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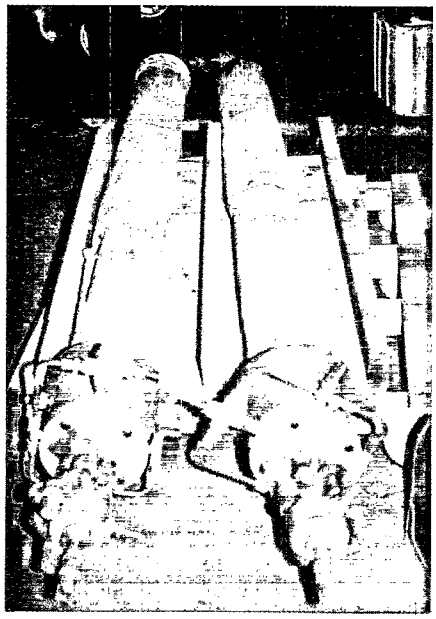
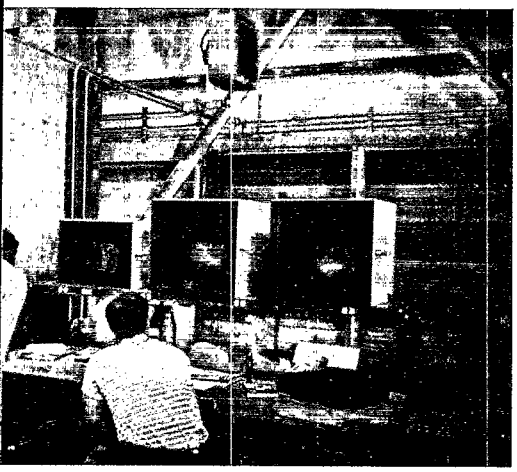
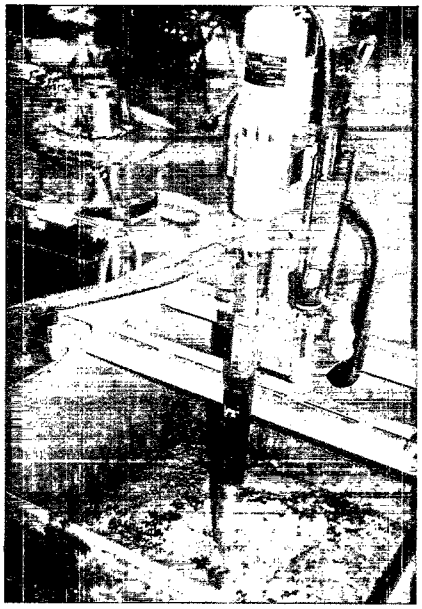
Retech, Inc., Plasma Centrifugal Furnace

Applications Analysis Report







SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

EPA/540/A5-91/007
June 1992

Retech, Inc., Plasma Centrifugal Furnace

Applications Analysis Report

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

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Notice

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Foreword

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

This project consistss of an analysis of the Retech, Inc. Plasma Centrifugal Furnace. A series of Demonstration Tests took place at the Department of Energy's Component Development and Integration Facility located in Butte, MT. The demonstration effort was directed at obtaining information on the performance and cost of the process in order to assess the potential applications at other hazardous waste sites. The Technology Evaluation Report describes the field activities and laboratory results from the Demonstration Tests. This Applications Analysis Report provides an interpretation of the available data, an economic analysis, and a discussion of the potential applicability of the technology.

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

E. Timothy Oppelt, Director

Risk Reduction Engineering Laboratory

Abstract

This document is an evaluation of the performance of the Retech, Inc. Plasma Centrifugal Furnace (PCF) and its applicability as a treatment for soils contaminated with organic and/or inorganic compounds. Both the technical and economic aspects of the technology were examined.

A demonstration of the Retech furnace was conducted under the SITE Program at the Department of Energy's Component Development and Integration Facility in Butte, MT. Operational data, along with sampling and analysis information, were carefully compiled to establish a data b ase against which other available data, as well as the vendor's claims for the technology, have been compared and evaluated. Conclusions concerning the technology's suitability for use in immobilizing contaminants in the feed soil were reached, and extrapolations regarding applications at other sites with different contaminants and soil types were made.

