United States
Environmental Protection
Agency

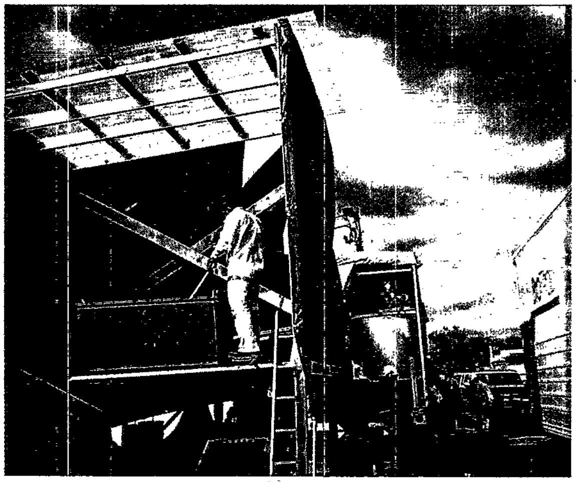
Research and
Development
(RD 681)

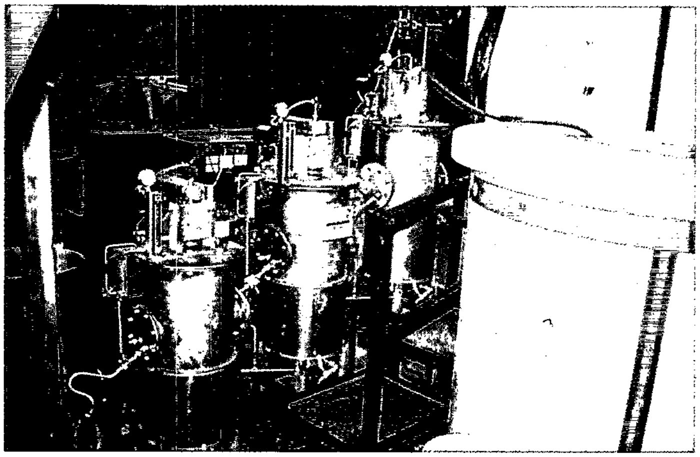
EPA/540/A5-91/003
February 1992

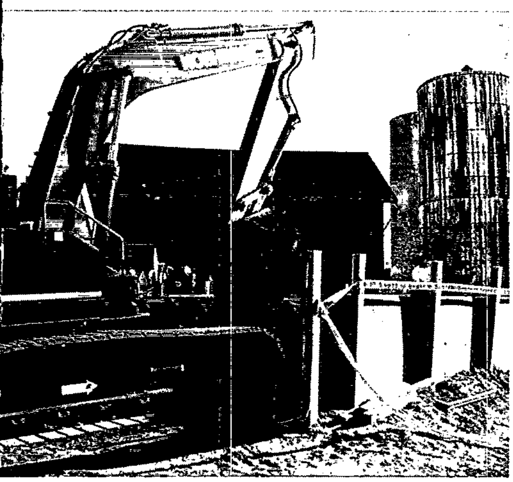
EPA

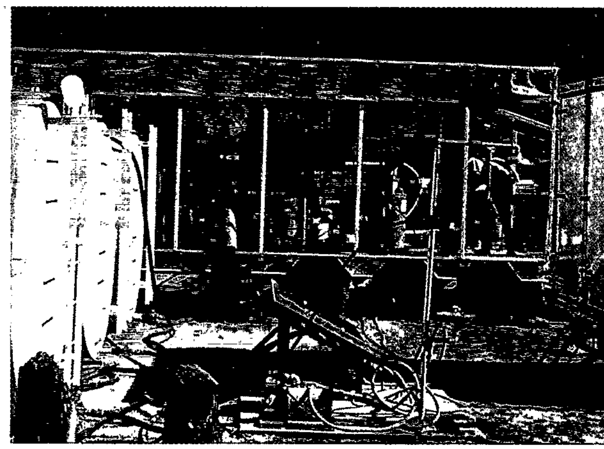
BioTrol Soil Washing System for Treatment of a Wood Preserving Site

Applications Analysis Report









SITE

SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

EPA/540/A5-91/003
February 1992

BioTrol Soil Washing System for Treatment of a Wood Preserving Site

Applications Analysis Report

Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH 45268

Printed on Recycled Paper

Notice

The information in this document has been funded by the U.S. Environmental Protection Agency under the auspices of the Superfund Innovative Technology Evaluation (SITE) Program under Contract Nos. 68-03-3485 and 68-CO-0048 to Science Applications International Corporation. It has been subjected to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

Foreword

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments. The Program is a joint effort between EPA's Office of Research and Development and Office of Solid Waste and Emergency Response. The purpose of the program is to assist the development of hazardous waste treatment technologies necessary to implement new cleanup standards which require greater reliance on permanent remedies. This is accomplished through technology demonstrations designed to provide engineering and cost data on selected technologies.

This project consisted of a demonstration of BioTrol, Inc.'s sequence of three processes for treatment of contaminated soil. It consists of (1) soil washing to wash and segregate coarse, relatively uncontaminated soil from more heavily contaminated fines; (2) biodegradation of the organic contamination on the soil fines in a slurry bioreactor; and (3) fixed-film, amended biological treatment of process water recycled in the soil washing operation. Extensive analysis was used to assess the effectiveness of each stage in the system. The study was carried out at the MacGillis and Gibbs Company site in New Brighton, Minnesota, where wood preserving operations have been carried out over several decades using the traditional wood preserving chemicals: first creosote, later pentachlorophenol, and most recently, chromated copper arsenate. In 1984 the site was added to the National Priorities List as one where soil and groundwater were contaminated with hazardous chemicals. The goals of this study were to evaluate the technical effectiveness and economics of a treatment process sequence to concentrate and then eliminate pentachlorophenol and polynuclear aromatic hydrocarbons from contaminated soil and to assess the potential applicability of the process to other wastes and/or other Superfund and hazardous waste sites.

Additional copies of this report may be obtained at no charge from EPA's Center for Environmental Research Information, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268, using the EPA document number found on the report's front cover. Once this supply is exhausted, copies can be purchased from the National Technical Information Service, Ravensworth Bldg., Springfield, VA, 22161, 703-487-4600. Reference copies will be available at EPA libraries in their Hazardous Waste Collection. You can also call the SITE Clearinghouse hotline at 1-800-424-9346 or 202-382-3000 in Washington, D.C. to inquire about the availability of other reports.

E. Timothy Oppelt, Director

Risk Reduction Engineering Laboratory

Abstract

This project was an evaluation of the BioTrol, Inc. Soil Washing System (BSWS), consisting of a proprietary mechanical soil washer and separation system, a Slurry Bio-Reactor (SBR) provided by EIMCO Process Equipment Co., and BioTrol's proprietary Aqueous Treatment System (BATS), a fixed-film, aerobic biological treatment process. In this study, both biological processes use bacterial populations selected to specifically degrade pentachlorophenol (penta).

This report summarizes and analyzes the results of the Superfund Innovative Technology Evaluation (SITE) Program's demonstration at the MacGillis and Gibbs Company wood preserving site in New Brighton, MN during the Fall of 1989. Extensive sampling and analysis were carried out to establish a data base against which the vendor's claims for the technology could be evaluated reliably. Data from other investigations by BioTrol are included to support the demonstration results. Conclusions were reached concerning the technological effectiveness and economics of the process and its suitability for use at other sites.

The primary conclusions from the demonstration study are:

(1) The Soil Washer effectively segregates the local soil into a coarse, relatively uncontaminated fraction constituting the largest output portion, smaller fractions of coarse and fine woody debris, and a contaminated fine fraction accounting for about 10% of the input solids weight.

(2) Starting with soils containing either 130 mg/kg or 680 mg/kg of penta, the removal efficiency for penta in the Soil Washer, defined as the change in contaminant concentration (weighted average) between the feed soil and the washed soil output stream, ranged between 89% and 87%. Removal efficiencies for polynuclear aromatic hydrocarbons were slightly lower, 83% and 88%, in tests with two soils. Concern about the efficiency of the extraction step during analysis of the feed soil, leading to low penta and PAH values, suggests that these values may be biased low. The vendor claims a 90% removal efficiency.

(3) Based on the demonstration study, 27.5% to 33.5% of the pentachlorophenol mass is concentrated in the fine particle cake fraction (as-is weight basis), between 18 and 28% is found in the coarse and fine oversize, and 34% to 39% is found in the processing water. The washed soil retains only about 9%. Thus, while washing or extraction of pentachlorophenol takes place, the predominant effect of the soil processing was segregation of coarse and fine particles. Similar distribution occurs with PAHs except that extraction into the aqueous fraction is much smaller due to the much lower solubilities.

(4) While steady-state operation was not achieved in the anticipated acclimation time (one week), the Slurry Bio-Reactor did achieve pentachlorophenol removals as high as 93% and, based on extrapolation of the data, may well be capable of even higher removal levels.

(5) The BATS successfully degraded between 91 and 94% of the pentachlorophenol in the aqueous process liquor, the Combined Dewatering Effluent (CDE).

(6) Combined capital and operating costs for the integrated system are estimated at $168/ton of feed soil, based on the MacGillis and Gibbs site. The Soil Washer accounts for about 90% of the cost, followed by slurry biodegradation of the fine particle slurry (about 2%) and treatment of the aqueous stream (about 1%). Unassigned

costs contribute about 5% to the total cost. Incineration of the woody debris found in the soil is a major component of the Soil Washer costs, contributing about 80% of the cost.

(7) On an individual unit basis, costs for the process were:

Soil Washer	\$185/metric ton or \$154/short ton of soil or \$197/yd^3 (including incineration)
SBR	\$9.22/1000 L or \$34.39/1000 gal of 20% slurry
BATS	\$0.44/1000 L or \$1.65/1000 gal of water treated

Secondary conclusions that have been reached on the basis of the demonstration study and other data provided by the vendor include:

(1) The Soil Washer also separates highly contaminated coarse oversize (wood chips) and fine oversize (sawdust) fractions, typical of wood preserving facilities. These fractions may be incinerated.

(2) The nature of the soil has a significant effect on the efficiency of soil washing and/or the segregation into coarse and fine fractions that can be achieved. The soil character (e.g., particle size) must be considered in evaluating the applicability of the Soil Washing System.

(3) Depending on the nature and concentration of contaminants of concern, acclimation of the Slurry Bio-Reactor may take considerably longer than the expected one week. Laboratory scale experiments would be needed in each case to establish the acclimation period. This may be important in scheduling and integrating units for a particular site.

(4) The system is not without mechanical problems and complexities that still need to be resolved. For example, clogging in the soil feed system forced a reduction in Soil Washer operating rates, and foaming in the BATS, probably due to thickening agent added for dewatering of the fines, created operational problems.

(5) The units evaluated in the demonstration study may not be appropriately-sized for integrated operation. Similarly, for a full scale system, calculations have indicated that a BATS capacity of about 300 gpm would be needed for the proposed 20 ton/hour soil processing rate. However, as discussed in the report, reuse of at least a portion of the process water without treatment may be possible.

Contents

Figures

Tables

Abbreviations and Symbols

BATS	BioTrol Aqueous Treatment System
BOD	biochemical oxygen demand (mg oxygen/liter)
BSWS	BioTrol Soil Washer System
BTEX	benzene, toluene, ethyl benzene, and xylenes
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
cfm	cubic feet per minute
COD	chemical oxygen demand (mg oxygen/liter)
GC/MS	gas chromatograph/mass spectrometer
gpd	gallons per day
gpm	gallons per minute
HPLC	high pressure liquid chromatograph
HSWA	Hazardous and Solid Waste Amendments to RCRA - 1984
kwh	kilowatt-hour
mg/kg	milligrams per kilogram (ppm)
mg/L	milligrams per liter (ppm)
NPL	National Priorities List
O/G	oil and grease
ORD	Office of Research and Development (EPA)
OSWER	Office of Solid Waste and Emergency Response (EPA)
PAHs	polynuclear aromatic hydrocarbons
Penta	pentachlorophenol (also PCP)
POTW	publicly owned treatment works
ppb	parts per billion
ppm	parts per million
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act of 1976
RI/FS	Remedial Investigation/Feasibility Study
RREL	Risk Reduction Engineering Laboratory (EPA)
SAIC	Science Applications International Corporation
SARA	Superfund Amendments and Reauthorization Act of 1986
SBR	Slurry Bio-Reactor

SITE	Superfund Innovative Technology Evaluation
TOC	total organic carbon (mg carbon/liter)
TRPH	total recoverable petroleum hydrocarbons
TSS	total suspended solids (mg solids/liter)
μg/kg	micrograms per kilogram (ppb)
μg/L	micrograms per liter (ppb)

Conversion Factors

	English (US)	*Metric (SI)*
Area:	1 ft^2	$9.29 \times 10^{-2} m^2$
	1 in^2	6.45 cm^2
Flow Rate:	1 gal/min	$6.31 \times 10^{-5} m^3/s$
	1 gal/min	$6.31 \times 10^{-2} L/s$
	1 Mgal/d	43.81 L/s
	1 Mgal/d	$3.78 \times 10^{3} m^3/d$
	1 Mgal/d	$4.38 \times 10^{-2} m^3/s$
Length:	1 ft	0.30 m
	1 in	2.54 cm
	1 yd	0.91 m
Mass:	1 lb	$4.54 \times 10^{2} g$
	1 lb	0.45 kg
Volume:	1 ft^3	28.32 L
	1 ft^3	$2.83 \times 10^{-2} m^3$
	1 gal	3.79 L
	1 gal	$3.79 \times 10^{-3} m^3$

ft = foot, ft^2 = square foot, ft^3 = cubic foot

in = inch, in^2 = square inch

yd = yard

lb = pound

gal = gallon

gal/min (or gpm) = gallons per minute

Mgal/d (or MGD) = million gallons per day

m = meter, m^2 = square meter, m^3 = cubic meter

cm = centimeter, cm^2 = square centimeter

L = liter

g = gram

kg = kilogram

m^3/s = cubic meters per second

L/s = liters/sec

m^3/d = cubic meters per day

Acknowledgments

This project was directed and coordinated by Mary K. Stinson, EPA SITE Project Manager in the Risk Reduction Engineering Laboratory - Cincinnati, Ohio.

Preparation of this report for EPA's Superfund Innovative Technology Evaluation (SITE) Program was coordinated by Herbert S. Skovronek of Science Applications International Corporation for the U.S. Environmental Protection Agency under Contract Nos. 68-03-3485 and 68-CO-0048. Contributors were William R. Ellis, Omer Kitaplioglu, Jorge McPherson, Venkat Rao, Susan Roman, Sanjiv Shah and others.

The cooperation and participation of Dennis D. Chilcote, Steven B. Valine, Thomas J. Chresand and supporting staff of BioTrol, Inc. throughout the course of the project and in review of this report are gratefully acknowledged, as is the assistance of A.J. Bumby of MacGillis and Gibbs.

Mark Lahtinen of the Minnesota Pollution Control Agency (MPCA) and Rhonda McBride, Linda Kern, and Darryl Owens, the Remedial Project Managers of USEPA's Region V, provided assistance and guidance in initiating the project and in interpreting and responding to regulatory needs of the project.

Michael Borst, Douglas Grosse, and Gordon M. Evans of USEPA's Risk Reduction Engineering Laboratory provided technical reviews of the draft report.

Section 1
Executive Summary

Introduction

One configuration of BioTrol, Inc.'s Soil Washing System (BSWS) has been used to treat pentachlorophenol-contaminated soil at a site on the Superfund National Priorities List. Operational and cost data were collected for that investigation and serve as the primary basis for an evaluation of the utility of this sequence of processes for remediation of other sites across the Nation. Supporting data from other studies and evaluation of one or more of the processes at other sites are discussed in Appendix D.

Conclusions

Based on the results of the SITE demonstration project at the MacGillis and Gibbs site in New Brighton, MN and information concerning other studies provided by the vendor, BioTrol, Inc., for different wastes at other sites, several conclusions can be drawn.

- The Soil Washer is capable of segregating a penta-contaminated feed soil (FS) into a major fraction of washed soil (WS) retaining little (~10% by weight) of the penta; smaller coarse and fine oversized (CO, FO) fractions retaining contamination (~20-30%), probably as woody debris; a fine particles (FPC) fraction retaining the bulk of the contamination (~30%) in a small mass; and a penta-contaminated (~30%) aqueous stream called the Combined Dewatering Effluent (CDE).

- Removal efficiencies for penta removal, defined as the change in concentration from the feed soil to the washed soil output stream (1-WS/FS), averaged 89% in the soil washer test for a soil with a low penta concentration (130 mg/kg) and 87% in the test with the high penta (680 mg/kg) soil. These values are only slightly less than the vendor's claim for a 90% removal efficiency. The removal efficiencies for total polynuclear aromatic hydrocarbons (PAHs) were slightly lower, 83% and 88% in the two tests.

- Once acclimated, the Slurry Bio-Reactor (SBR) should be capable of biologically degrading over 90% of the penta contamination in the fine particle fraction. Concentrations of polynuclear aromatic hydrocarbons are also extensively reduced (>70%). Because of longer-than-anticipated acclimation attributed to very high penta concentration in the slurry, the system was not at steady-state for much of the 14 day test. Consequently, the removal achievable under steady-state operation could not be determined.

- The fixed-film biological treatment system (BATS) is capable of destroying at least 91% of the pentachlorophenol in the process water from the soil washer after acclimation with a penta-specific bacterium. Because of low influent concentrations and high detection levels, removal of PAHs could not be determined.

- The removal of PAHs from the bulk of the soil and concentration in the fines fraction appears to parallel the behavior of the pentachlorophenol, except that little is found in the process water, the Combined Dewatering Effluent, probably due to lower solubility.

- Other constituents commonly encountered at such sites, including oils and heavy metals, were removed from the washed soil to varying degrees (removal efficiency: oil: 80-90%; copper, chromium, and arsenic: 50-70%).

- Predicting operating costs for other sites is difficult since one or more of the three processes may not be needed (or the most attractive alternative) for a particular site. Sizing of each process unit also must be considered within a particular scenario and will be dependent on time constraints for a cleanup, volume/characteristics of soil, etc.

- On the basis of an assumed 30,000 yd^3 of soil to be processed in a commercial system at the MacGillis and Gibbs site using a 20 ton/hr Soil Washer coupled with appropriately sized Slurry Bioreactor (23 gpm) and BATS (three 100 gpm) units, the cost (amortized capital plus operating), based primarily on the demonstration study, is estimated at $168/ton of feed soil.

- The Soil Washer accounts for 90% of the total cost, with incineration of the woody debris contributing about 80% to the calculated Soil Washer cost. Slurry biodegradation accounts for 2% of cost and aqueous treatment accounts for 1% of the cost. Unassigned costs contribute the remaining 5%.

- Since all three unit operations may not be necessary for a site, the following unit costs were also developed:

Soil Washer	$154/ton or $197/yd^3
Slurry BioReactor	$34.39/1000 gal of 20% slurry
BATS	$1.65/1000 gal of process water

- Operating labor was a major operating cost factor for all three units.

- A major contributor to the cost for the Slurry Bio-Reactor is the volume or mass of fines produced per unit mass of feed soil, which translates directly into the volume of slurry that will need to be treated. The developer indicates that the Soil Washer System is effective with soils containing less than 25% fines.

- While contaminant concentrations and flow rate attainable would be major contributors to the operating cost of the BATS, these factors are not major considerations in the overall economics, assuming that regulatory requirements for return of the washed soil to the site can be satisfied.

- One advantage of the Slurry Bio-Reactor and the BATS processes over other biological treatment processes is that they generate minimal quantities of sludge that would require solids separation and disposal.

- Auxiliary equipment needed to support this process is comparable to that for other aboveground treatment systems, such as excavation and prescreening of soil to remove oversized material and debris, oil/water separators and clarifiers for pretreatment of process water going to the BATS, and polishing filters, carbon adsorbers, etc. that may be needed for the effluent to meet local discharge requirements.

Discussion of Conclusions

The mobile pilot system tested at the MacGillis and Gibbs site consisted of a Soil Washer (SW) with a nominal capacity of 500 lb/hr wet (as is), a Slurry Bio-Reactor (SBR) with a throughput capacity of about 0.024 L/min (0.38 gal/hr) as a 2-10% slurry, and a pilot scale BioTrol Aqueous Treatment System (BATS) with a nominal hydraulic capacity of about 10 gpm. All units can be transported to a site for use in an evaluation.

Extensive data were collected over various segments of a six week period to assess the ability of the system to concentrate and then degrade pentachlorophenol and polynuclear aromatic hydrocarbons from the soil at the site; to establish the operational requirements of the system and its individual components; and to arrive at the costs of operation in such a manner that future decisions could be made as to the viability of one or all of the units for other sites. The data from this study serve as the primary basis for the foregoing conclusions. Additional supporting evidence was provided from other studies by BioTrol.

An extensive Quality Assurance (QA) program was conducted by SAIC under the supervision of EPA's QA program, including audits and data review along with corrective action procedures and special studies to resolve specific data quality problems. These programs are the basis for the quality of the data derived from the SITE project. Discussion of the QA program and the results of audits, data reviews, and special studies can be found in the Technology Evaluation Report.

Two feed soils, containing different penta concentrations, were prepared from the available soil for the study. The "low penta" concentration soil was prepared by mixing slightly contaminated soil from a former penta processing area with a more highly contaminated soil previously excavated at the site by BioTrol. The "high penta" soil was used as excavated. The primary variables studied were:

A. In the Soil Washer:
  a. input and output stream flow rates and totals
  b. penta concentration of input and output streams
  c. PAH concentrations of input and output streams
  d. soil characteristics

B. In the Slurry Bio-Reactor:
  a. overall penta concentration
  b. penta distribution between solids and liquid
  c. PAH distribution

C. In the BATS:
  a. penta concentration
  b. effect of metals, oil, etc.

The results of the SITE project demonstrated that the soil washing process successfully segregated coarse soil (major fraction) from fine clay and silt (small fraction). While the bulk of the mass remains in the coarse soil, the bulk of the penta and PAHs are in the fines fraction. In addition, woody debris was removed as coarse and fine oversize fractions, and an aqueous stream containing considerable penta but little PAHs was generated. Of these, the key product streams were the washed soil and the fine particle cake (clay/silt), although the coarse oversize fraction also retained a significant mass of penta, probably in woody debris.

While one option may be off-site disposal of the highly contaminated but small volume and weight of fine particle material, a more attractive option may be treatment of that material on-site in equipment such as the Slurry Bio-Reactor. This unit was tested on a small portion of the fine particle output stream. Over 90% of the pentachlorophenol and over 70% of the PAHs were removed in the SBR when the system had been stabilized, leaving a fine particle slurry with minimal contamination.

The system is a net consumer of water, absorbing about 10% of the 1200-1500 gallons introduced to transport and process each ton of soil. Municipal water, treated effluent from the BATS, and a dewatering polymer stream fed to the thickener provide this water. Dewatering of the solid fractions produces wastewater (Combined Dewatering Effluent, CDE) contaminated with the pollutants of concern, in this case penta and PAHs. The penta concentrations in the aqueous stream, up to its solubility limit of 80 ppm in the test with the high penta soil, appear to validate BioTrol's claim that the soil is washed or extracted as well as segregated by particle sizes.

BioTrol's fixed-film aerobic reactor (BATS) successfully treated this wastewater (at 3 gpm), degrading over 90% of the penta and producing an effluent suitable for recycle or discharge at the MacGillis and Gibbs site. In retrospect, there is some question whether there is a need to or benefit from treating all of this water before recycle. Losses to the various soil fractions, replaced by uncontaminated municipal water, may avoid buildup of penta (and perhaps metals). One option may be to treat a blowdown of the wastewater before recycle to assure that penta and other contaminants do not affect the quality of the washed soil product. Obviously, considering the capital cost for the BATS at $250,000 for 300 gpm capacity, this could lead to considerable savings.

While the primary factor in the evaluation of the system is the amount of penta on particular fractions of the soil, a second critical factor is the concentration of key pollutants that can be tolerated in the feed to the SBR and the BATS. At least on a small scale, this study demonstrated that the Slurry Bio-Reactor is capable of tolerating up to 5500 ppm of penta (dry weight basis) on the incoming fines in the slurry. At such a level, the solid surfaces may be inhibitory or toxic to penta-degrading bacteria. Nevertheless, the fine solids may serve as a reservoir of penta for the liquid phase until the adsorbed film finally reaches a concentration amenable to biodegradation on the surface. The dispersed bacterial population would only see and degrade the soluble penta (under 100 ppm), which is much more tolerable based on BATS results obtained by BioTrol in other studies.

Secondary pollutants such as oil and metals (including copper, chromium, and arsenic from current CCA wood treatment) did not appear to interfere with any of the three processes, at least not at the concentrations present in the soils (20-40 ppm each for arsenic, copper, and chromium in the high penta soil test) and the duration of the tests during the demonstration. If necessary, oil removal could be incorporated into the soil washing sequence or into the BATS. The centrifuge used to separate the fine particle cake from water can also separate oil if present. While there was some indication that metals were building up as the wastewater was recycled from BATS to soil washing, the short duration of this investigation did not make it possible to establish if an inhibitory effect might be observed in continuous operation. Clearly, such problems are surmountable, as by the incorporation of metal precipitation, but overall treatment cost would increase accordingly and additional hazardous wastes would have to be managed.

Several of the polychlorinated dioxins and furans were found in the soil and in some of the output streams at widely varying but low concentrations. Of these, the octachloro dioxin was the major isomer and the critical isomer, 2,3,7,8-TCDD, was not detected. While concern over these pollutants as byproducts from the manufacture of penta has, to date, delayed disposal of the wastes from the demonstration, their presence is not expected to affect large scale remediation once safe disposal levels are established and approved disposal routes are designated.

Section 2
Introduction

The SITE Program

The EPA's Office of Solid Waste and Emergency Response (OSWER) and the Office of Research and Development (ORD) established the Superfund Innovative Technology Evaluation (SITE) Program in 1986 to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its sixth year, the SITE Program is helping to provide the treatment technologies necessary to meet new federal and state cleanup standards aimed at permanent remedies, rather than short-term corrections. The SITE Program includes two major elements: the Demonstration Program and the Emerging Technologies Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data on selected technologies. EPA and the developers participating in the program share the cost of the demonstration. Developers are responsible for demonstrating their innovative systems at sites, usually Superfund sites agreed to by EPA and the developer. EPA is responsible for sampling, analyzing, and evaluating all test results. The outcome is an assessment of the technology's performance, reliability, and cost. This information, used in conjunction with other data, enables EPA and state decision-makers to select the most appropriate technologies for the cleanup of Superfund sites.

Developers of innovative technologies apply to the Demonstration Program by responding to EPA's annual solicitation. To qualify for the program, a new technology must have a pilot or full scale unit and offer some advantage over existing technologies. Mobile technologies are of particular interest to EPA.

