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EPA RREL's Mobile Volume Reduction Unit

Applications Analysis Report

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

Notice

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Foreword

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments. The Program is a joint effort between the U.S. Environmental Protection Agency's (EPA) Offrce of Research and Development and Office of Solid Waste and Emergency Response. The purpose of the program is to enhance the development of hazardous waste treatment technologies necessary for implementing new cleanup standards that require greater reliance on permanent remedies. This is accomplished by performing technology demonstrations designed to provide engineering and economic data on selected technologies.

This project consists of an analysis of the EPA Risk Reduction Engineering Laboratory's mobile Volume Reduction Unit. The Demonstration Test took place at the Escambia Treating Company Superfund Site in Pensacola, Florida. The goals of the study, summarized in this Applications Analysis Report, are: 1) to evaluate the technical effectiveness and economics of this technology relative to its ability to treat soils contaminated with organics; and 2) to establish the potential applicabilty of the process to other wastes and Superfund sites. The primary technical objective of this project is to determine the abiity of the process to reduce the concentration of organic contaminants in contaminated soil through particle size separation and solubilization.

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E. Timothy Oppelt, Director
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Abstract

This document is an evaluation of the performance of the U.S. Environmental Protection Agency (EPA) Risk Reduction Engineering Laboratory's (RREL's) mobile Volume Reduction Unit (VRU) and its applicability as a treatment technique for soils contaminated with organics. Both the technical and economic aspects of the technology were examined.

A demonstration of the VRU was conducted in the fall of 1992 using RREL's pilot-scale unit at the Escambia Treating Company Superfund Site in Pensacola, Florida. Operational data and sampling and analysis information were carefully compiled to establish a database against which other available data, as well as the project objectives for the demonstration, could be compared and evaluated. Conclusions concerning the technology's suitability for use in treating contaminated soils with organic compounds through particle size separation and solubiition were reached. Extrapolations regarding applications to different contaminants and soil types were made.

Under optimal conditions, when surfactant was added and pH and temperature of the wash water were increased, the VRU achieved average removal efficiencies of 97 percent for pentachlorophenol (PCP) and 95 percent for polynuclear aromatic hydrocarbon (PAH) contaminants. In addition, 86 percent of the solids in the feed soil were returned as washed soil (on a normalized basis).

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Abbreviations

AAR	Applications Analysis Report
ARAR	Applicable or Relevant and Appropriate Requirements
ASTM	American Society for Testing and Materials
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfm	cubic feet per minute
CFR	Code of Federal Regulations
CPI	Corrugated Plate Interceptor
CPR	cardiopulmonary resuscitation
CWA	Clean Water Act
DRE	destruction and removal efficiency
EPA	U.S. Environmental Protection Agency
gph	gallons per hour
gpm	gallons per minute
kWh	kilowatt hours
MCL	maximum contaminant level
MSW	Municipal Solid Waste
NAAQS	National Ambient Air Quality Standards
NPDES	National Pollutant Discharge Elimination System
ORD	Office of Research and Development
OSC	On-scene Coordinator
OSHA	Occupational Safety and Health Act
OSWER	Office of Solid Waste and Emergency Response
PAH	polynuclear aromatic hydrocarbon
PCB	polychlorinated biphenyls
PCP	Pentachlorophenol
PPE	personal protective equipment
ppm	parts per million
POTW	Publicly-Owned Treatment Works
psi	pounds per square inch
psig	pounds per square inch gauge
RCRA	Resource Conservation and Recovery Act
RPM	Remedial Project Manager
RREL	Risk Reduction Engineering Laboratory
SARA	Superfund Amendments Reauthorization Act
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SVOC	semi-volatile organic compound
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids

Abbreviations (Continued)

TER	Technology Evaluation Report
TOC	total organic carbon
tph	tons per hour
tpd	tons per day
TR	total residue
TSD	Treatment, Storage, and Disposal
TSS	total suspended solids
VOC	volatile organic compounds
VRU	Volume Reduction Unit

Acknowledgments

This report was prepared under the direction and coordination of Teri Richardson, U.S. Envimomental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program Manager in the Risk Reduction Engineering Laboratory (RREL), Cincinnati, Ohio. The EPA (RREL, Cincinnati) contributors and reviewers for this report were Ms. Laurel Staley and Mr. Jack Hubbard. The EPA (RREL, Edison) contributor and reviewer was Mr. Richard Griffith.

This report was prepared for EPA's SITE Program by the Technology Evaluation Division of Science Applications International Corporation (SAIC) in Cincinnati, Ohio for the U.S. EPA under Contract No. 68-CO-0048. The Work Assignment Manager for this project was Ms. Margaret M. Groeber.

This report is dedicated to the memory of Mr. Patrick Augustin.

Section 1

Executive Summary

1.1 *Introduction*

This report summarizes the findings of an evaluation of the mobile Volume Reduction Unit (VRU) developed by the U.S. Environmental Protection Agency (EPA) Risk Reduction Engineering Laboratory (RREL). The study was conducted under the Superfund Innovative Technology Evaluation (SITE) Program. A demonstration test and an evaluation of the VRU technology were performed by EPA as part of this study. The results of this test and supporting data from other testing performed by RREL constitute the basis for this report.

1.2 *Conclusions*

The demonstration took place at the former Escambia Wood Treating Company site in Pensacola, Florida between November 5 and November 13, 1992. The 26-acre facility, now closed, used pentachiorophenol (PCP) and creosote to treat wood products from 1943 to 1982. The site is currently undergoing a Superfund cleanup being managed by EPA Region IV.

During the demonstration, the VRU operated at a feed rate of approximately 100 lbs/h with a wash water-to-feed ratio of about 6 to 1. The physical condition of the wash water was modified during the demonstration as follows:

* Condition 1: no surfactant, no pH adjustment, no temperature adjustment

- Condition 2: surfactant addition, no pH adjustment, no temperature adjustment

  Condition 3: surfactant addition, pH adjustment, temperature adjustment

The VRU soil washing system successfuliy separated the contaminated soil into two unique streams: washed soil and fines slurry. The washed soil was safely returned to the site following treatment. The fines slurry, which carried the majority of the pollutants from the feed soil, underwent additional treatment to separate the fines and contaminants from the water.

A review of the demonstration test data, as compared to the established project objectives, indicates the following results:

- One of the project objectives was to demonstrate the VRUs abilty to achieve an average PCP removal from the feed soil of 90 percent or greater. Average PCP removals were 76, 92, and 97 percent for Conditions 1, 2, and 3, respectively.

- A second project objective was to demonstrate the VRUs abilty to achieve an average creosote-fraction polynuclear aromatic hydrocarbon (PAH) removal from the feed soil of 90 percent or greater. Average PAH removals were 70, 83, and 95 percent for Conditions 1, 2, and 3, respectively.

- The average percentages of feed soil returned as washed soil on a normalized basis were 90, 88, and 86 for Conditions 1, 2, and 3, respectively. The remaining solids were contained in the fines slurry and underwent further treatment.

- Total material balances in the soil washing segment of the VRU achieved closures of 104, ll3, and 98 percent for Conditions 1, 2, and 3, respectively. The closures obtained for Conditions 1 and 3 met the project objective of total material balance closures between 90 and 110 percent. Although a closure of 113 percent was obtained for Condition 2, a sampling procedure may have inflated this closure.

- Mass balances of total dry solids in the soil washing segment of the VRU achieved closures of 106, 108, and 94 percent for Conditions 1, 2, and 3, respectively. The project objective for this mass balance was closure between 85 and 115 percent.

- The project objectives for mass balances of PCP and creosote-fraction PAHs in the soil washing segment of the VRU were to demonstrate whether closures between 80 and 175 percent could be achieved. Closures within this range were achieved only for Condition 1, which demonstrated closures of 101 and 87 percent for PCP and PAHs, respectively. Surfactant added during Conditions 2 and 3 may have adversely affected the PCP and PAH analyses, which would have affected the mass balance calculations.

- The cost to remediate 20,000 tons of contaminated soils using a lo-ton-per-hour (tph) soil washer is estimated at $136.67 per ton when the system is on-line 90 percent of the time.

I.3 Results

The objectives of this Applications Analysis Report (AAR) are to assess the ability of the VRU process to comply with Applicable or Relevant and Appropriate Requirements (ARARs) and to estimate the cost of using this technology to remediate a Superfund site. This analysis includes determining percent removals of PCP and creosote-fraction PAHs. Table 1 summarizes the performance during the demonstration test.

EPA has established target cleanup levels for the soil at the Escambia Wood Treating Company Superfund site. Although meeting these cleanup criteria was not a project objective for this demonstration, they can be used for comparison purposes. The target cleanup levels are 30 ppm PCP, 50 ppm carcinogenic creosote, and 100 ppm total creosote. The target cleanup level for PCP was easily met during Conditions 2 and 3 but was not met during Condition 1. The cleanup criteria for total creosote was easily met during Condition 3 but was not met during Condition 1 or Condition 2. The target cleanup level for carcinogenic creosote was met by the washed soil produced during all three conditions.

Table 1. VRU SITE Demonstration Test Results

Parameter (%)	Condition 1	Condition 2	Condition 3
PCP removal			
Average	76	92	97
Range	69-81	91-93	97-98
PAH removal			
Average	70	83	95
Range	59-77	83-84	95-96
Feed soil collected as washed soil			
Average	95	95	82
Range	85-114	86-103	69-94
Feed soil collected as washed soil, normalized basis			
Average	90	88	86
Range	89-90	85-90	85-87

Section 2

Introduction

2.1 The SITE Program

In 1986, the U.S. EPA Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) established the Superfund Innovative Technology Evaluation (SITE) Program to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its eighth year, the SITE Program is helping to provide the treatment technologies necessary to implement new Federal and State cleanup standards aimed at permanent remedies rather than quick fixes. The SITE Program is composed of four major elements: the Demonstration Program, the Emerging Technologies Program, the Measurement and Monitoring Technologies Program, and the Technology Transfer Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data for selected technologies. EPA and developers participating in the program share the cost of the demonstration. Developers are responsible for mobilization, operation, and demobilization of their innovative systems at chosen sites, usually Superfund sites. EPA is responsible for sampling, analyzing, and evaluating all test results. The result is an assessment of the technology's performance, reliability, and costs. This information is used in conjunction with other data 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. EPA also accepts proposals any time a developer has a Superfund waste treatment project scheduled. To qualify for the program, a new technology must be field-ready and offer some advantage over existing technologies. Mobile technologies are of particular interest to EPA.

Once EPA has accepted a proposal, EPA and the developer work with the EPA regional offices and State agencies to identify a site containing waste 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. The duration of a demonstration varies from a few days to several years, depending on the length of time and quantity of waste needed to assess the technology. After the completion of a technology demonstration, EPA prepares two reports, which are explained in more detail in the following subsections. 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 bench- and pilot-scale. Successful validation of these technologies can lead to the development of a system ready for field demonstration and participation in the Demonstration Program. The third element of the SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative technologies that can be used to characterize Superfund sites better. Technical information is disseminated to the public and private sectors through the **Technology Transfer** Program.

2.2 SITE Program Reports

The analysis of a technology participating in the Demonstration Program is contained in two documents: a Technology Evaluation Report (TER) and an AAR. The TER contains a comprehensive description of the demonstration sponsored by the SITE Program and its results. It gives detailed descriptions of the technology, the waste used for the demonstration, sampling and analysis during the test, the data generated, and the Quality Assurance Program.

The scope of the AAR is broader than the TER's scope; it encompasses estimations of Superfund applications and costs of a technology based on all available data. This report compiles and summarizes the results of the SITE demonstration, the developer's design and test data, and other laboratory and field applications of the technology. It discusses the advantages, disadvantages, and limitations of the technology.

Costs of the technology for different applications are estimated based on available data on pilot- and full-scale applications. The AAR discusses the factors, such as site and waste characteristics, that have a major impact on costs and performance.

The amount of available data for the evaluation of an innovative technology varies widely. Data may be limited to laboratory tests on synthetic waste or may include performance data on actual wastes treated at the pilot- or full-scale level. In addition, there are limits to conclusions regarding Superfund applications that can be drawn from a single field demonstration. A successful field demonstration does not necessarily ensure that a technology will be widely applicable or fully developed to the commercial scale. The AAR attempts to synthesize the information that is available and draw reasonable conclusions. This document is very useful to those considering a technology for Superfund cleanups and represents a critical step in the development and commercialization of the treatment technology.

2.3 Key Contacts

For more information on the VRU demonstration, please contact:

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Section 3

Technology Applications Analysis

3.1 Introduction

This section addresses the applicability of soil washing to soils contaminated with PCP and creosote-fraction PAHs. Recommendations are based on the results obtained from the SITE demonstration of the VRU as well as additional data provided by the developer. The results of the demonstration provide the most extensive database, conclusions on the technology's effectiveness, and information regarding its applicability to other potential cleanups. A thorough description of the VRU technology is provided in Appendix A. The developer's claims are presented in Appendix B, a summary of the demonstration results is provided in Appendix C, and other case studies are presented in Appendix D.

3.2 Conclusions

The soil washing segment of the VRU successfully separated the contaminated soil into two unique streams: washed soil and fines slurry. The washed soil was safely returned to the site following treatment, while the fines slurry, which carried the majority of the pollutants from the feed soil, underwent additional treatment to separate the fines from the water. The water was further polished and then discharged onsite, while the fines were disposed in a secure area of the site.

In order to address system performance thoroughly under a number of operating conditions, varying combinations of caustic, surfactant, and temperature were used to modify the physical conditions of the wash water as follows:

- Condition 1: no surfactant, no pH adjustment, no temperature adjustment
- Condition 2: surfactant addition, no pH adjustment, no temperature adjustment
- Condition 3: surfactant addition, pH adjustment, temperature adjustment

Three runs, 4 hours in duration, were performed for each of Conditions 1 and 2. Two runs, 6 hours in duration, were performed under Condition 3.

A review of the demonstration test indicates the following results:

- One of the project objectives was to demonstrate the VRU's abiity to achieve an average PCP removal from the feed soil of 90 percent or greater. Average PCP removals were 76, 92, and 97 percent for Conditions 1, 2, and 3, respectively.
- A second project objective was to demonstrate the VRU's ability to achieve an average creosote-fraction PAH removal from the feed soil of 90 percent or greater. Average PAH removals were 70, 83, and 95 percent for Conditions 1, 5 and 3, respectively.
- The average percentages of feed soil returned as washed soil on a normalized basis were 90, 88, and 86 for Conditions 1, 2, and 3, respectively. The remaining solids were contained in the fines slurry and underwent further treatment.
- Total material balances in the soil washing segment of the VRU achieved closures of 104, 113, and 98 percent for Conditions 1, 2, and 3, respectively. The closures obtained for Conditions 1 and 3 met the project objective of total material balance closures between 90 and 110 percent. Although a closure of 113 percent was obtained for Condition 2, a sampling procedure may have inflated this closure.
- Mass balances of total dry solids in the soil washing segment of the VRU achieved closures of 106, 108, and 94 percent for Conditions 1, 2, and 3, respectively. The project objective for this mass balance was closure between 85 and 115 percent.

- The project objectives for mass balances of PCP and creosote-fraction PAHs in the soil washing segment of the VRU were to demonstrate whether closures between 80 and 175 percent could be achieved. Closures within this range were achieved only for Condition 1, which demonstrated closures of 101 and 87 percent for PCP and PAHs, respectively. Surfactant added during Conditions 2 and 3 may have adversely affected the PCP and PAH analyses, which would have affected the mass balance calculations.