The following were derived mainly from the results of the Demonstration Tests and supported by other available data: (1) the treated soil did not leach any RCRA metals at levels above the regulatory limits; (2) the process achieved a Destruction and Removal Efficiency (DRE) of greater than 99.99% for the Principal Organic Hazardous Constituent (POHC), hexachlorobenzene; (3) the air pollution control system did not reduce the level of particulate emissions to below the RCRA limit; (4) a high percentage of the metals fed to the furnace are encapsulated in the treated soil; (5) the PCF is advantageous over conventional incineration technologies in that it can successfully immobilize heavy metals in the slag. However, this treatment option can be comparatively more expensive.

Contents

Foreword iii
Abstract iv
Figures vii
Tables viii
Abbreviations and Symbols ix
Acknowledgments xi

1. Executive Summary 1
   1.1 Introduction 1
   1.2 Conclusions 1
   1.3 Results 1

2. Introduction 3
   2.1 The SITE Program 3
   2.2 SITE Program Reports 3
   2.3 Key Contacts 4

3. Technology Applications Analysis 5
   3.1 Introduction 5
   3.2 Conclusions 5
   3.3 Technology Evaluation 6
      3.3.1 Toxicity Characteristic Leaching Procedure 6
      3.3.2 Destruction and Removal Efficiency 7
      3.3.3 Acid Gas Removal and Particulate Emissions 7
      3.3.4 Air Emissions 8
      3.3.5 Test Soil and Treated Slag 9
      3.3.6 Scrubber Liquor 11
      3.3.7 Continuous Emission Monitors 11
      3.3.8 Furnace Operation 11
   3.4 Ranges of Site Characteristics Suitable for the Technology 12
      3.4.1 Site Selection 12
      3.4.2 Surface, Subsurface, and Clearance Requirements 12
      3.4.3 Topographical Characteristics 12
      3.4.4 Site Area Requirements 12
      3.4.5 Climate Characteristics 12
      3.4.6 Geological Characteristics 12
      3.4.7 Utility Requirements 13
      3.4.8 Size of Operation 13
   3.5 Applicable Wastes 13
   3.6 Regulatory Requirements 14
      3.6.1 Federal EPA Regulatioons 14
      3.6.2 State and Local Regulations 15
   3.7 Personnel Issues 15
      3.7.1 Operator Training 15
      3.7.2 Health and Safety 16
      3.7.3 Emergency Response 16
   3.8 Summary 16
4. Economic Analysis 17

4.1 Introduction 17
4.2 Results of Economic Analysis 19
4.3 Basis for Economic Analysis 19
4.3.1 Site and Facility Preparation Costs 19
4.3.2 Permitting and Regulatory Costs 20
4.3.3 Equipment Costs 20
4.3.4 Startup and Fixed Costs 22
4.3.5 Labor Costs 22
4.3.6 Supplies Costs 22
4.3.7 Consumables Costs 22
4.3.8 Effluent Treatment and Disposal Costs 23
4.3.9 Residuals and Waste Shipping, Handling and Transport Costs 23
4.3.10 Analytical Costs 23
4.3.11 Facility Modification, Repair and Replacement Costs 23
4.3.12 Site Restoration Costs 24
4.4 Future Development of a Transportable PCF 24
References 24
Appendix A - Process Description 25
A.1 Introduction 25
A.2 The Thermal Treatment System 25
A.3 Exhaust Gas Treatment System 26
Appendix B - Vendor's Claims 27
B.1 Treatment Effectiveness 27
B.2 Community Acceptance 28
B.3 Comparative Economics 28
B.3.1 Effects of Scale 28
B.3.2 Treatment Costs with the PCF-8 28
B.3.3 Costs for Hazardous Landfill 29
B.3.4 Costs for Shredding Plus Kiln Burning Plus Ash Stabilization 29
B.3.5 Summary Statement 29
Appendix C. - SITE Demonstration Results 31
C.1 Toxicity Charactistic Leaching Procedure 31
C.2 Destruction and Removal Efficiency 31
C.3 Acid Gas Removal and Particulate Emissions 32
C.4 Air Emissions 32
C.5 Test Soil and Treated Slag 33
C.6 Scrubber Liquor 33
C.7 Continuous Emission Monitoring 34
Appendix D. - Case Studies 35
D.1 Preliminary Testing 35
D.1.1 Description 35
D.1.2 Testing Protocol 35
D.1.3 Major Conclusions Based on Preliminary Testing 35
D.1.4 Data Summary 36
D.2 MSE Plasma Arc Furnace Equipment
D.2.1 Description 36
D.2.2 Testing Protocol 37
D.2.3 Major Conclusions Based on PAFE ACTs 37
D.2.4 Data Summary 37
D.3 Plasmox® Waste Treatment Facility 37
D.3.1 Description 37
D.3.2 Testing Protocol 39
D.3.3 Major Conclusions Based on Plasmox® Waste Treatment Facility 39
D.3.4 Data Summary 39
References for Appendices 39