Once EPA accepts a proposal, EPA and the developer work with the EPA Regional offices and state agencies to identify a site containing wastes suitable for testing the capabilities of the technology. EPA prepares a detailed sampling and analysis plan designed to evaluate the technology thoroughly and to ensure that the resulting data are reliable. A demonstration may require a few days to several months, depending on the type of process and the quantity of waste needed to assess the technology. Thus, while it may be possible to obtain meaningful results in a demonstration of one week using an incineration process, where contaminants are destroyed in seconds, this is not the case for a process sequence such as that offered by BioTrol, where operational reliability, integration of outputs from one unit to others, and biological and system acclimation and stability must be examined. In order to evaluate such parameters, it was determined that a minimum of six weeks of operations was necessary to evaluate the Soil Washer at two different penta concentrations, provide the input streams for the Slurry Bio-Reactor and BATS, and allow steady-state operation of the biological reactors for about two weeks each. After completing a demonstration, EPA prepares two reports which are explained in more detail below. Ultimately, the Demonstration Program leads to an analysis of the technology's overall applicability to Superfund problems.

The second principal element of the SITE Program is the Emerging Technologies Program, which fosters the further investigation and development of treatment technologies that are still at the laboratory scale. Successful validation of these technologies could lead to the development of systems ready for field demonstration. A third component of the SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative technologies to better characterize Superfund sites.

SITE Program Reports

The results of the SITE Demonstration Program are incorporated in two documents, the Technology Evaluation Report and the Applications Analysis Report. The former provides a comprehensive description of the demonstration and its results for engineers responsible for detailed evaluation of the technology relative to other specific sites and waste situations. These technical evaluators will want to understand thoroughly the performance of the technology during the demonstration, and the advantages, risks, and costs of the technology for the given application.

The Applications Analysis Report is directed to officials responsible for selecting and implementing remedial actions for specific sites. This report provides sufficient information for a preliminary determination of whether the technology merits detailed consideration as an option in cleaning up a specific site. If the candidate technology described in the Applications Analysis appears to meet the needs of the site engineers, more thorough assessment can be made based on the Technology Evaluation Report and information from remedial investigations for the specific site. In summary, the Applications Analysis will assist in determining whether the specific technology should be considered further as an option for a particular cleanup situation.

Purpose of the Applications Analysis Report

Each SITE demonstration evaluates the performance of a technology while treating the particular waste matrix found at the demonstration site. Additional data from other projects carried out by the developer also is presented where available.

Usually, the waste and/or soil at other sites requiring remediation will differ in some way from the waste matrix tested. Waste characteristic differences could affect waste treatability and use of the demonstration technology at other sites. Successful demonstration of a technology at one site does not assure that the same technology or configuration will work equally well at other locations. The operating range over which the technology performs satisfactorily can only be determined by examining a broad range of wastes and sites. This report provides an indication of the applicability of the BioTrol Soil Washer, the Slurry Bio-Reactor, and the BioTrol Aqueous Treatment System, both as individual operating units and as an integrated system, by presenting and examining not only the demonstration test data but also data available from other applications of the technology by the developer.

To enable and encourage the general use of demonstrated technologies, EPA considers the probable applicability of each technology to sites and wastes in addition to those tested, and strives to estimate the technology's likely costs in these applications. The results of these analyses are made available through the Applications Analysis Report.

Key Contacts

For more information on the demonstration of the BioTrol Soil Washing System for contaminated soil or on the companion evaluation of the BATS for contaminated groundwater, please contact:

1. Vendor concerning the process:

BioTrol, Inc.
11 Peavey Road
Chaska, Mn 55318
612-448-2515
Mr. Dennis D. Chilcote, Vice-President, Engineering
Mr. Thomas J. Chresand, Development Engineer

2. EPA Project Manager concerning the SITE Demonstration:

Ms. Mary K. Stinson
U.S. EPA - ORD
Technical Support Branch (MS-104)
2890 Woodbridge Avenue
Edison, NJ 08837-3679
908-321-6683

3. State contact concerning the MacGillis and Gibbs site:

Ms. Cathy O'Connell
Minnesota Pollution Control Agency
Site Response Section
Groundwater and Soil Waste Division
520 Lafayette Road
St. Paul, MN 55155
612-296-7775

4. EPA Regional contact concerning the MacGillis and Gibbs site:

Mr. Darryl Owens
U.S. EPA, Region V
230 South Dearborn Street
Chicago, IL 60604
312-886-7089

Section 3
Technology Applications Analysis

Introduction

This section addresses the potential applicability of the BioTrol Soil Washing System (BSWS) to other soils and Superfund site situations where pentachlorophenol and/or polynuclear aromatic hydrocarbons are the pollutants of primary interest. The demonstration at the MacGillis and Gibbs site provides an extensive data base as a foundation for conclusions on the effectiveness and the applicability to other cleanups. This data base is expanded somewhat by information from treatability studies concerning other soils, other wastes, and combinations of the two that have been provided by the vendor.

The following subsections summarize observations and conclusions drawn from the current study and supporting information. Included are discussions of factors such as site and soil characteristics, impact of state and federal environmental regulations, unique handling requirements, resource needs, and personnel factors. Additional information on the BioTrol technology, including a process description, vendor claims, a summary of the demonstration test results, and case studies of treatability studies are provided in the Appendices.

Conclusions

Based on the results of the demonstration test program at the MacGillis and Gibbs site, the vendor's claims for removal efficiency are largely substantiated.

Removal efficiency, defined as [1-(Washed Soil conc/ Feed Soil conc)], averaged 89% and 87% for pentachlorophenol (penta) in the tests with low penta- and high penta-contaminated soils, respectively. Polynuclear aromatic hydrocarbon removals were 83% and 88% in the two tests, with removal values for some individual PAHs well above 90%.

The process can segregate a penta-contaminated soil that is largely sand into a relatively uncontaminated coarse sand fraction representing the bulk of the volume and weight of the soil. The process is attractive where the washed soil meets cleanup requirements and can be returned to the site without further treatment. A smaller volume and weight of a highly contaminated fines fraction (clay/silt) is also produced. Coarse and fine oversize fractions containing penta-contaminated woody debris also are separated. These materials could be containerized and disposed of relatively inexpensively as a hazardous waste, e.g., by incineration. Thus, the Soil Washer acts as a waste volume reduction process.

Treating the contaminated fines fraction in a unit such as the Slurry Bio-Reactor, using a bacterial strain acclimated to the penta, may be more attractive than other destructive means. Although based on only limited data, it appears that the small-scale Slurry Bio-Reactor tested in this project can achieve over 90% destruction of the penta and 70% or higher removal of the associated PAHs, leaving a relatively uncontaminated fine particle slurry (clay/silt). Disposal requirements for all of these output streams from a particular site will be dependent on both the material characteristics and applicable state and federal regulations.

The water used to process (transport, agitate, abrade, extract, and classify) the soil becomes contaminated with penta, both by solubilization (washing/extraction) and by entraining fine particles bearing penta. This water, called the Combined Dewatering Effluent (CDE) and containing as much as 80 ppm penta in the demonstration study, can be treated successfully with BioTrol's Aqueous Treatment System (BATS). Over 90% degradation of penta is achieved when the CDE influent to the BATS contains 44 ppm penta. Based on this study and the groundwater study of the BATS in the companion SITE project, effluent concentrations of 1 ppm and significantly lower are achievable. Conversion of penta to inorganic chloride, water and carbon dioxide (mineralization) rather than to intermediate organics appears to take place.

The concentration of PAHs from the feed soil into the fines fraction probably reflects adsorption on the large surface area of the fines. Biodegradation in the Slurry Bio-Reactor achieved concentrations below detection limits for several of the individual PAHs (10-100 ppb) even though the unit had clearly not reached steady-state operation for much of the test. Estimated removals between 70% and 99% were attained.

The costs for the system were examined on both an integrated and on a unit process basis. This will help decision makers decide if one, two, or all three of the processes are needed and appropriate for a particular remediation. Extrapolating the demonstration study to full scale treatment of the MacGillis and Gibbs site, the integrated cost, including both operating costs and capital costs amortized over an assumed 10 years, was \$168/ton of feed soil. As individual units, the costs were as follows:

Soil washing/ segregation:	$154/ton soil treated (includes incineration of woody debris)
Slurry Bio-Reactor:	$34.39/1000 gal of 20% slurry
BioTrol Aqueous Treatment System:	$1.65/1000 gal of process water

How a system is designed, i.e., which processes are employed, the sizes selected, how frequently they operate, etc., obviously can affect total capital and contributing operating factors significantly. Section 4 of this report presents the cost analysis in more depth along with the assumptions used in arriving at the costs.

Discussion of Conclusions

The SITE program evaluation of one configuration of the BioTrol Soil Washer System at the MacGillis and Gibbs Company facility in New Brighton, MN demonstrated that the contamination in the bulk of a soil can be greatly reduced. The penta and PAHs are concentrated in a much smaller volume of fines that can be further treated to biodegrade the penta and PAHs. In the case of soluble contaminants such as penta, contaminated process water is also produced and can be treated biologically. Depending on the characteristics of the soil (e.g., percent of fines, distribution of contaminants) and the level of penta and PAH contamination, the washing process will be more or less successful in segregating uncontaminated sandy material (washed soil) and contaminated fines. Because of the nature of this SITE study, the discussion is presented in terms of the process units evaluated, i.e., Soil Washer, Slurry Bio-Reactor, and BioTrol Aqueous Treatment System. Figure 1 provides a schematic of the entire BSWS.

Soil Washing

To help in properly evaluating the effect of the soil washing, it is important to understand the size distribution of the original soil and the distribution of penta in the soil fractions. It should, however, be recognized that the particle size analysis itself, using water, may have altered the distribution of penta by extracting additional penta. Consequently, the particle size analysis may not be directly parallel to the soil washing operation. Both particle size and contaminant distribution can be significant factors in the utility of the BSWS.

Feed Soil Characterization

Two soil piles were prepared for the SITE study. The "high penta" soil consisted of indigenous soil containing about 600 ppm penta based on a composite analysis. The "low penta" soil was prepared by mixing relatively uncontaminated soil from a former penta processing area with another highly contaminated soil excavated at the site earlier by BioTrol. The mixed soil had an average penta concentration of 133 ppm.

Samples of both the low and high penta concentration soils used to demonstrate the BioTrol Soil Washing System were subjected to particle size analysis by wet sieving. The Unified Soil Classification System (USCS) was used to classify the soils into four characteristic soil fractions based on size ranges, as follows:

Fraction	Size Range
Cobbles	>76.2mm (3 inch)
Gravel	76.2mm to #4 sieve (4.75mm)
coarse gravel	76.2mm to 19.05mm
fine gravel	19.05mm to #4 sieve (4.75mm)
Sand	#4 to # 200 sieve (4.75mm to .075mm)
coarse	#4 to #10 sieve (4.75mm to 2.0mm)
medium	#10 to #40 sieve (2.0mm to .425mm)
fine	#40 to #200 sieve (.425mm to .075mm)
Fines (silts and clays)	Below #200 sieve (<.075mm)

The low penta concentration soil sample was composed of 5.74% gravel by weight, 71.2% sand, and 4.54% silt and clay with 81.5% recovery of the original sample weight. The high penta soil was composed of 2.53% gravel, 83.03% sand, and 7.4% silt and clay with 93.0% recovery (Table 1).

Table 1. Particle-Size Distributions-Low & High Penta Contaminated Soil

Soil Fraction	Size Range	Retained on Sieve: Low Penta feed gm[1]	Low Penta feed %[2]	Low Penta out %[2]	High Penta feed gm[1]	High Penta feed %[2]	High Penta out %[2]
Gravel	76.2mm to #4 sieve	61.8	5.74	7.0	11.7	2.53	2.7
Sand-coarse	#4 to #10 sieve	158.6	14.75	18.1	28.5	6.14	6.6
Sand-medium	#10 to #40 sieve	461.8	42.94	52.7	155.3	33.48	36.0
Sand-fine	#40 to #200 sieve	145.2	13.51	16.6	201.4	43.41	46.7
Fines (Silt/Clay)	below #200 sieve	48.4	4.54	5.6	34.3	7.4	8.0
	% Recovery		81.5			93.0	

[1] gm refers to the dry weights of the feed soil sample fractions
[2] Feed results are based on material as recovered

After wet sieving, solid fractions were analyzed for pentachlorophenol (penta), polynuclear aromatic hydrocarbons (PAHs), and copper, chromium, and arsenic (CCA). The fractions were grouped as follows for analyses:

- Material retained on the #4 and #10 sieves
- Material retained on the #20 and #40 sieves
- Material retained on the #60, #140, and #200 sieves
- Solid material passing the #200 sieve
- Aqueous solution passing the #200 sieve.

Table 2 summarizes the chemical analyses for the low penta concentration soil sample. While the analyses do not quite parallel the USCS classification of the soil shown in Table 1, the highest concentrations of contamination are found in the fraction with the smallest grain sizes (<200 mesh), equivalent to the fine particle cake from the Soil Washer, and the fraction with the largest grain sizes (>10 mesh), which would be equivalent to the coarse and fine oversize fractions. The medium and fine fractions most closely match up with the washed soil from the Soil Washer. Similar results were obtained for the high penta concentration soil (Table 3). Figures 2 and 3 graphically show the distribution of penta mass and the percent of soil represented by each size range in

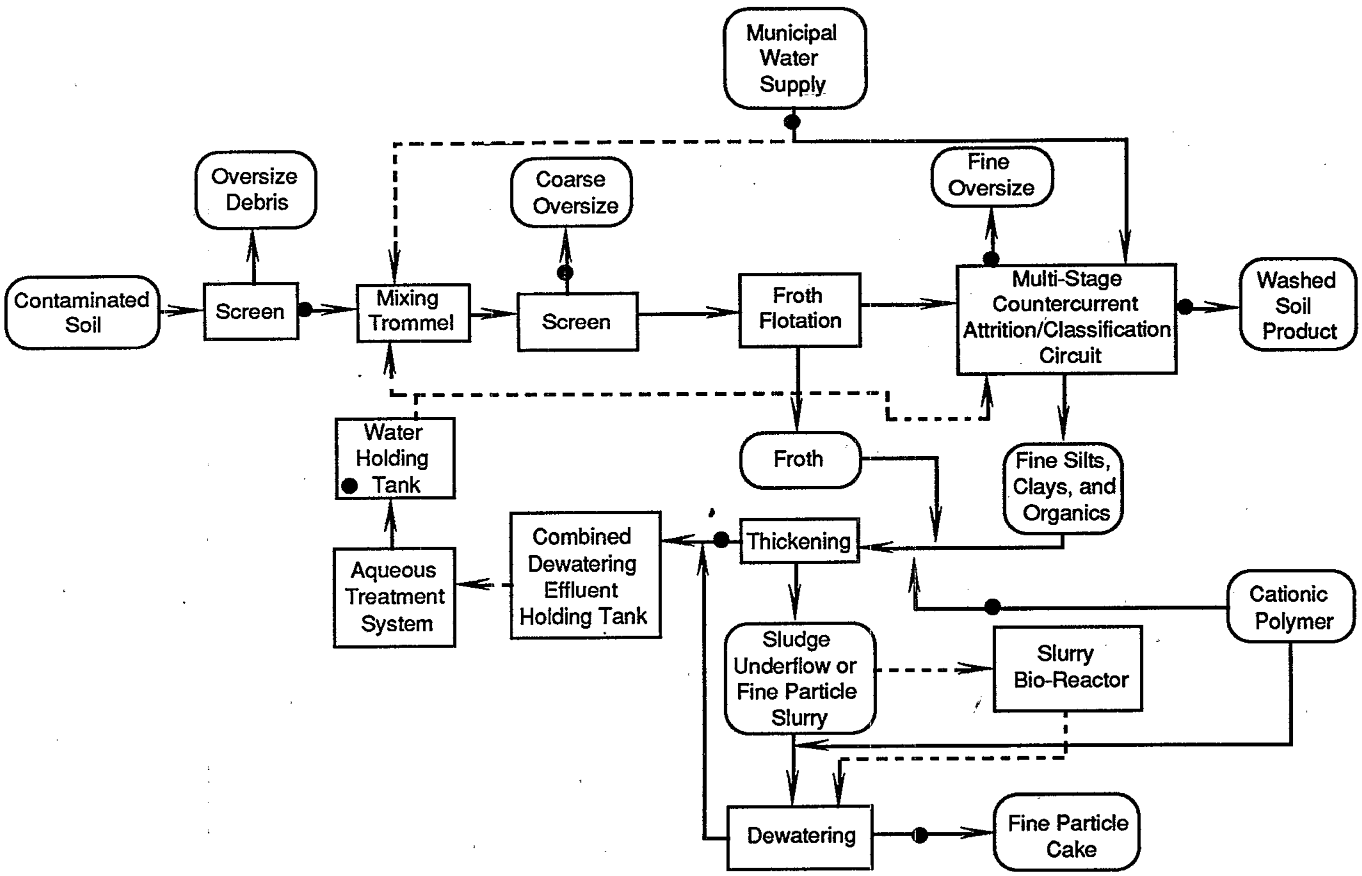


Figure 1. Flow Diagram of the Soil Washing System (SWS) with Sample Points.

the two soils. In both cases, the gravel and coarse sand contribute the largest mass of penta while accounting for 25% or less of the soil weight. While a significant portion of the penta may have dissolved into the aqueous solution, as found later in the demonstration study, the solutions were not analyzed due to laboratory problems.

It should be noted that the coarse fraction retained globules of tar or "tar balls", which did not break up readily and which may contribute to the high penta concentration.

Solid Process Stream Characterizations

Samples of the solid process streams from both the low penta soil washer test and the high penta test also were subjected to particle-size and chemical analysis. These process streams (see Figure 1) were as follows:

- Washed Soil (WS)
- Fine Particle Cake (FPC)
- Fine Oversize (FO)
- Coarse Oversize (CO).

On the USCS basis, the washed soil (WS) would be classified as a medium-grained sand with 89% and 96% of the particles for the low and high tests, respectively, falling in the sand range. The fine particle cake would be classified as fines (silts and clays) with 75% and 62% of the particles in the fines range.

Table 2. Chemical Analysis of Fractions - Low Penta Concentration Soil

	Fraction					
	feed soil*	gravel/ coarse sand	medium sand	fine sand	silt/ clay	aqueous
% of sample **	—	25.16	52.72	16.58	5.53	—
% of orig. sample	100	20.49	42.94	3.51	4.54	3.05
	mg/kg					
pentachlorophenol	133	240	42	48	240	NA
PAHs						
fluorene	11.5	ND	3.4J	1.1J	14	NA
phenanthrene	25.3	15	7.1	3.1	31	NA
anthracene	118.5	140	45	13	230	NA
fluoranthene	16.4	16	4.8	2.2	21	NA
pyrene	28.0	29	6.4	2.8	40	NA
benzo(a)anthracene	4.1J	ND	1.2J	ND	ND	NA
chrysene	9.9	12	2.8J	1.3J	16	NA
benzo(b)fluoranthene	3.1J	ND	1.0J	ND	ND	NA
arsenic	13.1	13.3	2.9	2.4	17.5	3.6
chromium	15.5	14	5.5	5.4	46	3.2
copper	13.0	13.2	4.2	3.7	22.7	2.9

NA = not analyzed; ND = not detected
J = estimated, <PQL but >0. if necessary.
* = organic analyses are averages of eight samples, metals are from composite sample.
** % = *100 x (sample wt. on screen/total sample wt. recovered).*

Table 3. Chemical Analysis of Fractions - High Penta Concentration Soil

	feed soil*	gravel/ coarse sand	medium sand	fine sand	silt/ clay	aqueous
	Fraction					
% of sample **	100	9.32	36.02	46.70	7.96	—
% of orig. sample	100	8.67	33.48	43.41	7.40	4.23
	mg/kg					
penta	512	1200	250	160	1100	NA
PAHs						
acenaphthene	19.6	27	6.6	4.7	22	NA
fluorene	20.8	25	4.6	4.4	19	NA
phenanthrene	76.2	97	18	17	130	NA
anthracene	35.5	66	19	8.5	32	NA
fluoranthene	69.5	89	29	21	200	NA
pyrene	69.6	99	26	19	160	NA
benzo(a)anthracene	17.0	24	6.3	4.2 J	18	NA
chrysene	26.9	40	14	7.4 J	30	NA
benzo(b)fluoranthene	11.5	10	4.9	ND	13	NA
benzo(k)fluoranthene	9.9	ND	4.5	ND	10	NA
benzo(a)pyrene	5.3	ND	2.4J	ND	8.4	NA
arsenic	21.9	41.1	5.9	7.2	67	0.38
chromium	32.1	64.5	20.8	7.6	97.4	0.28
copper	28.5	55	10.4	6.7	78.6	0.34

NA = not analyzed; ND = not detected
J = Estimated, <PQL but >0
* = Organic analyses are averages of 12 samples, metals are from composite sample
** % = 100 x (sample wt. on screen/total sample wt. recovered)

The fine oversize fractions would be classified as medium-grained sand with 85% and 77% of the particles falling in the sand range. It had the appearance of peat moss and consisted largely of very small organic fibers. Based on this laboratory description and using the USCS, the fine oversize could be classified as a highly organic soil. The coarse oversize would be classified as a coarse-grained sand, with the predominant particle-size falling in the sand range (72% and 82% respectively). It also contained gravel (30% in the low penta soil and 21% in the high penta soil).

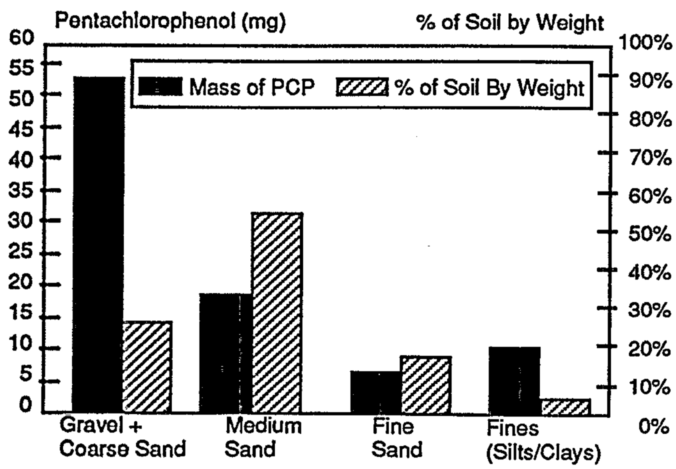


Figure 2. Particle-Size Fraction Analysis Low Penta Concentration Soil Sample. (1075 gm sample)

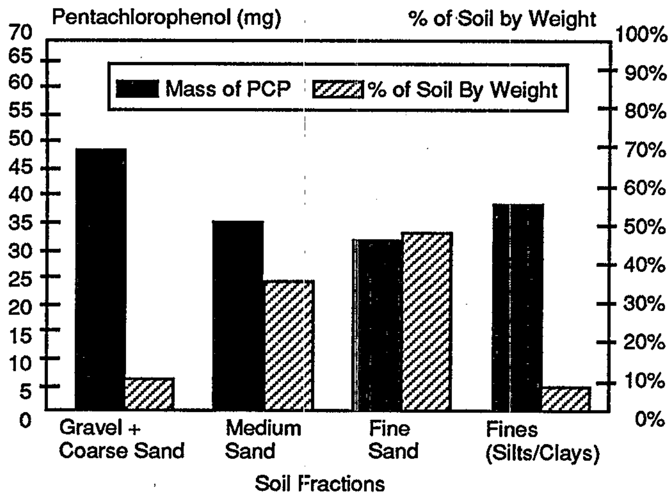


Figure 3. Particle-Size Fraction Analysis High Penta Concentration Soil Sample. (464 gm sample)

The highest concentrations of penta and PAHs occur in the coarse oversize (gravel, wood particles, and coarse sand) and fine particle cake (silts and clays) streams. Distribution of PAHs and chromium, copper, and arsenic follow a similar pattern, in general, with higher concentrations on fine particle cake and coarse and fine oversize fractions. Particle size and contaminant distribution are summarized in Tables 4 and 5.

Particle-size analysis of the individual process streams confirms that the BioTrol Soil Washing System succeeded in separating the soil into specific particle-size fractions.

The following observations can be made by comparing the results from the particle-size analysis and chemical analysis of particle-size fractions of the feed soils and the solid process streams:

- The highest concentrations of contamination occur in the oversize (>10 mesh) and fines (<200 mesh) particles.
- The oversize (>10 mesh) and fines (<200 mesh) contribute more than 50 % of the penta mass while making up only 20-30 % of the soil weight.

Mass Distribution - Soil Washer

Overall, the soil washing process results can be summarized for the low and high penta contaminated soils as shown in Figures 4 and 5. The major portion of the penta is found on the fine particle cake (33.5% and 27.5%, respectively in low penta and high penta soil washer tests). The total (carcinogenic and non-carcinogenic) PAHs follow a similar pattern with 61% and 55%, respectively, on the fine particle cake. Much less of the relatively insoluble PAHs are extracted into the aqueous phase. In spite of the careful use of proper procedures in making all measurements, the output rates of solids, penta, and PAHs are higher than the input rates, as summarized in Table 6. While there are no explanations for

Table 4. Particle-Size Analysis and Chemical Analysis of Solid Process Streams - Low Concentration Soil Test

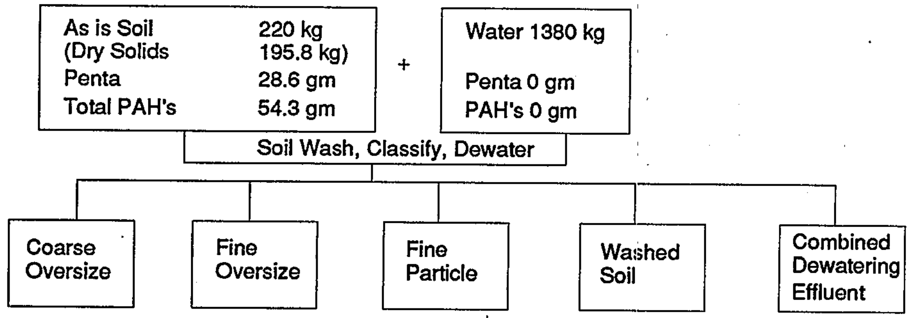
Process Stream: Particle-Size Results Sieve #/Fraction Size	Washed Soil % Soil on Sieve	Fine Particle Cake % Soil on Sieve	Fine Oversize % Soil on Sieve%	Coarse Oversize Soil on Sieve
#3/8 / 9.50 mm	+	+	+	9%
#4 / 4.75 mm	+	+	+	21%
#10 / 2.00 mm	+	+	+	30%
#20 / .850 mm	3%	+	76%	38%
#40 / .425 mm	76%	8%	3%	1%
#60 / .250 mm	7%	5%	2%	1%
#140 / .106 mm	6%	3%	3%	1%
#200 / .075 mm	1%	3%	1%	1%
Pan < .075 mm	2%	75%	6%	3%
Total % Recovery	95%	94%	91%	105%
Analytical Results*				
Pentachlorophenol	19	210	130	190 E
Fluorene	ND	43	33	15
Phenanthrene	0.870 J	120	74	38
Anthracene	5.2	490	260	68 E
Fluoranthene	1.5 J	42	18	14
Pyrene	2.9	83	15	21
Benzo(a)anthracene	0.33 J	12	3.7 J	3.3
Chrysene	1.2 J	34	9.8 J	8.8
Benzo(b)fluoranthene	ND	6.5 J	2.4 J	1.7 J
Copper	5	44.9	8.8	15
Chromium	6.4	47.6	9.7	22.4
Arsenic	3.9	41.9	7.5	5.6

+ - Sieve not used in particle-size analysis of this sample.
* - All analytical results are reported in mg/kg.
E - Exceeds the calibration.
J - Estimated value; less than the sample quantitation limit but greater than zero.
ND - Analyzed, not detected.