3.3 Technology Evaluation

The 100~lb/h VRU is a mobile research unit that was developed for soil washing treatability studies on soils containing a wide variety of contaminants. This unit is composed of two distinct treatment segments: the soil washing subsystem and the water treatment subsystem. The soil washing portion of the VRU is used to separate contaminated soils into two streams: washed soil and fines slurry. Ideally, the washed soil is clean enough to return to the site or to use in some other capacity. The fmes slurry, which carries the majority of the pollutants present in the feed soil, requires additional treatment using the water treatment subsystem. By isolating and concentrating the contaminants within the fmes, the volume of material requiring additional treatment is significantly reduced.

The VRU was developed by EPA, which by law cannot develop commercial treatment systems. EPA can co-develop technologies with private companies or license EPA-developed technologies to private companies through the Federal Technology Transfer Act of 1986 (15 USC 3702-3714) [l].

In November 1992, the VRU soil washing system was tested under the SITE Program. Soil contaminated with PCP and creosote-fraction PAHs was excavated from the former Escambia Wood Treating Company site in Pensacola, Florida and then treated by the VRU. Contaminant levels in the soil ranged from the low parts per million (ppm) to percent levels. For the SITE demonstration, the excavated soil was homogenized and manually processed through a 1/4-inch screen before it was fed to the VRU. Average contaminant concentrations in the feed soil on a dry weight basis after homogenization and screening are summarized in Table 2.

The PAH concentrations presented in Table 2 do not include all PAHs. Analyses were conducted for creosote-fraction PAHs, and five compounds from the standard set of 16 creosote-fraction PAHs were not consistently detected in the field soil. These five PAHs were not included in this evaluation and are not included in the PAH concentrations shown in Table 2.

Table 2. Contaminant Concentrations in the Feed Soil (ppm, dry weight basis)

Contaminant	Average	Range
PAHs	980	550 to 1,700
PCP	140	48 to 210

3.3.1 VRU Operating Conditions

The VRU used during the demonstration test was designed to be flexible in terms of equipment and wash water additives used. During the demonstration test, varying combinations of caustic, surfactant, and temperature were employed to modify the physical conditions of the wash water. Water is a polar substance; PCP and PAHs (and other organic contaminants) are nonpolar. Because polar substances do not dissolve nonpolar substances well, the addition of a nonpolar surfactant to the wash water can improve organic contaminant removal significantly. Adjusting the pH and temperature of the wash water can also increase contaminant solubilities and improve removal efficiencies.

In July 1992 EPA conducted treatability studies at the Escambia Wood Treating Company site. Twenty different combinations of wash water temperature, pH, and surfactant concentration were tested. These studies provided the basis for the parameters tested during the demonstration. During the treatability studies, PCP and PAH removal efficiencies in excess of 90 percent were achieved under selected operating conditions.

Surfactant concentration and wash water pH and temperature were monitored to determine whether the VRU was functioning at the operating conditions specified in the Demonstration Plan. The surfactant concentration was determined by calculating the ratio of surfactant-to-wash water on a mass basis. The pH was determined by measuring the pH of the fines slurry stream. The temperature was determined by measuring the temperature of the wash water just before it entered the soil washing segment of the VRU. Actual operating conditions are summarized in Table 3.

Table 3. VRU SITE Demonstration Operating Conditions

	Feed Rate (lb/h)	W/F Ratio	Surfactant Flow (lb/h)	pH	Surfactant Concentration in Wash Water (%)	Water Temperature (°F)
Condition 1						
Average	84	8	0	–	–	57
Range	64-95	7-10	0	7.1-7.3	–	55-60
Condition 2						
Average	104	6	13.7	–	0.22	61
Range	97-108	6	13.4-14.1	6.9-7.0	0.22	59-65
Condition 3						
Average	133	5	11.4	–	0.18	142
Range	117-148	4-5	11.0-11.7	10.1-10.2	0.17-0.18	139-145

3.33 Contaminant Removal Efficiencies

Most organic and inorganic contaminants present in soil bind to fine-sized clay and silt particles (fines) primarily by physical processes. Washing processes that separate the fine particles from the coarser soil particles effectively concentrate the contaminants into a smaller volume. The clean larger fraction can be returned to the site for continued use. This process can also remove some contaminants by dissolving or suspending them in the wash water.

One of the main objectives of the demonstration test was to assess the VRU technology's ability to achieve contaminant removals of 90 percent for PCP and creosote-fraction PAHs.

Removal efficiencies for PCP and PAHs were determined by comparing the total mass of each contaminant, on a dry weight basis, detected in the washed soil with the total in the feed soil. Removal efficiencies are calculated using the following equation:

PCP removal efficiencies were calculated for Conditions **1, 2,** and 3. Under Condition 3, which employed surfactant addition and pH and temperature adjustment, an average of 97 percent of the PCP was removed. Under Condition 2, which employed surfactant addition only, an average of 92 percent of the PCP was removed. These removal efficiencies achieve the project objective of demonstrating that the unit is capable of removing an average of 90 percent of the PCP from the bulk of the feed soil. An average of only 76 percent of the PCP was removed from the feed soil treated under Condition **1. These** data, which illustrate the impact of surfactant addition and pH and temperature adjustment on PCP removal efficiencies, are listed in Table 4. PCP removal efficiency is clearly enhanced by surfactant addition and pH and temperature adjustment.

Creosote-fraction PAH removal efficiencies were calculated for Conditions 1, 2, and 3. Under Condition 3, which employed surfactant addition and pH and temperature adjustment, an average of 95 percent of the PAHs were removed. This removal efficiency achieves the

$$\%\ removal = \left[\frac{\text{Concentration of contaminant in feed} - \text{concentration of contaminant in washed soil}}{\text{concentration of contaminant in feed}}\right] \times 100$$

Table 4. PCP Reductions from Feed Soil to Washed Soil (%, dry weight basis)

	Average	Range
Condition 1	76	69-81
Condition 2	92	91-93
Condition 3	97	97-98

project objective of demonstrating that the unit is capable of removing an average of 90 percent of the PAHs from the bulk of the feed soil. Average PAH removals of only 70 percent and 83 percent were obtained for Conditions 1 and 2, respectively. These data, which illustrate the impact of surfactant addition and pH and temperature adjustment on PAH removal effkiencies, are listed in Table 5. PAH removal efficiency is clearly dependent on surfactant addition and pH and temperature adjustment.

Table 5. PAH Reductions from Feed Soil to Washed Soil (%, dry weight basis)

	Average	Range
Condition 1	76	69 to 81
Condition 2	92	91 to 93
Condition 3	97	97 to 98

EPA has established target cleanup levels for the soil at the Escambia Wood Treating Company Superfund Site. Although meeting these cleanup criteria was not a project objective for this demonstration, they can be used for comparison purposes. The target cleanup levels are 30 ppm PCP, 50 ppm carcinogenic creosote, and 100 ppm total creosote; the concentrations of these contaminants in the washed soil on a dry weight basis are presented in Table 6.

For all three conditions, the average concentration of PCP in the washed soil was below the target cleanup level of 30 ppm. This target was, however, exceeded for Run 3 of Condition 1. The cleanup criteria for total creosote was easily met during Condition 3 but was not met during Condition 1 or Condition 2. The target cleanup level for carcinogenic creosote was met by the washed soil produced during all three conditions.

Table 6. Washed Soil Residual Contaminant Concentrations (ppm, dry weight basis)

	PCP	Total Creosote PAHs	Carcinogenic Creosote PAHs
Condition 1			
Run 1	28	240	18
Run 2	36	310	19
Run 3	43	350	29
Condition 2			
Run 1	15	180	14
Run 2	13	160	12
Run 3	14	130	11
Condition 3			
Run 1	2.4	44	3.5
Run 2	3.5	46	3.3

3.3.3 Washed Soils Recovery

As soil travels through the VRU system, the sand and gravel fraction of the soil are separated from the contaminated fines (i.e., fine clay and silt particles). The relatively nonhazardous sand and gravel fraction exits the system as washed soil. By comparing the mass of dry solids in the feed soil with the mass of dry solids in the washed soil, average solids recoveries of 96, 95, and 81 percent were calculated for soils treated under Conditions 1 through 3. Also calculated were normalized recoveries, which were determined by dividing the mass of dry solids in the washed soil by the total mass of dry solids exiting the system the washed soil and fines slurry). The recoveries shown in Table 7 achieve the project objective of demonstrating that an average of at least 80 percent of the solids present in the feed soil would be returned to the site as washed soil.

Table 7. Feed Soil Recovered as Washed Soil (dry weight basis)

	% Recovered	% Recovered, normalized basis
Condition 1		
Average	95	90
Range	85 - 114	89 - 90
Condition 2		
Average	95	88
Range	86 - 103	85 - 90
Condition 3		
Average	82	86
Range	69 - 94	85 - 87

3.3.4 Mass Balances

Mass balances are prepared by comparing the mass entering a system to the mass exiting the system. Mass balance closure (or recovery) is calculated as follows:

$$\textit{Mass Balance Closure} = \left[\frac{\textit{Mass Exiting System}}{\textit{Mass Entering System}}\right] \times 100$$

The mass balance closures calculated for the VRU demonstration are summarized in Table 8. Recoveries were calculated for all materials present (total material balance) and for specific materials (dry solids, PCP, and creosote-fraction PAHs). For the total material balance, the recovery is the percentage of the material entering the system as feed soil and wash water that was recovered from the system as washed soil and fines slurry. The total material balances conducted for the demonstration yielded average recoveries of 104 percent for Condition 1, 113 percent for Condition 2, and 98 percent for Condition 3. The project objective for the total material balances was average closures of between 90 and 110 percent. Except for high recovery obtained for Condition 2 average closures for total material balances met the project objectives. During Condition 2, the operating procedure for mass flow measurement of fines slurry was modified and may have inflated the measurement. During Condition 3, the procedure was readjusted to its original form, and the balance closures returned to the acceptable range. This observation indicates that measurement of the fines slurry generated a high bias in the total materials balance for Condition 2.

Table 8. Average Mass Balance Closures (%)

	Total material	Dry solids	PCP	PAHs
Condition 1	104	106	101	87
Condition 2	113	108	19	28
Condition 3	98	94	13	13

Total dry solids recoveries during the VRU demonstration ranged from 94 to 109 percent, meeting project objectives of recoveries between 85 and 115 percent. Under Condition 1, the average mass balance closures for PCP and PAHs were 101 and 87 percent, respectively. These closures met the project objectives of PCP and PAH mass balance closures between 80 and 175 percent. The average PCP and PAH recoveries for Conditions 2 and 3 were well below project objectives and indicate the presence of a substantial negative bias. A closer inspection of the data, including laboratory QA indicators, reveals that fines slurry data are a likely source of negative bias. A possible explanation for the poor data in Conditions 2 and 3 is surfactant addition. During sample preparation, it is possible that competition between the surfactant (which tries to keep pollutants in solution) and the extraction solvent (which tries to remove pollutants from solution for analysis) may have had a detrimental effect. The fines slurry samples were difficult to filter. As a result, a large number of particles were included in the liquid portion of the sample, which probably retained significant concentrations of PCP and PAHs. The liquid samples, with a significant mass of particulates, were extracted by liquid extraction procedures, which are less rigorous for particulates. Since PCP and PAHs were not well accounted for, these data were of limited use.

3.3.5 Particle Size and Fines Distribution

The VRU system's effectiveness is based on its abiity to separate soil fines (particles that will pass through a 100-mesh screen) from the coarser gravel/sand fraction of the soil (particles that will not pass through a 100-mesh screen). Significant contaminant concentration reductions can be realized by the VRU, provided the majority of the contaminants present in the feed soil concentrate within the fines. By analyzing the dry solids mass balance data and particle size distribution, the disposition of fines and coarse gravel/sand can be calculated. Table 9 indicates the percentage of the soil fines and coarser gravel/sand fraction from the feed stream that were recovered in the washed soil and in the fines slurry. The data indicates that the majority of the small particles were partitioned to the fines slurry.

Table 9. Distribution of Fines and Coarse Gravel and Sand (%, dry weight basis)

	Soil Fines			Coarser Gravel/Sand Fraction		
Condition	1	2	3	1	2	3
Washed Soil	31	41	54	104	102	82
Fines Slurry	75	83	110	1	2	2
Closure	106	124	164	105	104	84

The partitioning of the coarser gravel/sand fraction to the washed soil stream was excellent. Only 1 to 2 percent of the coarser gravel/sand particles from the feed stream were detected in the fines slurry. The partitioning of the soil fines to the fines slurry was less complete, although the majority of these small particles did partition to the fines slurry. As shown in Table 8, 31 to 54 percent of the soil fines from the feed stream were recovered in the washed soil. A more complete partitioning of the soil fines to the fines slurry would, theoretically, lead to increased contaminant removals from the washed soil.

3.3.6 Water Treatment Effectiveness

Pollutants were removed from the fines slurry stream by a water treatment sequence consisting of settling, flocculation, filtration, and carbon adsorption. Following treatment in the Corrugated Plate Interceptor (CPI), where the fines were separated by gravity, the overflow was pumped to a flocculation/clarification system for additional fines partitioning. Table 10 lists ranges of PCP and PAH concentrations in the CPI and floe/clarifier solids on a dry weight basis. As previously discussed in Subsection 3.3.4, these samples were difticult to filter and the analytical methods were inadequate, which resulted in questionable data.

Clarified water was then pumped from the floe overflow tank through cartridge polishing filters operated in parallel to remove soil lines that would not pass through a 4 x 10^{-4} inch (lo-micron) screen. Water exiting these filters then passed through activated carbon drums for hydrocarbon removal. The claritied water was analyzed for total organic carbon (TOC) and total residue **(TR),** which is the sum of total suspended solids (TSS) and total dissolved solids (TDS). Table 10 lists the TOC and TR levels from the floe tank overflow, effluent from the filters, activated carbon, and wash water into the VRU.

The TR reduction from the filter unit was minimal, indicating that a finer-sized filter is needed. The TOC reduction decreased significantly when surfactant was introduced into the system during Conditions 2 and 3. The efficiency was affected because surfactant was adsorbed on the carbon along with the contaminants. TOC efficiency could be improved by removing the surfactant before it enters the carbon canisters or by utilizing another TOC removal technology.

The VRU was designed with the ability to recycle water treatment subsystem effluent to the mini-washer. This option was not evaluated during the demonstration because the developer chose to operate the system without recycling. Because water quality criteria for recycling have not been defined, it is not possible to determine whether the treated water produced during the demonstration was appropriate for recycling. Based on the data presented in Table 11, the levels of both TOC and **TR** during Condition 1 were potentially low enough to permit recycling; however, much higher levels were detected in Conditions 2 and 3. During these conditions, additional treatment may have been necessary to recycle the effluent from the carbon canisters.

Table 10. Average PCP and PAH Concentrations in CPI Underflow Solids and Floc/Clarifier Solids (dry weight basis)

	PCP (ppm)			PAHs (ppm)		
Condition	1	2	3	1	2	3
CPI underflow solids	51-69	46-85	*	1300-1,800	370-1,100	*
Floc/clarifier solids	92-6,500	190-1,300	83-150	58-2,000	910-1,800	940-1,200

* = Unacceptable analysis resulted in questionable data.

