org*>.

Some of these sources (e.g., ASR, FRTR reports, and Engineered Approaches to *In Situ* Bioremediation of Chlorinated Solvents) can be ordered free of charge from the National Service Center for Environmental Pollution (NSCEP) by telephone at (513) 489-8190, by facsimile at (513) 489-8695, or on line at <*http://www.epa.gov/ncepihom/*>. NSCEP also can be contacted in writing at:

National Service Center for Environmental Publications
P.O. Box 42419
Cincinnati, OH 45242

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| | | | | ***Ex Situ* Source Treatment - Land Treatment (33 sites)** | | |
| 3 | Atlantic Wood Industry - OU 1 | VA | 1995 | 2,3,7,8-Tetrachlorodibenzodioxins (TCDD)<br>Pentachlorophenol (PCP) | Predesign/Design | Ronnie M. Davis<br>EPA<br>(215) 814-3230 |
| 3 | Naval Weapons Station Yorktown - OU 2 | VA | 1999 | Volatile organic compounds (VOCs) | Operational | Robert W. Stroud<br>EPA<br>(410) 305-2748 |
| 3 | Naval Weapons Station - Yorktown OU 13 | VA | 1999 | 2,4,6-Trinitrotoluene (TNT) | Operational | Robert W. Stroud<br>EPA<br>(410) 305-2748 |
| 3 | Tonolli Corp | PA | 1999 | Total petroleum hydrocarbons (TPH) | Predesign/Design | John Banks<br>EPA<br>(215) 814-3214 |
| 4 | Benfield Industries | NC | 1995 | Creosote | Operational | Jon Bornholm<br>EPA - Region 4<br>(404) 562-8820 |
| 4 | Brown Wood Preserving | FL | 1988 | Creosote | Completed | Randall Chaffins<br>EPA<br>(404) 562-8929 |
| 5 | Burlington Northern Railroad Tie Treating Plant | MN | 1986 | Creosote<br>Phenol | Completed | Linda Kern<br>EPA<br>(312) 886-7341 |
| 5 | Galesburg/Koppers | IL | 1989 | Creosote<br>PCP<br>Phenol | Operational | Fred Nika<br>Illinois EPA<br>(217) 782-3983 |
| 5 | Jennison Wright Corporation, Inc. | IL | 1999 | TCDD<br>Benzene<br>Benzo(a)anthracene<br>Benzo(a)pyrene<br>Benzo(b)fluoranthene<br>Carbazole<br>Dibenzo(a,h)anthracene<br>Indeno(1,2,3-cd)pyrene<br>Naphthalene<br>PCP | Predesign/Design | Fred Nika<br>Illinois EPA<br>(217) 782-3983 |
| 5 | Joslyn Manufacturing and Supply Co. | MN | 1989 | Acenaphthene<br>Anthracene<br>Benzo(a)anthracene<br>Benzo(a)pyrene<br>Benzo(b)fluoranthene<br>Naphthalene<br>PCP | Completed | David Douglas<br>Minnesota Pollution Control Authority<br>(651) 296-7818 |
| 5 | Ritari Post And Pole - OU 1 | MN | 1994 | PCP | Predesign/Design | Miriam Horneff<br>Minnesota Pollution Control Authority<br>(651) 296-7228 |
| 6 | Atchison, Topeka, & Santa Fe Clovis/Santa Fe Lake - TPH Lake Sediments | NM | 1988 | Petroleum hydrocarbons | Completed | Petra Sanchez<br>EPA<br>(214) 665-6686 |
| 6 | Gulf Coast Vacuum Services - OU 1 | LA | 1995 | Benzene<br>Polycyclic aromatic hydrocarbons (PAHs) | Operational | Kathleen Aisling<br>EPA<br>(214) 665-8509 |