Table 5. Particle-Size Analysis and Chemical Analysis of Solid Process Streams - High Concentration Soil Test

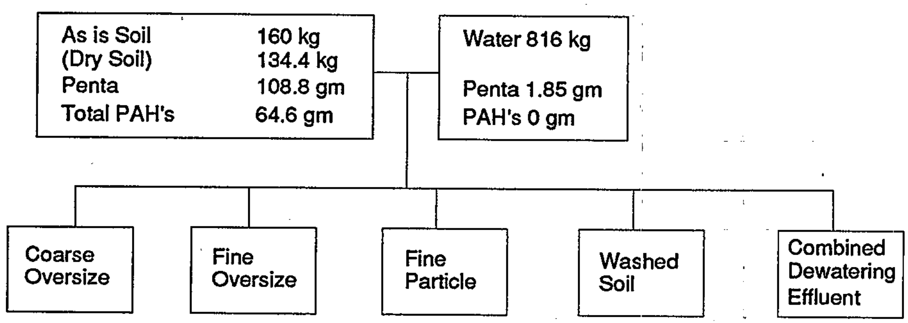
Process Stream: Particle-Size Results Sieve #/Fraction Size	Washed Soil % Soil on Sieve	Fine Particle Cake % Soil on Sieve	Fine Oversize % Soil on Sieve%	Coarse Oversize Soil on Sieve
#3/8 / 9.50 mm	+	+	+	5%
#4 / 4.75 mm	+	+	+	16%
#10 / 2.00 mm	+	+	+	28%
#20 / .850 mm	4%	+	73%	48%
#40 / .425 mm	63%	4%	1%	2%
#60 / .250 mm	19%	12%	1%	2%
#140 / .106 mm	9%	11%	1%	3%
#200 / .075 mm	1%	11%	1%	1%
Pan < .075 mm	2%	62%	24%	3%
Total % Recovery	98%	100%	101%	106%
Analytical Results*				
Pentachlorophenol	110	1500	430	1000
Fluorene	4.3	56	14	22
Phenanthrene	16	240	47	81
Anthracene	6.7	130	42 B	33 J
Fluoranthene	17	180	39	74
Pyrene	11	200	35	60
Benzo(a)anthracene	3.1 J	59 J	9.1	14
Chrysene	5.6	65 J	17	26
Benzo(b)fluoranthene	1.9	31	6	7.8 J
Copper	20.6	120	17.3	36.7
Chromium	33	113	24.8	80.8
Arsenic	11.8	80.8	16.8	36.6

+ - Sieve not used in particle-size analysis of this sample.
* - All analytical results are reported in mg/kg.
B - Found in the associated method blank.
J - Estimated value; less than the sample quantitation limit but greater than zero.



As is wt.	32 kg	13 kg	48 kg	260 kg	1100 kg
Dry wt.	22.1 kg	1.04 kg	14.4 kg	189.8 kg	0
Penta wt.	5.44 gm	1.25 gm	12.96 gm	3.64 gm	15.4 gm
% Total Penta	14.0%	3.2%	33.5%	9.4%	39.8%
PAH's	9.88 gm	2.71 gm	37.33 gm	10.93 gm	0.55 gm
% of PAH's	16.1%	4.4%	60.8%	17.8%	0.9%

Figure 4. Low Penta Soil Washer Test - Weighted Hourly Rates.



As is wt.	28 kg	9.1 kg	36 kg	210 kg	720 kg
Dry wt.	13.2 kg	1.4 kg	12.6 kg	144.9 kg	0
Penta wt.	39.2 gm	8.2 gm	46.8 gm	18.3 gm	57.6 gm
% Total Penta	23.0%	4.8%	27.5%	10.8%	33.9%
PAH's	14.75 gm	4.13 gm	36.88 gm	9.89 gm	1.38 gm
% of Total PAH's	22.0%	6.2%	55.0%	14.8%	2.0%

Figure 5. High Penta Soil Washer Test - Weighted Hourly Rates.

Table 6. Average Mass/Hour Balance

Low Penta Soil Washer Test:

material	input/hr	output/hr	mass balance
dry soil solids	195.8 kg	227.3 kg	+16%
water	1404.2 kg	1225.7 kg	-13%
penta	28.6 gm	38.7 gm	+35%
PAHs	54.3 gm	61.4 gm	+13%

High Penta Soil Washer Test:

material	input/hr	output/hr	mass balance
dry soil solids	134.4 kg	173.2 kg	+29%
water	841.6 kg	829.9 kg	- 1%
penta	110.6 gm	170.1 gm	+54%
PAHs	64.6 gm	67.0 gm	+ 4%

the poor soil mass balance, it has been postulated that the higher total penta and PAH concentrations and masses measured in the output streams may be the result of improved accessibility for the analytical extractions from the breakdown of agglomerated soil during the soil washing.

Only low concentrations of any of the dioxins and furans were detected in any of the feed or output streams from the soil washing. The key isomer of concern, 2,3,7,8-TCDD, was not detected. The distribution of dioxins and furans to the output streams also followed the general pattern observed with penta, with the highest concentration of combined species, as "Total CDD/CDFs", in the fine particle cake and the lowest in the washed soil in both the low penta and the high penta soil washer tests. On this basis, the removal efficiencies (1-WS/FS) were 92% and 97%, respectively.

On a mass basis, the fine particle cake accounted for 63% (low penta) and 71% (high penta) of the Total CDD/CDFs. The washed soil from the two tests accounted for only 12% (low penta) and 5% (high penta) of the Total CDD/CDFs mass.

Slurry Bio-Reactor Effectiveness

The fine particles from the soil washing can simply be dewatered, containerized, and disposed of as a hazardous waste, probably by incineration. By eliminating the bulk of the soil, the mass of contaminated material is drastically reduced to about 20% of the feed soil weight on an as-is basis and such disposal may, in certain circumstances, be the most cost-effective route. However, to demonstrate a more environmentally attractive alternative, the output of 1 day of the fine particle slurry production was collected during the high penta soil washer test and then treated in the Slurry Bio-Reactor over about fourteen days after first acclimating the system for five days. With an average retention time in the system of about 5.2 days, the system did not reach steady-state until about the fifth day of evaluation. Only after 9 days of operation did degradation of penta begin to level off, at almost 95% removal (Figure 6). Other operating difficulties (e.g., insufficient nutrient for high penta concentrations, frozen lines) also made the results of the earlier days non-representative. It should also be noted that the size of the equipment used and the resulting throughput rate, 24 ml/min, are significantly smaller than for the Soil Washer or the BATS.

On the basis of these results it appears that in a commercial operation, where the acclimation period would be less important, consistent removals of at least 90% of penta can be achieved from the fines. Removal of the PAHs also appeared to parallel that of penta, with removals of between 70% and over 90% being achieved for various species in the later days of the test.

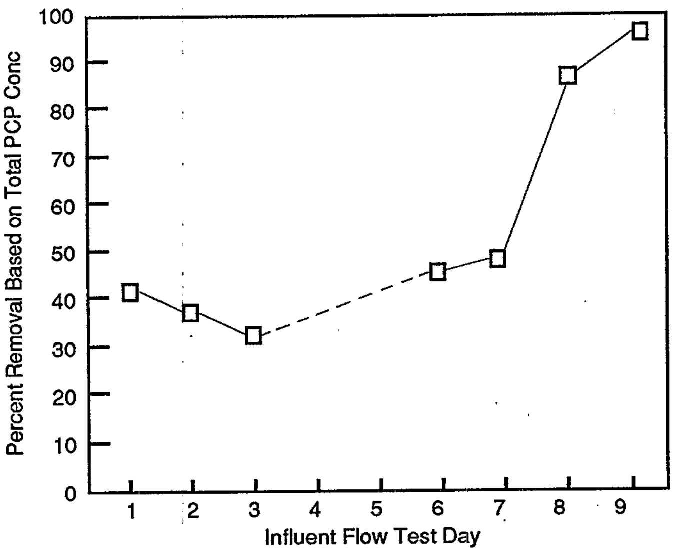


Figure 6. Overall Penta Removal Efficiency in SBR.

The fines in the slurry from this high penta test that are fed to the Slurry Bio-Reactor contain about 5500 ppm of penta on a dry weight basis. At this level, biodegradation may be inhibited on the surface of the solid. Instead, the solids may be serving as a reservoir or ballast for penta. As penta is consumed in the aqueous phase, more is dissolved from the solid. Only when the concentration on the solids has decreased to some non-toxic level is it likely that biodegradation on the surface of the fines begins to play a role. This may be a contributing factor for the delay in attaining steady-state conditions in the reactor.

BioTrol Aqueous Treatment System

The process water generated by the attrition/classification sequence is separated from the soil fractions. Since a significant volume of water is retained by the solids, it is beneficial to recycle as much of the water as possible.

BioTrol's Aqueous Treatment System is well suited to treatment of this wastewater. Having been studied in depth in the companion study, investigation of the BATS in this project was limited to a demonstration of its effectiveness for the wastewaters generated from the low penta and the high penta soil washing to assure that no new or unexpected effects were encountered when using an influent other than groundwater. The mobile (nominal 10-gpm) system was used for this purpose. Once the system was acclimated and inoculated with penta-specific bacterium, it operated effectively on the two wastewaters, achieving over 90% penta removal and producing a reusable effluent (Table 7).

Makeup water requirement of the soil washing process is such (≈1200 gal/ton soil) that a very large BATS would be required to treat all of the output water. For a 20 ton/hour commercial soil washer, BATS units with 300 gpm capacity would be needed. However, in light of the much higher concentration and mass of penta in certain output soil streams, treating all of the recycle water may not be necessary. This would be a much more attractive option from both an operational and a cost point of view.

Table 7. Effectiveness of BATS System for Aqueous Stream (CDE)

	Influent Penta* mg/L	Effluent Penta* mg/L	Removal %
low penta test	15	1.4	90.6
high penta test	44	3.0	93.2

* All concentrations are weighted averages derived from the total mass of penta divided by the total flow during a sampling period

PAH concentrations were below detection limits (2-15 µg/L in the low penta test and 1-400 µg/L in the high penta test) in the influent to the BATS; consequently, no determination can be made as to the ability of the BATS to remove these materials. However, the influent to the BATS from the low penta and high penta soil washer tests (after storage) did contain PAHs, at total concentrations of about 0.41 mg/L and 1.5 mg/L, respectively. In a pilot scale study of the BATS at another wood preserving site, >80% removal of PAHs was demonstrated. Those results also indicated that both biodegradation and absorption on biomass contributed to PAH removal from the aqueous waste stream.

Mineralization of Pentachlorophenol

Limited analyses of influent and effluent for chloride and total organic chlorine were carried out in an effort to confirm that the removal of penta occurred by total degradation to water, carbon dioxide, and chloride ions rather than to partially chlorinated products not detected by the analytical protocol. While the changes in these parameters were consistent with total degradation (mineralization) of the penta, insufficient data were gathered to allow a conclusion concerning mineralization. The companion study using the BATS on groundwater as well as published studies with carbon isotopes provide a more defensible basis for concluding that mineralization is the primary mechanism.

Operational Reliability/Stability

Soil Washer (SW)

The only major operating problem encountered during the SW tests occurred during the transfer of soil from the feed hopper to the conveyor belt. The feed hopper was a new feed system being used for the first time during this demonstration. Coating of the screws in the feed hopper with soil required an increase in the auger rate from 10% to 80% to maintain the same feed rate. This higher auger rate is subject to greater variability in output. The problem was attributed to a higher-than-expected moisture content of the soil. Aeration of the feed soils to decrease their moisture content and modification of the feed hopper with a vibrating device and inclined wooden walls helped keep the augers clear and enabled the demonstration tests to be completed, although at a lower input rate. In a commercial scale system, a different means of delivering soil to the conveyor belt will be needed.

Minor problems that were encountered included blown fuses, a broken shim on an attrition machine, and failures of the centrifuge and various pumps. In a commercial operation, back-up equipment or parts would need to be readily available to avoid shut-down of the system, or two soil washers might need to be run in a parallel configuration to allow for the shut-down of one unit for routine maintenance.

BioTrol Aqueous Treatment System (BATS)

Operational problems encountered during the demonstration included a leaking influent pump, a leaking recycle line, worn bearings in the influent pump, and overheating of the BATS reactor. Repairs of the pumps and recycle line were relatively minor but did require the cut-off of feed to the system for short periods of time. Having replacement pumps on hand would avoid any loss of feed for more than a few minutes. The overheating of the BATS reactor occurred due to a major decrease in flow rate (from 3 gpm down to 0.5 gpm) when the bearings in the influent pump wore out. This decrease in flow rate should have been accompanied by a corresponding decrease in the thermostat setting on the heater; overheating occurred when the thermostat was not manually readjusted. The result was thermal deactivation of the biomass due to extreme temperatures in the BATS reactor. Since this occurred on the 10th day of the demonstration and considerable data had already been collected, the demonstration was terminated.

The system proved to be quite stable and required a minimum of attention during the study. Other than emergency repairs noted above, routine checking of pH, and preparation of nutrient solutions, there was little need for an operator. With a large reservoir of relatively constant feed water such as that provided by the soil washer system, the operator attention required would be minimal. In a larger system, some means of on-line monitoring to alert an operator to out-of-compliance conditions or other failures may be desirable when the operator is occupied elsewhere.

Slurry Bio-Reactor (SBR)

Operating problems encountered during the demonstration of the SBR included clogging of the lines connecting the cells of the reactor, rupture of the line in the effluent pump, overloaded circuit breakers, and frozen lines due to ambient temperatures below freezing. A rubber mallet was used to loosen material caught between reactor cells; in a larger system this is not expected to be a problem. The line in the effluent pump was replaced following each occurrence of a rupture. The overloaded circuit breaker was reset as soon as it was discovered, which was immediately upon occurrence.

Because the capacity of the SBR was significantly lower than the output from the soil washer, the fine particle slurry was collected in a reservoir tank for about one day during the middle of the high penta soil washer test. The slurry in the tank was circulated to minimize settling and a portion was diverted as feed to the SBR for 6 sec/min, using a timer and solenoid valve, throughout the 14 day test of the SBR. If power were lost for any extended period of time, this timer would need to be reprogrammed. Although the reactor cells are equipped with automatic temperature controls, the feed tank was not. A propane heater was used inside the temporary structure on extremely cold nights to keep the feed from freezing.

Costs

Cost data were developed for the system as demonstrated at the MacGillis and Gibbs site and by applying other information provided by BioTrol. Scaling up the entire system can require or allow some changes in equipment selection (and cost) for soil handling; the effect on operating costs such as labor and electrical use are not, however, expected to be significant. The equipment used in the commercial-scale Soil Washer is commonly used by the mineral processing industry.

Based on this demonstration test, the Slurry Bio-Reactor is simply not well enough developed at this point to be able to anticipate any changes in operating costs that might occur on scale-up. As with scale-up of the BATS, other than some savings achievable by buying nutrients and acid/base in bulk, the major factor in operating cost is the labor to oversee the operation; larger systems will require less attention on a volume throughput basis.

In the case of the BATS, the developer has indicated that the proposed three parallel trains of bioreactor cells would provide some cost saving since fewer pumps and monitoring instruments would be required.

Applicable Wastes

It should be emphasized that treatability tests should be done to determine the feasibility of the soil washing process for specific soils and contaminants at a particular site.

BioTrol has demonstrated its soil washing technology in such treatability tests at the laboratory scale on soils with a variety of contaminants. Organic contaminants on the washed soil, the primary soil output stream, are reduced by 87-89% and heavy metals by 46-72% in this demonstration and somewhat higher based on other data provided by the vendor. Where the contaminants are associated principally with the fine particle fraction, the amount of silt and clay, i.e., the weight of soil passing a 200 mesh screen (<0.075 mm), should not normally exceed 25-35 percent of the feed soil in order to achieve an economical volume reduction (see Reference 4). Fluctuations in the particle size distribution of the feed soil also may upset soil washing. These constraints have been verified (References 19 and 31) by vendors whose primary experiences have been in Europe. Furthermore, high organic matter and high moisture content may interfere with the use of soil washing as a cost-effective remediation option.

While this study of the BioTrol Soil Washer System was limited to two contaminated soils derived from a single site and data on other soils is limited, the results of the study along with other information provided by the vendor suggest that the technology would have wide applicability to other contaminated sites. Interest in soil washing is clearly reflected in the design and marketing efforts of other vendors.

The BioTrol system should be readily applicable to other Superfund sites where wood preservation was carried out with penta or creosote. In each case, the soil would need to be characterized to assure that it met the coarse/fine (under ~30% fines) needs of the BioTrol system and that moisture content (from rainfall, water table, etc.) would not hinder processing. And, while this study does not provide any insight into the fundamental chemistry of the soil at the MacGillis and Gibbs site, such studies may be necessary to predict the adsorption/desorption equilibrium for other contaminant/soil matrices. This could affect the role washing/extraction plays as well as the distribution of contaminants between fine and coarse material.

The very different nature of the key chemical species, pentachlorophenol and polynuclear aromatic hydrocarbons, suggests that at many Superfund sites where hydrophobic organic chemicals are of concern soil washing could be useful for volume reduction by particle size segregation. This might, for example, include contaminants such as dioxins and polychlorinated biphenyls (PCBs) where concentration into a particular fraction for a specific destruction process might be economically attractive. At this time it is not possible to state whether the Slurry Bio-Reactor would be an effective means of degrading concentrates of such pollutants.

Further, if a washing/extraction phenomenon does occur with a particular soil and contaminants, it suggests an avenue for removal and concentration of a variety of organic and inorganic contaminants, either with water alone or, perhaps, with aqueous solutions of various reagents (e.g., acid/base, surfactants, etc.). More hydrophilic organics (e.g., acetone, methyl ethyl ketone, phenol, etc.) would be expected to partition more into the aqueous phase, while oils, hydrocarbons, and halogenated hydrocarbons would be retained by fine soil particles and be partitioned to a lesser extent into the aqueous phase. Simple additives (acids, bases, wetting agents, etc.) may increase solubility or solubilization rate. For example, the addition of acid to the processing water may improve metal extraction from soil; caustic would be expected to increase the extraction of phenols (including pentachlorophenol) by conversion to the more water-soluble phenate ions. Of course, such contaminated extracts may require additional treatment and impose additional cost for their disposal.

The experience at MacGillis and Gibbs with the Slurry Bio-Reactor and the BATS did not indicate nor suggest a particular sensitivity to temperature, dissolved oxygen, metals, or oil beyond that which is inherent in aerobic biological treatment. Thus, with minor pretreatment, a variety of contaminated slurries and aqueous waste streams from soil washing may be adaptable to treatment in these units - with or without pollutant-specific inocula.

Site Characteristics

The first consideration at any site would be the type and amount of debris that can be expected during excavation. Bulky materials must be removed before the soil washing process is implemented. The time and cost of such operations can play a role in the overall cost-effectiveness of any soil remediation project.

While this project did not specifically investigate the effect of soil character and particle size distribution on the nature of the output, such factors can affect the efficiency of washing and the volumes and masses of different output fractions; pollutant distribution may behave in the same or a different manner. Any soil being considered for the BSWS would benefit from a particle size distribution and pollutant distribution analysis, even though the results probably can only be used in a general sense in predicting performance during soil washing. As noted earlier, too high a fines content may interfere with operation of the soil washer equipment (clogging) and produce a relatively small yield of coarse sand and large amounts of fines requiring off-site disposal or treatment in equipment such as the Slurry Bio-Reactor. And, only if washing and segregation partition the contaminants of interest into the water and/or onto one predominant solids stream (e.g., the fines), would the process provide the desired benefits.

In the demonstration program, mobile pilot plant units were used. These required only a level base (a concrete pad), power, and water. The process is a significant consumer of water, the amount depending on the moisture content of the soil and the ability and need to dewater coarse and fine output streams before returning them to the site or transporting them for off-site disposal. Reuse of aqueous streams from dewatering of solid streams, from the Slurry Bio-Reactor, and from the BATS will almost be mandatory to provide the large amount of water for the soil washer and to minimize the volume/mass of material requiring off-site disposal. There remains some question, which may be site and contaminant specific, to what extent water that is recycled must be treated in the BATS.

Where a site requires cleanup of the soil, it is likely that the groundwater below that site also is contaminated. Decontamination of groundwater with the BATS may provide a means of treating the groundwater and simultaneously providing the water needed for the soil washer. This can only be determined after volumes and contamination levels of soils and groundwater have been estimated.

Climate could play a small role in the effectiveness of the BioTrol system, as it would with any biological treatment. Significantly colder ambient temperatures can reduce biological reaction rates. The BATS is equipped with a heat exchanger and heater to minimize this effect and extremely low ambient temperatures can be overcome by a small increase in heat input, since most of the heat is reclaimed. In addition, processing during very cold periods could encounter problems due to freezing of transfer lines and vessels. At the MacGillis and Gibbs site in the late fall there was some concern about freezing in the Slurry Bio-Reactor storage tank. In a full-scale system, many of these concerns could be readily overcome with heaters and heated lines.

Environmental Regulation Requirements

Under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and the Superfund Amendments and Reauthorization Act of 1986 (SARA), EPA is responsible for determining the methods and criteria for the removal of waste and residual contamination from a site. The utility and cost effectiveness of the BioTrol system would be dependent on the extent of decontamination necessary for site restoration and the combination of treatment units appropriate to achieve the required cleanup levels for a particular site. If a waste exhibits a characteristic hazard (e.g., toxicity) or is a listed hazardous waste (newly promulgated wood preserving wastes: F032, F034, and F035), treatment will be required. Since the level of necessary decontamination has not yet been defined for the MacGillis and Gibbs site, wood preserving sites in general, nor, in a more generic sense, for pentachlorophenol, it is unknown whether the washed soil or even the fine particle cake treated in the Slurry Bio-Reactor would be acceptable for return to the site as clean material. Similarly, without such target levels, the benefits of additional treatment with the BSWS (e.g., two passes through the soil washer) cannot be assessed, nor can the cost of such increased (or decreased) treatment be estimated. Nevertheless, since the use of remedial actions by treatment that "...permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances" is strongly recommended (Section 121 of SARA), the BioTrol Soil Washer System would appear to be an attractive candidate for remediation of sites contaminated with hydrophobic organic chemicals.

SARA also added a new criterion for assessing cleanups that includes consideration of potential contamination of the ambient air. This is in addition to general criteria requiring that remedies be protective of human health and the environment. Other than normal concerns for workers handling large volumes of contaminated soils and the dust generated during those operations, there appears to be minimal opportunity for exposure by workers or neighbors to the contaminants. Since the soil washing is a wet process, air emissions are minimal. The companion demonstration on the BATS established that no pentachlorophenol and only very low levels of PAHs (maximum found: 2-methyl naphthalene at 47 ppb) are emitted to the ambient air.

Because of concern about dioxin and furan isomers as byproducts in the production and degradation products of chlorophenolics, these materials are strictly regulated. Without testing, it is impossible to state whether the treated and untreated soil and fines from any site contaminated with similar constituents would be suitable for landfill, incineration, or permanent disposal in another fashion. As a precaution because of this concern over dioxins and anticipated regulations at the outset of the project, the wastes generated from this demonstration were containerized. Subsequent analytical testing of the MacGillis and Gibbs soil and product fractions indicated that low concentrations of certain chlorodioxins/ furans isomers (other than 2,3,7,8-TCDD) were present. The levels are such that the soil and the output fractions do not exceed the current dioxin listing criteria.

Additional regulatory aspects that would need to be addressed include permits for wells that might be drilled to treat groundwater (and provide water for soil processing) and any excavation authorization that may be necessary. Runoff from soil piles awaiting treatment may also need to be treated in systems that themselves require permits. Depending on the size of the site being remediated and the roles of the Slurry Bio-Reactor and BATS, storage tanks may be necessary as reservoirs and to provide needed equalization. Such tanks may need permits, spill contingency plans, etc. depending on their size and whether they are above or below ground. For a large site and a large soil washer system processing masses such as 20 tons/hour, water storage capacity could be large enough to require basins instead of tanks. This would, of course, raise additional regulatory questions about liners, secondary containment, leachate collection, etc.

Even assuming that BATS-treated water would be recycled during operation, discharge of the residual water and decontamination of all equipment will be necessary at the termination of operation. It is probable that the treated effluent would be suitable for direct discharge or discharge to a POTW as pretreated. A NPDES permit (or state equivalent) would be required. While the SITE project is exempted from permit requirements under the Resource Conservation and Recovery Act of 1976 (RCRA), the Hazardous and Solid Waste Amendments of 1984 (HSWA), and state regulations, a commercial site will require a RCRA permit for the entire treatment system to operate as a hazardous waste treatment facility. This would include storage tanks, all treatment equipment/reactors, effluents, and if applicable, air emissions.

Materials Handling Requirements

Soil Washer (SW)

Materials handling is a significant factor for both the feed soil and the solid process streams. Prior to treatment, conventional earth-moving equipment is needed to excavate and screen (to <1/2 inch) the soil. Soil should then be stored in a relatively sheltered area to await transfer to the feed hopper. After the solid process streams are dewatered, those requiring further treatment need to be containerized and transported to the treatment location. The contaminated process water (CDE) may need to be stored and pumped to a treatment system (the BATS) prior to discharge or recycle.

BioTrol Aqueous Treatment System (BATS)

The only special requirements for the influent to the BATS are a pH in the range of 7.0 to 8.5 and a temperature in the range of 15-35°C. Caustic or acid addition to maintain this constant pH is controlled by the on-line pH instrumentation. The influent temperature is maintained using a heat exchanger and by adjusting an electric heater with a thermostat as needed. If necessary, pretreatment units such as oil/water separators and clarifiers can be incorporated into the system to improve the quality of the influent. If treated effluent is to be discharged off-site, polishing such as with carbon adsorption may be necessary or desirable.

Slurry Bio-Reactor (SBR)

In addition to solids content, pH, and nutrient concentrations, five other variables must be controlled for proper operation of the Slurry Bio-Reactor system. They are influent flow rate, temperature, dissolved oxygen, gas flow rate, and rake arm speed. The influent flow rate is controlled by a variable speed peristaltic pump. The system is equipped with a heater and automatic temperature control. The dissolved oxygen concentration in the reactors is a function of the gas flow rate, the oxygen concentration in the gas, and the rate of uptake by the microorganisms. If a gas recirculation system is used, the oxygen in the gas can be controlled by the rate at which new air or oxygen is fed to the recirculation system. If gas recirculation is not used, the dissolved oxygen concentration in the liquid can be controlled by the air flow rate. The rake arm speed is controlled by a variable speed drive.

If slurry must be stored awaiting treatment in the SBR, some means of avoiding settling may be required.