Table 11. Water Treatment Subsystem Effluent Quality (ppm)

	TOC			TR		
Condition	1	2	3	1	2	3
Wash water	<1.0	<1.5	<1.02	70	73	62
Floc-tank Overflow	11.5	1,045	825	260	2,200	6,075
Filter Effluent	11	1,075	697.5	247.5	2,025	5,075
Activated Carbon Effluent	<1.0	283	305	115	557.5	2,550

3.4 Range of Site Characteristics Suitable for the Technology

3.4.1 Site Selection

The VRU is a mobile research unit mounted on two heavy-duty tractor trailers. The VRU is composed of a number of subsystems (e.g., screening, gravity separation, flocculation/ clarification, filtration, and carbon adsorption). It is designed to be flexible, so that the combination of subsystems and wash water additives used can be modified to achieve cleanup goals cost-effectively, based on site requirements. The system can be assembled within the contaminated soil area or placed offsite so that soil can be transported to the unit. The treatment unit can be placed inside either a permanent or a temporary building or it can be operated in the open. The pilot-scale unit can be barge mounted.The VRU can be scaled to a full-scale unit for site remediation. For purposes of this document, a full-scale unit is based on a processing rate of 10 tons per hour (tph) of soil or sediment. Larger processing rates for a full-scale unit could be used. Additional details on the scale-up factors used and assumptions made for economic analyses are provided in Section 4.

3.4.2 Load, Surface, and Subsurface Requirements

A level, graded area that is capable of supporting able to support the weight of the unit, which was determined by the developer to be 3,500 pounds per square inch (psi) for both the pilot- and full-scale units. Additional road construction may be necessary to support oversize and heavy equipment.

Subsurface preparation is not required since all unit processes occur above the ground. If the soil is to be excavated and treated onsite, however, all subsurface obstacles (underground cables, piping, etc.) must be removed prior to excavation.

3.4.3 Clearance and Site Area Requirements

The site must be cleared to allow the unit to be assembled and operated. The extent of clearing is dependent upon the operational configuration selected. Cleared areas for stockpiling, storage, and loading/unloading activities are required. Clearing, other than for excavation of contaminated soil, is not an issue if treatment is to be conducted offsite.

The surface area required for the VRU soil washing equipment is approximately 40 x 60 feet for the pilot-scale unit and 300 x 400 feet for the full-scale unit. The vertical height of the system is based on the height of the settling tank as erected; 13.5 feet for the pilot-scale or 23 feet for the full-scale unit. The system conliguration will dictate whether or not a concrete pad is required to support the equipment. Additionally, separate areas should be provided for storage for both feed materials and any waste generated during the treatment process. The shape of the site should allow convenient access to the equipment.

3.4.4 Climate Characteristics

The critical climate requirements for the operation of this system include temperature range and wind conditions. Low ambient temperatures will either adversely affect treatment efficiency (if the wash water is not heated) or increase energy costs (if the wash water is heated). Temperatures below freezing would hinder the operating capabilities of the soil washing system because the system uses a significant amount of water in the treatment process. Also, the slurries created from the treatment process are adversely affected by freezing temperatures. Windy conditions may affect the excavation, transport, and feed of dry soils. Hazardous operating conditions would also exist in severe storm conditions.

To diminish the effects of climate, the system may be erected in an enclosure. For the pilot-scale unit, this may be a fixed structure or a tent covering the system. The full-scale unit requires a fixed structure.

3.4.5 Geological and Topographical Characteristics

Except for soil-bearing capacity requirements applicable to any heavy machinery, there are no geologic characteristics that restrict the implementation of this technology. The treatment unit must be flat, level, and stable. Currently the unit has been used at land-based facilities only.

3.4.6 Utility Requirements

Electricity and water are required to operate the VRU soil washing system. The pilot-scale system is equipped to operate using a generator to supply electrical power. Otherwise a 3-phase power supply from the local electric company is required. The full-scale system will require a 3-phase electrical system to operate. The pilot-scale system uses approximately 3.3 kilowatt hours (kWh) per ton of soil processed during operation. This requirement increases to 6.6 kWh/ton for the full-scale system.

Water required to operate the pilot-scale system is approximately 80 gallons per hour (gph). This assumes a recycle rate of 0 percent and an operational rate of 100 lbs/h process feed material. The full-scale system requires 1,600 gph. This assumes a 90 percent recycle rate and a process throughput of 10 tph of process feed material. Au abundant water supply must be readily available and accessible to operate the system. It is not required that the water be potable, but it must be free of debris. Water sources with debris may be used provided the water is filtered prior to its use in the system. Water need not be obtained from the local utility but could be from sources such as rivers, streams, lakes, or wells. If the unit is operated with elevated wash water temperatures, a water heater is required. Propane was used to heat water in the pilot-scale unit; natural gas could be used for a full-scale unit. The full scale unit would require approximately I20 cubic feet per minute (cfm) of natural gas.

Other utilities required include diesel fuel to operate the generator and natural gas or fuel oil for the steam boiler. The steam is required for the removal of volatile organic compounds (VOCs) from the feed material prior to soil washing. In this process, the steam is used to heat the screw conveyor jacket, thereby increasing the temperature to a point at which the volatile organics are released from the soil. These are then collected and treated by air stripping or some other treatment process. The amount of steam required for the pilot-scale unit is 600 lbs/h at of 50 psi, which requires approximately 10 cfm of natural gas or 4 gph of No. 2 fuel oil. Since no substantial quantity of VOCs was present, the steam jacket was not used during the demonstration.

3.4.7 Size of Operation

The capacity of the pilot-scale system used during the demonstration test was 100 lbs/h. The processing rate for the full-scale system is assumed to be 10 tph. Currently, the VRU Soil Washing System has only been tested as a pilot-scale unit. No full-scale units exist at this time.

3.5 Applicable Wastes

This technology may be used to treat soil contaminated primarily with volatile and semivolatile organic compounds. When the system is used to treat soils with volatile organics, steam stripping and vapor phase adsorption equipment is used. The unit has not been tested on sediments, though it is potentially capable of treating them.

The contaminated soil or sediment should contain no more than 30 to 40 percent fines, and maximum particle diameter should be no more than ½ inch. However, during the demonstration the pilot-scale was fed material 1/4-inch or less. The process is also less cost effective when the surfactant concentration is high. A high surfactant concentration also causes a foam problem that can inhibit the ability of the unit to remove the contaminants from the soil effectively.

The VRU soil washing system can be effectively used to treat organic compounds such as PAHs, PCP, and pesticides. In general, a wide variety of chemical contaminants can be removed or concentrated through soil washing applications. It has been shown that soil washing is effective on coarse sand and gravel contaminated with a wide range of organic and inorganic contaminants. Based on other soil washing systems, potential contaminants that may be suitable for soil washing include petroleum and fuel residues and cyanides.

3.6 Regulatory Requirements

Operation of the VRU for treatment of contaminated soil requires compliance with certain Federal, State, and local regulatory standards and guidelines. Section of the

Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) requires that, subject to specified exceptions, remedial actions must be undertaken in compliance with ARARs, Federal laws, and more stringent promulgated State laws (m response to release or threats of release of hazardous substances, pollutants, or contaminants) as necessary to protect human health and the environment.

The ARARs that must be followed in treating contaminated media onsite are outlined in the Interim Guidance on Compliance with ARARs, Federal Register, Vol. 52, pp. 32496 et seq [2]. These are:

- Performance, Design, or Action-Specific Requirements. Examples include Resource Conservation and Recovery Act (RCRA) incineration standards and Clean Water Act (CWA) pretreatment standards for discharge to publicly-owned treatment works (POTWs). These requirements are triggered by the particular remedial activity selected to clean a site.

- Ambient/Chemical-Specific Requirements. These set health-risk-based concentration limits based on pollutants and contaminants, e.g., emission limits and ambient air quality standards. The most stringent ARAR must be met.

- Locational Requirements. These set restrictions on activities because of site locations and environs.

Deployment of the VRU will be affected by three main levels of regulation:

- Federal EPA air, water, and solid/hazardous waste regulations

- State air, water, and solid/hazardous waste regulations

- Local regulations, particularly Air Quality Management District requirements

These regulations govern the operation of all technologies. Other Federal, State, and local regulations are discussed in detail in the following subsections as they apply to the performance, emissions, and residues evaluated from measurements taken during the demonstration test.

3.6.1 Federal Regulations

3.6.1.1 *Clean Air Act (CAA)*

The CAA establishes primary and secondary ambient air quality standards for the protection of public health and emission limitations for certain hazardous air pollutants. Permitting requirements under the CAA are administered by each state as part of the State Implementation Plans developed to bring each state into compliance with the National Ambient Air Quality Standards (NAAQS). The ambient air quality standards listed for specific pollutants may be applicable to operation of the VRU due to potential emissions when processing volatile compounds. When volatile compounds are present in the feed, an air pollution control device may be required. Other regulated emissions may be produced, depending on the waste feed. The allowable emissions will be established on a case-by-case basis depending on whether the site is located in an area that is in attainment with the NAAQS.

3.6.1.2 ***CERCLA***

CERCLA, as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986, provides for Federal funding to respond to releases of hazardous substances to air, water, and land. Section 121 of SARA, Cleanup Standards, states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It strongly recommends that remedial action use onsite treatment that ". ..permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances." In addition, general factors that must be addressed by CERCLA remedial actions include:

- Overall protection of human health and the environment

- Compliance with ARARs

- Long-term effectiveness and permanence

- Reduction of toxicity, or volume

- Short-term effectiveness

- Implementabiity

- cost

- State acceptance

- Community acceptance.

The ability of the VRU to concentrate the organic contaminants originally present in the feed, as demonstrated by removal efficiencies of 90 percent or greater for PCP and PAH contaminants, indicates the VRU is capable of significantly reducing the quantity of contaminated waste requiring subsequent treatment or disposal.

3.6.1.3 *RCRA*

The RCRA is the primary Federal legislation governing hazardous waste activities. Although a RCFL4 permit is not required for onsite remedial actions at Superfund sites, the VRU must meet all of its substantive requirements. Administrative RCRA requirements such as reporting and recordkeeping, however, are not applicable for onsite action. Subtitle C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste. Compliance with these requirements is mandatory for CERCLA sites producing hazardous waste onsite. In order to maintain compliance with RCRA, sites employing the VRU must obtain an EPA generator identification number and observe storage requirements stipulated under 40 Code of Federal Regulations (CFR) 262. Alternatively, a Part B Treatment, Storage, and Disposal (TSD) permit of interim status may be obtained. Invariably, a hazardous waste manifest must accompany offsite shipment of waste, and transport must comply with Federal Department of Transportation hazardous waste transportation regulations. Without exception, the receiving TSD facility must be permitted and in compliance with RCRA standards. The technology or treatment standards applicable to the media produced by the VRU will be determined by the characteristics of the material treated and the waste generated. The RCRA land disposal restrictions (40 CFR 268) preclude the land disposal of hazardous wastes which fail to meet the stipulated treatment standards. Wastes which do not meet these standards must receive additional treatment to bring the wastes into compliance with the standards prior to land disposal, unless a variance is granted.

3.6.1.4 *CWA*

The CWA regulates direct discharges to surface water through the National Pollutant Discharge Elimination System (NPDES) regulations. These regulations require point-source discharges of wastewater to meet established water quality standards. The discharge of wastewater to the sanitary sewer requires a discharge permit or, at least, concurrence from State and local regulatory authorities that the wastewater is in compliance with regulatory limits.

If the treated water cannot be reused as wash water, then it must be disposed. Disposal options include discharge to a local POTW, discharge to surface water, or onsite treatment. Discharge to a POTW will typically be regulated according to the industrial wastewater pretreatment standards of the POTW. These standards are specified in the CFR for certain industries. Depending on the site, the treated wash water may fall into one of the specific industrial categories. If it does not, the pretreatment standards for the wash water will be determined by the POTW and depend on site-specific parameters such as the flow rate of the wash water, the contaminants present, and the design of the POTW. Alternatively, the wash water can be treated onsite. Pursuant to the National Contingency Plan, the administrative and permitting requirements of RCRA do not apply. However, substantive requirements of RCRA do apply to onsite treatment facilities.

3.6.1.5 *Safe Drinking Water Act (SDWA)*

SDWA establishes primary and secondary national driig water standards. CERCLA refers to these standards, and Section 121(d)(2) explicitly mentions two of these standards for surface water or groundwater: Maximum Contaminant Levels (MCLs) and Federal Water Quality Criteria. Alternate Concentration Limits may be used when conditions of Section 121 (d)(2)(B) are met and cleanup to MCLs or other protective levels is not practicable. Included in these sections is guidance on how these requirements may be applied to Superfund remedial actions. The guidance, which is based on Federal requirements and policies, may be superseded by more stringent promulgated State requirements, resulting in the application of even stricter standards than those specified in Federal regulations.

3.6.1.6 Toxic Substances Control Act (TSCA)

TSCA grants EPA the authority to prohibit or control the manufacturing, importing, processing, use, and disposal of any chemical substance that presents an unreasonable risk of injury to human health or the environment. These regulations may be found in 40 CFR 761. With respect to hazardous waste regulation, TSCA focuses on the use, management, disposal, and cleanup of polychlorinated biphenyls (PCBs). Materials with less than 50 ppm PCB are classified as non-PCB; those with PCB concentrations between 50 and 500 ppm are classified as PCB-contaminated, and those with PCB concentrations greater than or equal to 500 ppm are classified as PCBs. State PCB regulations may be more stringent than TSCA.

While the soil used for the demonstration did not contain PCBs, it is reasonable to assume that the full-scale VRU could be utilized to clean soils that may contain PCBs. The separation process could result in elevated PCB concentrations in some output streams. If the concentrations of PCBs in an output stream are too high, the output stream will need to be handled as a TSCA-regulated waste.

3.6.2 State and Local Regulations

Compliance with ARARs may require meeting State standards that are more stringent than Federal standards or that are the controlling standards in the case of non-CERCLA treatment activities. Several types of State and local regulations that may affect operation of the VRU include:

- Permitting requirements for construction/operation
- Limitations on emission levels
- Nuisance rules

3.7 Personnel Issues

3.7.1 Training

Since selected personnel involved with sampling or working close to the VRU (especially the grizzly screen and feed hopper) are required to wear respiratory protection, 40 hours of Occupational Safety and Health Act (OSHA) training covering personal protective equipment (PPE) application, safety and health emergency response procedures, and quality assurance/quality control are required. Additional training addressing the site activities, procedures, monitoring, and equipment associated with the technology is also recommended. Personnel should also be briefed when new operations are planned, work practices change, or if the site or environmental conditions change.

3.7.2 Health and Safety

Personnel should be instructed on the potential hazards associated with the operation of the VRU, recommended safe work practices, and standard emergency plans and procedures. Health and safety training covering the potential hazards and provisions for exposure, monitoring, and the use and care of PPE should be required. When appropriate, workers should have medical exams. Health and safety monitoring and incident reports should be routinely filed and records of occupational illnesses and injuries (OSHA Forms 102 and 200) should be maintained. Audits ensuring compliance with the health and safety plan should be carried out.

Proper PPE should be available and properly utilized by all onsite personnel. Different levels of personal protection will be required based on the potential hazard associated with the site and the work activities.

Site monitoring should be conducted to identify the extent of hazards and to document exposures at the site. The monitoring results should be maintained and posted.