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| ***Ex Situ* Source Treatment - Land Treatment (33 sites, continued)** | | | | | | |
| 6 | North Cavalcade Street | TX | 1988 | Creosote | Operational | Dan Switek<br>Texas Natural Resource Conservation Commission<br>(512) 239-4132 |
| 6 | Oklahoma Refining Co. - Hazardous Landfill | OK | 1992 | Benzene<br>Benzo(a)anthracene<br>Phenol<br>Toluene<br>Xylene | Operational | Earl Hendrick<br>EPA<br>(214) 665-8519 |
| 6 | Oklahoma Refining Co. - Nonhazardous Landfill | OK | 1992 | Benzene<br>Benzo(a)anthracene<br>Phenol<br>Toluene<br>Xylene | Operational | Earl Hendrick<br>EPA<br>(214) 665-8519 |
| 6 | Old Inger Oil Refinery | LA | 1984 | Benzene<br>Ethylbenzene<br>Petroleum hydrocarbons | Operational | Tom Stafford<br>Louisiana Department of Environmental Quality<br>(504) 765-0487 |
| 6 | Popile | AR | 1993 | Creosote<br>PCP | Predesign/Design | Shawn Ghose<br>EPA<br>(214) 665-6782 |
| 6 | Prewitt Abandoned Refinery | NM | 1992 | Benzene<br>Benzo(a)anthracene<br>Benzo(a)pyrene<br>Toluene<br>Xylene | Completed | Gregory Lyssy<br>EPA<br>(214) 665-8317 |
| 7 | Vogel Paint & Wax | IA | 1989 | Toluene<br>Xylene | Operational | Bob Drustrup<br>Iowa Department of Natural Resources<br>(515) 281-8900 |
| 8 | Broderick Wood Products - OU 2 (Soils) | CO | 1992 | PCP | Operational | Armando Saenz<br>EPA<br>(303) 312-6559 |
| 8 | Burlington Northern (Somers Plant) | MT | 1989 | Creosote<br>Phenol | Operational | James C. Harris<br>EPA<br>(406) 441-1150, ext. 260 |
| 8 | Idaho Pole Company | MT | 1996 | Anthracene<br>Benzo(a)pyrene<br>Chrysene<br>PCP<br>Phenol | Operational | James C. Harris<br>EPA<br>(406) 441-1150, ext. 260 |
| 8 | Libby Groundwater Contamination | MT | 1989 | Benzene<br>Creosote<br>PCP | Operational | James C. Harris<br>EPA<br>(406) 441-1150, ext. 260 |
| 8 | Montana Pole and Treating Plant | MT | 1993 | Anthracene<br>Naphthalene<br>PCP<br>Pyrene | Operational | James C. Harris<br>EPA<br>(406) 441-1150, ext. 260 |
| 8 | Wasatch Chemical | UT | 1991 | Toluene<br>Xylene | Completed | Erna Waterman<br>EPA<br>(303) 312-6762 |

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| ***Ex Situ* Source Treatment - Land Treatment (33 sites, continued)** | | | | | | |
| 9 | Fort Ord - Fort Ord Soil Treatment Area (Fdsta), OU 4 | CA | 1994 | Benzene<br>Diesel fuel<br>Ethylbenzene<br>Gasoline<br>Petroleum hydrocarbons<br>Toluene<br>Xylene | Completed | John Chesnutt<br>EPA<br>(415) 744-2324 |
| 9 | Luke AFB - OU 2/Dp23 | AZ | 1994 | Benzo(a)pyrene | Completed | Sean Hogan<br>EPA<br>(415) 744-2384 |
| 9 | Mather AFB - Soil and Groundwater OU, Mather Soils Biofarm | CA | 1996 | Benzene<br>Diesel fuel<br>Ethylbenzene<br>Gasoline<br>Petroleum hydrocarbons<br>Toluene<br>Xylene | Operational | Debbie Lowe<br>EPA<br>(415) 744-2206 |
| 9 | Mather AFB - OU 04 | CA | 1998 | Petroleum-related solvents | Operational | Debbie Lowe<br>EPA<br>(415) 744-2206 |
| 10 | Bonneville Power Administration - OU A | WA | 1993 | Creosote<br>PCP | Completed | Nancy Harney<br>EPA<br>(206) 553-6635 |
| 10 | Elmendorf AFB - OU 5 | AK | 1995 | Diesel fuel | Operational | Kevin Oates<br>EPA<br>(907) 271-6323 |
| 10 | Pacific Car and Foundry | WA | 1992 | Diesel fuel<br>TPH | Completed | Lynda Priddy<br>EPA<br>(206) 553-1987 |
| ***Ex Situ* Source Treatment - Composting (8 sites)** | | | | | | |
| 4 | Dubose Oil Products Co. | FL | 1990 | 1,1-Dichloroethene (DCE)<br>Acenaphthylene<br>Benzene<br>Benzo(g,h,i)perylene<br>PCP<br>Trichloroethene (TCE)<br>Xylene | Completed | Mark Fite<br>EPA<br>(404) 562-8927 |
| 4 | Milan Army Ammunition Plant - OU 3 & 4, Industrial Soil | TN | 1996 | TNT<br>1,3,5-trinitro-1,3,5-triazine (RDX) | Operational | Peter Dao<br>EPA<br>(404) 562-8508 |
| 4 | Stauffer Chemical Company | FL | 1996 | Nonhalogenated volatiles<br>Organochlorine pesticides | Design Completed/Being Installed | Brad Jackson<br>EPA<br>(404) 562-8925 |
| 5 | Joliet Army Ammunition Plant Soil and Groundwater (LAP) OU | IL | 1999 | TNT<br>Dinitrotoluene<br>RDX<br>Tetryl<br>Trinitrobenzene (TNB) | Operational | Diana Mally<br>EPA<br>(312) 886-7275 |
| 5 | Joliet Army Ammunition Plant Soil and Groundwater-MFG OU | IL | 1999 | TNT | Operational | Diana Mally<br>EPA<br>(312) 886-7275 |