Personnel Issues

Soil Washer

The Soil Washer tested in this demonstration was fully automated except for the filling of the feed hopper and collection of the output streams. Contaminated soil feed rate is maintained by an automatic feed-back control system that adjusts the feed rate from the conveyor belt to the mixing trommel. Water inputs are adjusted manually using rotameters. Thus, while the actual operation of the system is not labor intensive, several operators must be available to monitor feed rate, water input, and thickener input and to make equipment adjustments and repairs.

In a commercial system where the feed rate is 20 tons/hr, a fully automated system of feeding soils and collecting output streams would be desirable. Commercial earth-moving equipment and operators would be needed for soil excavation and the initial screening to remove debris before the screen undersize could be dropped directly to the conveyor belt entering the mixing trommel. Output streams could be collected in roll-off dumpsters (5 cubic yd capacity or greater) and hauled away for further treatment or ultimate disposal. Thus, transportation and management of the output streams could require considerable effort in a full scale system and would depend upon the size of the site, the remediation time, and the need for further treatment. Attention should be given to minimizing the exposure of operators to contaminated dust and debris during all of these operations.

Slurry Bio-Reactor

After the initial period of biomass acclimation, the system requires little operator attention. On-line pH adjustment and automatic nutrient addition minimize labor requirements. The operator only monitors (with the use of a control panel) influent flow rate, temperature (15-35° C), dissolved oxygen, gas flow rate, and rake arm speed in addition to checking equipment, nutrient and pH adjustment chemical supplies, and effluent levels. Operators should be provided with skin and respiratory protection against exposure by contact with liquid or mist since the material being processed has increased concentrations of contaminants.

BioTrol Aqueous Treatment System

After biomass acclimation, this system also requires little operator attention. Nutrient addition and pH adjustment are carried out automatically. Labor is needed only to assure that all pumps are operating, the thermostat is adjusted (if the heater is in use), nutrient and pH adjustment chemical supplies are adequate, and that the effluent is meeting discharge or recycle requirements. Additional labor may be required if oil/water separation, suspended solids removal, or effluent polishing are required at a particular site. Operators may need to be equipped with skin and respiratory protection because exposure can occur by contact with liquid or mist when opening the bioreactor, or to air emissions from the system.

Testing Issues

The GC/MS method for analysis of semivolatiles (EPA Method 8270) was used to analyze all of the samples for this demonstration because this is the only EPA-approved method for pentachlorophenol that provides the desired mass spectrographic confirmation. It is a time consuming and costly procedure. Because of the complexity of the procedure and other factors, results were unavailable until several months after the field demonstration was finished. Upon review of these results, it became apparent that the Slurry Bio-Reactor system never reached a steady state of operation during the fourteen day test period. A method with more rapid turnaround and on-site availability to assess process control would have indicated that the test should be delayed until acclimation had been completed and then extended until steady-state operation was reached. BioTrol has developed a faster HPLC procedure for liquids that may be useful to site management and regulatory personnel for routine use. A comparison of the BioTrol HPLC procedure and the EPA method conducted as part of the companion demonstration on the BATS indicated that the BioTrol method is accurate for samples containing penta concentrations of 1 ppm or higher. An immunoassay test for dissolved penta is under development by EPA. It will allow rapid turnaround of results with minimal experience.

In addition to the time factor, inefficiency in the GC/MS extraction procedure was reflected in the Soil Washer mass balances. For both the low penta and the high penta soil washer tests, the mass balances for all materials achieved good closure (±9%), but the mass balances for penta indicated an overall increase of +35% and +54%, respectively. This apparent increase in overall penta mass may be attributable to the extraction step of the GC/MS procedure. A decision had been made to use sonication rather than soxhlet extraction. It is suggested that extraction of the feed soils was poor because the penta was tightly adsorbed/absorbed by the soil matrix and in soil aggregates. Extraction of the output solid streams was much more complete after the soil washing operation made the penta more accessible and easier to extract. The difficulties in obtaining meaningful, accurate analyses of solid matrices is well known and efforts to overcome such problems are ongoing. In retrospect, a study of penta concentration changes with extraction time or a shift to an alternate extraction procedure might have avoided this problem.

Water inputs to the Soil Washer System were measured using rotameters (which were already part of the BioTrol system) during this demonstration. This involved obtaining the rate of water input at several times and then calculating a volume of water input during each time interval. The rotameters were hard to read accurately because the rate was constantly fluctuating. The use of totalizers instead of rotameters would have made the measurement of water inputs much easier and more accurate.

Section 4
Economic Analysis

Introduction

The primary purpose of this economic analysis is to estimate costs (excluding profit) for commercial-scale remediation using the BioTrol mobile Soil Washing System. With realistic costs and a knowledge of the bases for their determination, it should be possible to estimate the economics for operating similar-sized systems at other sites utilizing scale-up cost formulas. Among such scale-up cost formulas available in the literature for chemical process plant equipment is the "six-tenths rule"[1]. Since the equipment used here is not as complicated, this was modified to a "three-tenths rule".

This economic analysis is based on assumptions and costs provided by BioTrol, on results and experiences from this SITE demonstration, and on best engineering judgement as practiced by the authors. The results are presented in such a manner that if the reader disagrees with any of the assumptions made here, other conclusions can be derived from such other assumptions.

Although this demonstration tested three different technologies in a "system" configuration, BioTrol intends to market equipment either separately or as an integrated system, depending on a particular customer's needs. For the purposes of this analysis, it is assumed that the commercial-scale system utilizes the same three technologies evaluated in the demonstration. It is also assumed that the performance of commercial-scale equipment will be the same as that demonstrated here.

Certain actual or potential costs were omitted because site-specific engineering aspects beyond the scope of this SITE project would be required. Certain functions were assumed to be the obligation of the responsible party or site owner and also were not included in the estimates.

Cost figures provided here are "order-of-magnitude" estimates, generally +50%/-30%, and are representative of charges typically assessed to the client by the vendor exclusive of profit.

The reader is also urged to obtain and review the Applications Analysis Report for the companion study, in which a more extensive evaluation of the BATS and its economics was carried out.

[1] Perry, R.H., Chilton, C.H., Chemical Engineer's Handbook, Fifth Ed., 1973, pg. 25-16.

Conclusions

- The total cost to clean up 22,938 m^3 (30,000 yd^3) or 34,724 metric tons (38,273 short tons) of contaminated soil at the MacGillis and Gibbs Superfund site using an 18.2 MT/hr (20 short ton/hr) soil washer, three 378.5 L/min (100 gpm) aqueous treatment units connected in parallel, and an 87 L/min (23 gpm) slurry bioreactor would be about $185/metric ton ($168/short ton), including incineration of the fine and coarse oversize woody debris from the soil washer. If incineration costs were not included, this would drop to $44/metric ton ($40/short ton).

- The Soil Washer accounted for at least 90% of the total cleanup cost primarily due to the incineration of the fine and coarse woody debris.

- Cost component distribution was highly technology dependent. Generally, labor and consumables and supplies were two of the three largest cost components, while startup and utility costs were one of the smallest. On a percentage basis, equipment costs were lowest for the Soil Washer, highest for the SBR, and a relatively intermediate value for the BATS. This was primarily due to the fact that the SW incurred effluent treatment and disposal costs whereas the BATS and SBR did not.

- Unit costs in terms of individual process streams that each technology in the system had to treat were as follows:

SW	$170/metric ton ($154/short ton) or $257/$m^3$($197/yd^3)
BATS	$0.44/1,000 L ($1.65/1,000 gal)
SBR	$9.22/1,000 L ($34.39/1,000 gal)

The cost for the SW if incineration were not included would drop to $29/metric ton ($27/short ton) or $44/$m^3$ ($34/$yd^3$).

This information will help anyone considering using a single technology to gauge the relative costs.

- Two of the twelve cost categories as well as further treatment and disposal of effluent from the BATS or SBR were not considered in this economic analysis. These factors could add substantially to the cleanup costs depending on permits and regulatory requirements, and site cleanup and restoration requirements. These were considered to be the responsible party's (or site owner's) obligation.

Issues and Assumptions

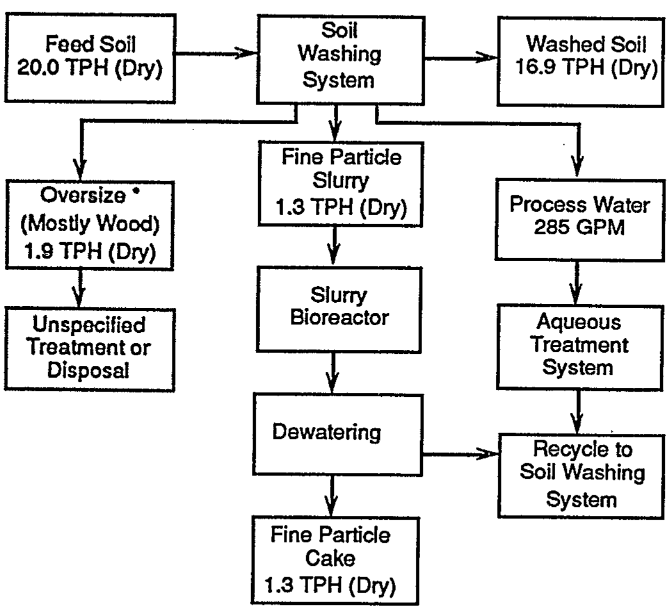
This section summarizes the major issues and assumptions used to evaluate the cost of BioTrol's soil treatment system. In general, assumptions are based on information provided by BioTrol. Certain assumptions were made to account for variable site and waste parameters and will, undoubtedly, have to be refined to reflect site specific conditions. For purposes of this economic analysis, a hypothetical commercial scale clean-up of the MacGillis and Gibbs Superfund site was assumed.

Waste Volumes and Site Size

The volume of soil to be treated at the MacGillis and Gibbs Superfund site has not yet been determined because cleanup objectives have not yet been established. For the purposes of this economic analysis, Mark Lahtinen, Project Officer with the Minnesota Pollution Control Agency (MPCA), has estimated the volume of contaminated soil to be approximately 22,938 m^3 (30,000 yd^3) with 10% moisture and a bulk density of 1,682 kg/m^3 (105 lb/ft^3). The soil weight on a dry basis is then 34,724 metric tons (38,273 short tons).

System Design and Performance Factors

Figure 7 shows a simplified flowsheet of BioTrol's commercial Soil Washing System (BSWS) proposed for the cleanup of the MacGillis and Gibbs site. It consists of an 18.2 MT/hr



* Includes both fine and coarse oversize

Figure 7. Simplified Treatment Flowsheet for MacGillis and Gibbs Soil.

(20 ton/hr) mobile Soil Washing System (SW), three 378.5 L/min (100 gpm) aqueous treatment system (BATS) units connected in parallel, and an 87 L/min (23 gpm) Slurry Bio-Reactor (SBR).

In the BATS, 1079 L/min (285 gpm) of process water from the Soil Washer will be treated. A 1,325 L/min (350 gpm) circular thickener would precede the SBR. Only the thickener underflow, at 87 L/min (23 gpm), is sent to the SBR. The thickener overflow goes to dissolved air flotation for further solids removal prior to recycle to the Soil Washer or treatment in the BATS. A retention time of 5 days in the SBR, similar to what was evaluated in the SITE program, was assumed. On these bases, the required total reactor volume was calculated to be 627,175 L (165,700 gal). This volume would be assembled as three parallel trains of three reactors in series, each with a volume of 68,130 L/reactor (18,000 gallons/reactor). The fine solids coming out of the SBR are assumed to be clean enough to be returned to the site. The washed soil is also assumed to be clean enough to be returned to the site without further treatment, although it is recognized that clean up objectives not yet established would have to be satisfied.

The only residuals from the Soil Washer requiring treatment consist of fine and coarse oversized woody debris. It is assumed that these will be incinerated off-site and the estimated cost has been included with the SW costs.

System Operating Requirements

Tables 8 and 9 summarize the SITE demonstration soil washing mass balance data for the "low penta" and "high penta" concentration tests, respectively. Total wet weights of all process streams were adjusted to a dry weight basis using percent solids data. On a dry weight basis, the two soils behaved similarly.

Mass flow rate calculations for a 18.2 MT/hr (20 ton/hr) soil washing system are summarized in Table 10. A mean value of product dry weights for the "low penta" and "high penta" concentration tests were used. The product dry flow rates were estimated by multiplying the 18.2 MT/hr (20 ton/hr) feed soil rate into the Soil Washer by the appropriate dry weight percent. The percent solids level is BioTrol's reasonable expectation in a commercial system. It should be noted that these numbers are not necessarily reflective of the pilot-scale operation demonstrated in the SITE program. The wet flow rates are calculated by dividing the dry flow rates by the appropriate solids percent. Process water flow rate was determined by a proprietary mathematical model developed by BioTrol.

It was assumed that the soil washing system would operate 24 hours per day (three 8-hour shifts per day), 7 days per week. Four crews of four would be assigned to a standard shift rotation schedule, with each person working 40 hours per week, with 8 overtime hours during each 4 week rotation. Twenty hours per week (4 hours per shift) of the lead operators' time would be devoted to the biological treatment systems. The remaining 22 hours per week would be devoted to the Soil Washer. A maintenance mechanic is scheduled to be

Table 8. Soil Washing System Mass Balance - Low Penta Soil

Process Stream	Total Wet Weight kg (lb)	Mean Solids (Percent)	Total Dry Weight kg (lb)	Dry Weight (Percent of Products)
Feed Soil	11,204 (24,700)	89	9,957 (21,950)	87.1
Washed Soil	12,928 (28,500)	74	9,526 (21,000)	83.6
Coarse Oversize	1,588 (3,500)	68	1,089 (2,400)	9.5
Fine Oversize	635 (1,400)	10	66 (145)	0.6
Fine Particle Cake	2,359 (5,200)	31	726 (1,600)	6.4
Total Products			11,406 (25,145)	

Table 9. Soil Washing System Mass Balance - High Penta Soil

Process Stream	Total Wet Weight kg (lb)	Mean Solids (Percent)	Total Dry Weight kg (lb)	Dry Weight (Percent of Products)
Feed Soil	17,554 (38,700)	83	14,570 (32,120)	76.6
Washed Soil	22,816 (50,300)	70	15,967 (35,200)	84.0
Coarse Oversize	3,130 (6,900)	51	1,588 (3,500)	8.4
Fine Oversize	998 (2,200)	16	159 (350)	0.8
Fine Particle Cake	3,924 (8,650)	33	1293 (2,850)	6.8
Total Products			19,006 (41,900)	

Table 10. Estimated Product Flow Rates from Soil Washing 18.2 MT/Hr (20 Tons/Hr) Treatment of MacGillis and Gibbs Site

Process Stream	Dry Weight (%)	Dry Flow MT/hr (ton/hr)	Solids (%)	Wet Flow MT/hr (ton/hr)	Wet Flow L/min (gal/min)
Feed Soil	100.0	18.2 (20.0)	90.0	20.2 (22.2)	NA
Washed Soil	83.8	15.3 (16.8)	90.0	17.0 (18.7)	NA
Oversize (1)	9.6	1.7 (1.9)	50.0	3.4 (3.8)	NA
Fine Particle Slurry	6.6	1.2 (1.3)	20.0	5.9 (6.5)	24
Process Water (2)	NA	NA	0.0	64.7 (71.3)	1079 (285)

Notes: (1) Includes both coarse and fine oversize products (predominantly wood).
(2) Includes only water requiring treatment - the total recycle water flow rate is about 1609 to 1703 L/min (425 to 450 gal/min); the balance of recycled process water will be used untreated at the front end of the process.

on the day shift, 5 days per week. The 12 operators that would be required would be hired locally. Labor rates include salaries, benefits, administration/overhead costs, and per diem living expenses and rental car costs for non-local personnel.

Utilization Rates and Maintenance Schedules

It would take about 80 days to treat 34,724 metric tons (38,273 short tons) at 18.2 MT/hr (20 tons/hr). To account for both scheduled maintenance and unscheduled shutdowns, a 10% downtime was judged to be adequate. This would result in an actual treatment time of 89 days or roughly 13 weeks. Scheduled maintenance would be performed by a maintenance mechanic during the day shift. Two weeks for mobilization and training and one week for demobilization were added to the treatment time for a total time on site of 110 days (16 weeks).

Financial Assumptions

For the purpose of this analysis, capital equipment costs were amortized over a 10 year period with no salvage value. Interest rates, time-value of money, etc. were not taken into account because the clean up time (4 months) is so short.

Basis for Economic Analysis

In order to compare the cost-effectiveness of technologies in the SITE program, EPA breaks down costs into 12 categories shown in Table 11 using the assumptions already described. The assumptions used for each cost factor are described in more detail below.

Site Preparation Costs

The amount of preliminary preparation will depend on the site and is assumed to be performed by the responsible party (or site owner). Site preparation responsibilities include site design and layout, surveys and site logistics, legal searches, access rights and roads, and preparations for support facilities, decontamination facilities, utility connections, and auxiliary buildings. These preparation activities are assumed to be completed in 500 staff hours. At a labor rate of $50/hr this would equal $25,000 as shown in Table 11.

Permitting and Regulatory Costs

Permitting and regulatory costs are generally the obligation of the responsible party (or site owner). These costs may include actual permit costs, system health/safety monitoring, and analytical protocols. Permitting and regulatory costs can vary greatly because they are very site- and waste-specific. No permitting costs are included in this analysis; however, depending on the treatment site, this may be a significant factor since permitting can be an expensive and time-consuming activity.

Equipment Costs

Capital equipment costs are broken down into the three technologies demonstrated under the SITE program, i.e., Soil Washer (SW), BioTrol Aqueous Treatment System (BATS), and Slurry Bio-Reactor (SBR). For comparison purposes, equipment costs for all three technologies have been amortized over 10 years and it is assumed there is no salvage value at the end of the 10 year period.

Soil Washer

Soil washing is not an "off the shelf" process and must be modified for site specific conditions on a case-by-case basis. Factors such as contaminant type and level, cleanup criteria, soil mineralogy, and soil particle size distribution must be considered when designing a treatment system. The soil is first characterized to determine the nature and location of the contaminants. A strategy is then developed to effect the separations necessary to achieve the volume reduction required to meet regulatory goals. This is accomplished by concentrating the contaminants in a small volume of material while producing a washed soil product meeting appropriate cleanup criteria. The number, size and type of unit operations required to accomplish the necessary separations will have an impact on the capital cost.

The construction cost of a complete 18.2 MT/hr (20 ton/hr) mobile soil washing system was estimated by BioTrol to be $3 million. This was independently verified using outside sources, past purchasing experience, and good engineering judgement. Table 12 summarizes this analysis. The equipment list and quantity was compiled from a process flow diagram submitted in BioTrol's original proposal to EPA for participation in the SITE program. It should be mentioned that the commercial-scale equipment envisioned here by BioTrol may contain different unit operations than what was used in the demonstration test equipment. Nevertheless, costs for appropriately sized equipment to handle 18.2 MT/hr (20 short tons/hr) were compiled from a variety of sources from different years. Hence, they all needed to be indexed to 1991 dollars. This was done by using the U.S. 20 city average construction cost index figures from the March 25, 1991 issue of Engineering News-Record (ENR) magazine (pg. 47) and an appropriate ratio to correct the equipment total cost figures to 1991 dollars. These indexed equipment costs were summed to arrive at the indexed total equipment cost of $1.9 million. It was assumed that other ancillary equipment (pipes, valves, fittings, etc.) and labor for assembly would add an additional 50% to this figure, bringing the grand total equipment cost to $2.85 million.

Amortizing the $3 million construction cost over 10 years (120 months) yields $25,000/month or $100,000 for the 16 week total treatment time.

BioTrol Aqueous Treatment System

Biological treatment of process water from the Soil Washer at a flow rate of 1,079 L/min (285 gpm) would be required. Three of BioTrol's 100 gpm BATS units would be run in parallel, with the clarified process water being divided into three equal flows. The reactors would be mounted on one skid, while common nutrient and defoamer delivery systems, blowers, and a control panel would be mounted on a separate equipment skid to minimize cost. BioTrol estimates the cost of this system to be $250,000.

Table 11. Estimated Costs for MacGillis and Gibbs Site

Cost Component	SW	%	BATS	%	SBR	%	Total	%
1. Site Preparation Costs	—		—		—		25,000	—
2. Permitting & Regulatory Costs	N/A		N/A		N/A		N/A	
3. Equipment Costs (amortized over 10 years)	125,000	2	11,840	20	46,660	46	183,500	3
4. Startup	10,000	—	4,350	7	4,350	4	18,700	—
5. Labor	387,100	6	16,000	27	16,000	16	419,100	7
6. Consumables and Supplies								
Health & Safety Gear	11,500	—	5,750	9	5,750	6	23,000	—
Maintenance Supplies	41,300	1	5,900	10	11,800	12	59,000	1
Flocculant	331,200	6					331,200	5
Fuel (for front end loader)	4,300	—					4,300	—
Nutrient			1,225	2	500	—	1,725	—
Caustic			8,540	14			8,540	—
Defoamer			2,190	4	590	—	2,780	—
7. Utilities								
Tel.	800	—	700	1	700	1	2,200	—
Elec.	98,600	2	2,870	5	11,500	11	112,970	2
Sewer/Water	7,200	—					7,200	—
8. Effluent Treatment & Disposal	4,870,000	83	—		—		4,870,000	76
9. Residuals/Waste Shipping, Handling and Transport Costs	—		—		—		282,000	5
10. Analytical Costs	—		—		—		53,400	1
11. Facility Modification, Repair & Replacement	10,000	—	830	1	3,600	4	14,430	—
12. Demobilization Costs	—		—		—		—	
Total	5,897,000	100	60,195	100	101,450	100	6,419,045	100

Table 12. Soil Washer Capital Equipment Cost Analysis

Equipment List	Quantity	Equipment Unit Cost[A] ($)	Equipment Total Cost ($)	Cost Index[B]	Index Ratio[C]	Indexed Equipment Costs ($)
1. Hopper	1	2,000[2] (1986)	2,000	4231	1.13	2,300
2. Conveyor	4	3,000[2] (1981)	12,000	3384	1.41	17,000
3. Bucket Elevator	1	3,000[2] (1981)	3,000	3384	1.41	4,200
4. Trommel	1	3,000[2] (1981)	3,000	3384	1.41	4,200
5. Mesh Screen	2	2,500[1] (1986)	5,000	4231	1.13	5,700
6. Dewatering Screen	1	2,500[1] (1986)	2,500	4231	1.13	2,800
7. Pump	10	1,000[3] (1991)	10,000	4773	1.00	10,000
8. Froth Flotation Tank	2	100,000[1] (1978)	200,000	2693	1.77	350,000
9. Attrition Tank	2	100,000[1] (1978)	200,000	2693	1.77	350,000
10. Classifier	3	15,000[1] (1982)	45,000	3721	1.28	58,000
11. Centrifuge	1	700,000[1] (1982)	700,000	3721	1.28	900,000
12. Thickener	1	100,000[1] (1978)	100,000	2693	1.77	180,000
Indexed Total Equipment Cost						1,900,000
Ancillary Equipment & Assembly Labor						950,000
Grand Total Equipment Cost						2,850,000

A. Number in parentheses indicates year that cost figure was obtained for. Superscript indicates source of information as follows:
1. K. Wagner, et al, "Remedial Action Technology for Waste Disposal Sites", 2nd ed., Noyes Data Corp., 1986.
2. Equipment costs were judged to be similar to equipment found in Source 1.
3. From past purchasing experience.

B. Assumed to be for month of March in year of interest.

C. Index Ratio = Cost Index for 1991 (4773) divided by Cost Index for year of interest.

This value was independently verified using cost figures given in reference 1 of Table 12 for activated sludge treatment units. A construction cost of $82,000 (in 1984 dollars) for a 379 L/min (100 gpm) unit was linearly interpolated between a 265 L/min (70 gpm) unit ($78,500) and a 530 L/min (140 gpm) unit ($85,600), using the same ENR cost indices as were used in Table 12. This $82,000 in 1984 dollars (cost index - 3/84 = 4118) is $95,000 in 1991 dollars (cost index - 3/91 = 4773). Therefore three units would cost approximately $285,000. As noted earlier, cost savings could be realized by combining some systems.

The $250,000 cost, amortized over a 10 year equipment life span, amounts to $2,085/month or $8,340 for the 16 week total treatment time.

Slurry Bio-Reactor

Capital cost data for full-scale slurry reactors were provided to BioTrol by EIMCO Process Equipment Co. of Salt Lake City, Utah, which supplied the pilot-scale slurry reactors used in the SITE demonstration. The only major piece of equipment that would be added to the pilot-scale unit would be a 1,325 L/min (350 gpm) circular thickener before the SBR. The thickener overflow would go to dissolved air flotation for further solids removal prior to treatment in the BATS. The thickener underflow at 87 L/min (23 gpm) would be sent to the bioreactors. For a 5 day residence time, this would require a total reactor volume of 625,000 L (165,700 gal).

To provide the required reactor volume, nine transportable 68,130 L (18,000 gallon) reactors would be assembled as three parallel trains of three reactors in series. Based on information supplied by EIMCO, the total estimated capital cost for the slurry treatment system and ancillary equipment (blowers, thickener, splitter box, transfer pump, piping, instrumentation, and electrical) is $1.1 million.

As far as it could be determined, EIMCO is the only company manufacturing these types of slurry bioreactors. Hence, there was no independent way to verify costs. Instead, EIMCO's estimate was checked against a price quote given for another SITE project for a different size reactor. The "three-tenths factor" for different sized equipment was then applied to determine if their price was reasonable. EIMCO quoted a price of $28,000 for a 450 L (120 gal) reactor[2]. To estimate the cost of a 68,130 L (18,000 gal) reactor, the following "three-tenths factor" was used:

$$C_n = r^{0.3}C$$

where C_n is the new equipment cost, C is the previous equipment cost, and r is the ratio of new to previous capacity. Therefore:

$$C_n = \left(\frac{68{,}130\ L}{450\ L}\right)^{0.3} (\$28{,}000) = \$125{,}000$$

For nine reactors, this would total $1.1 million; which confirms EIMCO's estimate. Monthly equipment costs amortized over 10 years is $9,165 or $36,660 for the 16 week total treatment time.

[2] Personal communication. Dr. Derek Ross, ERM INC., Exton, PA. July 18, 1991

Additional equipment to operate the facility is presumed to include a field office trailer, decontamination trailer, and front end loader. The total cost is approximately $38,500, which has been apportioned among the three technologies in the following manner: $25,000-SW, $3,500-BATS, $10,000-SBR.

Startup

All three of BioTrol's technologies are mobile units designed to move from site to site. Transportation costs are only charged to the client for one direction of travel and are usually included with mobilization rather than demobilization. Transportation costs are variable and dependent on site location as well as on applicable oversize/overweight load permits, which vary from state to state. The total cost will depend on how many state lines are crossed.

Assembly is a labor intensive operation consisting of unloading equipment from trucks and trailers used for transportation, as well as actual assembly. It is estimated that mobilization and training would take about 2 weeks and this time is included in the total time on site (110 days). The startup labor cost is included in the total labor cost component and includes living expenses.