3.7.3 Emergency Response

In the event of an accident, illness, explosion, hazardous situation at the site, or intentional acts of harm, assistance should be immediately sought from the local emergency response teams and first aid or decontamination should be employed when appropriate. To ensure a timely response in the case of an emergency, workers should review the evacuation plan, firefighting procedures, cardiopulmonary resuscitation (CPR) techniques, emergency decontamination procedures, and routes to local hospitals before operating the system. Fire extinguishers, spill cleanup kits, emergency eye washes, alarms, evacuation vehicles, and an extensive first aid kit should be onsite at all times.

3.8 References

1. Federal Technology Transfer Act of 1986. 15 USC 3702-3714.

2. Interim Guidance on Compliance with ARARs - Federal Register, 52: pp.32496 et. seq.

Section 4

Economic Analysis

4.1 Introduction

The primary purpose of this economic analysis is to estimate costs (not including profits) for a commercial treatment system utilizing the mobile VRU. This analysis is based on the results of a SITE demonstration which utilized a pilot-scale soil washing system. The pilot-scale unit operated at a feed rate of 100 lbs/h of contaminated soil. It is projected the commercial unit will be capable of treating approximately 10 tph of contaminated soil.

4.2 Conclusions

The commercial-scale VRU proposed by EPA appears to be suited to the remediation of soils and other solid wastes contaminated with organic compounds. Treatment costs appear to be competitive with other available technologies. The cost to remediate 20,000 tons of contaminated soil using a lo-tph VRU is estimated at $137 per ton if the system is on-line 90 percent of the time. Treatment costs increase as the percent on-line factor decreases. Projected unit costs for a smaller site (10,006 tons of contaminated soil) are $171 per ton; projected unit costs for a larger site (200,000 tons) are $106 per ton.

4.3 Issues and Assumptions

Because the VRU appears to be capable of effectively treating soils contaminated with organics, it is considered potentially applicable to the remediation of Superfund sites. In the following economic analysis, the costs associated with this technology are calculated based on the treatment of a small-to-medium hazardous waste site that has approximately 20,000 tons of contaminated soil suitable for treatment by soil washing. Approximately 3,600 pounds of contaminated soil were treated during the SITE demonstration. While the pilot-scale VRU was designed for the treatment of VOCs, the SITE demonstration did not involve the treatment of VOCs. It is assumed that the 10-tph VRU will have and use equipment designed for the treatment of VOCs.

Costs that are assumed to be the obligation of the responsible party or site owner have been omitted from this cost estimate and are indicated by a line (---) in all tables.

Important assumptions regarding operating conditions and task responsibiities that could significantly affect the cost estimates are presented in the following subsections.

4.3.1 Costs Excluded from Estimate

The cost estimates presented are representative of the charges typically assessed to the client by the vendor but do not include profit.

Many other actual or potential costs were not included as part of this estimate. These costs were omitted because site-specific engineering designs are beyond the scope of this SITE project. Certain functions were assumed to be the obligation of the responsible party or site owner and were not included in this estimate.

Costs such as preliminary site preparation, permits, regulatory requirements, initiation of monitoring programs, waste disposal, sampling and analyses, and post-treatment site cleanup and restoration are considered to be the responsible party's (or site owner's) obligation and are not included. These costs tend to be site-specific and it is left to the reader to perform calculations relevant to each specific case. Whenever possible, applicable information is provided on these topics so the reader may perform calculations to obtain relevant economic data.

4.3.2 Utilities

To support the operation of the 10-tph VRU, a site must have clean water available at a flow rate of at least 24 gpm, assuming recycling with 10 percent blowdown. This water will be used in the miniwasher and the floe clarifier. Other uses of the water include cooling and miscellaneous onsite applications such as cleaning and rinsing.

A natural gas source and the required piping must be available and accessible to accommodate a natural gas usage of approximately 7,800 cubic feet per hour at standard conditions (60° F and 30 inches of mercury). Alternatively, provisions may be made for the use of oil as a supplemental fuel. The pilot-scale unit used for the demonstration utilized propane as a fuel source for the water heater. The steam boiler was not utilized since VOCs were not present in the feed soil.

Electrical power is required for the operation of the pumps, mixers, vibrating screens, and many smaller pieces of equipment. The pilot-scale unit utilized an electrical generator, but for the full-scale unit it is anticipated that electrical power will be supplied from offsite source. It is assumed that the cost of connecting the full-scale VRU to an outside electrical source, including the transformer, is the responsibility of the site owner. Maximum electrical power consumption is estimated to be 66 kWh per ton of contaminated soil treated.

For these cost calculations, it is assumed the site will support all of these requirements. The cost of preparing a site to meet these requirements can be high and is not included in this analysis.

4.3.3 Operating Times

It is assumed the treatment operations will be conducted 24 hours per day, 5 days per week. It is further assumed that site preparation will be conducted 8 hours per day, 5 days per week. Assembly and disassembly are assumed to be carried out 8 hours per day, 7 days per week. Startup and testing will be accomplished in one shift working 8 hours per day, 5 days per week. Training will be concurrent with startup activities and be conducted 8 hours per day for 3 days. Excavation activities for site preparation will be concurrent with treatment (and may be concurrent with assembly and shakedown and testing as well). Assembly and disassembly are both assumed to require 3 weeks. Shakedown, testing, and training are expected to take 1 week. Except where noted, these calculations are based on the treatment of a total of 20,000 tons of waste using a I0-tph system.

4.3.4 Labor Requirements

Treatment operations for a typical shift are assumed to require five workers. These workers include a shift supervisor, a maintenance person, a nonlocal operator, and two local operators. With 3 shifts, there will be 24 hours of coverage for those directly involved in operating the system. In addition, a project manager, safety officer, and local administrative person will each work a standard 40-hour schedule at the site. When the safety officer is off-duty, the shift supervisors will assume all safety responsibilities.

4.3.5 Capital Costs

The purchased equipment cost consists of the VRU and additional equipment such as VOC treatment system, water heater, steam generator, and trailers. The fixed capital investment (i.e., capital costs) consists of the purchased equipment cost and other fixed costs such as freight, sales tax installation, piping electrical instrumentation, engineering, and supervision. The percentage of these major cost components are presented in Table 12. Assumed proportions are based on ranges of estimates given by Peters and Timmerhaus [l]. Since the total equaled less than 100 percent the items were normalized. Once the purchased equipment costs (including freight and sales tax) are known, the total fixed capital investment can be determined. Freight and sales tax are estimated as percentages of the purchased equipment cost, while the other fixed costs are estimated as percentages of the total fixed capital investment.

Table 12. Proportional Costs of Major Fixed Capital Investment Components

	Assumed % of Total	Normalized % of Total
Equipment (Including Freight & Sales Tax)	40	47
Equipment Installation	9	11
Instrumentation (Installed)	6	7
Piping (Installed)	13	15
Electrical (Installed)	5	6
Engineering & Supervision	12	14
Total	85	100

4.3.6 Equipment and Fixed Costs

Annualized equipment costs and other fixed costs have been prorated for the duration of time that the equipment is onsite. The costs for equipment, contingency, insurance, and taxes accrue during assembly, shakedown and testing, treatment, and disassembly; scheduled maintenance costs accrue during treatment only.

4.4 Basis of Economic Analysis

The cost analysis was prepared by breaking down the overall cost into 12 categories. The cost categories, some of which do not have costs associated with them for this particular technology, are:

- Site preparation
- Permitting and regulatory
- Equipment
- Startup and fixed
- Labor
- Supplies
- Consumables
- Effluent treatment and disposal
- Residuals and waste shipping, handling, and transport
- Analytical
- Facility modification, repair, and replacement
- Site demobilization

The 12 cost factors as they apply to the VRU and the assumptions employed are described in the following subsections.

4.4.1 Site Preparation Costs

It is assumed that preliminary site preparation will be performed by the responsible party (or site owner). The amount of preliminary site preparation will depend on the site. Site preparation responsibilities include site design and layout, surveys and site logistics, legal searches, access rights and roads, preparations for support and decontamination facilities, utility connections, and auxiliary buildings. Since these costs are site-specific, they are not included as part of the site preparation costs in this cost estimate.

Certain site preparation activities, such as excavating hazardous waste from the contaminated site, will be required at all sites and are therefore included in this estimate. Cost estimates for site preparation are based on rental costs for operated heavy equipment, labor charges, and equipment fuel costs. An excavation rate of 27 tph is assumed for all cleanup scenarios using the I0-tph VRU. It is assumed that the minimum rental equipment required to achieve an excavation rate of approximately 27 tph includes nine excavators, three box dump trucks, and three backhoes. The operation of this equipment will consume approximately 42 gph of diesel fuel. It is also assumed that excavation activities will be conducted 8 hours per day, 5 days per week. Excavation costs are itemized in Table 13.

Table 13. Excavation Costs

Item	Cost
Excavator	$1,260/week
Box dump truck	$525/week
Backhoe	$585/week
Supervisor	$40/hour
Excavator operator	$30/hour
Dump truck operator	$30/hour
Backhoe operator	$30/hour
Diesel fuel	$1/gallon

4.4.2 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 monitoring requirements, or the development of monitoring and analytical protocols. Permitting and regulatory costs can vary greatly because they are site- and waste-specific. No permitting or regulatory costs are included in this analysis. Depending on the treatment site however, this may be a signiticant factor since permitting activities can be both expensive and time consuming.

4.4.3 Equipment Costs

The commercial-scale VRU will be capable of treating 10 tph of contaminated soil. System accessories will include a steam generator for stripping volatile organics from the feed soil, off-gas treatment system, and waste-water treatment system. Major pieces of equipment include:

- Heated soil conveyor
- Trommel screen miniwasher
- Water heater
- Floe-clarifier
- Steam boiler
- Membrane filter press
- VOC treatment system

Miscellaneous equipment such as screens, pumps, mixers, and tanks are included in equipment costs.

The developer supplied equipment and utility costs for the pilot-scale and the lo-tph system. Total purchased equipment cost for the lo-tph unit was estimated to be **$1,240,000;** the total fixed capital investment (icluding freight and sales tax, installation, instrumentation, piping, electrical, and engineering and supervision during construction) was projected to be $3,110,000.

It is assumed that no rental equipment or purchased support equipment will be required for operation (with the exception of trailers). Support equipment refers to purchased equipment necessary for operation but not integral to the system.

The total equipment cost is calculated and annualized using the following formula:

$$A = C \frac{i(1 + i)}{(1 + i)^n - 1}$$

where: A = annualized cost, $
C = capitalized cost, $
i = interest rate, %
n = useful life, years

The annualized cost (rather than depreciation) is used to calculate equipment costs incurred by a site. It is assumed that the interest rate will be 10 percent. For the lo-tph unit, a useful life of 10 years is assumed. The annualized equipment cost is prorated to the actual time the unit is commissioned to treat a hazardous waste (including assembly, shakedown and testing, treatment, and disassembly). The prorated annualized cost is estimated to be $271,000. The prorated cost is then normalized relative to the tons of soil treated.

4.4.4 Startup and Fixed Costs

Mobilization includes both transportation and assembly. Transportation activities include moving the system and the workers to and from the site. As a rough estimate, it is assumed that five oversize and one legal load size tractor trailers will be required to transport the commercial-scale soil washing system. In addition, one legal load size tractor trailer will be required for miscellaneous equipment and spare parts. Travel costs were developed based on 1,300 road miles at a rate of $1.65 per mile per legal load and $3.30 per mile per oversized load (including drivers). Transportation costs for the 11 nonlocal onsite workers are based on two $220 one-way airfares per person. Two one-way airfares were used instead of a round-trip airfare due to the restrictions of a round-trip ticket and the difficulties in predicting when the project would end.

Assembly consists of unloading the system from the trucks and trailers and reassembling the VRU. It is assumed that unloading the equipment will require the use of a 50-ton crane and operator for 3 weeks at a cost of $6,360 per week. Assembly is assumed to require 10 people (8 construction workers and 2 shift supervisors) working 8 hours per day, 7 days per week, for 3 weeks. Table 14 lists fully burdened salaries for all onsite personnel involved with assembly as well as other phases of the project (e.g., startup and testing, training, treatment, and disassembly). Labor charges during assembly consist of wages and living expenses for nonlocal personnel (refer to Subsection 4.4.5) including two rental cars.

This cost estimate assumes that 1 week of shakedown and testing will be required after assembly and prior to the commencement of treatment. During this time, the system components are tested individually. It is estimated that eight workers will be required for 8 hours per day, 5 days per week during shakedown and testing. The 8 workers include a project manager, shift supervisor, safety officer, maintenance worker, operator, administrator, and two local operators. In addition, the four local operators will be trained for 3 days during this week. Labor costs consist of wages and living expenses for nonlocal personnel (refer to subsection 4.4.5) including two rental cars.

Working capital consists of the amount of money currently invested in supplies, energy, spare parts, and labor kept on hand [l]. The working capital for this system is based on maintaining a l-month inventory of these items. For the calculation of working capital, 1 month is defined as one-twelfth of 1 year, or approximately 21.8 working days.

For the purposes of this estimate, insurance is assumed to be 6 percent of the total purchased equipment costs; property taxes are assumed to be 3 percent of the total fixed capital investment [1]. These costs are annual and have been prorated to the actual time the VRU is commissioned to treat contaminated waste on a site (including assembly, shakedown and testing, treatment, and disassembly).

Table 14. Fully Burdened Salaries for Ousite Persouuel Usiug IO-tph VRU

Title	Local	Salary ($/h)
Project Manager	No	50
Shift Supervisor	No	40
Safety Officer	No	35
Non-local Operator	No	30
Maintenance Worker	No	20
Local Operator	Yes	20
Construction Worker	Yes	20
Administrative Personnel	Yes	12

The cost for the initiation of monitoring programs has not been included in this estimate. Depending on the site, local authorities may impose specific guidelines for monitoring programs. The stringency and frequency of monitoring required may have a significant impact on the project costs.

An annual contingency cost of 10 percent of the annualized equipment capital costs is allowed to cover additional costs caused by unforeseen or unpredictable events, such as strikes, storms, floods, and price variations [l]. The annual contingency cost has been prorated to the actual time the lo-tph VRU is commissioned to treat hazardous waste (including assembly, shakedown and testing, treatment, and disassembly).

4.4.5 Labor Costs

Labor costs consist of wages and living expenses. Personnel requirements are discussed in Subsection 4.3.4. Fully burdened rates are given in Table 14.

Living expenses depend on several factors: the duration of the project, the number of local workers hired, and the geographical location of the project. Living expenses for all personnel who are not local hires consist of per diem and rental cars, both charged at 7 days per week for the duration of the treatment. Per diem varies by location, but for the purposes of this report, it is assumed to be $70 per day per person. Four rental cars are required for 24 hour operation and are available for $30 per day per car. Depending on the length of the project, it may be more practical to hire only local personnel and train them in the operation of the unit, eliminating living expenses.

4.4.6 Supplies Costs

For this estimate, supplies consist of chemicals and spare parts. Surfactant, alkali (sodium carbonate), alum, polyelectrolyte (flocculent), and sulfuric acid requirements for the VRU are estimated to cost approximately $420,000 for the entire project. Annual spare parts costs are estimated to be 5 percent of the total purchased equipment cost or approximately $22,000 for the entire project. Expenses for personal protective equipment are included in spare parts costs.

4.4.7 Consumables Costs

In order to heat wash water and steam strip VOCs from the feed, the VRU consumes natural gas at a rate of approximately 7.7 million Btu/h. The cost of natural gas is estimated as $4.00 per million Btu with no monthly fee, yielding a fuel cost of approximately $13,400 per month or $31 per hour of operation.