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| ***Ex Situ* Source Treatment - Composting (8 sites, continued)** | | | | | | |
| 10 | U.S. Naval Submarine Base - OU 6 Site D & OU 2 Site F | WA | 1994 | TNT<br>Cyclotetramethylene tetranitramine (HMX)<br>RDX | Operational | Craig Thompson<br>Washington Department of Ecology<br>(360) 407-7234 |
| 10 | Umatilla Army Depot Activity | OR | 1992 | TNT<br>HMX<br>RDX | Completed | Harry D. Craig<br>EPA<br>(503) 326-3689 |
| 10 | Umatilla Chemical Depot (Lagoons) - Soil OU | OR | 1992 | TNT<br>HMX<br>RDX | Completed | Harry D. Craig<br>EPA<br>(503) 326-3689 |
| ***Ex Situ* Source Treatment - Biopile (3 sites)** | | | | | | |
| 4 | Stauffer Chemical (Cold Creek Plant) - OU 2 | AL | 1995 | Butylate<br>Cycolate<br>Molinate<br>Pebulate<br>Thiocarbonate<br>Vernolate | Operational | Michael Arnett<br>EPA<br>(404) 562-8921 |
| 5 | Macgillis and Gibbs/Bell Lumber and Pole - OU-1 | MN | 1999 | PCP<br>PAHs | Predesign/Design | Darryl Owens<br>EPA<br>(312) 886-7089 |
| 9 | Jasco Chemical Co. | CA | 1992 | 1,1-Dichloroethane<br>Acetone<br>Methylene chloride<br>Vinyl chloride<br>Xylene | Completed | Ellen Manges<br>EPA<br>(415) 744-2228 |
| ***Ex Situ* Source Treatment - Slurry Phase (2 sites)** | | | | | | |
| 4 | Cabot/Koppers - Koppers OU | FL | 1990 | Acenaphthene<br>Anthracene<br>PCP<br>Phenanthrene | Predesign/Design | Maher Budeir<br>EPA<br>(404) 562-8917 |
| 6 | Sheridan Disposal Services - Source Lagoon OU | TX | 1989 | Benzene<br>Grease<br>Oil<br>Phenol<br>Toluene | Predesign/Design | Gary A. Baumgarten<br>EPA<br>(214) 665-6749 |
| ***Ex Situ* Source Treatment - Other (3 sites)** | | | | | | |
| 3 | Naval Weapons Station - Yorktown - OU 03 | VA | 1998 | Not reported | Operational | Robert W. Stroud<br>EPA<br>(410) 305-2748 |
| 3 | Standard Chlorine Of Delaware, Inc. | DE | 1995 | Benzene<br>Chlorobenzene<br>Toluene | Predesign/Design | Hilary Thornton<br>EPA<br>(215) 814-3323 |
| 4 | T.H. Agriculture & Nutrition (Montgomery - OU 02) | AL | 1998 | Not reported | Predesign/Design | Brian Farrier<br>EPA<br>(404) 562-8952 |
| ***In Situ* Source Treatment - Bioventing (24 sites)** | | | | | | |
| 1 | Loring AFB - OU 9, Auto Hobby Shop Area | ME | 1995 | Diesel fuel<br>Petroleum hydrocarbons<br>Solvents | Operational | Mike Nalipinski<br>EPA<br>(617) 918-1268 |

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| ***In Situ* Source Treatment - Bioventing (24 sites, continued)** | | | | | | |
| 2 | Naval Air Engineering Center - Site 16 Under Area C | NJ | 1996 | 2-Methylnaphthalene<br>Petroleum hydrocarbons | Operational | Paul Ingrisano<br>EPA<br>(212) 637-4337 |
| 3 | Delaware Sand & Gravel Landfill - OU 4 and OU 5 | DE | 1993 | 1,2-dichloroethane<br>Benzene<br>bis-2-chloroethyl ether<br>Methylene Chloride | Operational | Philip Rotstein<br>EPA<br>(215) 814-3232 |
| 3 | Dover AFB - Target Area 3 of Area 6 | DE | 1995 | DCE<br>1,2-Dichloroacetic acid (DCA)<br>Tetrachloroethene (PCE)<br>TCE | Design Completed/Being Installed | Darius Ostrauskas<br>EPA<br>(215) 814-3360 |
| 5 | Onalaska Municipal Landfill | WI | 1990 | Naphthalene<br>Toluene | Completed | Tim Prendiville<br>EPA<br>(312) 886-5122 |
| 5 | Penta Wood Products - OU 01 | WI | 1998 | PCP | Predesign/Design | Anthony Rutter<br>EPA<br>(312) 886-8961 |
| 6 | Petro-Chemical Systems, Inc. - OU 2 | TX | 1998 | Benzene<br>Ethylbenzene<br>Naphthalene<br>Toluene<br>Xylene | Predesign/Design | Chris Villarreal<br>EPA<br>(214) 665-6758 |
| 6 | Tinker AFB - Soldier Creek and Building 3001 | OK | 1990 | Petroleum hydrocarbons<br>TCE | Operational | Hal Cantwell<br>Oklahoma Department of Environmental Quality<br>(405) 702-5100 |
| 8 | Broderick Wood Products - OU 2 (Groundwater) | CO | 1992 | PCP<br>Phenol | Operational | Armando Saenz<br>EPA<br>(303) 312-6559 |
| 9 | George AFB - OU 3 FT19a | CA | 1999 | Benzene<br>Ethylbenzene<br>Toluene<br>TPH<br>TCE<br>Xylene | Operational | James Chang<br>EPA<br>(415) 744-2158 |
| 9 | George AFB - OU 3 OT51 | CA | 1999 | Benzene<br>Ethylbenzene<br>Toluene<br>TPH<br>Xylene | Operational | James Chang<br>EPA<br>(415) 744-2158 |
| 9 | J.H. Baxter - Area B | CA | 1998 | Not reported | Operational | Beatriz Bofill<br>EPA<br>(415) 744-2235 |
| 9 | Mather AFB - OU 04 (site 18,23 & 59) | CA | 1998 | Diesel fuel<br>Gasoline<br>VOCs | Predesign/Design | Debbie Lowe<br>EPA<br>(415) 744-2206 |
| 9 | Tracy Defense Depot (U.S. Army) - OU 01 | CA | 1998 | 1,1,1-Trichloroethane | Predesign/Design | Michael Work<br>EPA<br>(415) 744-2392 |