The cost of monitoring programs has been broken down into two components - OSHA training, estimated at $4,300, and medical surveillance, estimated at $14,400. The total cost of $18,700 has been apportioned among the three technologies in the following approximate manner: 50%-SW, 25%-BATS, 25%-SBR. Depending on the site, however, local authorities may impose specific guidelines for monitoring programs. The stringency and frequency of monitoring required may have significant impact on the project cost.

Labor

Labor costs may be broken down into two major categories: salaries and living expenses. Living expenses for all on-site personnel consist of per diem and rental cars, both estimated at 7 days/week for the entire time spent on-site (110 days). Per diem is assumed to be $125 per day per person, but may vary widely by location. Three rental cars are assumed to be obtained at a rate of $55/day. The per diem and car rental costs have been included under the Soil Washer technology.

Supervisory and administrative staff will consist of an off-site program manager and an on-site project manager. Professional and technical staff will consist of a project engineer and crew of four with 1 lead operator and 3 operators. The soil treatment system will operate 24 hours per day (3-8 hours shifts per day), 7 days per week. Four crews will be assigned to a standard shift rotation schedule, with each person working 40 hours per week and 8 overtime hours during each 4 week rotation. A maintenance mechanic is also scheduled 5 days per week on the day shift. The soil washing labor requirements and rates are detailed in Table 13.

Note that each operator is shown to work an average of 42 hours per week (one overtime shift every 4 weeks). Also, each lead operator will devote 22 hours per week to the Soil

Table 13. Soil Washing Labor Requirements and Rates

Position	Number of People	Hours Per Week	Rate(1) ($ Per Hours)
Program Manager	1	8	52.50
Project Manager	1	40	42.50
Project Engineer	1	40	35.00
Lead Operator	4	22	25.00
Operator(2)	12	42	20.00
Mechanic	1	40	25.00
Total	20		

Notes: (1) Includes salary, benefits, and administration/overhead costs but excludes profit.
(2) This position will be filled by persons hired locally.

Washer and the remaining 20 hours per week to the biological systems (4 hours per shift - 2 hours for the BATS and 2 hours for the SBR).

Consumables and Supplies

There are two items that are common to all three technologies. These are health and safety gear which include hard hats, safety glasses, respirators and cartridges, protective clothing, gloves, safety boots, and a photoionization detector monitor, all estimated at $23,000. This cost has been apportioned among the three technologies in the following manner: 50%-SW, 25%-BATS, 25%-SBR. The second item is maintenance supplies (spare parts, oils, greases and other lubricants, etc.) estimated at $59,000. This cost has been apportioned among the three technologies in the following manner: 70%-SW, 10%-BATS, 20%-SBR.

Soil Washer

The amount of flocculant consumed in thickening can vary from 0.2 to 2.3 kg (0.5 to 5 lb) of flocculant per ton of soil (dry) depending on the soil characteristics and contaminants. An average flocculant usage rate of 1.4 kg per ton (3 pounds per ton) of soil has been assumed here. Flocculant cost can range from $3.30 to $6.60 per kg ($1.50 to $3.00 per pound). A conservative figure of $6.34/kg ($2.88/lb) was assumed to arrive at the total cost of flocculant consumed, $331,200.

Diesel fuel for the front end loader is estimated at $39/day for the full 110 day treatment period resulting in a cost of $4,300.

BioTrol Aqueous Treatment System

The cost for nutrient is based on a commercially available liquid fertilizer formulation of 25% nitrogen and 5% phosphorus added to achieve a COD:N:P ratio of 100:5:1. Using 47 L/day (12.5 gal/day) at a cost of $0.29/L ($1.10/gal) would yield $13.75/day or $1,225 for the 89 day treatment period.

Caustic usage would be determined by the pH and alkalinity of the incoming water to be treated. For purposes of this cost estimate, usage was assumed to be the same as that demonstrated under this SITE project [0.34 L (0.09 gal) of 50% solution per 3,785 L (1000 gal) of water treated]. More or less caustic may be required at another site; however, caustic use should remain essentially constant throughout the treatment of a specific waste. For a commercial scale cleanup, a cost of $0.69/L ($2.60/gal) of 50% solution was assumed. Thus, the cost would be $0.06/1000 L ($0.24/1000 gal) of water or $8,540 to treat 138 x 10^6 L (36.5 x 10^6 gal).

Use of a standard wastewater treatment defoamer at a concentration of 5 ppm and cost of $3.17/kg ($1.44/lb) was assumed. Total defoamer cost would be $2,190 for 89 days of treatment.

Slurry Bio-Reactor

The costs of consumables and supplies for biological slurry treatment are similar to those for biological water treatment. Nutrients are assumed to be added at a rate of 19 L/day (5.1 gal/day). If the cost is once again assumed to be $0.29/L ($1.10/gal), the total treatment cost would be $500 for 89 days.

Defoamer and acid or caustic for pH control are assumed to be added together. A cost of $0.05 per 1000 L ($0.20 per 1,000 gal) of slurry was taken as an estimated average based on results from previous laboratory treatability studies. Therefore, the cost to treat 11 x 10^6 L (2.95 x 10^6 gal) of slurry would be $590.

Utilities

Telephone charges are estimated at $500/month plus an additional 10% for fax service or $550/month. This will total $2,200 for the 110 days (4 months) spent on-site. This number has been apportioned approximately equally among the three technologies.

Soil Washer

BioTrol estimated that unit operations for an 18.2 MT/hr (20 ton/hr) Soil Washer would correspond to 1030 horsepower. At $0.06/kw-hr, electricity usage would cost approximately $98,600 for 89 days of treatment.

Since the process water is assumed to be recycled back to the soil washer, very little make-up water would be required. Water usage by site personnel was estimated to be 115 L/day/person (30 gal/day/person). If 20 people a day are assumed to be at the site, then the daily water usage would be 2,270 L (600 gal) or 250,000 L (66,000 gal) for the 110 day duration of treatment. Assuming combined sewer and water usage costs $0.05 per 1,000 L ($0.02 per 1,000 gal), this would amount to an inconsequential cost of about $15.

Aqueous Treatment System

The electrical demand for the BATS was estimated by BioTrol to be about 30 horsepower. At a cost of $0.06/kw-hr, the total cost of electricity would be $2,870.

Slurry Bio-Reactor

The electrical demand was estimated by BioTrol to be about 120 horsepower. Using the same cost of electricity as above would yield a cost of $11,500.

Effluent Treatment and Disposal

The process water treated in the BATS will be recycled to the Soil Washer. Hence, no disposal costs are associated with the process water stream.

The fine particle cake resulting from dewatering the SBR effluent is assumed to meet local, state or federal requirements for return to the site. Hence, no disposal costs are associated with the fine particle slurry stream.

The fine and coarse oversize streams coming off the Soil Washer do need to be treated. It was assumed that incineration would be used to dispose of these effluent streams. Incineration costs were derived from the demonstration test. Two hundred fifty - 208 L (55 gal) drums of fine and coarse oversize debris were generated during the test program. Assuming the waste has a density of 2400 kg/m^3 (20 lb/gal), each drum would weigh about 500 kg (1000 lb). Preliminary pricing prior to acceptance and approval by the incinerator facility was approximately $600/drum. Hence, it would cost $150,000 to incinerate 125 tons of debris or $1200/ton.

Using this figure for the commercial-scale clean-up the cost to treat 1.9 tons/hr of fine and oversized debris for 89 days would be about $4.87 million.

Residuals/Waste Shipping, Handling and Transport Costs

Waste disposal costs including storage, transportation and treatment costs are assumed to be the obligation of the responsible party (or site owner). It is assumed that residual or solid wastes generated from this process would consist only of contaminated health and safety gear, used filters, spent activated carbon, etc. Landfilling is the anticipated disposal method for this material and costs were once again derived from the demonstration test. Fifty-five 208 L (55 gal) drums of waste were generated during the demonstration test. Assuming this waste has a density of 1200 kg/m^3 (10 lb/gal), each drum would weigh about 250 kg (500 lb). The cost to landfill these drums by the same disposal facility that would be used to incinerate the penta-contaminated woody debris was given as $180/drum. Hence, it would cost $9,900 to landfill 15 tons of waste or $660/ton.

Based on the demonstration test, it was assumed that the amount of residual waste would be about 10% of the effluent stream. For the commercial-scale cleanup this would amount to about 0.2 tons/hr for 89 days. Using the above cost figure of $660/ton, the cost for residuals handling, shipping, and transport is estimated to be $282,000.

Analytical Costs

Standard operating procedures for BioTrol do not require planned sampling and analytical activities. Periodic spot checks may be executed at BioTrol's discretion to verify that equipment is performing properly and that cleanup criteria are being met, but costs incurred from these actions are not assessed to the client. The client may elect, or may be required by local authorities, to initiate a sampling and analytical program at their own expense.

For this cost analysis, one sample per day for 89 days at $600/sample was assumed to be required by local authorities for monitoring and permitting purposes. This would total approximately $53,400 for the 13 week test period.

Facility Modification, Repair and Replacement Costs

Since site preparation costs were assumed to be borne by the responsible party (or site owner), any modification, repair, or replacement to the site was also assumed to be done by the responsible party (or site owner). These costs were assumed not to exceed 10% of the respective technology's capital costs and are so indicated on Table 11.

Demobilization Costs

Site demobilization will include shutdown of the operation, final decontamination and removal of equipment, site cleanup and restoration, permanent storage costs, and site security. Site demobilization costs will vary depending on whether the treatment operation occurs at a Superfund site or at a RCRA-corrective action site. Demobilization at the latter type of site will require detailed closure and post-closure plans and permits. Demobilization at a Superfund site does not require as extensive post-closure care; for example, 30-year monitoring is not required. This analysis assumed site demobilization costs are limited to the removal of all equipment and facilities from the site. It is estimated that demobilization would take about one week and this is included in the total time on site (110 days). Labor costs include salary and living expenses. See "Labor Costs" for information on labor rates.

Grading or recompaction requirements of the soil will vary depending on the future use of the site and are assumed to be the obligation of the responsible party (or site owner).

Results

Table 11 shows the total cleanup cost to be $6.4 million itemized by cost category and technology. It should be noted that the dollar totals for each technology do not add up to the total cleanup cost because some cost categories (i.e., site preparation, analytical, and residuals/waste shipping, handling and transport costs) were not distributed among the different processes. Nevertheless, of the total cost, at least 90% can be attributed to the Soil Washer. The main factor for this is that the fine and coarse oversized woody debris from the Soil Washer were assumed to be incinerated. Although these streams represent less than 10% of the total product, the cost for their disposal represents over 80% of the cost of cleanup associated with the Soil Washer. Hence, it can be observed from Table 11 that the cost distribution is highly dependent on the technology. The next largest cost components are labor (6%), and consumables and supplies (7%) followed by equipment costs (2%), and utilities (2%).

For the BATS, the largest cost component is consumables and supplies (39%), followed in order by labor (27%), equipment (20%), startup (7%), and utilities (6%). For the SBR, equipment costs (46%) were followed in order by consumables and supplies (18%), labor (16%), utilities (12%), facility modification, and startup each at 4%. Labor, and consumables and supplies were two of the three largest cost components, while startup, utility, and facility modification costs were generally one of the smallest cost components. Interestingly, on a percentage basis, equipment costs were lowest for the Soil Washer, highest for the SBR, and at a relatively intermediate value for the BATS. This was primarily due to the fact that the SW incurred effluent treatment and disposal costs (woody debris incineration) whereas the BATS and SBR did not.

Based on 34,724 metric tons (38,273 short tons) of contaminated soil treated, the total unit cost is $185/metric ton ($168/short ton). If the cost of incineration were not included, the cost would drop to $44/metric ton ($40/short ton). The breakdown by technology is shown below:

	Unit Cost	
	($/metric ton)	($/short ton)
Soil Washer	$170.00	$154.00
Aqueous Treatment System	$ 1.73	$1.57
Slurry Bioreactor	$ 2.92	$ 2.65
Total	$174.65	$158.22

The difference in cost figures between the total unit cost of $185/metric ton ($168/short ton) and the above $175/metric ton ($158/short ton) represents other cost components that were not included in each technology (i.e., site preparation, analytical, and residuals/waste shipping, handling and transport costs). However, these additional components account for only about 5% of the costs based on $/ton and would not have had a significant impact.

As stated in the introduction to this section, BioTrol intends to market its technologies both independently of one another as well as in an integrated system as demonstrated here. It is therefore instructive to express unit costs not in terms of total soil treated in the front end of the system but rather in terms of individual process streams that each technology in the system had to treat. For the Soil Washer this is still $170/metric ton ($154/short ton) or $257/m^3 ($197/yd^3) (based on 22,938 m^3 (30,000 yd^3) treated). If incineration were not included this would drop to $29/metric ton ($27/short ton) or $44/m^3 ($34/yd^3).

For the BATS, 1079 L/min (285 gpm) of process water is assumed to be treated for 89 days for a total of 138 x 10^6 L (36.5 x 10^6 gal). The BATS treatment unit cost is then calculated to be $0.44/1000 L ($1.65/1,000 gal): ($60,195 ÷ 138 x 10^3 L (36.5 x 10^3 gal)). For the SBR, 87 L/min (23 gpm) of a 20% solids slurry is assumed to be treated for 89 days for a total of 11 x 10^6 L (2.95 x 10^6 gal). The SBR treatment unit cost is then calculated to be $9.22/1,000 L ($34.89/1000 gal): ($101,450 ÷ 11 x 10^3 L (2.95 x 10^3 gal)).

In all of the above analyses, it should be remembered that costs for 10 out of the 12 cost components were considered. One of the cost components not included here was permitting and regulatory expenses. Additionally, effluent treatment and disposal for the BATS and SBR were assumed not to be required. If these factors are taken into account, costs could significantly increase.

Section 5
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Appendix A
Process Description

Introduction

Previous tests conducted by BioTrol indicate that most soil contaminants usually are associated with the fine particle fraction (below 0.075 mm) of a bulk soil. Separation of the fines fraction concentrates the contaminants into a small portion of the original soil, which greatly reduces the amount of material requiring disposal or further treatment.

The Soil Washer (SW) separates slightly contaminated, coarse, washed soil particles from heavily contaminated fine particles. Solubility of contaminants in the processing water can also be a significant factor in the ultimate distribution. The fine particles may be treated in the Slurry Bio-Reactor (SBR), which reduces contaminant concentration by biological destruction. The process water used in the SW is treated in the BioTrol Aqueous Treatment System (BATS) prior to discharge or recycle. The actual arrangement and operation of the individual technologies will depend on site characteristics and the contaminants present. All three technologies operate in continuous feed mode. However, the SBR used in the demonstration was considerably smaller in capacity than either the SW or the BATS.

Process Description

Soil Washer

The SW is an intensive, countercurrent scrubbing system for treating excavated contaminated soils. The process flow diagram is shown in Figure A-1. Following excavation, large debris is removed from the soil by a vibrating screen. The remaining soil is fed via conveyor to a mixing trommel where it is mixed with water to form a slurry. The slurry flows from the mixing trommel and passes across a vibrating screen where oversize (CO) material is removed. The coarse oversize product is stored in drums for disposal. The screen undersize product is fed to a flotation unit where hydrophobic constituents are removed in a froth phase. Underflow then enters an intensive, multi-stage, countercurrent scrubbing circuit consisting of attrition and classification equipment. The intense scrubbing action of the attrition equipment disintegrates soil agglomerates and separates "piggybacking" fines from the coarser particles. Abrasion between the coarser particles provides additional cleaning of their surfaces. The classification equipment separates the fines from the coarse soil particles. The fine clays and organic matter retain considerable amounts of contaminants, even after undergoing intensive attrition scrubbing. The fine soil particles, which are suspended in the process water from the scrubbing circuit, are fed to a thickening operation along with the froth from the flotation unit. Just before thickening, a polymeric flocculating agent is added to the slurry of fine particles to improve settling and separation from the process water. The thickened solids (underflow) are then dewatered using a horizontal centrifuge to form a fine particle cake (FPC) which is drummed for disposal. The FPC contains most of the organic contaminants from the feed soil and requires further treatment, for which the Slurry Bio-Reactor was evaluated, using the fine particle slurry prior to thickening or dewatering. Process water from thickening and dewatering processes is sent to the BATS for treatment.

Slurry Bio-Reactor

The EIMCO Slurry Bio-Reactor (SBR) is a microbiological system for degrading penta and PAHs absorbed or adsorbed on the surface of organic and clay particles. BioTrol used the SBR to remove contamination from the clay and silt from the SW.

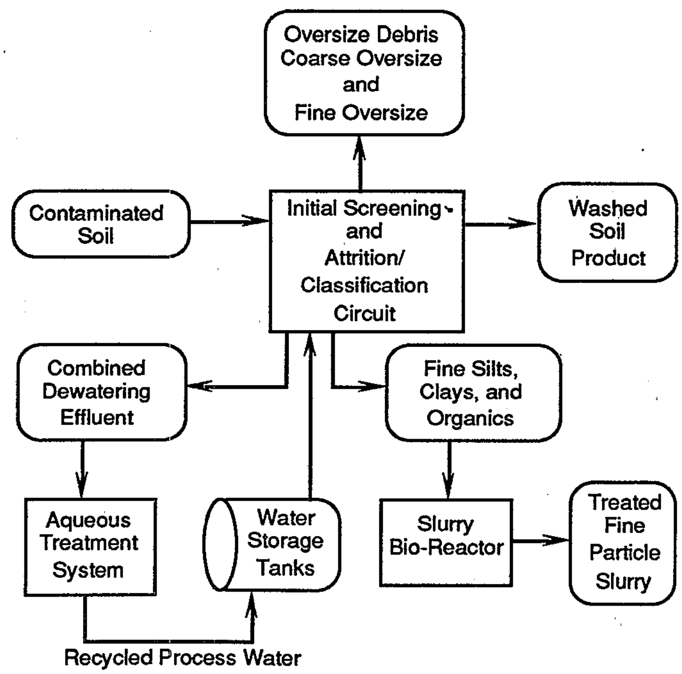

Figure A-1. Flow Diagram of the BioTrol Soil Washing System (BSWS).

The pilot-scale SBR (Figure A-2) which was provided by EIMCO for the demonstration consists of three upright, continuously stirred, stainless steel reactors in series, each with a capacity of 60 liters (16 gallons). Each one is a modified thickener incorporating an airlift which pumps settled solids that have been raked to the center column back to the top and redistributes them. Flexible membrane diffusers mounted on stainless steel rotating rake arms provide fine bubble aeration and turbulence for mixing with minimal shear. The membrane diffusers are of a non-clog type made of an elastomeric material which is chemically resistant to the contaminants. The reactors are gas sealed and all gases are vented through an activated carbon canister to prevent emission of organic compounds into the environment.

The three reactors are arranged in a cascading system, permitting gravity feed and overflow. The slurry enters the first reactor where easily degraded contaminants are consumed by the pre-inoculated and acclimated microbial population. As the slurry flows to each successive tank, the more refractory contaminants are eventually broken down. Variables that must be controlled for proper operation of the Slurry Bio-Reactor system include: suspended solids concentration, pH, nutrient concentrations, influent flow rate, temperature, dissolved oxygen concentration, gas flow rate, and rake arm speed.

The influent flow rate is controlled by a variable speed peristaltic pump. The system is equipped with automatic temperature control. The dissolved oxygen concentration is a function of the gas flow rate, the oxygen concentration in the gas, and the rate of intake by the microorganisms. The dissolved oxygen concentration is controlled by the air flow rate and is measured using a dissolved oxygen probe. All gas flow rates are monitored by rotameter. The rake arm speed is controlled by a variable speed drive.

The reactor system is best operated at steady-state to minimize operator attendance and maximize the biological degradation rate.

BioTrol Aqueous Treatment System

The BioTrol Aqueous Treatment System (BATS) is a multi-cell, submerged, packed-bed reactor which serves to biologically degrade penta- and PAH-contaminated process water from the SW. The system used in this demonstration consists of a single trailer (20 ft) on which all the vessels, pumps, etc. for the entire process are installed (Figure A-3).

The process flow is shown in Figure A-4. Incoming wastewater is pumped on a time cycle to a 100 gallon tempering tank inside the trailer. In the tempering tank, the pH of the contaminated water is adjusted to approximately 7.3 by the addition of caustic or acid and a concentrated nutrient mixture of trisodium phosphate and urea dissolved in water is metered in.

From the tempering tank the stream is pumped to the base of the first of three cells in the bioreactor by passing under an influent baffle and through the heat exchanger (see Figure A-4). Each of the three cells is filled with a corrugated polyvinyl chloride (PVC) medium (Figure A-5) which serves as the substrate for microbial attachment. With the PVC media in place, each cell can hold approximately 150 gallons. Air is injected at the base of each reactor cell using a sparger tube

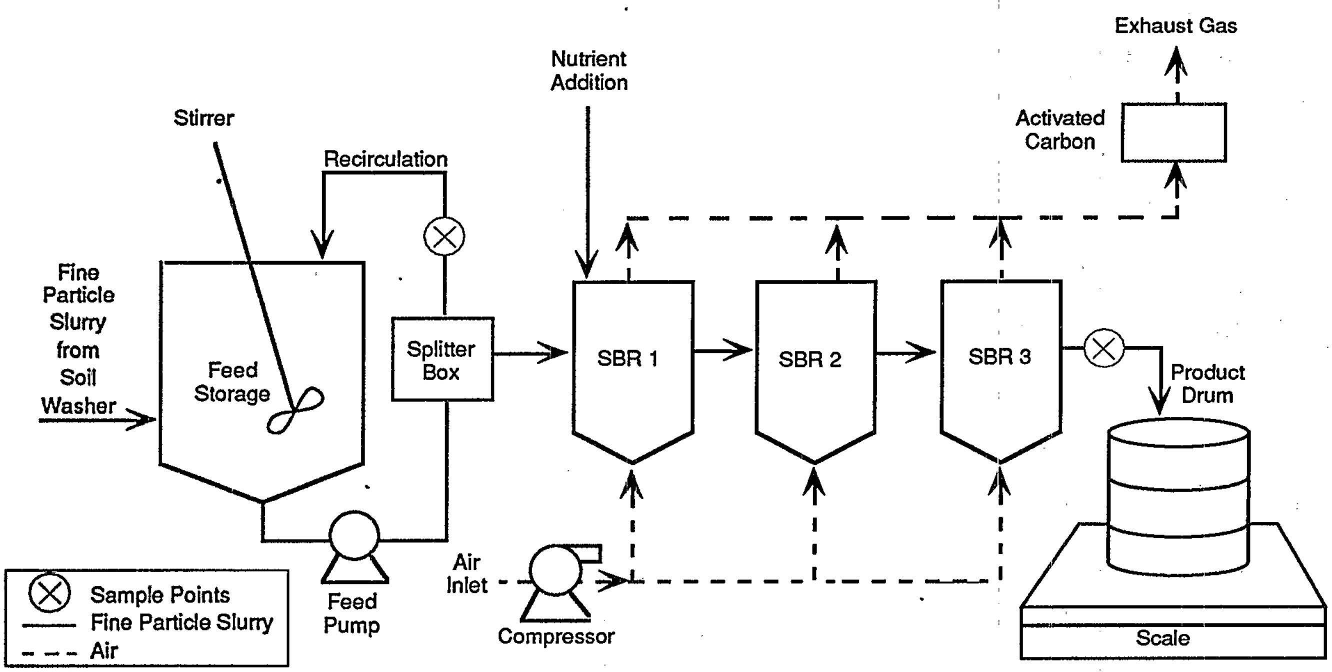

Figure A-2. Slurry Bio-Reactor Process Flow Diagram.

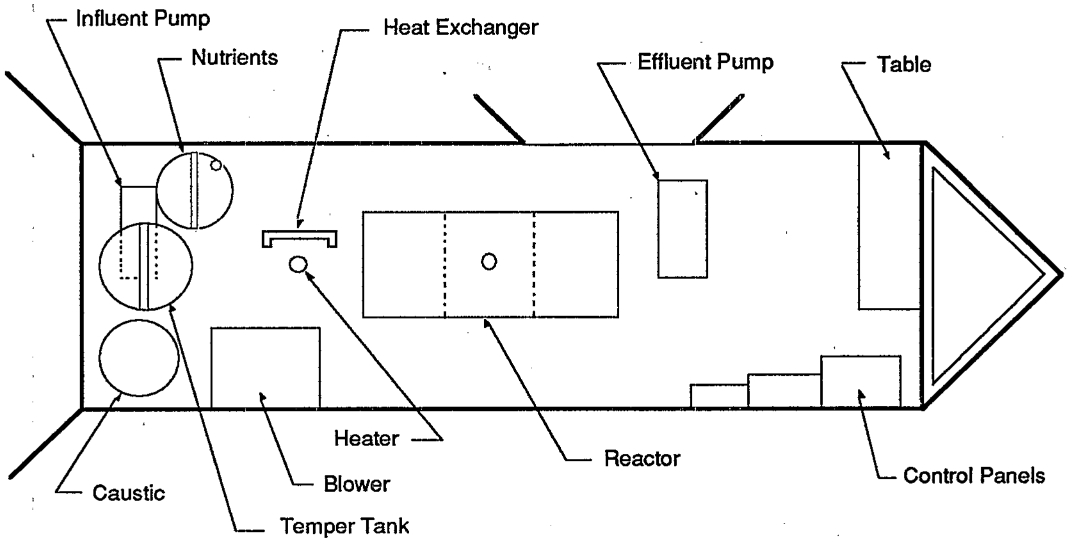

Figure A-3. BioTrol, Inc. Mobile Aqueous Treatment System.