The electricity requirement for the screw conveyor, pumps, and mixers is approximately 66 kWh per ton of soil treated. The estimated cost of electricity is $25,000 per month or $48 per hour of operation. The cost estimate assumes that electricity can be obtained for a flat rate of $0.08 per kWh with no monthly charge.

The VRU has an estimated water requirement of 1,420 gallons per ton of soil treated. It is assumed that 90 percent of the water can be recovered and treated for reuse (i.e., only about 24 gpm of makeup is needed). The other 10 percent is discarded as blowdown or lost with clean solids during separation processes. Water costs are estimated at $2 per 1,000 gallons. One month's supply of water (667,000 gallons) costs about $1,330, and the cost per hour of operation is $2.56.

4.4.8 Effluent Treatment and Disposal Costs

The clean solids generated during the SITE demonstration remained onsite. It is assumed that clean solids from a full-scale cleanup will be used as fill material if found to be nonhazardous. The fines will require further processing by another technology. Recovery of at least 80 percent of the solids present in the feed as washed soil is one of the project objectives. The remainder (less than 20 percent) is incorporated into the fines slurry.

Most of the water from the water treatment system should be suitable for recycling as wash water in the mini-washer. A fraction of this water will be removed as blowdown and require disposal or treatment. The responsible party or site owner should obtain a discharge permit from the local municipality if possible. If no sewer service is available, the site owner or responsible party must obtain a direct discharge permit or arrange for disposal by other means. It should not be necessary to treat the blowdown water prior to discharge, but this must be determined on a site-specific basis.

Onsite treatment and disposal costs are restricted to onsite storage of the blowdown water (if necessary) and are assumed to be the obligation of the site owner or responsible party. Offsite treatment and disposal costs consist of wastewater disposal fees and are assumed to be the obligation of the responsible party (or site owner). These costs may significantly add to the total cleanup cost. The cost of additional treatment of the tines is assumed to be the obligation of the responsible party (or site owner).

4.4.9 Residuals and Waste Shipping, Handling, and Transport Costs

It is assumed that the residuals generated by this process will include the clean solids, fmes, filters, spent carbon canisters, and spent PPE. Residuals will also be generated when the unit is decontaminated. Potential waste disposal costs include storage, transportation, and treatment costs and are assumed to be the obligation of the responsible party (or site owner). These costs could significantly add to the total cleanup cost.

4.4.10 Analytical Costs

No analytical costs are included in this cost estimate. Standard operating procedures do require sampling and analytical activities to determine when breakthrough has occurred in equipment such as aqueous or vapor-phase carbon absorption, reverse osmosis, or ultrafiltration systems. The client may elect or may be required by local authorities to initiate a sampling and analytical program at their own expense. If specific sampling and monitoring criteria are imposed by local authorities, these analytical requirements could contribute significantly to the cost of the project.

4.4.11 Facility Modification, Repair, and Replacement costs

Maintenance labor and material costs vary with the nature of the waste and the performance of the equipment. For estimating purposes, total annual maintenance costs (labor and materials) are assumed to be 10 percent of annual equipment costs. Maintenance labor typically accounts for two-thirds of the total maintenance costs and has been discussed in Subsection 4.45. Maintenance material costs are estimated at one-third of the total maintenance cost and are prorated to the entire period of treatment. Costs for design adjustments, facility modifications, and equipment replacements are included in the maintenance costs.

4.4.12 Site Demobilization Costs

Demobilization costs are limited to disassembly costs; transportation costs are included under mobilization. Disassembly consists of taking the VRU apart and loading it onto trailers for transportation. It requires the use of a 50-ton crane with operator, available at $6,360 per week, for 3 weeks. Additionally, disassembly requires a lo-person crew (8 construction workers and 2 shift supervisors) working 8 hours per day, 7 days per week, for 3 weeks. Labor costs consist of wages (see Table 14) and living expenses (refer to Subsection 4.45) including 2 rental cars.

Site cleanup and restoration are limited to the removal of all equipment from the site. These costs have been previously incorporated in the disassembly costs. Requirements regarding the filling grading or recompaction 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).

4.5 Results of Economic Analysis

The costs associated with the operation of the VRU, as presented in this economic analysis, are defined by 12 cost categories that reflect typical cleanup activities encountered on Superfund sites. Each of these cleanup activities is defined and discussed; together they form the basis for the cost analysis presented in Table 15. The percentage of the total cost contributed by each of the cost categories is shown in Table 16.

Table 15. Treatment Costs for lo-tpb VRU Treating 20,000 Tons of Contaminated soil

	Cost ($/ton)		
Item	**70% on-line**	**80% on-line**	**90% on-line**
Site preparation	34.61	34.61	34.61
Permitting and regulatory	—	—	
Equipment	16.13	14.68	1356
Startup and fixed	29.91	30.03	30.29
Labor	32.04	28.03	24.92
Supplies	21.33	21.15	21.01
Consumables	8.65	8.65	8.65
Effluent treatment and disposal	—	—	—
Residuals and waste shipping, handling, and transport	—	—	
Analytical	—		—
Facility modification, repair, and replacement	0.54	0.49	0.45
Site demobilization	3.18	3.18	3.18
Total **operating costs**	146.39	140.82	136.67

Table 16. Treatment Costs as Percentages of Total Costs for lo-tph VRU Treating 20,000 Tons of Contaminated Soil

	Cost (as % of total cost)		
Item	70% on-line	80% on-line	90% on-line
Site preparation	23.6	24.6	25.3
Permitting and regulatory	—	—	—
Equipment	11.0	10.4	9.9
Startup and fixed	20.4	21.3	22.2
Labor	21.9	19.9	18.2
Supplies	14.6	15.0	15.4
Consumables	5.9	6.1	6.3
Effluent treatment and disposal	—	—	—
Residuals and waste shipping, handling, and transport	—	—	—
Analytical	—	—	—
Facility modification, repair, and replacement	0.4	0.3	0.3
Site demobilization	2.2	2.3	2.3
Total operating costs	100	100	100

The developer claims that the VRU can operate with an on-line factor of over 90 percent. On-line factors of 90, 80, and 70 percent were used in the cost calculations in order to determine the impact of this parameter. The on-line factor is used to adjust the unit treatment cost to compensate for the fact that the system is not on-line constantly because of maintenance requirements, breakdowns, and unforeseeable delays. Through the use of the on-line factor, costs incurred while the system is not operating are incorporated in the unit cost.

The VRU is believed to be capable of operating continuously (24 hours per day, 7 days per week) for extended periods of time; however, it was assumed that it will be operated only 5 days per week. If the VRU is to be to operated continuously, adjustments must be made to prorated cost estimates.

The feed rate during the SITE Demonstration Test was approximately 100 lb/h and the pilot-scale system consumed approximately 66 kWh per ton and 71 gph of water (no recycling). The pilot-scale unit used propane to heat the wash water; no steam was required since VOCs were not present in the feed soil. Based on the pilot-scale system, chemical usage rates per ton of soil for surfactant, alkali, alum, and polyelectrolyte were 24, l2, and 18 and 0.18 lbs, respectively.

The developer provided cost and capacity information for both the pilot- and full-scale (lo-tph) VRU units. All costs are for 1993. It is assumed the commercial-scale unit will have a feed rate of 10 tph and will require approximately 24 gpm of water (assuming 90 percent recycling), 66 kWh/ton of electricity, and 7.7 million Btu/h of natural gas. For this feed rate, the results of the analysis show a unit cost ranging from $137 per ton to $147 per ton for 90 and 70 percent on-line conditions, respectively.

Based on the information provided by the developer, the estimated purchased equipment cost for a larger (100 tph) VRU unit was calculated using the following formula:

$$F = P(R)$$

where: F = Full-scale cost
P = Pilot-scale cost
R = Scale-up ratio (full-scale capacity/pilot-scale capaci y)
n = Scale-up factor

This formula represents a typical cost verses capacity curve [2]. Knowing the cost and capacity of the pilot and lo-tph equipment, the scale-up factors were determined. These values ranged from 0.32 to 0.97, but were typically between 0.4 and 0.7. Using the same factors and estimated scale-up ratios, equipment costs for the 100-tph VRU unit were calculated.

These costs are considered order-of-magnitude estimates as defined by the American Association of Cost Engineers. The actual cost is expected to fall between 70 and 150 percent of the estimated cost when scaling-up from a full-scale unit to a larger full-scale unit. Since these costs were estimated from scaling-up a pilot-scale unit to a full-scale unit, the range may actually be wider.

Table 17 compares estimated unit treatment costs for sites containing 10,000, 20,000, and 290,000 tons of contaminated soil, Table 18 shows the percentage of the treatment costs contributed by each of the 12 cost categories. All variables except total amount of contaminated soil are held constant. In particular, all three estimates utilize a 10-tph VRU and a 90 percent on-line factor. If the lo-tph VRU is used to remediate a site containing less than 20,000 tons of contaminated soil (all other variables remaining constant), the startup and fixed costs will become more of a factor. Unit costs derived from startup, demobilization, and from fixed expenses will be higher, but unit costs derived from operating expenses will remain approximately the same.

For example, if this system is applied to a site containing 10,000 tons of contaminated soil, the unit treatment costs (using a 90 percent on-line factor) are estimated at $171 per ton of soil. If the lo-tph VFW is used at a site containing over 20,000 tons of contaminated soil (all other variables remaining constant), the startup, demobilization, and fixed costs will become less of a factor. Unit costs derived from startup, demobilization, and fixed expenses will be lower, but unit costs derived from operating expenses will remain approximately the same.

If this system is applied to the remediation of a site containing 200,000 tons of contaminated soil, the unit treatment costs (using a 90 percent on-line factor) are estimated at $106 per ton of soil.

It will take nearly 4 years to remediate a site containing 290,000 tons of contaminated soil with the 10-tph system. For this volume of soil, one or more larger units would be more appropriate. In order to make a comparison, a preliminary cost estimate was prepared for a system capable of treating 100 tph of contaminated soil.

Table 17. Treatment Costs for 10-tph VRU Operating with a 90% On-line Factor

	Cost ($/ton)		
Item	10,000 tons	20,000 tons	200,000 tons
Site preparation	34.61	34.61	34.61
Permitting and regulatory	—	—	
Equipment	18.12	1356	9.45
Startup and fixed	56.70	30.29	652
Labor	24.92	24.92	24.92
Supplies	21.01	21.01	21.01
Consumables	8.65	8.65	a.65
Effluent treatment and disposal	—	—	—
Residuals and waste shipping, handling, and transport	—		
Analytical	—	—	—
Facility modification, repair, and replacement	0.60	0.45	0.31
Site demobilization	6.36	3.18	0.32
Total operating costs	170.97	136.67	105.79

Table 18. Treatment Costs as % of Total Costs for 10-tph VRU Operating With a 90% On-line Factor

	Cost (as % of total cost)		
Item	10,000 tons	20,000 tons	200,000 tons
Site preparation	20.2	25.3	32.7
Permitting and regulatory	—	—	—
Equipment	10.6	9.9	8.9
Startup and fixed	33.2	22.2	6.2
Labor	14.6	18.2	23.6
Supplies	12.3	15.4	19.9
Consumables	5.1	6.3	8.2
Effluent treatment and disposal		—	—
Residuals and waste shipping, handling, and transport			
Analytical costs	—	—	—
Facility modification, repair, and replacement	0.4	0.3	0.3
Site demobilization	3.7	2.3	0.3
Total operating costs	100	100	100

This formula represents a typical cost verses capacity curve [2]. Knowing the cost and capacity of the pilot and lo-tph equipment, the scale-up factors were determined. These values ranged from 0.32 to 0.97, but were typically between 0.4 and 0.7. Using the same factors and estimated scale-up ratios, equipment costs for the lOO-tph VRU unit were calculated.

These costs are considered order-of-magnitude estimates as defmed by the American Association of Cost Engineers. The actual cost is expected to fall between 70 and 150. percent of the estimated cost when scaling-up from a full-scale unit to a larger full-scale unit. Since these costs were estimated from scaling-up a pilot-scale unit to a full-scale unit, the range may actually be wider.

Table 17 compares estimated unit treatment costs for sites containing 10,000, 20,000, and 200,000 tons of contaminated soil; Table 18 shows the percentage of the treatment costs contributed by each of the 12 cost categories. All variables except total amount of contaminated soil are held constant. In particular, all three estimates utilize a lo-tph VRU and a 90 percent on-line factor. If the lo-tph VFW is used to remediate a site containing less than 20,000 tons of contaminated soil (all other variables remaining constant), the startup and fixed costs will become more of a factor. Unit costs derived from startup, demobilization, and from fixed expenses will be higher, but unit costs derived from operating expenses will remain approximately the same.

For example, if this system is applied to a site containing 10,000 tons of contaminated soil, the unit treatment costs (using a 90 percent on-line factor) are estimated at $171 per ton of soil. If the lo-tph VRU is used at a site containing over 20,000 tons of contaminated soil (ail other variables remaining constant), the startup, demobilization, and fixed costs will become less of a factor. Unit costs derived from startup, demobiition, and fixed expenses will be lower, but unit costs derived from operating expenses will remain approximately the same.

If this system is applied to the remediation of a site containing 200,000 tons of contaminated soil, the unit treatment costs (using a 90 percent on-line factor) are estimated at $106 per ton of soil.

It will take nearly 4 years to remediate a site containing 200,000 tons of contaminated soil with the lo-tph system. For this volume of soil, one or more larger units would be more appropriate. In order to make a comparison, a preliminary cost estimate was prepared for a system capable of treating 100 tph of contaminated soil.

Table 17. Treatment Costs for lo-tpb VRU Operating with a 90% On-line Factor

	Cost ($/ton)		
Item	10,000 tons	20,000 tons	200,000 tons
Site preparation	34.61	34.61	34.61
Permitting and regulatory	—	—	—
Equipment	18.12	1356	9.45
Startup and fixed	56.70	30.29	652
Labor	24.92	24.92	24.92
Supplies	21.01	21.01	21.01
Consumables	8.65	8.65	8.65
Effluent treatment and disposal	—	—	—
Residuals and waste shipping, handling, and transport	—		
Analytical	—	—	—
Facility modification, repair, and replacement	0.60	0.45	0.31
Site demobilization	6.36	3.18	0.32
Total operating costs	170.97	136.67	105.79

Table 18. Treatment Costs as % of Total Costs for lo-tpb VRU Operating With a 90% On-line Factor

	Cost (as % of total cost)		
Item	10,000 tons	20,000 tons	200,000 tons
Site preparation	20.2	25.3	32.7
Permitting and regulatory	—	—	—
Equipment	10.6	9.9	8.9
Startup and fixed	33.2	22.2	6.2
Labor	14.6	18.2	23.6
Supplies	12.3	15.4	19.9
Consumables	5.1	6.3	8.2
Effluent treatment and disposal	—	—	—
Residuals and waste shipping, handling, and transport	—	—	—
Analytical costs	—	—	—
Facility modification, repair, and replacement	0.4	0.3	0.3
Site demobilization	3.7	2.3	0.3
Total otwating costs	100	100	100

Table 19 compares estimated unit treatment costs for the use of lo-tph and lOO-tph systems at a site containing 200,000 tons of contaminated soil; Table 20 shows the percentage of the treatment costs contributed by each of the 12 cost categories. All process variables except feed rate are held constant. In particular, both estimates utilize a 90 percent on-line factor. This preliminary analysis indicates that it will cost $72 per ton to remediate a site containing 200,000 tons of contaminated soil using the lOO-tph system (assuming a 90 percent on-line factor). When the larger system is used, the treatment time is approximately 0.4 years and the equipment is onsite for approximately 0.54 years. Transportation and onsite assembly of the larger unit, however, could present difficulties. More trailers and labor will be required for mobilization and demobilization. It was assumed that one extra local operator would be required per shift to operate the larger unit. Scale-up to 100 tph from 10 tph was accomplished by either increasing the scale-up ratio or the number of units or a combination of both.