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| ***In Situ* Source Treatment - Bioventing (24 sites, continued)** | | | | | | |
| 9 | Williams AFB - OU 3 | AZ | 1996 | Benzene<br>Ethylbenzene<br>JP-4 fuel<br>Petroleum hydrocarbons | Operational | Sean Hogan<br>EPA<br>(415) 744-2384 |
| 10 | Eielson AFB - OU 1 (Power Plant) | AK | 1994 | Benzene<br>Ethylbenzene<br>JP-4 fuel<br>Petroleum hydrocarbons | Operational | Mary Jane Nearman<br>EPA<br>(206) 553-6642 |
| 10 | Eielson AFB - OU 1 (Refueling Loop) | AK | 1992 | Benzene<br>Chrysene<br>Diesel fuel<br>Ethylbenzene<br>JP-4 fuel<br>Naphthalene<br>Petroleum hydrocarbons | Operational | Mary Jane Nearman<br>EPA<br>(206) 553-6642 |
| 10 | Eielson AFB - OU 2 (Fuel Area) | AK | 1994 | Benzene<br>Chlorobenzene<br>Chloromethane<br>Ethylbenzene<br>Naphthalene<br>TPH | Operational | Mary Jane Nearman<br>EPA<br>(206) 553-6642 |
| 10 | Eielson AFB - OU 3 (Refueling Loop USTs) | AK | 1994 | Benzene<br>Ethylbenzene<br>JP-4 fuel<br>Petroleum hydrocarbons | Operational | Mary Jane Nearman<br>EPA<br>(206) 553-6642 |
| 10 | Elmendorf AFB - OU 4 | AK | 1995 | Diesel fuel<br>Gasoline<br>JP-4 fuel | Operational | Kevin Oates<br>EPA<br>(907) 271-6323 |
| 10 | Fairchild AFB - Priority 1 OUs (OU 2) Ft-1 | WA | 1993 | Benzene | Operational | Ali Raad<br>Washington Department of Ecology<br>(360) 407-7181 |
| 10 | Fairchild AFB - Priority 2 Sites, OU 3, Sub Area Ps-1 | WA | 1996 | Petroleum hydrocarbons<br>Solvents | Operational | Ali Raad<br>Washington Department of Ecology<br>(360) 407-7181 |
| 10 | Naval Air Station Whidbey Island - Ault Field, OU 5, Areas 1, 31, and 52 | WA | 1996 | Benzene<br>Ethylbenzene<br>Toluene<br>TPH<br>Xylene | Operational | Nancy Harney<br>EPA<br>(206) 553-6635 |
| 10 | Union Pacific Railroad Tie Treatment - Vadose Zone Soils | OR | 1996 | Chrysene<br>Creosote<br>Naphthalene<br>PCP | Predesign/Design | Brian McClure<br>Oregon Department of Environmental Quality<br>(541) 298-7255, ext. 32 |
| ***In Situ* Source Treatment - Slurry-Phase Lagoon Aeration (2 sites)** | | | | | | |
| 6 | French Limited | TX | 1988 | 1,1-Dichloroethane<br>Benzo(a)pyrene<br>PCP<br>PAHs<br>Polychlorinated biphenyls (PCBs)<br>Volatile chlorinated organics<br>VOCs | Completed | Ernest R. Franke<br>EPA<br>(214) 665-8521 |