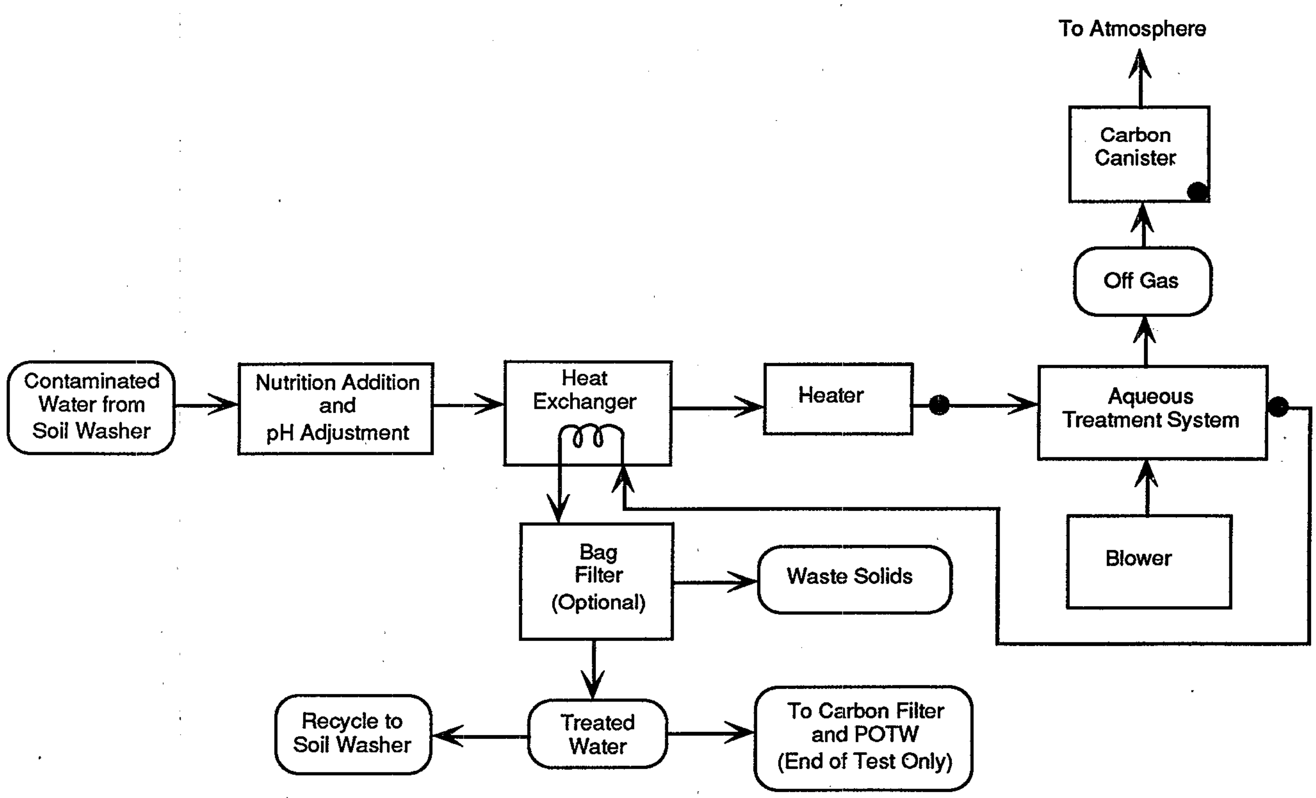

Figure A-4. Flow Diagram of BioTrol Aqueous Treatment System (BATS) with Sample Points.

crobes. As the plug-flow stream reaches the top of a cell, the water spills into an overflow weir. The weir directs the flow to the base of the next cell for further treatment. The process is repeated through cells two and three in the reactor.

The initial bacterial population, derived from the local soil, has some resistance to the toxicity of the local contaminants and has developed a population distribution which favors the destruction of those chemicals. After this bacterial source has been allowed to acclimate on the matrix, an inoculum of a *Flavobacterium* specific to the target chemical, pentachlorophenol in this case, is added and further acclimation is allowed to occur using the subject wastewater in a total recycle mode. The system is then ready for once-through treatment of process water. Since the BATS had only recently completed operation with penta-contaminated groundwater at the site, much of this acclimation was already completed and only two residence times with process water from the Soil Washer was necessary to complete the acclimation process.

After passage through the three cells of the BATS, the stream then passes through a non-contact heat exchanger where heat is transferred to the incoming water to minimize the operation of the heater in maintaining an influent water temperature of about 21°C (70°F). The treated water leaves the BATS trailer and is pumped to a holding tank.

The effluent from the BATS reactor can contain up to 30 mg/L of sloughed biomass during normal operation. Over a period of time (approx. 6 months), a biomass film may form inside the heat exchanger necessitating backflushing. While the influent fed to the BATS during the demonstration test contained 500-800 ppm of solids, these were primarily fine clay particles and no fouling problems were observed during the test.

Air emissions from the BATS cells are vented outside the trailer. For the demonstration, the lid over the reactor was fitted with flexible tubing so that the offgases could be passed through a carbon adsorption canister. After passing through the carbon canister, air emissions are discharged to the atmosphere.

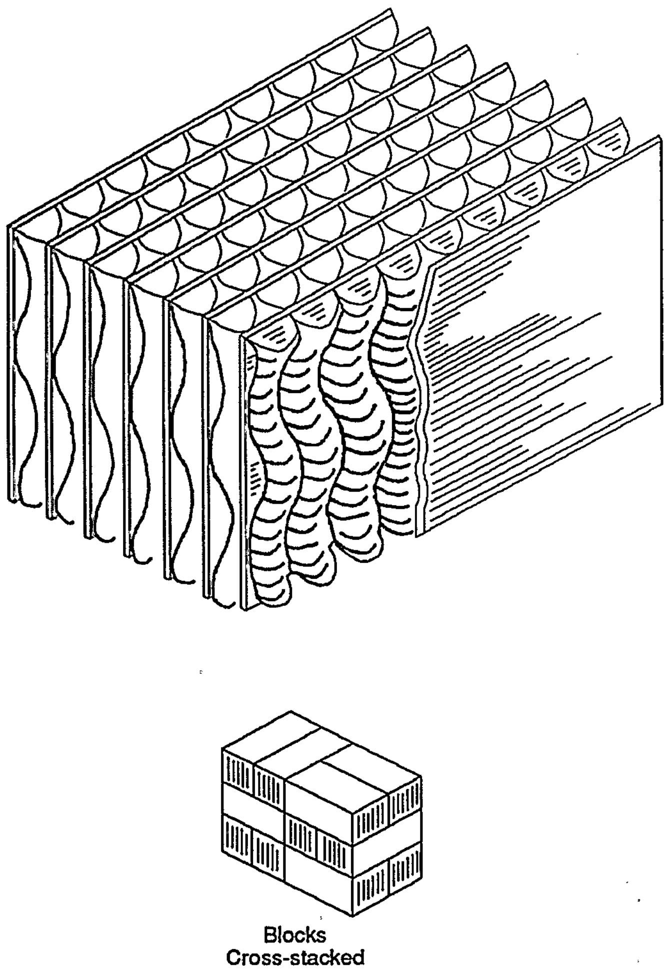

Figure A-5. Corrugated Polyvinyl Chloride Media.

system mounted beneath the packing support grid and a positive displacement blower. The wastewater flows upward from the base of each cell and contacts the fixed-film mi-

[NOTE: This Appendix was provided by the vendor.]

Appendix B
BioTrol® Soil Washing System

Technology Description

The BioTrol® Soil Washing System (U.S. Patent No. 4,923,125) is a water-based volume reduction process for treating excavated soil. Soil washing is based on the premise that: (1) contaminants tend to be concentrated in the fine size fraction of soil (silt, clay, and soil organic matter), and (2) contaminants associated with the coarse soil fraction (sand and gravel) are primarily surficial. The objective of the process is to reduce the volume of material while producing a washed soil product which meets appropriate clean-up criteria.

Following debris removal, soil is mixed with water and subjected to various unit operations common to the mineral processing industry. Process steps may include mixing trommels, pug mills, vibrating screens, froth flotation cells, attrition scrubbing machines, hydrocyclones, screw classifiers, and various dewatering operations.

Intensive scrubbing is the technology at the core of the process. For the gravel fraction, scrubbing is accomplished with a mixing trommel, pug mill, or ball mill. For the sand fraction, a multi-stage, counter-current, attrition scrubbing circuit with inter-stage classification is used. This scrubbing action disintegrates soil aggregates, freeing contaminated fine particles form the sand and gravel fraction. In addition, surficial contamination is removed from the coarse fraction by the abrasive scouring action of the particles themselves. Contaminants may also be dissolved as dictated by solubility characteristics or partition coefficients. To improve the efficiency of soil washing, the process may include the use of surfactants, detergents, chelating agents, pH adjustment, or heat. In many cases, however, water alone is sufficient to achieve the desired level of contaminant removal while minimizing cost.

These three mechanisms: (1) dispersion and separation of contaminated fine particles, (2) scouring of coarse particle surfaces, and (3) dissolution of contaminants each operate to varying degrees, depending upon the characteristics of the soil and contaminant(s).

A significant reduction in the volume of material which requires additional treatment or disposal is accomplished by separating the washed, coarse soil components from the process water and contaminated fine particles. A simplified flowsheet of the system is shown in Figure B-1.

The contaminated residual products can be treated by other methods. Process water is normally recycled after biological or physical treatment. Options for the contaminated fines can include off-site disposal, incineration, stabilization, or biological treatment.

Applicability

Soil washing systems can be tailored to remove both organic and inorganic contaminants. Research by the U.S. Department of Energy and U.S. EPA has also shown this technology to be directly applicable to radiologically contaminated soil.

For cases where the contaminants are associated principally with the fine size fraction, the amount of silt and clay, i.e., the weight of soil passing a 74 microns (No. 200) sieve, should not normally exceed 25 to 35 percent in order to achieve an economic volume reduction. The fraction of silt and clay in the soil may not be a factor when dissolution of contaminants is the primary mechanism, i.e., the leaching of metals or soluble organics.

Performance

BioTrol has conducted laboratory-scale testing with soil samples from numerous contaminated sites. In general, organic contaminant levels in the washed soil are generally 90 to 99 percent lower than in the feed soil. Removal efficiencies are dependent upon the contaminant, the initial contaminant level, and the soil matrix. Typical testing results are provided in Table B-1. (The objective of tests shown below was to maximize organic contaminant removal. Although removal efficiencies for metals were somewhat lower, the levels achieved met customer requirements. If required, hydrometallurgical techniques can be used to significantly improve metals removal.)

Laboratory Testing Services

Because each site is unique with respect to soil and contaminant characteristics, it is necessary to conduct preliminary engineering studies (treatability testing) on representative soil samples. These studies are conducted at BioTrol's Chaska, Minnesota laboratory, and may include, but are not limited to:

- Sample preparation;

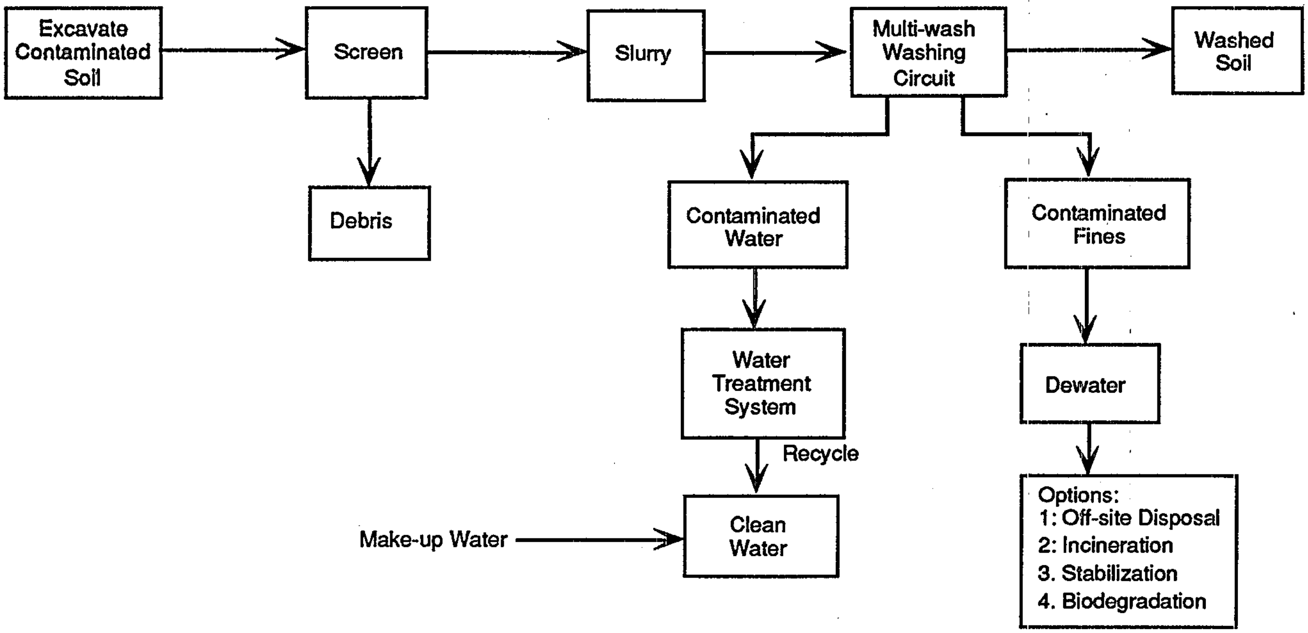

Figure B-1. Simplified Flowsheet - BioTrol® Soil Washing System.

Table B-1. Results of Laboratory-Scale Testing - BioTrol® Soil Washing System

Site Description	Contaminant	Before (mg/kg)	After (mg/kg)	Reduction (percent)	Washed Soil Weight (percent)
Wood Preserving (California)	Total PAHs (1)	4800	230	95	83
	Arsenic	89	27	70	
	Chromium	63	23	63	
	Copper	29	13	55	
	Zinc	345	108	69	
Wood Preserving (Florida)	Pentachlorophenol	380	4.0	99	90
	Pentachlorophenol	610	25	96	80
Wood Preserving (North Carolina)	Total PAHs (1)	100	5.1	95	90
	Carcinogenic PAHs (1)	11	1.6	85	
	Arsenic	289	64	78	
	Chromium	195	51	74	
Chemical Plant (Michigan)	Dichlorobenzidine	770	13	98	85
	Benzidine	1000	6.0	99	
	Azobenzene	2400	7.0	> 99	
Wire Drawing (New Jersey)	TPH(2)	4700	350	93	80
	VOC(3)	2.0	0.01	> 99	
	Copper	330	100	70	
	Nickel	110	60	45	
	Silver	25	4.0	84	
Town Gas (Quebec)	Total PAHs(1)	230	11	95	83
Pesticide Formulation (Colorado)	Chlordane	55	4.7	91	80
	Aldrin	47	7.5	84	
	4,4-DDT	25	5.0	80	
	Diedrin	46	7.0	85	

Notes: (1) Polynuclear aromatic hydrocarbons
(2) Total petroleum hydrocarbons
(3) Volatile organic compounds

- Sample characterization;
  - Chemical analysis
  - Sieve analysis with chemical analysis of size fractions
  - Mineralogy

- Leaching studies (to determine partition coefficients);

- Soil washing tests;

- Dewatering tests (contaminated fines);

- Treatment tests on contaminated process water and fines (in-house biodegradation or carbon treatment tests if applicable, or alternatively, other third party testing).

The preliminary engineering study can determine:

- The ability of soil washing to physically process and effectively treat the contaminated soil of interest;

- The flowsheet required to achieve the desired separations;

- Projected operating conditions for full-scale treatment;

- Estimated treatment costs for full-scale treatment with an accuracy of -30/+50 percent, based on a known volume of soil at a given treatment rate;

- Treatment options for the contaminated process water and fines.

On-site Demonstration Testing

BioTrol is equipped to conduct on-site demonstration testing using a pilot-scale soil washing system. The purpose of on-site testing is to confirm results obtained in the preliminary engineering study (treatability test) by using a continuous, pilot-scale system operating under actual site conditions. The demonstration can provide assurance to the customer and the appropriate regulatory agencies that the technology can achieve the treatment levels required. In addition, the pilot-scale tests can determine optimum system operating parameters to serve as the basis for more accurate full-scale design specifications.

The pilot system consists of the following components:

- Trailer-mounted soil washing system with a nominal treatment capacity of 500 to 1,000 pounds per hour;

- Up to 4 process water storage tanks, each with a nominal capacity of 8,000 gallons;

- Water treatment system (physical or biological);

- Mobile office/laboratory.

A demonstration typically lasts 1 to 3 weeks in addition to the time required for mobilization and feed preparation. During the demonstration, a *generalized test program is employed* which focuses on several key operating parameters and their effect on system performance. Parameters can include system configuration, soil feed rate, water addition rate, type and addition rate of chemical additives (if required), and dewatering conditions. During steady-state operation, key process streams are sampled at fixed intervals and composited prior to chemical analysis. An accurate mass balance for the system can be determined by collecting all exiting streams in drums and measuring net drum weights over set time intervals.

Full Scale Soil Washing Systems

BioTrol engineers can design and construct full-scale soil washing systems for the remediation of a wide variety of soil and contaminant conditions. Based on the results of a preliminary engineering study or if available, pilot-scale test results, a soil washing flowsheet will be engineered to achieve the necessary separations for a given contaminated soil. BioTrol uses a modular design approach to easily accomplish this task while minimizing engineering and construction costs.

The volume of contaminated soil will usually determine the treatment capacity of a system. For example, remediation of sites in the range of 5,000 to 100,000 cubic yards could be accomplished in less than one year with a 20 ton per hour system. For extremely large sites, or for a central facility, permanent or semi-permanent systems could be designed with treatment capacities in the range of 100 to 200 tons per hour.

Depending upon customer needs, systems can be leased or purchased. BioTrol can provide technical and supervisory staff, as well as operating and maintenance personnel. Alternatively, technical assistance and training could be provided by BioTrol under terms of a service contract.

A 20 ton per hour mobile system can be assembled on 6 semi-trailers. A typical layout of this mobile system is shown in Figure B-2. Approximately 0.3 to 0.5 acres is required for the complete system, including feed hopper with earthen approach ramp, various conveyers with associated product piles, process water storage tank(s), water treatment system, and field office.

Advantages

The BioTrol® Soil Washing System makes use of a patented intensive scrubbing technology, unlike other approaches which are based almost entirely upon simple leaching. Use of this intensive scrubbing process is *the* most effective approach to soil washing.

In addition, BioTrol utilizes a process development approach for each site. This, together with modular construction design, provides the most cost-effective method of applying soil washing to a contaminated site. Pre-engineered modules are simply arranged in the optimal configuration for the unique soil and contaminant conditions, avoiding unnecessary design and construction costs.

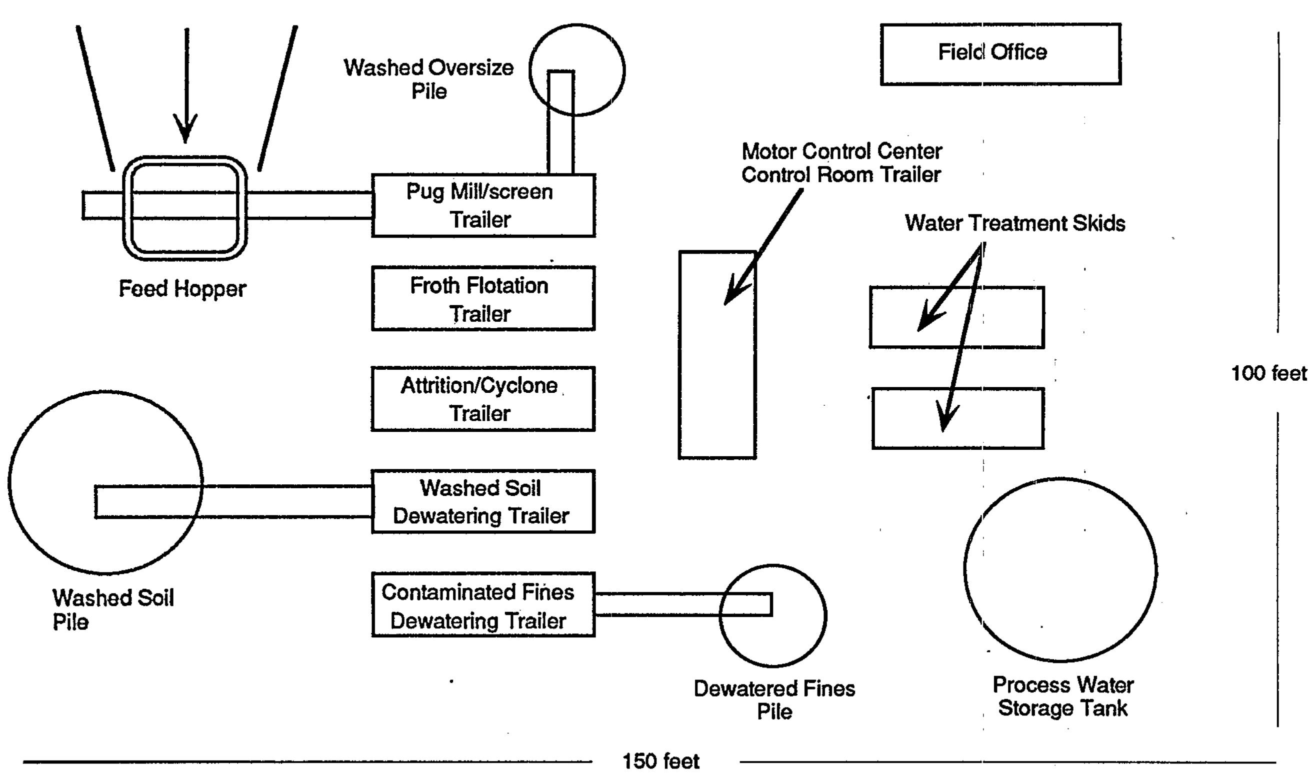

Figure B-2. Typical Plan View of a Mobile 20 Ton per Hour Soil Washing System.

BioTrol's biological treatment technologies can be coupled, where applicable, with soil washing for treatment of the residual products (process water, contaminated fines, and debris), minimizing overall remediation costs.

Costs

Estimated treatment costs for a mobile, commercial-scale, 20 ton per hour soil washing system are shown graphically in Figure B-3 as a function of tons processed. Costs include capital recovery (charged as an equipment leasing rate) and water treatment; not included are costs for excavation, debris removal, chemical additives, and treatment or disposal of residuals generated during treatment.

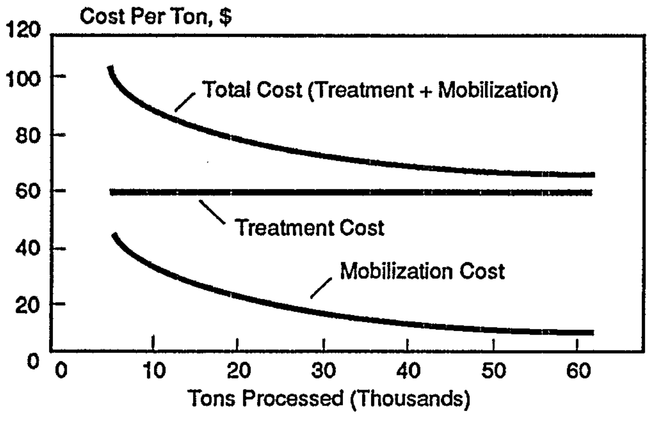

Figure B-3. Estimated Treatment Cost (typical) for a 20 Ton Per Hour Mobile Soil Washing System.

Total cost per ton is the sum of the mobilization and treatment cost components. The estimated treatment cost of roughly $60 per ton varies only slightly with tons processed. Mobilization cost per ton has the most impact at relatively small soil volumes.

For illustration, from Figure B-3, the estimated soil washing cost for 20,000 tons of soil would be approximately $71 per ton or $1.42 million. Costs for treatment or disposal of the residuals generated during soil washing must also be calculated to estimate total remediation costs. For example, soil washing of 20,000 tons of soil with characteristics similar to that of the MacGillis and Gibbs SITE project would generate 1,900 tons of woody debris and 1,300 tons of fines, both requiring additional treatment. Using incineration at $200 per ton for the woody debris and slurry-phase biodegradation for the fines at $100 per ton, treatment of residuals would cost an additional $510,000 or $25.50 per ton based on 20,000 tons. Total solid treatment costs, including treatment of residuals, is therefore estimated at $96.50 per ton or $1.93 million.

Soil washing unit costs will be significantly lower for systems with larger throughput capacities or for fixed central facilities. In these cases, total soil washing costs could be in the range of $25 to $50 per ton.

Appendix C
Site Demonstration Results

Introduction

The goal of this demonstration project was to study the effectiveness of the BioTrol SWS in removing penta and PAHs from contaminated soil at a wood treating site. The MacGillis and Gibbs site in New Brighton, MN was selected on the basis of the Remedial Investigation/Feasibility Study (RI/FS) and the site's inclusion on the National Priorities List in 1984 (Figure C-1).

The MacGillis and Gibbs site has been used for wood treatment since the early 1920s. Creosote was the preservative until the mid-1950's when a shift was made to pentachlorophenol in a light oil. Impregnation was carried out in open troughs, resulting in significant spills and drippage. In addition, the pentachlorophenol/oil mixture occasionally was used for weed control throughout the site. In the 1970's, pentachlorophenol was replaced by the newer chromated copper arsenate process and enclosed pressure kettles were substituted for the open troughs, thereby eliminating many of the sources of contamination.

Soil Washer Performance

Input and Output Flow Rate Stability

The planned feed soil (FS) rate was approximately 275 kg/hr (610 lb/hr) on an as-is weight basis. The Soil Washer ran the first 28 hours of the low penta contaminated test at 250 to 300 kg/hr (550 - 660 lb/hr). Starting at hour 28, clogging caused by soil compacted at the base of the feed hopper impeded the transfer of soil to the feed conveyer. Efforts to eliminate the problem were only partially successful. This resulted in a sharp decline in the feed soil rate to about 125 kg/hr (280 lb/hr), or 45% of the planned rate (Figure C-2).

The washed soil (WS) output rate appears to be very responsive to fluctuations in the feed soil rate, and is slightly higher than the feed soil rate, probably because the two streams are of comparable magnitude and the retention time within the system does not produce a significant response lag. The output rate exceeds the feed soil input rate because of water uptake during the soil washing process.

The minor solids streams — coarse oversize (CO), fine oversize (FO), and fine particle cake (FPC) — also reflect variations in the feed soil rate. However, the effect is less obvious for these streams because of their small volume (less than 75 kg/hr or 160 lb/hr).

Municipal water (MW) was the primary aqueous input stream, averaging 20 liters/min (5.3 gpm), while the thickener stream (polymer in water) contributed a steady but minor flow of 2.7 liters/min (0.7 gpm). After a few initial adjustments through hour 10, the municipal water flow rate stabilized between 18 and 20 liters/min (4.8 and 5.3 gpm). The flow rate eventually was lowered to approximately 14 liters/min (3.7 gpm) in response to the decrease in feed soil input rate. Figure C-3 compares the rates of the Soil Washer aqueous input and the output streams during the test with the low penta soil.

The combined dewatering effluent (CDE) is sensitive to fluctuations in the municipal water input rate and is approximately equal to the municipal water flow rate when process water is not recycled. The sensitivity again demonstrates that the retention time within the Soil Washer does not create a significant response lag. The combined dewatering effluent flow rate is equivalent to the municipal water flow rate because the net water consumption in the Soil Washer by the four solids-bearing output streams is approximately equal to the flow rate from the thickener.

In the second soil washer test, using the high penta soil, the feed soil rate stabilized between 140 and 150 kg/hr (310 - 330 lb/hr) for the first 40 hours, until mechanical problems with the feed system forced the Soil Washer to be operated at less than 120 kg/hr (260 lb/hr). After the scheduled break (in sampling but not operation) to deliver fine particle slurry to the Slurry Bio-Reactor (hours 50 to 80), a vibrating device was attached to the outside of the feed hopper in an attempt to correct the soil compaction problem. The vibrator was successful in producing a 50 kg/hr (110 lb/hr) jump in the feed soil rate to approximately 200 kg/hr (440 lb/hr) and the unit operated at this level for 30 more hours. For the remainder of the test, intermittent mechanical failures throughout the Soil Washer equipment caused both instability and a drop in the feed soil rate.

The washed soil output rate closely reflected changes in the feed soil rate, as during the test with the low penta soil. However, the difference between the two flow rates was greater, suggesting that the washed soil was generally wetter during this test, which was confirmed by moisture determinations. The other, smaller solids streams also behaved as in the test with the low penta soil. Figure C-4 summarizes the rates of the input and output solids streams during the high penta soil washer test.