Table 19. Treatment Costs for the Remediation of 200,000 Tons of Contaminated Soil Using the VRU Operating With a 90% On-line Factor

Item	Cost (S/ton) 10-tph System	100-tph System
Site preparation	34.61	25.26
Permitting and regulatory	—	—
Equipment	9.45	2.35
Startup and fixed	6.52	11.90
Labor	24.92	2.71
Supplies	21.01	20.40
Consumables	8.65	8.65
Effluent treatment and disposal	—	—
Residuals and waste shipping, handling, and transport		
Analytical		—
Facility modification, repair, and replacement	0.31	0.08
Site demobilization	0.32	0.64
Total operating costs	105.79	71.99

Table 20. Treatment Costs as Percentage sof Total Casts for VRU Treating 200,000 Tons of Contaminated Soil

Item	Cost (as % of total cost) lO-tph System	100-tph System
Site preparation	32.7	35.1
Permitting and regulatory	—	—
Equipment	8.9	3.3
Startup and fixed	6.2	165
labor	23.6	3.8
Supplies	19.9	28.3
Consumables	8.2	12.0
Effluent treatment and disposal	—	—
Residuals and waste shipping, handling, and transport		
Analytical costs		
Facility modification, repair, and replacement	0.3	0.1
Site demobilization	0.3	0.9
Total operating costs	100	100

The costs excluded from this cost analysis are described in Subsections 4.3 and 4.4. This analysis does not include values for 4 of the 12 cost categories, so the actual cleanup costs incurred by the site owner or responsible party may be significantly higher than the costs shown in this analysis. While the volume of waste treated can be significantly reduced, the contaminants are not destroyed or immobiid, so another treatment technology will be required to treat the fines removed from the VRU.

4.6 References

1. Peters, M.S. and Timmerhaus, KD. Plant Design and Economics for Chemical Engineers; Third Edition; McGraw-Hill, Inc., New York, 1980.

2. Baasel, W. D. Preliminary Chemical Engineering Plant Design; Elsevier Science Publishing Co., Inc., New York, 1976.

Appendix A
Process Description

A.1 Introduction

Section **121(b)** of CERCLA mandates EPA to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as a principal element." The VRU was developed to meet those objectives, as well as the objectives listed below:

- To make available to members of the research community and the commercial sector the results of government research on a flexible, multi-step, mobile, pilot-scale soil washer capable of running treatability studies on a wide variety of soils
- To demonstrate the capabilities of soil washing
- To provide data that facilitate scale-up to commercial-size equipment

The VRU is a mobile, pilot-scale soil washing system for stand-alone field use in cleaning soil contaminated with hazardous substances. Removal efficiencies depend on the contaminant as well as the type of soil. In general, soil washing is effective on coarse sand and gravel contaminated with a wide range of organic and inorganic contaminants.

A.2 Process Description

The VRU is a mobile research unit developed for treatabiity studies on soils contaminated with a wide variety of contaminants. It was designed to be extremely flexible in terms of equipment and wash water additives used. It was not designed to be a commercial treatment unit.

Soil washing is a water-based ex situ process for mechanically scrubbing soils to remove undesirable contaminants. The process removes contaminants from soils by either dissolving or suspending them in the wash solution (which is later treated by conventional wastewater treatment methods) or by concentrating them into a smaller volume of soil through simple particle size separation techniques. The concept of reducing soil contamination through the use of particle size separation is based on the finding that most organic and inorganic contaminants tend to bind to fine-sized clay and silt particles primarily by physical processes **[l].** Washing processes that separate fine clay and silt particles from the coarser sand and gravel soil particles effectively separate and concentrate the contaminants into a smaller volume of soil that can be further treated. The clean larger fraction can be returned to the site for continued use. This set of assumptions forms the basis for the volume-reduction concept upon which the VRU has been developed.

The VRU is designed to decontaminate certain soil fractions using state-of-the-art washing equipment.

The total system consists of process equipment and support utility systems mounted on two heavy-duty tractor trailers. The design capacity of the VRU is 100 lbs/h. The basic VRU system consists of the following subsystems:

- **Soil** handling and conveying (grizzly)
- Soil washing and coarse screening trommel screen (miniwasher and vibrating screens)
- Fines/floatables gravity separation (CPI tank)
- Fines flocculation/water clarification and solids disposal (floc clarifier)
- Water treatment (filter, carbon drums, blowdown tank, and makeup water tank)
- Utilities (electric generator, steam boiler, water heater and air compressor)

The electric generator, air compressor, water heater, filters/carbon drums, water recycling pump, and blowdown tank are located on the utility trailer. All remaining equipment is located on the process trailer. Figure A-l is a diagram of the typical VRU operational setup. (The VRU setup at the Escambia Treating Company site demonstration was modified slightly from this typical setup.) The VRU system is controlled and monitored by conventional industrial process instrumentation and hardware including safety interlocks, alarms, and shutdown features.

During the demonstration, feed soil was taken from prepared test piles and manually processed through a ¼-inch screen. After screening, the demonstration was conducted in accordance with the standard VRU operating procedure, a description of which follows.

The screened soil is collected in a bucket for transfer to the feed surge bin, and oversized soil is returned to the site. From the feed surge bin, the soil less than ¼ inch is conveyed through a screw conveyor to the miniwasher. The conveyor flow is adjusted by a speed controller on the conveyor motor. The solids pass through a motor-operated rotary valve (which prevents air infiltration), and then into the feed hopper of the miniwasher.

Soil is fed to the miniwasher at a controlled rate of approximately 100 lbs/h by the screw conveyor. Filtered wash water is added to the soil in the feed hopper and also sprayed onto an internal slotted trommel screen [with a lo-mesh **(2-mm)** slot opening] miniwasher. Five manually controlled levers can adjust the flow up to an approximately I3 to 1 overall water-to-soil ratio. Two vibrating screens continuously segregate soil into various size fractions. The screens can be set at a variety of mesh sizes. For the demonstration, lo-mesh (2-mm) and l00-mesh (0.150-mm) screens were used.

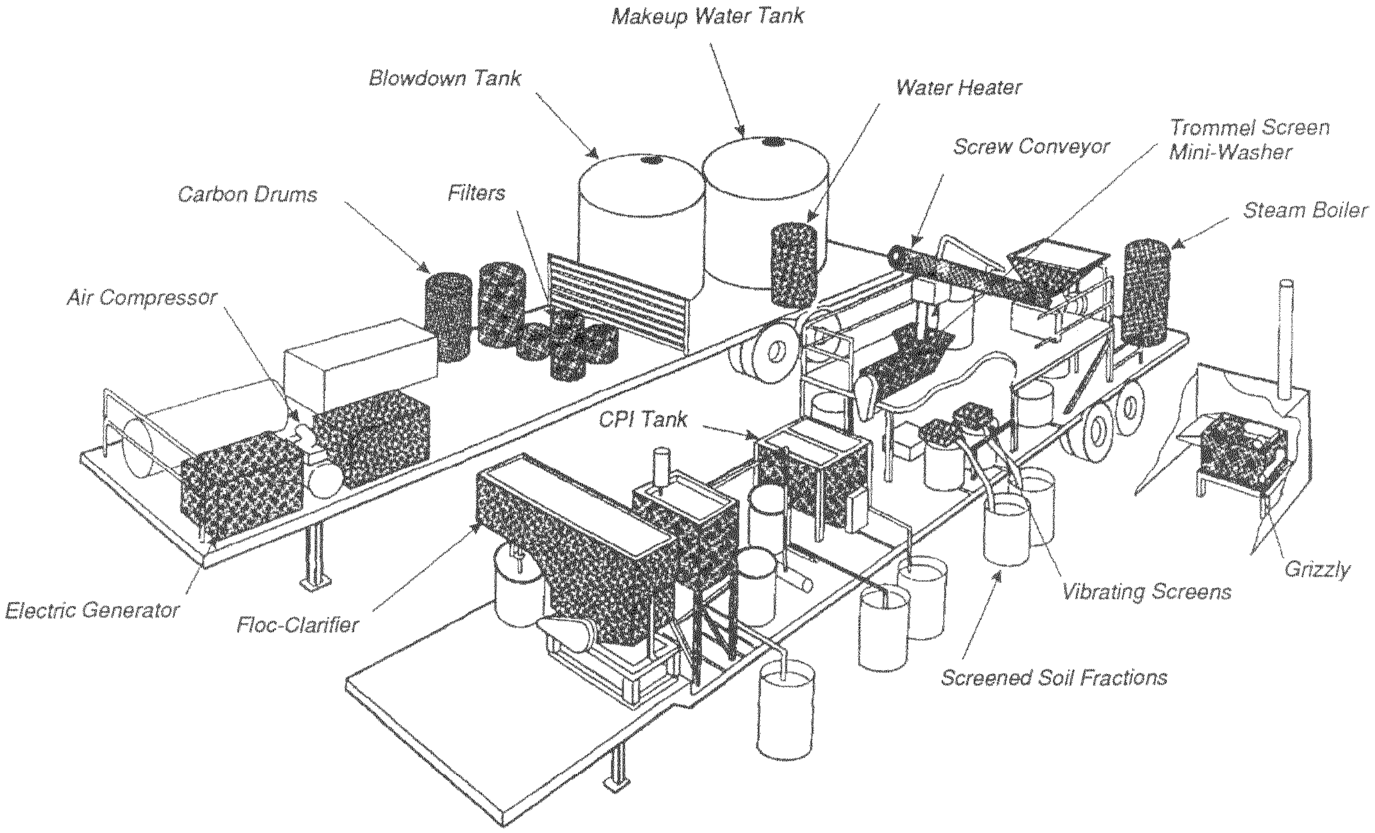

Figure A-1. Typical VRU Operational Setup.

Miniwasher overflow (the stream exiting the top of the washer), which contains the coarser solids, falls onto the first lo-mesh (2-mm) vibrascreen. The first vibrascreen overflow (less than ¼ inch, greater than lo-mesh) solids flow by gravity down to a recovery drum. The underflow (the stream exiting the bottom) is pumped at a controlled rate to the second lOO-mesh (O.l50-mm) vibrascreen where it is joined by the miniwasher underflow.

The overflow from the second vibrascreen [less than lo-mesh (2-mm), greater than lOO-mesh (O.l50-mm)] is gravity fed to the same recovery drum containing the other miniwashed coarse soil fraction. The second vibrascreen underflow (a fines slurry) drains into a tank with a mixer.

Slurry from the lOO-mesh (0.150-mm) screen (fines slurry) tank is pumped to the CPI. Materials lighter than water (floatables such as oil) flow over an internal weir, collect in a compartment within the CPI, and drain by gravity to a drum for disposal. CPI-settled solids [particles which will pass through a lOO-mesh (O.l50-mm) screen] are discharged by the bottom auger to a recovery drum.

An aqueous slurry, containing fines less than approximately 400 mesh (38 **μm),** overflows the CPI and gravity feeds into a tank with a mixer. The slurry is then pumped to a static mixer located upstream of the floe clarifier's mix tank. Flocculating chemicals, such as liquid alum and aqueous polyelectrolyte solutions, are metered into the static mixer tank to neutralize the repulsive electrostatic charges on colloidal particles (clay/humus) and promote coagulation. The slurry is then discharged into the floc chamber, which has a variable-speed agitator for controlled floe growth (sweep flocculation). Sweep flocculation refers to the adsorption of fine particles onto the floe (colloid capture) and continuing **floc** growth to promote rapid settling of the floe. The floe slurry overflows into the clarifier (another corrugated plate unit). Bottom solids are augured to a drum for disposal.

Clarified water is polished with the objective of reducing suspended solids and organics to low levels that permit recycling of spent wash water. Water is pumped from the floc settler overflow tank at a controlled rate through cartridge-type polishing filters operating in parallel in order to remove soil fines greater than 4 x 10^{-4} inch (10 **μm).** Water leaving the cartridge filter flows through activated carbon drums for removal of hydrocarbons. The carbon drums may be operated either in series or parallel. Hydrocarbon breakthrough is monitored by sampling, drums are replaced when breakthrough has been detected.

In order to recycle water and maintain suitable dissolved solids and organic levels, aqueous bleed (blowdown) to the boiler blowdown tank may be initiated at a controlled rate.

A.3 References

1. Ballard, R.B., B.J. Losack, and T.M. Murphy. Treatment of Hydrocarbon and Lead Contamination by Soil Washing at a Pipe Inspection Facility, Prudhoe Bay, Alaska. Presented at the 86th Annual Meeting of the Air & Waste Management Association, June 13-18, 1993.

Appendix B
Developer Claims

B.1 Introduction

The VRU is a mobile, pilot-scale soil washing system. It was designed to be a research platform to evaluate the effectiveness of soil washing as a technology to remove volatile organics, semivolatile organics and metals from soils, sludges, and sediments. Soil washing is a water-based process which extracts and concentrates the hazardous constituents into a smaller volume of soil and sludge using chemical extraction and physical separation methods.

The VRU is composed of two 40-foot trailers, a process trailer, and a utilities trailer. The unit has a flexible design to enable the formulation of wash fluids composed of different combinations of water, surfactants, caustic, acids, and chelating agents. In addition to soil washing and physical separation, there is an onboard steam generator and a jacketed screw conveyor to enable the evaluation and use of steam stripping or low temperature thermal desorption to remove volatile and semivolatile organics. The VRU also has a solids separation and water purification system to enable the treatment and recycling of the wash water and to evaluate the effectiveness of different water treatment chemicals (coagulants and flocculants) and equipment.

Several treatabiity studies have been performed in conjunction with EPA Regional staff and EPA's Environmental Response Team (ERT). The VRU has treated pentachlorophenol, creosotes, dioxin and furans at the Escambia Wood Treating Sites and herbicides and pesticides at the Sand Creek Superfund Site. These studies have been performed primarily to help the Remedial Project Managers (RPMs) and On-Scene Coordinators (OSCs) determine the feasibility of soil washing for their particular sites. The studies also enable RREL staff to evaluate the effect of varying process parameters such as the wash fluid temperature and pH, liquid-solid ratio, the system contact time, and screen mesh size were varied to evaluate their effect on the extraction efficiency of the system. Various wash formulations and surfactant concentrations have also been explored. Work at several other sites will be performed this year looking at contaminants such as diesel fuel, polychlorinated biphenyls (PCBs), and heavy metals.

The VRU is designed to easily accommodate the addition of other unit operations such as low temperature thermal systems, chemical extraction processes, electron beam oxidizers, and biotreatment units. Previous studies have evaluated these types of units for treating the effluent from the soil washing operation. RREL plans to publish the research and treatabiity findings so RPMs, OSCs, and project managers can make informed decisions about the effectiveness of soil washing technology on the particular sites.