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| ***In Situ* Source Treatment - Slurry-Phase Lagoon Aeration (2 sites, continued)** | | | | | | |
| 7 | Pester Refinery Co. - OU 1, Burn Pond Site | KS | 1992 | Benzo(a)anthracene<br>Chrysene | Operational | Catherine Barrett<br>EPA<br>(913) 551-7704 |
| ***In Situ* Source Treatment - Other (9 sites)** | | | | | | |
| 2 | Dayco Corp./L.E. Carpenter Co., NJ | NJ | 1994 | Bis(2-ethylhexyl)phthalate | Operational (aerobic) | Gwen Zervas<br>New Jersey Department of Environmental Protection<br>(609) 633-7261 |
| 4 | Cabot/Koppers - Koppers OU | FL | 1990 | Acenaphthene<br>Anthracene<br>Creosote<br>PCP<br>Phenanthrene | Predesign/Design | Maher Budeir<br>EPA<br>(404) 562-8917 |
| 4 | Helena Chemical Company (Tampa Plant) | FL | 1996 | Aldrin<br>Chlordane<br>Dichlorodiphenyldichloroethane (DDD)<br>Dichlorodiphenyltrichloroethane (DDT)<br>Dieldrin<br>Heptachlor<br>Toxaphene | Predesign/Design | Brad Jackson<br>EPA<br>(404) 562-8925 |
| 4 | Koppers Co., Inc. (Charleston Plant) - OU 01 | SC | 1998 | Not reported | Design Completed/Being Installed | Craig Zeller<br>EPA<br>(404) 562-8827 |
| 4 | Peak Oil/Bay Drum - OU 1 | FL | 1993 | Benzo(a)anthracene<br>Ethylbenzene<br>Naphthalene<br>Pyrene<br>PCE<br>Xylene | Predesign/Design (aerobic) | Caroline Robinson<br>EPA<br>(404) 562-8930 |
| 5 | Seymour Recycling Corp. | IN | 1987 | Halogenated volatiles<br>Non-halogenated semivolatiles | Completed (aerobic) | Jeffrey Gore<br>EPA<br>(312) 886-6552 |
| 6 | American Creosote Works, Inc. - Winnfield Plant (Groundwater) | LA | 1993 | Creosote<br>PCP | Operational (aerobic) | John Meyer<br>EPA<br>(214) 665-6742 |
| 7 | Peoples Natural Gas | IA | 1991 | Benzene<br>Benzo(a)pyrene<br>Naphthalene<br>Toluene | Predesign/Design (aerobic) | Diana Engeman<br>EPA<br>(913) 551-7746 |
| 9 | J.H. Baxter | CA | 1998 | PCP | Design (aerobic) Completed/Being Installed | Beatriz Bofill<br>EPA<br>(415) 744-2235 |
| ***In Situ* Groundwater - Biosparging (3 sites)** | | | | | | |
| 5 | Fisher-Calo | IN | 1990 | Bis(2-ethylhexyl)phthalate<br>Naphthalene | Operational | Jeffrey Gore<br>EPA<br>(312) 886-6552 |

# Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| ***In Situ* Groundwater - Biosparging (3 sites, continued)** | | | | | | |
| 5 | Wayne Waste Oil | IN | 1990 | DCE<br>Benzene<br>PCE<br>Toluene<br>TCE<br>Vinyl chloride<br>Xylene | Operational | Jeffrey Gore<br>EPA<br>(312) 886-6552 |
| 6 | Tinker AFB - Soldier Creek and Building 3001 | OK | 1990 | Petroleum hydrocarbons<br>TCE | Operational | Hal Cantwell<br>Oklahoma Department of Environmental Quality<br>(405) 702-5100 |
| ***In Situ* Groundwater - Other (17 sites)** | | | | | | |
| 1 | Hocomonco Pond - ESD | MA | 1985 | Benzene<br>Creosote<br>Ethylbenzene<br>Naphthalene<br>Toluene<br>VOCs<br>Xylene | Operational (aerobic) | Derrick Golden<br>EPA<br>(617) 918-1448 |
| 2 | FAA Technical Center - OU 1, Area D - Jet Fuel Farm | NJ | 1989 | Benzene<br>JP-4 fuel<br>Naphthalene<br>Toluene | Operational (aerobic) | Julio Vazquez<br>EPA<br>(212) 637-4323 |
| 2 | Naval Air Engineering Station Areas I and J Groundwater OU 26 | NJ | 1999 | 1,1,1-Trichloroethane<br>1,1-Dichloroethane<br>1,1-Dichloroethene<br>cis-1,2-Dichloroethene<br>PCE<br>Trichloroethene | Operational (aerobic) | Paul Ingrisano<br>EPA<br>(212) 637-4337 |
| 2 | Shore Realty (formerly Applied Environmental Services) - Groundwater OU | NY | 1991 | Benzene<br>Ethylbenzene<br>Toluene<br>Xylene | Operational (aerobic) | Maria Jon<br>EPA<br>(212) 637-3967 |
| 3 | Avco Lycoming | PA | 1997 | Chromium | Operational (anaerobic) | Jill Lowe<br>EPA<br>(215) 814-3123 |
| 3 | Dover AFB - Target Area 2 of Area 6 | DE | 1995 | 1,1-Dichloroethane<br>1,2-Dichloroethene<br>Benzene<br>Carbon tetrachloride<br>Ethylbenzene<br>PCE<br>Toluene<br>TCE<br>Vinyl chloride<br>Xylene | Predesign/Design (anaerobic) | Darius Ostrauskas<br>EPA<br>(215) 814-3360 |