Figures

1 Summary of Cost Breakdown for 12 Cost Categories 21

2 Summary of Overall Treatment Costs of a PCF-6 and PCF-8 21

A-1 Schematic of the Plasma Centrifugal Furnace 25

D-1 Typical THC Plot During ACTs 38

D-2 Typical CO Plot During ACTs 38

Tables

1. TCLP Results for Demonstration Tests 7
2. DRE Results for Demonstration Tests 9
3. Particulate Results for Demonstration Tests 9
4. Metals in the Feed Soil and Treated Soil 10
5. Estimated Costs in $/Ton of the PCF-6 18
6. Summary of Estimated Costs in $/Ton for Various Feed Rates and On-line Operating Conditions 18
7. Summary of Estimated Labor Costs in $/Ton for Various Feed Rates and On-line Operating Conditions 23

B-1. Specific Energy Data for Various Types of Equipment 28
C-1. Stack Gas Composition 32
C-2. Organic Compounds in the Feed Soil 33
C-3. Results of Scrubber Liquor Analysis for Metals 33
D-1. Summary of Test Resulsts and Land Disposal Restrictions 36
D-2. Summary of Stack Gas Resulsts and Regulatory Limits 37
D-3. Swiss Leach Test Results 39

Abbreviations and Symbols

A	Amps
ACL	Alternate Concentration Limit
AQMD	Air Quality Management District
ARAR	Applicable or relevant and Appropriate Requirements
BDAT	Best Demonstrated Available Treatment
BTEX	Benzene, Toluene, Ethyl benzene, and Xylene
CAA	Clean Air Act
CDIF	Component Development and Integration Facility
CEM	Continuous Emission Monitor
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cf	Cubic feet
CFR	Code of Federal Regulations
CWA	Clean Water Act
DAS	Data Acquisition System
DOE	Department of Energy
DOT	Department of Transportation
DRE	Destruction and Removal Efficiency
dscf	Dry standard cubic feet
$	U.S. Dollar
EPA	Environmental Protection Agency
°F	degree Fahrenheit
ft	Feet
FWQC	Federal Water Quality Criteria
gal	Gallons
gpm	Gallons per Minute
gr	Grains
hr	Hour
INEL	Idaho National Engineering Laboratory
kg	Kilograms
kW	Kilowatts
lb	Pounds
L	Liters
m	meters

MCLGs	Maximum contaminant Levels Goals
mg	Milligrams
NAAQS	National Ambient Air Quality Standards
NPDES	National Pollutant discharge Elimination System
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
PAFE	Plasma Arc Furnace Experiment
PCDD	Polychlorodibenzodioxin
PCDF	Polychlorodibenzofuran
PCF	Plasma Centrifugal Furnace
PIC	Product of Incomplete Combustion
POHC	Principal Organic Hazardous Constituent
POTW	Publicly Owned Treatment Work
ppbv	Parts per billion, by volume
ppm	Parts per million
ppt	Parts per trillion
PSD	Prevention of Significant Deterioration
psia	Pounds per square inch, absolute
psig	Pounds per square inch, gauge
%	Percent
RCRA	Resource Conservation and Recovery Act
SAIC	Science Applications International Corporation
SARA	Superfund Amendment and Reauthorization Act
scfm	Standard cubic feet per minute
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SSM	Standard Soil Matrix
TCDD	2,3,7,8-Tetrachlorodibenzodioxin
TCDF	2,3,7,8-Tetrachlorodibenzofuran
TCE	Tetrachloroethylene
TCLP	Toxicity Characteristic Leaching Procedure
THC	Total Hydrocarbons
TIC	Tentatively Identified Compound
TSD	Treatment Storage, and Disposal
V	Volts
VOST	Volatile Organic Sampling Train
wk	Week
yr	Year

Acknowledgments

This report was prepared under the direction and coordination of Laurel Staley, EPA Superfund Innovative Technology Evaluation (SITE) Program Manager in the Risk Reduction Engineering Laboratory (RREL), Cincinnati, Ohio. Contributors and reviewers for the report were Kim Lisa Kreiton, Randy Parker, and Robert Stenburg of EPA-RREL, Cincinnati, Ohio; Ron King and the staff of the U.S. Department of Energy, Technology Development and Integration Division, Idaho Falls, Idaho; and Dan Battleson, Corry Alsberg, Steve Kujawa, and the staff of MSE, Inc., Butte, Montana.