B.2 SITE Demonstration Claims

During the spring of 1992, EPA's ERT performed site investigations at four wood treating facilities. These sites, located in the southeastern U.S., were contaminated with organic (creosote and pentachlorophenol) and inorganic (copper, chromium, and arsenic) wood preservative compounds. Bench-scale soil washing studies were performed on the soil from two of the sites. Aqueous biodegradable surfactants were tested for their abiity to increase the solubiity of PCP and creosote compounds, and 280 ppm carcinogenic creosote compounds showed removals of greater than 99 percent, 92 percent, and 95 percent after several washes with Tergitol NP-10 surfactant at elevated pH and temperature. Dioxin and furan levels were also reduced more than 91 percent.

Pilot studies using the VRU were performed in July 1992 by RREL and RBC at the Escambia Wood Treating Site in Pensacola, Florida. Representative soil was homogenized and washed under varying pH, temperature, and surfactant concentrations. Twenty runs were performed over a 2-week period. Concentration levels were reduced from an initial concentration of 150 ppm **PCP,** 75 ppm carcinogenic creosote, and 1,250 ppm total creosote to 1.7 ppm PCP, 3.5 ppm carcinogenic creosote, and 80 ppm total creosotes. Nondetectable levels (< 1 ppm, > 99 percent removal) were achieved for PCP and carcinogenic creosote after a clean water rinse was applied to the washed coarse samples. The total creosote residual was reduced to less than 32 ppm, greater than 97 percent removal.

Analysis indicated that only 1 weight percent of the feed soil was below 115 mesh (0.125 mm). Thus, the VRU used lOO-mesh (O.l50-mm) screens as the cut point. Theoretically, volume reductions of 97 to 98 percent could be achieved. Due to inefficiencies of the screening units, the unit achieved volume reductions of approximately 90 to 93 percent.

The SITE Demonstration also took place at the Escambia Site. Thus, the project claims and tests conditions were based on the results of the previous treatabiity studies. The specific claims and project objectives of this study are as follows:

- The VRU will separate the coarse gravel and sand (material which will not pass through a lOO-mesh screen) from the finer silt and clay particles. A volume reduction of at least 80 percent will be achieved.

- The coarse soils exiting the VRU **will** contain residuals of total creosote and pentachlorophenol contaminants at least 90 percent lower than the initial values found in the feed soil.

Appendix C

SITE Demonstration Results

C.1 Introduction

This appendix summarizes the results of the SJTE Demonstration Test of the VRU developed by EPA. These results are also discussed in Sections 1 and 3 of this report. A more detailed account of the demonstration may be found in the TER.

The ability of the VRU to reduce the concentration of organic contaminants in excavated soils was evaluated. Results from this demonstration include: percent reductions for PCP, percent reductions for PAHs; percent solids returned to the site as washed soil, and mass balances for total material, dry solids, PCP, and PAHs. VRU operating conditions were verified and the water treatment system effectiveness was assessed based on wash water quality before and after treatment by the VRU system.

PAH- and PCP-contaminated soil from the former Escambia Treating Company site in Pensacola, Florida was treated during the demonstration. Contaminant levels in the excavated soil from the site ranged from the low parts per million to percent levels. For the SITE demonstration, the excavated soil was homogenized and manually processed through a **¼-inch** screen before it was fed to the VRU.

Average contaminant concentrations in the feed soil on a dry weight basis are summarized in Table C-l. Five compounds from the standard set of creosote-fraction PAHs were not detected in the feed soil samples. These compounds [naphthalene, benzo(k)fluoranthene, ideno(l,2,3_cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene] were not included as PAHs for this evaluation.

Table C-l. Average Contaminant Concentrations in the Feed Soil (dry weight basis)

Contaminant	@pm)
PAHS	
Acenaphthylene	3
Acenaphthene	120
Fluorene	130
Phenanthrene	330
Anthracene	59
Fluoranthene	180
Pyrene	110
Benzo(a)anthracene	29
Chrysene	27
Benzo(b)fluoranthene	12
Benzo(a)pyrene	8
PCP	140

C.2 Operating Conditions

The target operating conditions were specified in the Demonstration Plan [l]. Three runs, each 4 hours in duration, were performed for each of Conditions 1 and 2. Two **runs,** each 6 hours in duration, were performed under Condition 3. Sampling was conducted in accordance with the procedures outlined in the Demonstration Plan [l]. Surfactant concentration, and wash water and temperatures were monitored to determine whether the VRU was functioning at the specified operating conditions.

The surfactant concentration was determined by calculating the ratio of surfactant-to-wash water on a mass basis. The pH was determined by measuring the pH of the fines slurry stream. The temperature was determined by measuring the temperature of the wash water just before it entered the soil washing segment of the VRU. Table C-2 lists the operating conditions experienced during the demonstration.

By adding surfactant and increasing the pH and temperature of the wash water, contaminant removal efficiencies can be improved significantly. Water is a polar substance while the contaminants, PCP and PAHs (and other organic contaminants) are nonpolar. Because polar substances do not dissolve nonpolar substances well, the addition of a nonpolar surfactant to the wash water can improve organic contaminant removal significantly. Adjusting the pH and temperature of the wash water can also increase contaminant solubilities and improve removal efficiencies.

The conditions established for this demonstration were based on earlier treatabilty studies conducted by EPA at the Escambia Treating Company site. During these studies, PCP and PAH removal efficiencies under varying operating parameters (surfactant addition, pH and temperature increases) ranged from 92.6 to 98.9 percent and 85.2 to 97.1 percent, respectively.

The surfactant used during the demonstration was Tergitol. In bench-scale tests conducted by EPA prior to the demonstration, several surfactants were evaluated on the Escambia soils. Tergitol was considered to be the most effective in removing contaminants from the soil samples and was therefore selected for use in the demonstration.

C.3 Contaminant Removal

Table C-3 lists the contaminant concentrations and contaminant removal efficiencies obtained during the demonstration. Contaminant removal efficiencies were determined by comparing (on a dry weight basis) the mass of the contaminant in the feed soil with the mass of the contaminant in the washed soil. Removal efficiencies are calculated using the following equation:

$$\%\ removal = \left[\frac{\text{Concentration of contaminant in feed} - \text{concentration of contaminant in washed soil}}{\text{concentration of contaminant in feed}}\right] \times 100$$

Table C-2. VRU SITE Demonstration Operating Conditions

	Feed Rate (lb/h)	W/F Ratio	Surfactant Flow (lb/h)	pH	Surfactant Concentration in Wash Water (%)	Water Temperature (°F)
Condition 1						
Run 1	93	7	0	7.3	–	60
Run 2	64	10	0	7.2	–	56
Run 3	95	7	0	7.1	–	55
Condition 2						
Run 1	97	6	13.4	7.0	0.22	59
Run 2	106	6	13.7	6.9	0.22	60
Run 3	108	6	14.1	6.9	0.22	65
Condition 3						
Run 1	117	5	11.0	10.2	0.17	145
Run 2	148	4	11.7	10.1	0.18	139

Table C-3. Removal Efficiencies for PCP and PAHS (dry weight basis)

Parameter	PCP Feed Soil (ppm)	PCP Washed Soil (ppm)	PCP % Reduction	PAHS Feed Soil (ppm)	PAHS Washed Soil (ppm)	PAHS % Reduction
Condition 1						
Run 1	IS0	28	81	1,000	240	77
Run 2	170	36	78	1,200	310	74
Run 3	140	43	69	860	350	59
Range	130-180	21-52		770-1,500	200-520	
Condition 2						
Run 1	170	15	91	1,000	180	83
Run 2	180	13	93	1,000	160	84
Run 3	160	14	91	830	130	84
Range	150-210	8-19		900-1,200	120-220	
Condition 3						
Run 1	100	2.4	98	1,100	44	96
Run 2	110	3.5	97	960	46	95
Range	48-190	2-5		550-1,700	29-65	

PCP removal efficiencies were calculated for Conditions 1, 2, and 3. Under Condition 3, which employed surfactant addition and pH and temperature adjustment, the average PCP removal efficiency was 97 percent. Under Condition 2, which employed surfactant addition only, the average PCP removal efficiency was 92 percent. These removal efficiencies achieve the project objective of demonstrating that the unit is capable of removing 90 percent of the PCP from the bulk of the feed soil. The average PCP removal efficiency for Condition 1 was only 76 percent. These data illustrate the impact of surfactant addition and pH adjustment on PCP removal effkiencies. PCP removal efficiency is clearly surfactant-dependent and also appears to be slightly pH- and temperature-dependent.

PAH removal effkiencies were calculated for Conditions 1, 2, and 3. Under Condition 3, which employed surfactant addition and pH adjustment, the average PAH removal efficiency was 95 percent. This removal efficiency achieves the project objective of demonstrating that the unit is capable of removing 90 percent of the PAHs from the bulk of the feed soil. The average PAH removal effkiencies for Conditions 1 and 2 were only 70 percent and 83 percent, respectively. These results illustrate the impact of surfactant addition and pH and temperature adjustment on PAH removal efficiencies.

C.4 Washed Soils Recovery

The VRU system is designed to separate the sand and gravel fraction of the soil from the contaminated fines (i.e., fine clay and silt particles). The larger sand and gravel fraction exits the system as washed soil. By comparing the mass of dry solids in the feed soil with the mass of dry solids in the washed soil, solids recoveries of 95, 95, and 82 percent were calculated for soils treated under Conditions 1 through 3. These recoveries were also calculated on a normalized basis, yielding normalized recoveries of 90, 88, and 86 percent for Conditions 1, 2, and 3. These recoveries, shown in Table C-4, achieve the project objective of demonstrating that at least 80 percent of the solids present in the feed soil would be returned to the site as washed soil.

Table C-4. Feed Soil Recovered as Washed Soil (dry weight basis)

	Feed Soil (lb/h)	Washed Soil (lb/h)	Fines Slurry (lb/h)	% Recovery	% Recovery Normalized Basis
Condition 1					
Run 1	86	73	9	85	90
Run 2	62	71	9	114	89
Run 3	90	79	9	86	90
Average	--	--	--	95	90
Condition 2					
Run 1	90	90	9	97	90
Run 2	101	104	13	103	89
Run 3	104	88	15	86	85
Average	--	--	--	95	88
Condition 3					
Run 1	101	95	13	94	87
Run 2	132	90	15	69	85
Average	--	--	--	82	86

C.5 Mass Balances

Mass balances were performed to assess material and contaminant fate as well as system efficiency. Mass balances were conducted for total materials, dry solids, PCP, and PAHs. These balances were obtained by comparing the mass of a given substance entering the system (in all input streams) with the mass of that substance exiting the system (in all output streams). Mass balance closure (or recovery) is calculated as follows:

$$\text{Mass Balance Closure} = \left[\frac{\text{Mass Exiting System}}{\text{Mass Entering System}}\right] x\ 100$$

C.5.1 Total Material

The total mass of all **material** (feed soil and washwater) entering the VRU was compared to the total mass of all material (cleaned soil and fines slurry) exiting the system. The mass balances for the total material are presented in Table C-5. Closures of 104, ll3, and 98 percent were obtained during Conditions 1, 2, and 3, respectively.

During Condition 2, it was noted the mass flow rate measurement of the fines slurry may have been affected by sampling procedures employed during the demonstration. This resulted in inflated mass flow rates. The procedure was modified and the percent closures dropped to the acceptable range. Except for this inflated closure of 113 percent for Condition 2, average closures for total material balances met the project objectives of 90 **to 110 percent.**

C.5.2 Dry Solids

Dry solids mass balances were calculated by comparing the total dry weight of the solids entering soil washer per hour as feed soil with the total dry weight of the solids exiting the soil washer as washed soil and slurry fines. Except for Run 2 of Condition **1,** Run 2 of Condition 2, and Run 2 of Condition 3, the closures obtained during the demonstration are consistent with project objectives specifying closures of between 85 and **115** percent for solids treated within the soil washing portion of the system. Even though closures for individual runs were outside of the specified *range, the* average closures for Conditions 1, 2, and 3 met project objectives. The mass balances for dry solids are presented in Table C-6.

Table C-5. Total Material Mass Balance

	Inputs		Outputs		
	Feed Soil (lb/h)	Wash Water (lb/h)	Washed Soil (lb/h)	Fines Slurry (lb/h)	% Closure
Condition 1					
Run 1	93	692	88	697	100
Run 2	64	662	88	699	108
Run 3	95	626	95	666	105
Average	–	–	–	–	104
Condition 2					
Run 1	97	593	110	677	112
Run 2	116	587	130	688	116
Run 3	108	604	108	697	111
Average	–	–	–	–	113
Condition 3					
Run 1	117	622	121	644	101
Run 2	148	635	112	653	95
Average	–	–	–	–	98

Table C-6. Dry Solids Mass Balances

	Solid Inputs	Solid Outputs		
	Feed Soil (lb/h)	Washed Soil (lb/h)	Fines Slurry (lb/h)	% Closure
Condition 1				
Run 1	86	73	9	94
Run 2	62	71	9	128
Run 3	90	79	9	96
Average	–	–	–	106
Condition 2				
Run 1	93	90	9	108
Run 2	101	104	13	116
Run 3	104	88	15	101
Average	–	–	–	108
Condition 3				
Run 1	101	95	12	108
Run 2	132	88	15	80
Average	–	–	–	94

C.5.3 PCP

At Condition 1, the average mass balance closure for PCP was 101 percent, which meets the project objective of PCP mass balance closures between 80 and 175 percent. The average PCP closures for Conditions 2 and 3 were below 80 percent, and therefore did not meet the project objective.

Average PCP closures for Conditions 2 and 3 were 19 percent and 13 percent, respectively. Because the low PCP closures were experienced when surfactant was added to the wash water, it seems probable that the surfactant interfered with the PCP analyses. The PCP mass balances are presented in Table C-7.

C.5.4 PAHS

Like PCP, the majority of PAHs entering the VRU within the feed soil exited in the slurry fines. At Condition 1, the average mass balance closure for PAHs was 87 percent, which meets the project objective of PAH mass balance closures between 80 and 175 percent. The average PAH closures for Conditions 2 and 3 were below 80 percent, and therefore did not meet the project objective. Average PAH closures for Conditions 2 and 3 were 28 percent and 13 percent, respectively. Like PCP the low PAH closures were experienced when surfactant was added to the wash water, and it seems probable that the surfactant interfered with the PAH analyses. The PAH mass balances are presented in Table C-8.

Table C-7. PCP Mass Balance

	PCP Inputs	PCP Outputs		
	Feed Soil (lb/h)	Washed Soil (lb/h)	Fines Slurry (lb/h)	% Closure
Condition 1				
Run 1	13	2.0	9.0	85
Run 2	10	2.6	8.4	105
Run 3	12	3.3	10.0	113
Average	--	--	--	101
Condition 2				
Run 1	13	1.5	1.3	22
Run 2	19	1.4	2.1	18
Run 3	16	1.3	1.4	17
Average	--			19
Condition 3				
Run 1	10	0.54	1.3	15
Run 2	15	0.31	1.3	11
Average	--	--	--	13

Table C-8. PAH Mass Balance

	PAH Inputs	PAH outputs		
	Feed Soil (lb/h)	Washed Soil (lb/h)	Fines Slurry (lb/h)	% Closure
Condition 1				
Run 1	86	17	55	82
Run 2	77	22	51	95
Run 3	77	26	37	85
Average				87
Condition 2				
Run 1	82	17	8.8	31
Run 2	104	18	9.7	27
Run 3	88	12	9.7	25
Average				28
Condition 3				
Run 1	108	4.6	7.7	11
Run 2	130	4.2	16	15
Average				13

C.6 Particle Size and Fines Distribution

A number of steps were employed to control the size of the various streams entering and exiting the soil washing portion of the VRU system. The feed soil was screened so that only particles less than ¼ inch in size entered the unit. The washed soil was composed of particulate matter that would not pass through a lOO-mesh (O.l50-mm) screen while the fines slurry contained particles that would pass through a lOO-mesh (O.l50-mm) screen. Particle size distribution data for the feed, washed soil, and fines slurry are presented in Table C-9.