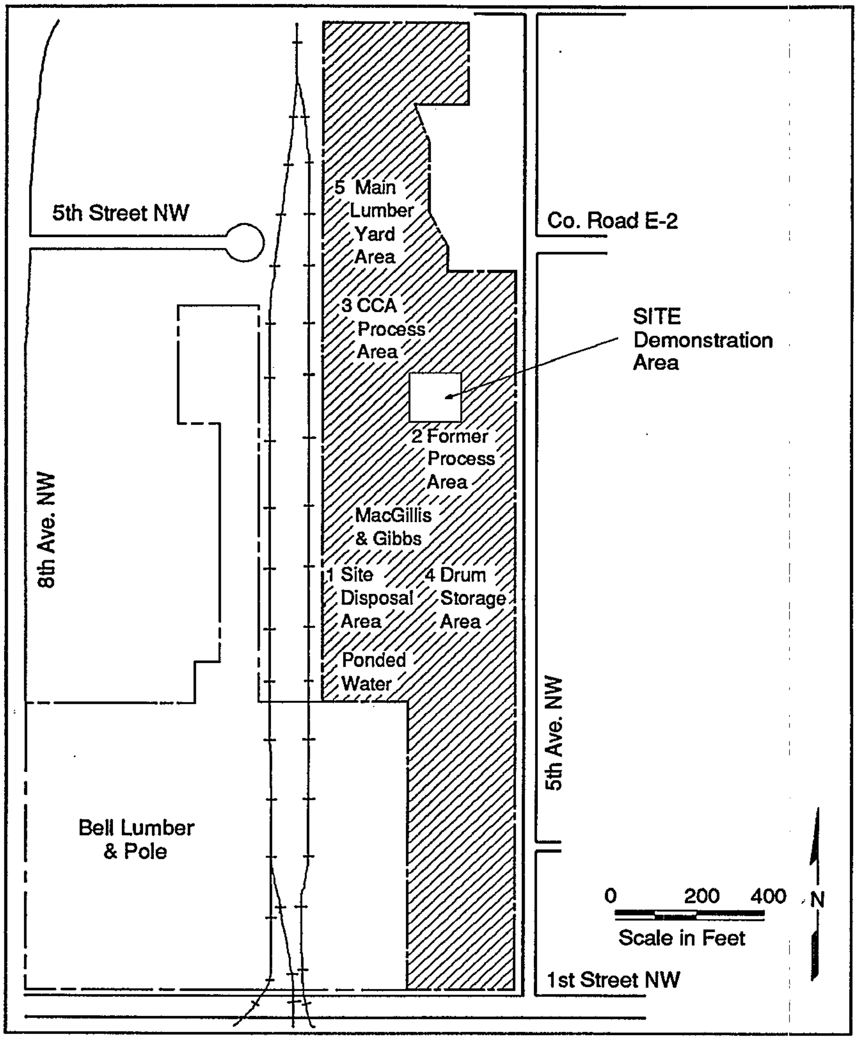

Figure C-1. Operations at the MacGillis & Gibbs Site.

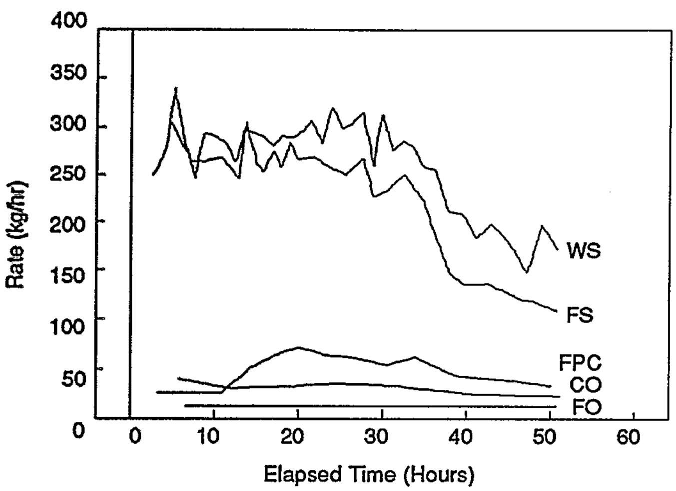

Figure C-2. Solid Stream Flows - Low Penta Soil Washer Test.

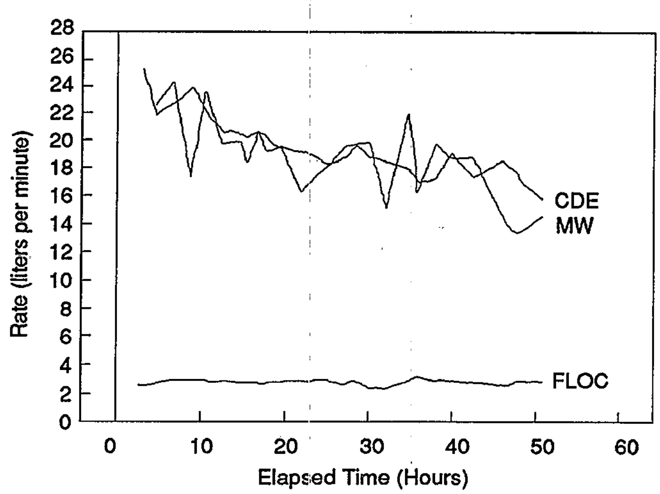

Figure C-3. Aqueous Stream Rates - Low Penta SW Test.

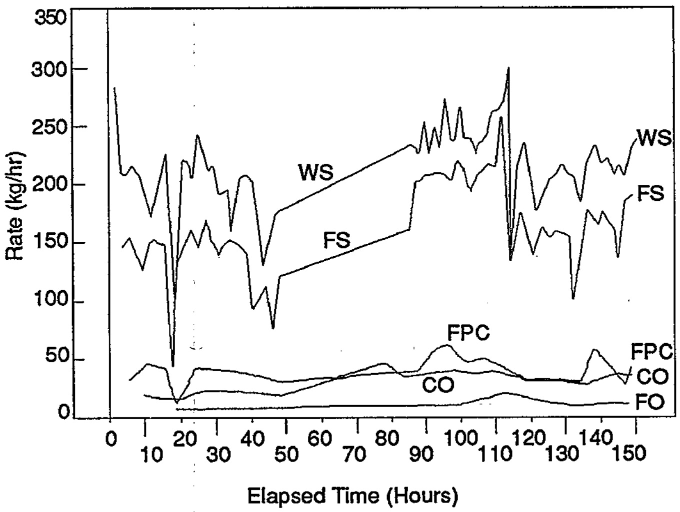

Figure C-4. Solid Stream Flows - High Penta Soil Washer Test.

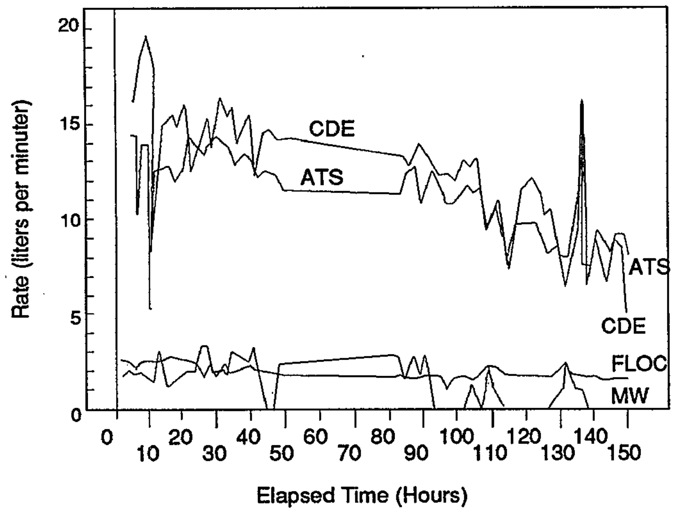

Figure C-5. Aqueous Streams - High Penta SW Test.

Water recycled from the BATS (i.e., BATS treated water) was the primary aqueous input stream during the test with the high penta soil, averaging 11 liters/min (2.9 gpm). The two other aqueous input streams, municipal water and thickener, provided 0.6 liters/min (0.2 gpm) and 2 liters/min (0.5 gpm), respectively. The BATS treated water flow rate was never stabilized during the test. The flow rate started off at about 14 liters/min (3.7 gpm) and gradually decreased to 7 liters/min (1.9 gpm). Municipal water supplied 1 to 3 liters/min (0.3 to 0.8 gpm) during the first 90 hours of operation, after which it was used only intermittently. The thickener stream was, once again, constant throughout the test. Figure C-5 illustrates the rates of aqueous inputs and outputs during the test with the high penta soil.

The conclusions drawn from examination of the gross input and output flow rates are:

1. The ability to operate with stability is critical. A full-scale operation can conceivably process several hundred tons of soil per day. The design, schedule, and cost of a remediation project hinges on a reliable throughput.
2. The primary cause of instability with BioTrol's Soil Washer was the feed delivery system. BioTrol feels that this problem is correctable.

Feed and Washed Soil Flow Rate Effects on Contaminant Removal

The sharp decline in the feed soil and washed soil rates during the test with the low penta soil raises the question, "How does flow rate affect contaminant removal?" Data summarized in Figure C-6 for feed soil and washed soil penta concentrations in these fractions, respectively, indicate that:

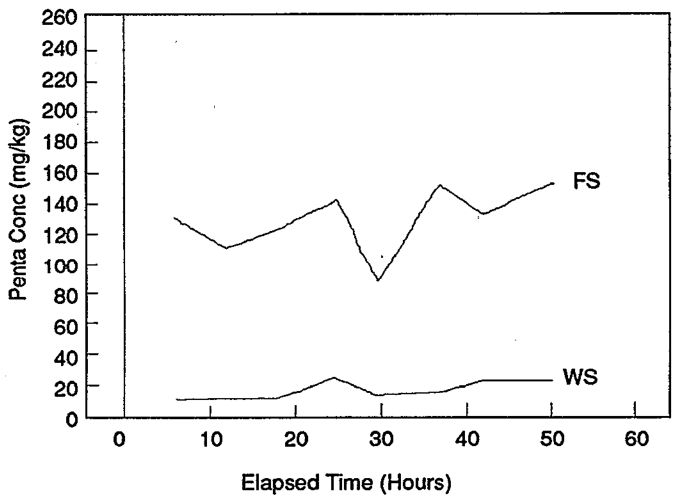

Figure C-6. Penta Concentration - Washed and Feed Soil. Low Penta Soil Washer Test.

1. penta concentration in the washed soil was not affected by the steep (55%) drop in feed and washed soil flow rates; and
2. penta concentration in the washed soil appears to reach a baseline of between 10 and 20 mg/kg while penta concentration in the feed soil ranged from 80 to 160 mg/kg.

During the Soil Washer test with the high penta soil, the Soil Washer operated under three distinct feed soil rate scenarios: a stable 150 kg/hr (330 lb/hr), a stable 200 kg/hr (440 lb/hr), and sporadic fluctuations between 150 and 200 kg/hr. Once again, the washed soil rate reflected changes in the feed soil input rate, just as it did during the low penta SW test. Analysis of the data (Figure C-7) indicates that:

1. penta concentration in the washed soil was not affected by either a stable increase or sporadic fluctuations in feed and washed soil flow rates; and

2. penta concentration in the washed soil appears to reach a baseline of 50 to 100 mg/kg for feed soil containing between 300 and 1100 mg/kg.

The concentrations of PAHs in the washed soil were similarly unaffected by variable soil flow rates during both the low penta and the high penta Soil Washer tests.

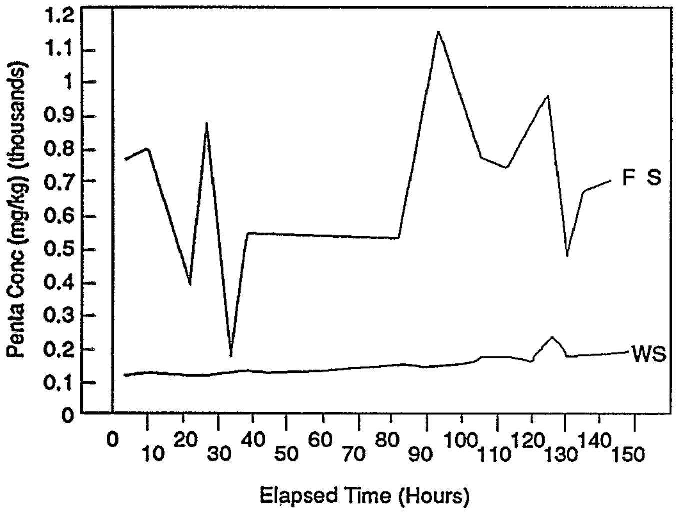

Figure C-7. Penta Concentration - Washed and Feed Soil. High Penta Soil Washer Test.

Removal efficiency for the Soil Washer is measured by comparing the concentration of contaminant in the feed soil to that in the washed soil and is defined by the following equation:

$$\text{Removal Efficiency} = 100 \times \left(1 - \frac{\text{concentration in washed soil}}{\text{concentration in feed soil}}\right)$$

The penta removal efficiency for the low penta Soil Washer test was 89%, based on weighted average concentrations in the feed and washed soil. In the test with the high penta soil, the penta removal was 87%. The mean PAH removal efficiency for the low penta test was 83%. In the high penta test, the mean removal efficiency for PAHs was 88%. The penta and PAH removal efficiencies were relatively unaffected by the variations in feed soil rates. There was, however, some indication that the extraction procedure used in the analytical procedure for pentachlorophenol and other semi-volatiles (sonication, Method 3550) was incomplete with the feed soils due to inaccessibility. While this was not verified, it would have led to underestimation of the penta concentrations in the feed soil and this, in turn, would have led to low values for removal efficiencies. The poor mass balance for penta would support this argument.

Higher removal efficiencies may be achievable in the Soil Washer by:

1. increasing the amount of unit energy (i.e., energy per pound of soil washed) in the attrition/scrubbing process to liberate more contaminant; and

2. using a water additive to enhance the transfer of contaminant from the washed soil to the aqueous phase.

Fate of Contaminants

Data show that 83% of the output solids from the Soil Washer leave the system as washed soil in both tests. It is presumed that washed soil is returned to the site with no further treatment, although this would require agency approval. If the Slurry Bio-Reactor is used to treat the fine particles (7% of output solids) leaving the system, then the total amount of solids requiring treatment by other technologies is reduced to under 10%. This represents a volume reduction of 90%. Table C-1 summarizes the fate of total mass, total solids, penta, and carcinogenic PAHs in the Soil Washer. These data can be interpreted to mean:

1. Water soluble contaminants such as penta accumulate largely in the combined dewatering effluent and the fine particle cake. Both of these output streams can be treated biologically (BATS and SBR).

2. Water insoluble compounds such as PAHs gather mostly in the fine particle cake, with much less in the process water.

3. A low percentage (about 10%) of the mass of pollutants entering the Soil Washer remains on the washed soil. However, since the washed soil has a large solids content, the resulting pollutant concentration is low.

4. For dioxins, the combined or Total CDD/CDFs, 63% and 71% of the output mass is found in the fine particle cake in the low and the high penta soil tests, respectively. Only 12% and 5% of the Total CDD/CDFs output mass remains in the corresponding washed soils (Table C-2).

Slurry Bio-Reactor Performance

The volumetric flow rate through the SBR was quite constant at about 0.024 L/min (0.38 gph). Since the total SBR volume was 180 liters, this corresponded to an average retention time of about 5 days.

Penta concentrations in the solid phase of the influent were approximately two orders of magnitude higher than for the liquid phase. It was felt that the main reason for this was that the penta solubility in water is limited to about 80 ppm. Penta concentrations in the liquid phase of the influent

Table C-1. Soil Washer Input and Output Streams Low and High Penta Soil Washer Tests

Low Penta SW Test Input Streams	Total Mass Rate	Total Mass % of Input	Total Solids Conc.	Total Solids % of Input	Pentachlorophenol Conc.	Pentachlorophenol % of Input	Total PAH's Conc.	Total PAH's % of Input	Carcinogenic PAH's Conc.	Carcinogenic PAH's % of Input
Feed Soil (s)	220 kg/hr	13.8	89%	99.9	130 mg/kg	100.0	247 mg/kg	100.0	204 mg/kg	100.0
Municipal Water (aq)	1200 kg/hr	75.0	260 mg/L	0.1	0.0 mg/L	0.1	0.0 mg/L	0.0	0 mg/L	0.0
Thickener (aq)	180 kg/hr	11.3	N/A	N/A	0.0 mg/L	0.0	0 mg/L	0.0	0 mg/L	0.0
Output Streams		% of Output	Conc.	% of Output	Conc.	% of Output	Conc.	% of Output	Conc.	% of Output
Washed Soil (s)	260 kg/hr	17.9	73%	83.1	14 mg/kg	9.4	42 mg/kg	17.8	3.9 mg/kg	16.3
Coarse Oversize (s)	32 kg/hr	2.2	69%	9.7	170 mg/kg	14.1	309 mg/kg	16.1	18 mg/kg	9.3
Fine Particle Cake (s)	48 kg/hr	3.3	30%	6.4	270 mg/kg	33.5	779 mg/kg	60.8	62 mg/kg	47.9
Fine Oversize (s)	13 kg/hr	0.9	8%	0.5	96 mg/kg	3.2	208 mg/kg	4.4	123 mg/kg	25.8
Combined Dewatering Effluent (aq)	1100 kg/hr	75.7	650 mg/L	0.3	14 mg/L	39.8	0.5 mg/L	0.9	0.04 mg/L	0.7

High Penta SW Test Input Streams	Total Mass Rate	Total Mass % of Input	Total Solids Conc.	Total Solids % of Input	Pentachlorophenol Conc.	Pentachlorophenol % of Input	Total PAH's Conc.	Total PAH's % of Input	Carcinogenic PAH's Conc.	Carcinogenic PAH's % of Input
Feed Soil (s)	160 kg/hr	16.4	84%	99.9	680 mg/kg	98.3	247 mg/kg	99.7	71 mg/kg	72.7
Municipal Water (aq)	36 kg/hr	3.7	310 mg/L	0.0	0.0 mg/L	0.0	0 mg/L	0.0	0 mg/L	0.0
Thickener (aq)	120 kg/hr	12.3	N/A	N/A	0.0 mg/L	0.0	0 mg/L	0.0	0 mg/L	0.0
ATS Treated Water (aq)	660 kg/hr	67.6	480 mg/L	0.2	2.8 mg/L	1.7	0.2 mg/L	0.3	0 mg/L	0.0
Output Streams		% of Output	Conc.	% of Output	Conc.	% of Output	Conc.	% of Output	Conc.	% of Output
Washed Soil (s)	210 kg/hr	20.9	51%	8.3	87 mg/kg	10.7	42 mg/kg	18.5	8.9 mg/kg	15.6
Coarse Oversize (s)	28 kg/hr	2.8	35%	7.3	1400 mg/kg	23.1	309 mg/kg	18.1	96 mg/kg	22.4
Fine Particle Cake (s)	36 kg/hr	3.6	16%	0.8	1300 mg/kg	27.5	779 mg/kg	58.7	179 mg/kg	53.7
Fine Oversize (s)	9.1 kg/hr	0.9	69%	83.2	900 mg/kg	4.8	208 mg/kg	4.0	86 mg/kg	6.5
Combined Dewatering Effluent (aq)	720 kg/hr	71.8	740 mg/L	0.3	80 mg/L	33.9	0.5 mg/L	0.8	0.3 mg/L	1.8

Notes: (aq) = aqueous stream; (s) = solid stream; % of input and output are on a mass basis

Table C-2. Dioxin/Furans Distribution in the Soil Washer

Stream	average rate kg/hr	Total CDD/CDFs conc (ppm)	mass/hr (mg)	% of output (%)
Low Penta SW Test				
Feed Soil	220	1.365	300.30	—
Municipal Water	1200	0	0.00	—
Thickener Stream	180	0	0.00	—
Input Total	1600		300.00	
Coarse Oversize	32	1.043	33.38	14.0
Fine Oversize	13	1.824	23.72	9.9
Fine Particle Cake	48	3.130	151.20	63.3
Washed Soil	260	0.109	28.31	11.8
Comb. Dewater Eff.	1148	0.002	2.30	1.0
Output Total	1501		238.91	
High Penta SW Test				
Feed Soil	160	2.508	401.28	—
Municipal Water	36	0	0.00	—
BATS Effluent	660	0	0.00	—
Thickener Stream	120	0	0.00	—
Input Total	976		401.28	
Coarse Oversize	28	2.319	64.93	18.9
Fine Oversize	9.1	1.235	11.23	3.3
Fine Particle Cake	36	6.818	245.45	71.4
Washed Soil	210	.078	16.38	4.8
Comb. Dewater Eff.	720	.0082	5.90	1.7
Output Total	1003.1		343.90	

decreased over the fourteen day test period whereas solid phase penta concentrations remained constant. Similar trends observed for the PAHs would indicate that some biodegradation was occurring in the holding tank prior to the SBR inlet.

Based on the analytical results, the acclimation period actually extended about 5 days more than originally anticipated. After this adjustment period, liquid phase penta reductions remained fairly constant at around 97% but asymptotically increased from 65% to 92% for the solid phase. This type of performance can probably be traced back to the contaminant concentrations of the liquid phase being two orders of magnitude less than the concentration of the solid phase. This insures that there are sufficient bacteria to consume just about all of the contaminant in the liquid phase. Conversely, the solid phase has such a high contaminant concentration that bacteria must be generated, thereby extending the acclimation period until a population large enough or aggressive enough to consume most of the contaminant has been produced — assuming the high concentration on the solid is not inhibitory or even toxic, as discussed earlier. Figure C-8 shows the variation in overall penta removal efficiency i.e., solid and liquid phases combined, as the test progressed. Had the SBR been allowed to operate for a longer period of time, its performance might have stabilized at a steady-state value that

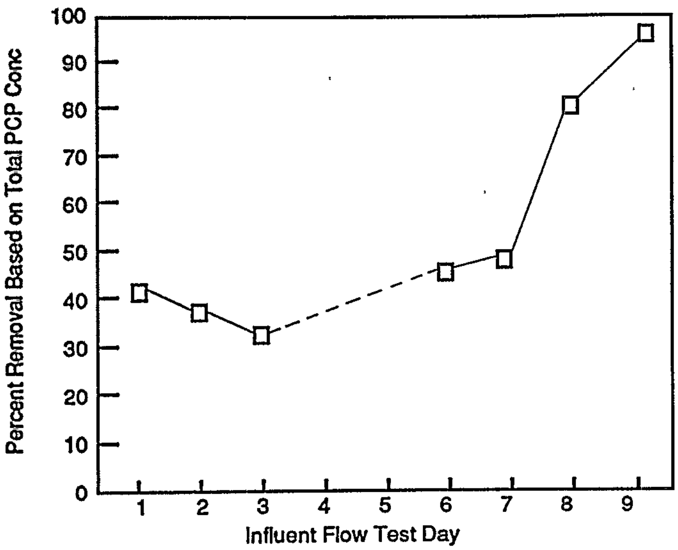

Figure C-8. Overall Penta Removal Slurry Bio-Reactor.

would have been more indicative of the unit's capability and BioTrol's penta removal claims of 90-95%.

After acclimation, PAH removal efficiency was at least 70% for all compounds of interest. Heavy metals did not appear to adversely affect the biodegradation process but instead appeared to pass through the system. Very little, if any, organic compounds were volatilized from the SBR based on analysis of the carbon in the exhaust line adsorber.

Biotrol Aqueous Treatment System Results

A biomass had already been established in the BATS in the earlier demonstration using contaminated groundwater. The field effort for that demonstration was finished on September 1, 1989 and the BATS continued to run with contaminated groundwater at a low flow rate to maintain the biomass until the start of the BioTrol Soil Washing System demonstration. On September 27, 1989, the system was switched from groundwater to SW process water and allowed to acclimate for two residence times before sampling was initiated. The BATS test consisted of two phases. During the first phase, process water from the low penta concentration Soil Washer test was treated. During the second phase, process water from the high penta concentration Soil Washer test was treated.

Test Procedures

The BATS influent and effluent were sampled around the clock using ISCO automatic samplers to composite six-hour samples. The samplers automatically collected 250 ml grab samples every 10 minutes and deposited them in a composite container. Fourteen composite samples were collected over a period of approximately 3.5 days in the first phase, using process water from the low penta SW test. Twenty-three composite samples were collected over a period of approximately 6.5 days in the second phase (high penta process water). The samples were kept on ice during compositing. The BATS carbon canister also was sampled at the end of the test. Four composite samples of the carbon canister were obtained, each consisting of four individual grab samples of 750 ml. Samples of the sludge in the bag filter also were planned, but the test ended ahead of schedule and no sample of the material in the bag filter was collected.

Field measurements were collected at various intervals over the course of the BATS tests. Every two hours, measurements of influent, effluent, and nutrient flow rates were taken by recording the depth of liquid in the respective tank. Every eight hours, measurements of pH and temperature were collected from grab samples of influent and effluent taken at "T" joints in the influent and effluent lines of the system. Power readings were recorded every eight hours from a standard domestic electric power meter. The pH adjusting chemicals, flow rate, and the weight of the carbon in the adsorption canister were measured using a direct-read floor scale.

Sampling and Analysis

All of the samples were analyzed for penta and full semi-volatile priority pollutant scans. Analyses for other constituents were performed on selected samples at varying frequencies. Included were heavy metals, total residue, total recoverable petroleum hydrocarbons, chemical oxygen demand, chloride ion, total organic halides, and polychlorinated dibenzodioxins and dibenzofurans. The BATS carbon canister was analyzed for penta, semi-volatiles, and total residue.

System Parameters

Flow rates remained very steady for both the influent and the effluent over the entire course of the tests. The mean influent flow rate was 10.2 L/min (2.69 gpm) in the first test and 10.1 L/min (2.67 gpm) in the second test. The mean effluent flow rate was 9.94 L/min (2.63 gpm) for the first test and 10.1 L/min (2.67 gpm) for the second test.

The heater was in use during this demonstration because of the low ambient temperatures encountered in Minnesota in late September. The average influent temperatures were 16.5°C for the first test and 14.6°C for the second test. The average effluent temperatures were 25.2°C and 24.7°C for the two tests, respectively. Some increase in temperature from influent to effluent was expected due to biodegradation in the BATS.

The influent pH range, after adjustment, was 7.03 to 7.5 in the first test and 6.6 to 9.07 in the second test. The effluent pH range was 7.21 to 7.83 for the first test and 6.64 to 9.19 during the second test. The vendor had specified a pH of approximately 7.3 as the ideal pH for the system and measurements indicate that this was achievable through the on-line pH adjustment system. The pH of the SW process water, before pH adjustment, varied over the course of the test, but was in the range of 6.64-8.03 standard units, which would be suitable for the BATS.

Total recoverable petroleum hydrocarbons were analyzed as a measure of the oil (which was used as a carrier for penta during wood treating operations at MacGillis & Gibbs) in the soil and subsequently in the process water leaving the soil washer and entering the ATS. The analyses showed total recoverable petroleum hydrocarbons in the low ppm range in both the influent to and the effluent from the BATS. If significant oil were present, an oil/water separator would need to be added as a pretreatment step prior to the BATS; the system is designed to accommodate this modification as a pretreatment step.