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

| Region | Site Name | State | ROD Year | Contaminants Treated | Project Status[1] (type of bioremediation) | Contact Name |
|---|---|---|---|---|---|---|
| ***In Situ* Groundwater - Other (17 sites, continued)** | | | | | | |
| 4 | American Creosote Works, Inc. - OU 2, Phase 2 | FL | 1994 | Acenaphthene<br>Anthracene<br>Benzene<br>Benzo(a)anthracene<br>Benzo(a)pyrene<br>Benzo(b)fluoranthene<br>Benzo(k)fluoranthene<br>Chrysene<br>Dibenzofuran<br>Fluoranthene<br>Fluorene<br>PCP<br>Phenanthrene<br>PAHs<br>Pyrene | Predesign/Design (aerobic) | Mark Fite<br>EPA<br>(404) 562-8927 |
| 5 | Kummer Sanitary Landfill - OU 3 - Amendment | MN | 1996 | 1,1,1-Trichloroethane<br>cis-1,2-Dichloroethene<br>Ether<br>Methane<br>TCE<br>Vinyl chloride | Completed (aerobic) | Gladys Beard<br>EPA<br>(312) 886-7253 |
| 6 | American Creosote Works, Inc. (Winnfield Plant) | LA | 1993 | Creosote<br>PCP | Operational (aerobic) | John Meyer<br>EPA<br>(214) 665-6742 |
| 6 | Petro-Chemical Systems, Inc. - OU 2 | TX | 1998 | Benzene<br>Ethylbenzene<br>Naphthalene<br>Toluene<br>Xylene | Operational (aerobic) | Chris Villarreal<br>EPA<br>(214) 665-6758 |
| 6 | Popile | AR | 1993 | Creosote | Predesign/Design | Shawn Ghose<br>EPA<br>(214) 665-6782 |
| 7 | Ace Services | KS | 1999 | Chromium | Predesign/Design (anaerobic) | Bob Stewart<br>EPA<br>(913) 551-7654 |
| 8 | Burlington Northern (Somers Plant) - Groundwater | MT | 1989 | Creosote<br>Phenol | Operational (aerobic) | James C. Harris<br>EPA<br>(406) 441-1150, ext. 260 |
| 8 | Idaho Pole Company | MT | 1992 | Anthracene<br>Benzo(a)pyrene<br>Chrysene<br>PCP<br>Phenol | Operational (aerobic) | James C. Harris<br>EPA<br>(406) 441-1150, ext. 260 |
| 8 | Libby Groundwater Contamination | MT | 1989 | Benzene<br>Creosote<br>PCP | Operational (aerobic) | James C. Harris<br>EPA<br>(406) 441-1150, ext. 260 |
| 8 | Montana Pole and Treating Plant - Groundwater OU | MT | 1993 | Anthracene<br>Naphthalene<br>PCP<br>Pyrene | Operational (aerobic) | James C. Harris<br>EPA<br>(406) 441-1150, ext. 260 |
| 9 | Koppers - Oroville Plant | CA | 1999 | Creosote<br>PCP | Operational (aerobic) | Charles Berrey<br>EPA<br>(415) 744-2223 |

## Appendix A: Selected Information about 104 Bioremediation Projects at Superfund Remedial Action Sites (FY 1982 through FY 1999) (continued)

[1] The project status listed in this table is the project status as of Summer 2000.

Abbreviations: DCA = 1,2-dichloroacetic acid; DCE = dichloroethene; DDD = dichlorodiphenyldichloroethane; DDT = dichlorodiphenyltrichloroethane; HMX = cyclotetramethylene tetranitramine; PAH = polycyclic aromatic hydrocarbon; PCB = polychlorinated biphenyl; PCE = tetrachloroethene; PCP = pentachlorophenol; RDX = 1,3,5-trinitro-1,3,5-triazine; TCDD = 2,3,7,8-tetrachlorodibenzodioxins; TCE = trichloroethene; TNB = trinitrobenzene; TNT = 2,4,6-trinitrotoluene; TPH = total petroleum hydrocarbons; VOC = volatile organic compounds

Source: EPA 2001

## APPENDIX B
## Additional Information about Development of Cost Curves for U.S. Air Force Bioventing Applications

The following approach was used in developing the cost curves for the cost compendium (EPA 2001a).

1. Both independent and dependent variables for each set of data (for example, volume of soil treated and unit cost, respectively) were transformed to their corresponding natural log values.