The underflows from the CPI and flocculation tank were also analyzed for particle size distribution characteristics. The underflow from the CPI should primarily contain particles which will pass through a lOO-mesh (0.150-mm) screen but will not pass through a 200-mesh (0.075mm) screen; the underflow from the flocculation tank should primarily contain particles which will pass through a 200-mesh screen. Particle size distribution data for the underflow streams from the CPI and the flocculation tank are presented in Table C-10.

The VRU's effectiveness is based on its ability to separate soil fines that will pass through a lOO-mesh (O.l50-mm) screen from the coarser gravel/sand fraction of the soil, which will not pass through a NM-mesh (0.150-mm) screen. Dry solids mass balance data defining the disposition of the fines and the gravel/sand portion of the feed can be found in Tables C-11 and C-12, respectively. Excellent results for partitioning the coarser sand/gravel fraction to the washed soil were achieved. Approximately 1 to 2 percent of these particles were detected in the fines slurry. While a majority of the soil fines partitioned into fines slurry, the partitioning was less complete. As shown in Table C-11,31 to 54 percent of the soil fines recovered in the output stream were located in the washed soils. A more complete partitioning of the soil fmes to the fines slurry would, theoretically, lead to increased contaminant removals from the washed soils.

C.7 Water Treatment Effectiveness

The fines slurry stream was stripped of pollutants by utilizing a settling, flocculation, filtration, and carbon adsorption treatment sequence. The solids in the CPI and floc clarifier were analyzed for PCPs and PAHs. The results are presented in Tables C-13 and C-14.

Wash water into the VRU and the clarified water were analyzed for TOC and TR, which is the sum of TSS and TDS. The results of these analyses are summarized in Tables C-15 and C-16.

Table C-9. Particle Size Distribution within the Feed Soil, Washed Soil, and Fines Slurry (% Finer)

	10 mesh (2,000 μm)	50 mesh (300 μm)	100 mesh (150 μm)	200 mesh (74 μm)	250 mesh (63 μm)	400 mesh (38 μm)	4 x 10^{-4} inch (10 μm)	2 x 10^{-4} inch (5 μm)
Feed Soil								
Condition 1								
Average	99	28	14	10.0	8.3	6.5	6.2	5.7
Range	99.1 - 100.0	23.1 - 31.2	12.0 - 17.2	8.6 - 13.6	7.4 - 9.8	5.9 - 7.2	5.7 - 6.7	5.2 - 6.1
Condition 2								
Average	99	25	12	9.0	7.6	5.9	5.7	5.4
Range	98.8 - 100.0	20.4 - 30.8	10.4 - 17.8	7.9 - 14.2	6.6 - 10.2	4.5 - 8.3	4.4 - 7.4	4.4 - 6.6
Condition 3								
Average	99	17	9.7	7.5	6.5	5.6	5.4	5.0
Range	98.1 - 100.0	13.3 - 20.5	8.9 - 10.9	6.8 - 8.6	5.9 - 7.1	4.8 - 6.9	4.8 - 6.4	3.8 - 5.9
Washed Soil								
Condition 1								
Average	100	18	4.6	3.1	2.0	1.1	0.9	0.8
Range	99.4 - 99.9	10.7 - 24.5	1.9 - 16.3	0.9 - 15.9	1.0 - 7.7	0.7 - 1.6	0.7 - 1.4	0.5 - 1.4
Condition 2								
Average	100	17	5.2	3.1	2.1	0.8	0.6	0.6
Range	99.3 - 99.9	13.2 - 25.6	1.9 - 16.7	0.6 - 15.8	1.0 - 7.6	0.3 - 1.9	0.3 - 1.1	0.1 - 1.0
Condition 3								
Average	98	15	6.5	6.0	3.1	0.5	0.3	0.3
Range	95.5 - 99.6	7.4 - 54.8	0.8 - 47.3	0.3 - 46.9	0.3 - 21.3	0.0 - 1.3	0.0 - 0.8	0.0 - 0.8
Fines Slurry								
Condition 1								
Average	100	100	91	63	59	52	46	40
Range	100.0 - 100.0	96.8 - 99.9	65.6 - 99.1	47.4 - 89.4	37.7 - 70.4	26.8 - 66.7	9.8 - 61.0	3.9 - 56.6
Condition 2								
Average	100	99	84	68	65	60	54	51
Range	100.0 - 100.0	98.2 - 100.0	54.6 - 99.2	33.7 - 94.5	31.1 - 94.9	25.3 - 95.4	21.9 - 82.8	21.0 - 79.8
Condition 3								
Average	100	99	88	66	64	60	56	50
Range	100.0 - 100.0	94.8 - 99.9	64.3 - 98.7	39.2 - 90.8	33.1 - 90.8	23.6 - 90.8	19.2 - 87.2	14.3 - 87.2

Table C-10. Particle Size Distribution within the Underflow from the CPI and Floc Tank (% Finer)

	10 mesh (2,000 μm)	50 mesh (300 μm)	100 mesh (150 μm)	200 mesh (74 μm)	250 mesh (63 μm)	400 mesh (38 μm)	4 x 10^{-4} inch (10 μm)	2 x 10^{-4} inch (5 μm)
CPI Underflow								
Condition 1								
Average	100	100	91	76	73	67	59	56
Range	100.0 - 100.0	98.7 - 100.0	79.7 - 95.1	55.6 - 88.3	51.2 - 87.0	42.6 - 84.1	30.6 - 80.6	27.6 - 78.1
Condition 2								
Average	100	100	99	96	95	94	88	81
Range	100.0 - 100.0	98.9 - 100.0	95.4 - 99.9	92.0 - 98.2	90.0 - 98.3	85.3 - 98.6	76.9 - 96.6	74.8 - 90.2
Condition 3								
Average	100	100	99	84	80	75	69	66
Range	100.0 - 100.0	99.8 - 100.0	97.7 - 99.3	78.1 - 90.7	72.3 - 88.7	62.1 - 87.9	58.5 - 80.8	51.1 - 77.3
Floc Tank Underflow								
Condition 1								
Average	100	75	69	65	64	60	50	38
Range	100.0 - 100.0	43.7 - 91.8	39.4 - 91.2	36.9 - 90.9	35.2 - 90.2	32.6 - 88.6	24.5 - 82.7	24.5 - 70.6
Condition 2								
Average	100	100	100	99	98	94	89	60
Range	100.0 - 100.0	99.4 - 100.0	99.1 - 100.0	98.8 - 99.7	93.9 - 99.6	78.6 - 99.1	70.1 - 98.5	34.7 - 95.5
Condition 3								
Average	100	91	84	80	77	67	56	49
Range	100.0 - 100.0	85.4 - 93.7	70.0 - 88.9	65.6 - 86.4	64.1 - 81.8	56.8 - 71.4	45.2 - 62.9	34.7 - 58.2

Table C-11. Disposition of Pines (dry weight basis)

	Feed Soil	Washed Soil		Fines Slurry		
	Flow Rate lb/h	Flow Rate lb/h	Recovered %	FIow Rate lb/h	Recovered %	Total % Recovered
Condition 1	11	3.4	31	8.2	75	106
Condition 2	12	4.9	41	10	83	124
Condition 3	11	5.9	54	12	110	164

Table C-12. Disposition of Coarse Gravel and Sand (dry weight basis)

	Feed Soil	Washed Soil		Fines Slurry		
	Flow Rate lb/h	Flow Rate lb/h	Recovered %	Flow Rate lb/h	Recovered %	Total % Recovered
Condition 1	68	71	104	1	1	105
Condition 2	87	89	102	2	2	104
Condition 3	10.5	86	82	2	2	84

Table C-13. Range of PCP Concentrations in Fines Slurry Solids (ppm)

	CPI Undertlow	Floc/Clarifier
Condition 1	51 - 69	92-6,500
Condition 2	46-85	190 - 1,300
Condition 3	•	83-150

• Unacceptable analysis resulted in questionable data.

Table C-14. PAH Concentration in Pines slurry Solids (ppm)

	CPI Underflow	Floc/Clarifier
Condition 1	1,300 - 1,800	58 - 2,000
Condition 2	370 - 1,100	910 - 1,800
Condition 3	•	94O-1,200

• Unacceptable analysis resulted in questionable data.

Table C-15. TOC Levels in Water streams (ppm)

	Wash Water	Floc-tank Overflow*	Filter Effluent*	Activated Carbon Effluent*
Condition 1	c 1.0	115	11	c 1.0
Condition 2	<1.5	1,045	1,075	283
Condition 3	< 1.02	825	697.5	305

* These streams were sampled on the last run of each condition only. Tbis was done to allow effluent water from previous conditions to drain from the system.

Table C-16. TR Levels in Water Streams @pm)

	Wash Water	Floc-tank Overflow	Filter Effluent*	Activated Carbon Effluent*
Condition 1	70	260	2475	115
Condition 2	73	2,200	2,025	557.5
Condition 3	62	6,075	5,075	255O

* These streams were sampled on the last run of each condition only to allow effluent water from previous conditions to drain from the system.

Prior to the demonstration the developer stated that the effluent after treatment is of sufficient quality to be recycled into the water tank for reuse as wash water. This option was not evaluated during the demonstration, as the developer chose to operate the VRU without recycling. Furthermore, because water quality criteria for recycling have not been defined, it is not possible to determine whether the treated water produced during the demonstration was appropriate for recycling. During Condition 1, the levels of both TOC and TR were considered low enough to permit recycling; however, much higher levels were detected in Conditions 2 and 3. Additional treatment may have been necessary to recycle the effluent from carbon canisters during these conditions.

The developer indicated that the CPI/floc-clarifier did not settle out as much as expected, allowing more solids and TOC to pass through the filters and carbon. The developer also stated that during Run 8, solids overflowed the clarifier tank. This indicated that the water treatment system was not operated in the most efficient manner during the demonstration.

The TR reduction from the filter unit was minimal, which indicates that a smaller filter is needed. The TOC reduction decreased significantly when surfactant was introduced into the system during Conditions 2 and 3. The efficiency was affected because the surfactant was being adsorbed on the carbon along with the contaminants. TOC effkiency could be improved by removing the surfactant before it enters the carbon canisters or by utilizing another TOC removal technology.

TOC and TR are considered important parameters for determining whether the treated water is appropriate for reuse as wash water. It is believed that excessive organic carbon in the wash water would tie up the surfactant and decrease the contaminant removal effkiency of the process. Excessive solids may have a similar impact or may adversely affect the process in other ways (by plugging water lines, etc.). The levels at which TOC or TR concentrations become excessive were not determined during the demonstration. The TOC and TR levels measured in the feed water used during the demonstration, however, were significantly lower than the levels measured in the effluent from the wastewater treatment system.

If the treated water cannot be reused as wash water, then it must be disposed. Disposal options may include discharge to a local POTW. Discharge to a POTW will typically be regulated according to the industrial wastewater pretreatment standards of the POTW. These standards are specified in the CFR for certain industries. Depending on the site, the treated wash water may fall into one of the specific industrial categories. If it does not, the pretreatment standards for the wash water will be determined by the POTW and depend on site-specific parameters such as the flow rate of the wash water, the contaminants present, and the design of the POTW.

C.8 References

1. **Demonstration Plan for USEPA RREL's Mobile Volume Reduction Unit. Prepared by Science Applications International Corporation.**

Appendix D

Case Studies

D.l Bench- and Pilot-Scale Treatment of Soil from a Wood Treating Facility

Bench-scale experimental studies were performed on contaminated soil samples from wood treating facilities to determine if soil washing was capable of removing creosote and PCP from a soil matrix and collecting them in a water matrix.

The effectiveness of the study was based on soil cleanup criteria set by EPA of 30 ppm PCP, 50 ppm carcinogenic creosote compounds, and 100 ppm total creosote compounds. Water-based biodegradable surfactants were tested for their ability to increase the solubiition of PCP and creosote compounds in water. Effects of elevated temperature and pH were also tested.

The bench-scale studies were performed on soil with initial contamination levels of approximately 420 ppm PCP; 4,200 ppm total creosote compounds, and 280 ppm carcinogenic creosote compounds. During these studies, the soil was subjected to three washes with Tergitol NP-100 surfactant at elevated pH and temperature. These studies achieved PCP, total creosote, and carcinogenic creosote removals of greater than 99, 92, and 95 percent, respectively. Dioxin and furan levels were also reduced more than 91 percent.

Due to the favorable results of the bench-scale studies, a pilot-scale study was performed to test the applicability of soil washing further. Representative soil samples were washed at various pHs, temperatures, and surfactant concentrations a VRU soil washer. Twenty runs were performed over a 2-week period. Under the best conditions, PCP concentrations were reduced from 120 ppm to less than 1 ppm (greater than 99.1 percent removal), total creosote concentrations were reduced from 2280 ppm to 2 ppm (greater than 99.9 percent removal), and carcinogenic creosote concentrations were reduced from 103 ppm to less than 1 ppm (greater than 99.0 percent removal). Cleanup criteria for PCP and carcinogenic ***creosote*** compounds ***were*** met during all pilot-scale runs; cleanup criteria for total creosote compounds were met during all but 1 of the 20 pilot-scale runs.

D.2 Pilot-Scale Treatment of Pesticide-Contaminated Soil

The VRU was used to perform a pilot-scale study to evaluate the abilty of soil washing to remediate soils primarily contaminated with organochlorine pesticides (e.g., dieldrin, heptachlor, chlordane, **4,4'-DDT),** herbicide (2,4-D), and metals (chromium and arsenic). The Record of Decision set cleanup levels of 0.155 ppm dieldrin and 0.553 ppm heptachlor.

The pilot-scale study included 23 runs conducted under varied conditions. Test variables included surfactant type, surfactant concentration, pH, temperature, liquid-to-soil ratio, soil type, and number of washes. The concentrations of heptachlor and dieldrin in the feed soil also varied widely. The results of this pilot-scale study are summarized in Tables D-l and D-2. Based on these results, it is not possible to determine conclusively whether soil washing is capable of meeting the cleanup levels. Achieving cleanup levels may require a multistage washing process that is more efficient than the single-stage VRU.

Table D-l. **Heptachlor** Results

	Minimum	Maximum	Average
Heptachlor concentration in feed, ppm	8	460	159
Heptachlor concentration in coarse treated solids, ppm	1.4	50	22
Heptachlor concentration in fine treated solids, ppm	4.4	340	88
Removal of heptachlor from feed to coarse treated solids, %	17	99	79
Removal of heptachlor from feed to fine treated solids, %	-107	97	34

Table D-Z. Dieldrin Results

	Minimum	Maximum	Averagc
Dieldrin concentration in feed, ppm	2.7	27	16
Dieldrin concentration in coarse treated solids, ppm	**1.5**[a]	6.8	3
Dieldrin concentration in fine treated solids, ppm	**0.93**[b]	37	11
Removal of dieldrin from feed to coarse treated solids, %	**-44**	91	71
Removal of dieldrin from feed to fine treated solids, %	-131	86	34

The coarse treated solids from two other runs had dieldrin concentrations below the detection limit of 1.6 ppm.
The fine treated solids from one other run had a dieldrin concentration below the detection limit of 1.6 ppm.