Chemical oxygen demand was included as a measure of the total potential oxygen demand (both biochemical and chemical) of the samples, which may include substances other than those being analyzed. The observed COD measurements indicated that chemical oxidation was occurring in the BATS, but a significant decrease from influent to effluent was not apparent. This could be attributed to other organic constituents which were not included in analyses and which were not degraded biologically or removed by other mechanisms in the BATS.

Pentachlorophenol Removal

During the first test, the weighted influent concentration of penta was 15 ppm and the weighted effluent concentration was 1.3 ppm. This corresponds to a 91% removal for penta. During the second test, using the water from the high penta SW test, the weighted influent concentration of penta was 44 ppm and the weighted effluent concentration was 3 ppm. This corresponds to a 93% removal of penta during the second test. The data have been plotted in Figure C-9 and C-10 for each test, respectively. After an initial period of biomass acclimation, effluent concentrations held fairly steady in the low ppm range even when influent concentrations varied significantly. The data confirm that the BioTrol Aqueous Treatment System is effective at removing pentachlorophenol from the SW process water (CDE), although it should be noted that there also was a significant decrease in the penta concentration in the CDE before it was introduced to the BATS, due to biodegradation in the storage tank or sedimentation of penta-rich solids.

Based on the mass of penta introduced to the system over each test, and assuming that all penta is lost by biological degradation, mass removals of >90% are achievable (Table C-3).

Table C-3. Mass Removal of Pentachlorophenol

Test	Total Penta in (gm)	Total Penta out (gm)	Removal (%)
Test One - Low Penta	740	60	91.9
Test Two - High Penta	3700	220	94.1

Mineralization of Penta

Samples were analyzed for chloride ion and total organic halides to ascertain whether the penta was being mineralized or if it was only being partially degraded to other organic compounds. Table C-4 summarizes the changes in chloride and total organic halide data and compares the results with calculated values based on penta removal. For the first four samples, chloride concentrations increase from influent to effluent as expected, but for the last two samples chloride concentrations decrease and there is no adequate explanation for this.

A decrease in total organic halides would indicate that the chloride leaving the system was inorganic. Looking at the data for total organic halides (also shown in Table C-4), only three of the samples show a decrease in concentration of TOX between influent and effluent; the other three samples show an increase.

Table C-4. Comparison of Chloride and TOX Changes with Penta Removal

SAMPLE	Penta Change (mg/L)	Increase In: Cl (fd) (mg/L)	Increase In: Cl (calc) (mg/L)	Decrease In: TOX(fd) (mg/L)	Decrease In: TOX (calc) (mg/L)
04-2	- 18.1	+ 9.5	+12.05	+ 1.1	+ 12.1
04-4	- 74.7	+29.4	+49.75	- 4.0	+ 49.8
05-2	- 76.8	+32.8	+51.15	- 8.0	+ 51.2
05-4	- 34.8	+32.5	+23.18	- 7.2	+ 23.2
06-2	- 37.1	-16.0	+24.71	+ 4.0	+ 24.7
06-4	- 41.3	-47.6	+27.51	+ 6.6	+ 27.5

fd = found
calc = calculated from change in penta; 0.67 mg Cl (or TOX) per mg of penta decrease.

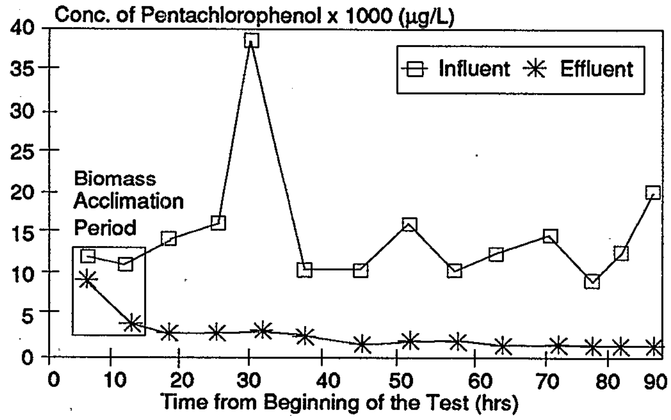

Figure C-9. BATS-Penta Concentration in Low Penta Test.

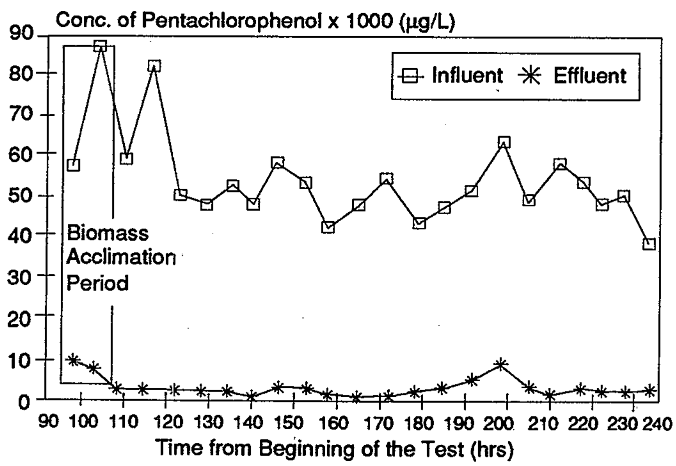

Figure C-10. BATS-Penta Concentration in High Penta Test.

Thus, no conclusions can be drawn from this data as to whether the chloride leaving the system is inorganic. The companion study, which concentrated on the BATS, and other published information do strongly indicate that mineralization is the predominant path for penta removal.

Analyses for total solids (suspended and dissolved) were performed on the influent and effluent samples of the BATS. Concentrations of solids in the 500 ppm range were encountered both in the influents and effluents during both tests. Results of a material inventory showed only an 8.5% loss of solids during the low penta test and a 4% gain in solids during the high penta test. The material inventory results confirm that the penta was not removed by entrapment of solids within the reactor. There was a slight build-up of solids during the first test which was later released during the second test.

Polynuclear Aromatic Hydrocarbon (PAH) Removal

Concentrations of the various PAHs were lower than anticipated in both the BATS influent and effluent. During the low penta test of the BATS, only one PAH, anthracene, was detected with any frequency. Analyses of effluent samples for this test yielded all non-detected values with method detection limits ranging from 2-15 ppb dependent on the specific compound. During the high penta test of the BATS, no PAH compounds were detected with any frequency. Method detection limits ranged from 1-400 ppb.

The lack of actual data values for PAHs in both influent and effluent to the BATS makes it impossible to assess the removal of these chemicals across the system.

Heavy Metals

Samples were analyzed for copper, chromium and arsenic (CCA) to determine the fate of the metals in the BATS. Concentrations of metals increased slightly in the influent to the BATS over the course of the demonstration, which suggests a build-up of metals in the aqueous stream as it was recycled within the SW system. Weighted averages for the metals in the two tests are shown in Table C-5. The presence of metals at concentrations of up to 90 µg/L did not appear to affect the biomass adversely.

Table C-5. Weighted Concentrations of Metals in BATS Tests (µg/L)

	Arsenic	Chromium	Copper
Low Penta test			
Influent	15.9	10.6	25.3
Effluent	15.7	7.9	13.0
High Penta test			
Influent	66.0	16.2	40.4
Effluent	54.3	12.3	25.5

Results of the material inventory for metals indicates that there was an accumulation of metals inside the reactor. In a commercial scale system operated with full recycle of all process water for several months, the metals could possibly build-up to concentrations which would be toxic to the microorganisms. Some purging of metals from the system might then be required and could be accomplished by providing treatment for metals prior to recycle of the process water. The exact nature of metals treatment would be dependent upon the concentrations of metals at a specific site, the length of remediation (several months to several years), the tolerance of the biomass for heavy metals, and regulatory standards.

The reader may be interested in the ranges of values for all flows and species as an indication of the uniformity or consistency of the processes, the soils, and the analytical procedures. While weighted averages have been used in this report to adjust for variations in flows in all processes and to minimize the impact of short term variations on removal efficiencies, the summary tables provided in the Technology Evaluation Report also present simple arithmetic averages and standard deviations.

Appendix D-1
Treatability Studies of Soil Washer System

Other than the current Demonstration under the SITE Program, no results for pilot or large scale evaluations of the Soil Washing System are available. Consequently, there are no comparable data for removal efficiencies or costs based on large sized systems. However, BioTrol has carried out several treatability and bench scale studies. The results of those studies are presented in this section. Subsequent sections of this Appendix do provide extensive data on pilot and full scale BATS installations.

Wood Treatment Site (Penta/PAHs)

The soil at a former wood treating (creosote and pentachlorophenol) facility was found to be a mixture of gravel-sized chert and clay. About 80% was larger than 10 mesh. The -10 mesh fraction contained 2300 ppm penta. During attrition scrubbing, the sand fraction (-10 mesh to +200 mesh) lost about 50% of its weight to the fines (<200 mesh) fraction. Removal of penta from the sand fraction during soil washing was about 75%. Slurry biodegradation of the -10 mesh fraction with the indigenous consortium of penta degrading bacteria was characterized by a lengthy induction phase, rapid initial remediation while the readily exchangeable penta was degraded, and a slow residual remediation phase. During this final phase, aqueous penta concentrations were <1 ppm. Overall, bioremediation was effective in degrading about 83% of the penta in the -10 mesh soil fraction. Overall degradation for phenanthrene, fluoranthene, and pyrene were >95%, 92%, and 77%, respectively.

Wood Treatment Site (Penta/TRPs)

Two samples of the soil at this site were evaluated, one containing a significant portion of decaying woody material and 603 ppm penta, and another containing 379 ppm of penta The latter sample was considered more representative of the site. Studies indicated that the rate of penta leaching into water was rapid for both samples, reaching near equilibrium conditions in about 3 hours.

Soil washing of the soil reduced the penta concentration in the "representative" soil to 3.6 ppm or less, with approximately 90% of the feed soil recovered as washed soil with that level. Washing of the woody soil (603 ppm penta) produced a washed soil with 25-30 ppm penta, which would not have met the site cleanup criteria. Experiments indicated that gravity separation would be effective in removing wood from this washed soil and thus reducing the penta concentration further.

Biodegradation of the woody sample indicated that penta-degrading organisms were present; at 5% solids the rate of degradation was about 10 mg penta/liter of slurry/day. A final penta concentration of about 100 ppm was achieved with the woody soil. Slurries of the representative soil could only be degraded after seeding with the woody soil, after which final concentrations of about 25 ppm could be achieved.

Pesticides Formulation Site

BioTrol carried out bench scale tests on soil from an inactive pesticide formulation facility on the National Priority List. The primary contaminants of concern were chlordane, aldrin, 4,4-DDT, and dieldrin at concentrations ranging from 20 ppm to about 80 ppm.

Particle size and chemical analyses determined that 15% of the sandy/silty soil (dry weight) was finer than 200 mesh (<75 micron) and that the pesticides were predominantly associated with the fines. Thus, soil washing could reduce by 85% the quantity of soil that would otherwise require remediation.

Using attrition scrubbing, inter-stage classification, and wet gravity separation, overall pesticide removal from the +200 mesh fraction were about 85%. Final pesticide concentrations in the washed +200 mesh soil were in the range of 5 to 7 ppm. Addition of two different surfactants did not enhance removal.

Industrial Chemical Site

Two samples of soil from beneath lagoons at a chemical production site were found to be contaminated with chlorinated and non-chlorinated semivolatile chemicals. One soil, considered the "worst case," contained about 1000 ppm of total contaminants. A process sequence was devised that consisted of agglomeration of tar, screening to remove the tar, soil washing to scour the surfaces of the sand, flotation to remove residual tar from the washed soil, and recovery of contaminated fines. The process was effective in removing 99+% of the non-chlorinated semivolatiles and about 98% of the chlorinated semivolatile contaminants. Excluding the treatment of residuals, the pile-to-pile cost for remediation was estimated at $45/cubic yard.

Metal Contaminated Site

Two samples of contaminated soil from a wire drawing operation were evaluated. The first sample, containing an average of 30% Total Petroleum Hydrocarbons (TRPs), did not respond adequately to efforts to remove metals by soil washing without surfactant. The second soil sample, which was considered more representative of the soil at the site, was treated more successfully. While particle disintegration did not appear to occur during the attrition scrubbing, the washed soil recovery was 80%. Contaminant concentrations were reduced as follows:

	TRP	Cu	Ni	Ag
Soil	5000	330	200	25
Washed Soil	350	100	85	4

An order-of-magnitude cost estimate was generated which indicated overall remediation could be carried out for $330/cubic yard, with capital cost for the system estimated at $1.5 million.

Appendix D-2
BATS Treatment at a Full Scale Wood Preserving Site

Introduction

The subject of this study is a wood preserving facility using the Boultonizing process that generates a process water contaminated with creosote-derived phenolics, polynuclear aromatic hydrocarbons, and aromatic compounds extracted from the wood. The BATS unit offered an opportunity to treat this wastewater biologically in a compact, efficient manner with minimal operator attention.

The process water to be treated contained significant oily material. It is treated in two stages for oil/water separation and then cooled in a cooling tower. Water from the cooling tower, which was previously discharged to an on-site lagoon, was treated in the pilot study and, subsequently, in the commercial unit. The character of the feedwater varied considerably, depending on the type of wood treated, rainfall, and evaporation rates (Table D-1).

Table D-1. Characteristics of Phenolic Process Water

constituent	average (ppm)	range (ppm)
Phenols	129	11-327
COD	1059	412-1912
BOD	752	75-1200
TSS	104	22-659
Oil/grease	28	8-270
pH		6-9
Temperature (F)		80-90

Pilot Scale Studies

A pilot scale demonstration study using a 3-celled mobile BATS unit with a 15 gpm flow capacity was carried out over six weeks at flow rates of 2 gpm and 1 gpm. Influent and effluent samples were collected daily as 24-hour composites while the bioreactor cells were grab-sampled. Key analyses were total recoverable phenolics (TRP) by Standard Method 510.B and chemical oxygen demand (COD) by the OI Corp. method. In addition, biochemical oxygen demand (BOD), oil and grease, and total suspended solids were also analyzed. On three occasions during the course of the pilot demonstration, samples were analyzed by EPA Method 610 for polynuclear aromatic hydrocarbons (PAHs).

Based on analytical results (Figure D-1), effluent concentrations of phenols were almost always below 1 ppm, corresponding to an average phenolics removal of >99%. Decreases in biochemical oxygen demand (BOD) and chemical oxygen demand (COD), while significant, were not as great, possibly due to sloughed biomass. Variations in total suspended solids (TSS) indicate a cyclic character to the TSS values and suggests that solids accumulation occurs followed by solids release. Polynuclear aromatic hydrocarbon removal was in the range of 80+%, but elevated PAH levels for total samples (including sloughed solids) from the middle cells suggest that adsorption of PAHs on solids as well as biodegradation is occurring (Figure D-2).

Commercial System Evaluation

Based on the success of the pilot scale demonstration in removing phenolics from the aqueous wastewater, a commercial (30 gpm) unit was installed in August 1988. After a two week acclimation period (no specific bacterium was added), the unit has been in continuous operation with the flow rate starting at 20 gpm and then increased to the design rate of 30 gpm. The effluent is discharged to a POTW. Based on the results for the first 5 months of operation (Table D-2), the system has produced effluent with an average phenolics concentration below 1 ppm with minimal operator attention.

Table D-2. Wood Preserving Wastewater Treatment by BATS

Month	Phenolics in Effluent (ppm)
August	0.12
September	0.058
October	0.14
November	0.20
December	1.11
5 Month Average:	0.33

Cost Data

Operating cost data were developed on the basis of operation of the commercial unit. Assuming a 30 gpm flow rate and an influent with 1000 ppm of BOD and 200 ppm of phenols, the operating costs were as shown in Table D-3.

Table D-3. Operating Cost for BATS Commercial Unit

Cost item	$/1000 gallons
Electricity (@ $0.06/Kwhr)	0.15
Nutrients (@ $0.71/gallon)	0.14
Labor (10 hr/wk @ $15/hr)	0.49
Total	0.78

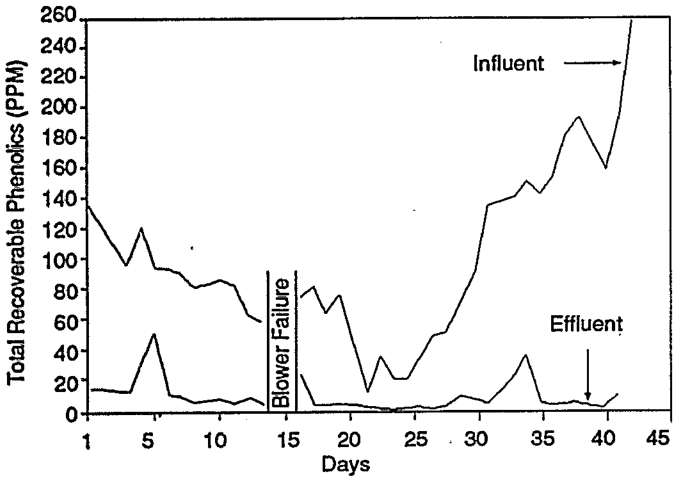

Figure D-1. Total Recoverable Phenols - using BATS.

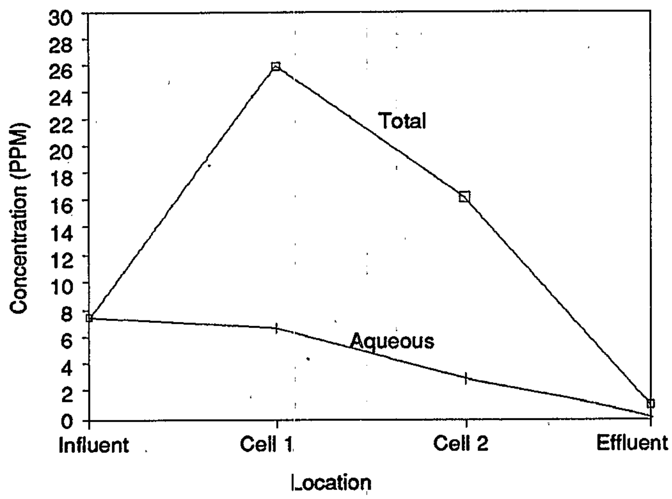

Figure D-2. PAH Removal by BATS.

Conclusions

Based on the pilot scale studies and operation of the commercial unit for several months, the BATS is a cost-effective means of removing phenolics and polynuclear aromatic hydrocarbons from this wastewater.

The nature of the BATS system is such that it requires a minimum of labor relative to conventional activated sludge systems where trained personnel may be needed to assure that optimum sludge separation and return is carried out.

Appendix D-3
BATS Treatment at a Tape Manufacturer
California

Introduction

A tape manufacturing facility in California produces about 15,000 gpd of solvent-contaminated process water. Contributing to a high COD are toluene, xylene, methyl ethyl ketone, tetrahydrofuran, and cyclohexanone. Currently, the plant uses activated carbon pretreatment prior to discharge to the POTW. Biological treatment was considered as an alternate, less costly treatment.

A bench scale continuous evaluation of biological treatment using the BATS was carried out. Because of high variability in wastewater loading, the goal of the investigation was to evaluate the effectiveness of the system at various organic loadings, in addition to the removal of specific contaminants.

Bench Scale Study

The bench scale continuous studies were carried out using a 55 gallon drum of process water shipped to the BioTrol facility. The system consisted of a 4 in. ID translucent PVC column packed to a depth of 12 in. with 1 in. Intalox PVC saddles to simulate the structured PVC packing used in a commercial unit. Air was injected at the base. The column was inoculated with activated sludge from a POTW and acclimated over 10 days. Continuous operation was then maintained for 1 week at each of 3 flow rates: 2, 4, and 8 liters/day, corresponding to loadings of 110, 235 and 485 lb COD/1000 cu ft of packing/day.

Results

Samples were removed by BioTrol and measured for the parameters noted in Table D-4 using standard methods.

Biological treatment effectively removed 99% of the specific components of concern with only slight fall off in efficiency when the loading rate was increased from 110 to 235 lbs/1000 cf/day. Final effluent with residual concentrations of 5 to 15 ppb were achieved at the lower loading and somewhat higher at the higher loading.

Table D-4. BATS Removal Efficiency - Tape Process Water

parameter	influent ppm	effluent ppm	removal %
Loading: 100 lb/1000 cf/day			
toluene, xylene	1.3	<0.01	>99
MEK	43.0	<0.005	>99.9
THF	5.7	0.014	>99.7
COD	3178	758	76
Loading: 235 lb/1000 cf/day			
toluene, xylene	1.3	0.06	95
MEK	43.0	0.55	98.7
THF	5.7	<0.05	>99.1
COD	3178	1413	55

The difference between removal efficiency for specific components and that for COD is consistent with the presence of other, more recalcitrant constituents. (Other tests indicate that stripping of volatile organics accounts for less than 10% of their removal.)

Cost Data

Using the removal data developed in the bench scale study, cost data were developed for a commercial system with a 10 gpm capacity. On that basis, the total anticipated operating cost would be $3.51/1000 gallons of wastewater, as shown in Table D-5.

Table D-5. Operating Cost for 10 GPM BATS System

item	$/1000 gal
Nutrients (liquid fertilizer)	0.32
Electricity (for pumps) (2 lb oxygen/hp-hr and10 gpm effluent pump @ 50 ft head)	0.37
Labor (10 hrs/wk @ $20/hr)	1.98
Base for neutralization (NaOH)	0.84
Total	$3.51

Appendix D-4
BATS Treatment of BTEX
Minnesota

Introduction

A truck stop in Minnesota experienced widespread soil contamination by gasoline from leaking underground storage tanks. In addition to removing the tanks and highly contaminated soil, it was necessary to treat soil beneath buildings and groundwater to prevent spread of a contaminated plume.

BioTrol proposed that both goals could be achieved by above-ground treatment of the groundwater in a BATS, followed by reinjection of the treated water to stimulate *in situ* bioremediation of the soil. Laboratory studies demonstrated that with proper additions of nutrients and oxygen, the indigenous microflora were capable of destroying benzene, toluene, ethyl benzene, and xylenes (BTEX) in the soil to below detectable levels in eight days. Since this remediation scheme depended on initial above-ground treatment to levels suitable for reinjection, a pilot scale evaluation of the BATS was deemed to be necessary.

Pilot Scale BATS

A single column pilot-scale BATS was installed at a gas station in the Minneapolis area. The reactor column was 1 foot in diameter and filled to nine foot depth with 1 in. Intalox PVC saddles to simulate the structured PVC packing used in the full scale unit. The system provided 1.6 hours of residence time.

The system was first acclimated for two weeks with no addition of bacteria except that in the groundwater. The reactor was then sampled daily for one week, using composite samples of influent and effluent taken with a zero headspace sampling device. Analyses of these samples confirmed that >99% removal of BTEX could be achieved with an influent ranging from 1900 to 15,000 ppb, and effluent concentrations of <20 ppb for individual components were achieved. The BTEX results are summarized in Table D-6.

Table D-6. BTEX Treatment with the BATS

day	influent ppb	effluent ppb	removal %
1	1962	<80	>96
2	4700	<80	>98
3	15300	<80	>99

Full Scale BATS

On the basis of the pilot study it was concluded that the process was very effective at removing BTEX. A two-stage reactor was installed at the contaminated site to be used in conjunction with a closed loop groundwater extraction system. Modelling of shallow groundwater flow was used to design the extraction well and infiltration gallery network.

The BATS is currently treating groundwater at a 15 gpm flow rate. With a groundwater temperature of 50° F, no heat input has been found necessary to maintain reactivity. With influent BTEX concentrations of approximately 4200 ppb, consistent reductions to <80 ppb have been achieved. Measurements of BTEX concentrations in the air exhaust from the reactor established that air stripping accounts for removal of only 5 - 10% of the removed BTEX.

Cost Data

The operating and maintenance cost of the combined in situ and above-ground treatment is expected to average about $9000/year. Total cost of remediation, including capital, maintenance and operation, but excluding groundwater monitoring and project management fees, is approximately $165,000 with a three-year anticipated project life. More detailed information is not available at this time.

Appendix D-5
Pilot Plant BATS
Minnesota

Introduction

In the fall of 1986, the feasibility of treating contaminated groundwater at a wood preserving site in Minnesota was evaluated in a nine-month pilot study using the BioTrol Aqueous Treatment System. The study was funded by a grant from the U.S. Geological Survey.

The purpose of the study was to establish the long term effectiveness of the BATS for such wastewaters, particularly for the removal of pentachlorophenol and, secondarily, for polynuclear aromatic hydrocarbons. These materials are commonly found contaminating sites where wood preserving operations using pentachlorophenol and creosote had been practiced over previous decades. The groundwater at the site contained 60-100 ppm of pentachlorophenol based on preliminary studies.

Pilot Scale Study

A simple 30-gallon packed bed reactor was used in the nine-month pilot study. The system was activated with indigenous microflora and later amended with inoculations of a *Flavobacterium* specific to pentachlorophenol. The unit was operated essentially in a continuous mode, over the length of the study, adjusting pH and adding nutrients as necessary. Air was continuously injected to maintain aerobic conditions.

BioTrol subsequently developed a proprietary bioreactor design specifically suited to treatment of contaminated groundwater with an amended, fixed film microbial system.

Results

The packed bed system effectively removed pentachlorophenol, polynuclear aromatic hydrocarbons, and other constituents that were found to be present. The specific rate of penta degradation was as high as 70 mg of penta/liter of reactor volume/hour, well beyond the values normally reported in the literature. In later work using the proprietary system design, penta removal rates between 40 and 50 mg penta/liter of reactor volume/hr were consistently achieved, with rates as high as 65 mg/liter/hr being achieved. All penta analyses were carried out using a HPLC method developed by BioTrol. Extensive removal of polynuclear aromatic hydrocarbons was also confirmed. While substantial reductions in COD also occurred, the levels in the effluent indicate the presence of considerable refractory material. Typical results are summarized in Table D-7.

Table D-7. Groundwater Treatment in 30-Gal Packed Reactor

constituent	well water ppb	effluent ppb	removal %
Pentachlorophenol	93,000	nd	~100
Acenaphthalene	4,402	nd	~100
Naphthalene	1,932	81	96
Acenaphthene	2,041	140	93
Phenanthrene	264	38	86
Anthracene	252	20	92
Fluoranthene	466	153	67
Pyrene	232	15	94
Benzo(a)anthracene	292	9	96
Chrysene	171	8	95
Benzo(b)fluoranthene	448	8	98
Benzo(k)fluoranthene	178	7	96
Benzo(a)pyrene	211	5	98
Dibenzo(a,h)anthracene	296	33	89
Benzo(g,h,i)perylene	315	4	99
Fluorene	545	nd	~100
Indo(1,2,3-c,d)pyrene	203	nd	~100
COD (ppm)	250-300	100-150	>40

While the influent and effluent data over the nine-month investigation did exhibit occasional elevated levels in the effluent, these usually were attributable to mechanical failures, such as loss of aeration, loss of heat, etc. Daily tabulation of influent and effluent data indicates that the system had excellent recovery capability after such upsets.

No cost data is available for this small scale study.

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