2. A linear best fit of the log-transformed data was determined. A statistical summary of the fit, including the coefficient of determination ($r^2$), provided a measure of how well the data fit the model, was prepared.

3. Residuals from the linear fit using the log-transformed data were examined to determine if they were distributed normally. The Shapiro-Wilk W test (goodness-of-fit test), in which the null hypothesis (Ho) is that the data are distributed normally, was used in that examination. If the probability of obtaining a value less than the value calculated using the W test (probability W) was less than 0.05, Ho was accepted, and it is concluded that the residuals were distributed normally.

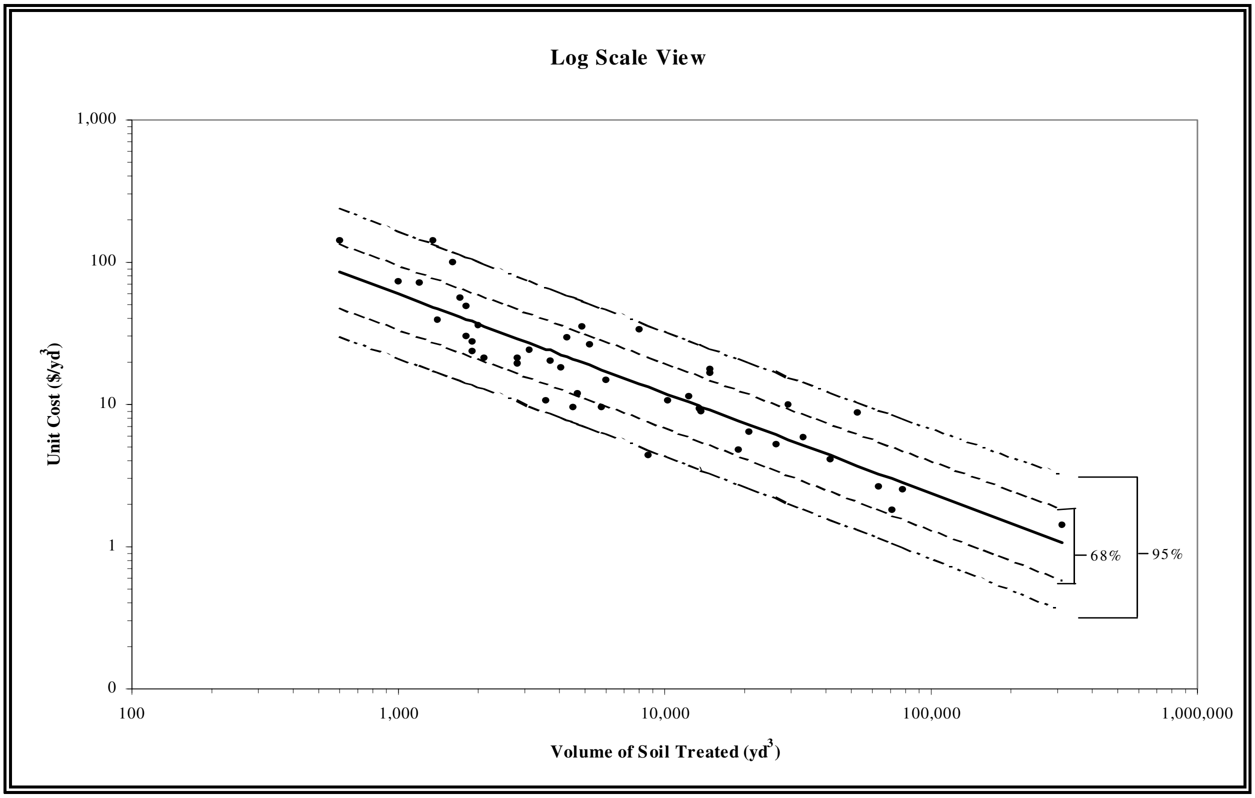
4. Individual predicted values, along with two sigma (95-percent) and one-sigma (68-percent) upper and lower confidence limits were calculated from the linear model (log-transformed scale).

5. The values then were plotted on a linear X-Y scale, and a subset of the plot enlarged to show clearly the smaller quantities of material treated. That step provided the decimal-scale view of the cost curves.

6. To portray the data in a linear manner, the predicted values were plotted on a $\log_{10}$-$\log_{10}$ scale, to provide the log-scale view of the plot .

The approach was developed on the basis of the cost data for bioventing applications. The coefficient of variation for the linear fit of the log-transformed data was 0.80, meaning that 80 percent of the variability in the data is explained by the model. Exhibits B-1 and B-2 present the log-scale view of the plot and detailed statistics used to develop the cost curves, respectively.

**Exhibit B-1. AFCEE Bioventing Applications – Unit Cost vs. Volume Treated (with 95- and 68-Percent Confidence Intervals)**




Notes:

1 The above plot shows a solid line based on a best fit of available data for 45 bioventing applications, and dashed lines for the upper and lower confidence intervals, using 95 percent and 68 percent degrees of confidence.

2 All reported costs were adjusted for location, as described in the text.

3 The coefficient of determination is 80 percent.

Source: EPA 2001a

# Exhibit B-2. Detailed Statistics Used to Develop the AFCEE Cost Curves

## Linear Fit

log(Cost/CY) = 8.9310144 - 0.7002108 log(CY)

### Summary of Fit

| | |
|---|---|
| RSquare | 0.799508 |
| RSquare Adj | 0.794845 |
| Root Mean Square Error | 0.494289 |
| Mean of Response | 2.760522 |
| Observations (or Sum Wgts) | 45 |

### Analysis of Variance

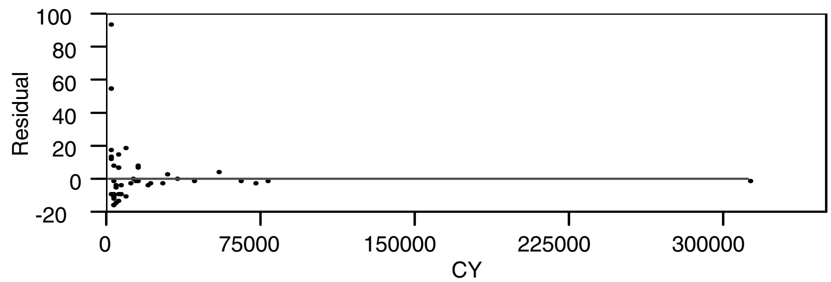
| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 1 | 41.894246 | 41.8942 | 171.4720 |
| Error | 43 | 10.505814 | 0.2443 | **Prob > F** |
| C. Total | 44 | 52.400060 | | <.0001 |

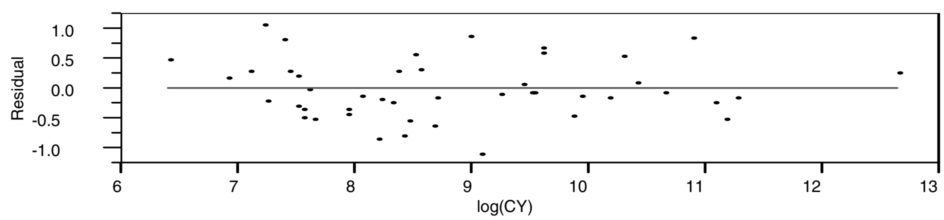
### Parameter Estimates

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| Intercept | 8.9310144 | 0.476946 | 18.73 | <.0001 |
| log(CY) | -0.700211 | 0.053473 | -13.09 | <.0001 |

## Fit Measured on Original Scale

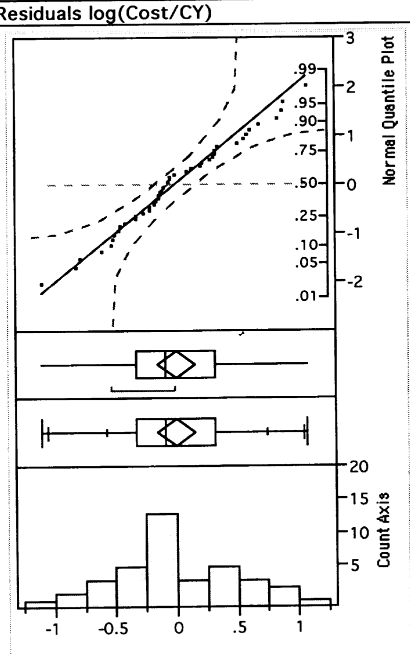
| | |
|---|---|
| Sum of Squared Error | 18372.596 |
| Root Mean Square Error | 20.670503 |
| RSquare | 0.6044654 |
| Sum of Residuals | 194.95537 |




## Distributions

### Residuals log(Cost/CY)




#### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 1.0791 |
| 99.5% | | 1.0791 |
| 97.5% | | 1.0500 |
| 90.0% | | 0.7424 |
| 75.0% | quartile | 0.3131 |
| 50.0% | median | -0.0931 |
| 25.0% | quartile | -0.3259 |
| 10.0% | | -0.5663 |
| 2.5% | | -1.0529 |
| 0.5% | | -1.0932 |
| 0.0% | minimum | -1.0932 |

#### Moments

| | |
|---|---|
| Mean | -1.5e-15 |
| Std Dev | 0.4886394 |
| Std Err Mean | 0.0728421 |
| upper 95% Mean | 0.146803 |
| lower 95% Mean | -0.146803 |
| N | 45 |
| Sum Wgts | 45 |
| Sum | -6.6e-14 |
| Variance | 0.2387685 |
| Skewness | 0.2063083 |
| Kurtosis | -0.25874 |
| CV | -3.31e+16 |

#### Goodness-of-Fit Test

Shapiro-Wilk W Test

| W | Prob<W |
|---|---|
| 0.979109 | 0.7261 |

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Use of Bioremediation at Superfund Sites

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