This report was prepared for EPA's SITE Program by the Process Technology Division of Science Applications International Corporation (SAIC) for the U.S. EPA under Contract No. 68-C0-0048.

Section 1

Executive Summary

1.1 Introduction

This report summarizes the findings of an evaluation of the Plasma Centrifugal Furnace (PCF) developed by Retech, Incorporated (Retech). The study was conducted under the Superfund Innovative Technology Evaluation (SITE) Program. A series of Demonstration Tests of the technology were performed by EPA as part of this Program. The results of these tests, along with supporting data from other testing performed by the U.S. Department of Energy (DOE) and other background information, constitute the basis for this report.

The Plasma Centrifugal Furnace is a thermal technology which uses the heat generated from a plasma torch to treat metal and organic contaminated waste. This is accomplished by melting metal-bearing solids and, in the process, thermally destroying organic contaminants. The molten soil forms a hard, glass-like non-leachable mass on cooling.

1.2 Conclusions

A number of conclusions may be drawn from the evaluation of this innovative technology. The most extensive data were obtained during the SITE Demonstration Tests; data from other testing activities have been evaluated in relation to SITE Program objectives. The conclusions drawn are:

- The technology can process media contaminated with both organic and inorganic regulated compounds which become non-leachable after treatment.
- The Destruction and Removal Efficiency (DRE) of organic compounds is greater than 99.99%.
- Based on a series of Demonstration Tests, particulate emissions from the process exceed the RCRA regulatory limit of 0.08 grains/dscf.
- NO_x concentrations in the stack gas are high, however, emission rates fall within regulatory limits because of the low gas stream flow rates.
- A high percentage of the metals from the feed soil are captured and retained in the vitreous slag. A proportion of the more volatile metals evolve from the feed and pass through the furnace and the gas scrubbing system.
- The scrubber used for the Demonstration Tests was not effectively designed for capture of volatile metal elements or removal of particulate matter from the exhaust gas stream.
- The process can treat a variety of soil and sludge types and contaminants. The type of feed dictates the selection of the feeder. Liquids can be processed by feeding the waste through a liquid injection lance.
- The PCF used during the Demonstration Tests (PCF-6) is not mobile. Retech estimates that setup time for a commercial PCF will be approximately 2 months. This time is required to install, erect, and shakedown all equipment prior to operation of the system.
- The present furnace must be erected within an enclosed facility. Onsite requirements include adequate power supply, cooling water, and cranes for lifting.
- The Plasma Centrifugal Furnace is effective for treating soils contaminated with both metal and organic compounds. However, the cost of this remediation technology is high because of the capital cost of the equipment and the labor requirements. The cost per ton for this technology is very dependent on the feed rate of the contaminant to the furnace. For a feed rate of 500 lb/hr and an on-line factor of 70%, the cost is estimated at $1,816/ton; for a feed rate of 2,200 lb/hr (70% on-line factor) the cost becomes $757/ton.

1.3 Results

The focus of the Applications Analysis is to assess the ability of the process to comply with Applicable or Relevant and Appropriate Requirements (ARARs) and to estimate the cost of using the technology to remediate a Superfund site. Where appropriate, ARARs are presented along with the reported data for comparison. To evaluate this technology, the leachability characteristics of treated waste along with DREs achieved by the technology are appraised as part of this report. Other results regarding acid gas removal and particulate emissions, air emissions, continuous emission monitoring, test soil and treated soil characterization, and scrubber liquor characterization are also addressed. Appendix C presents a full discussion of the Demonstration Test results and is sup-

ported by the data presented in the Case Studies in Appendix D.

- With regard to inorganic compounds, the Demonstration Test feed soil only exhibited significant leachability characteristics for calcium (175 mg/L) and the spiked zinc (982 mg/L). Sodium was also present in the leachate at 1,475 mg/L, but was not selected as a tracer compound since it behaves differently from typical metals. None of the TCLP characteristic metals found in the feed soil were above the regulatory limit. The treated soil did not exhibit strong leachability characteristics for any metals except sodium which leached at approximately the same level as in the feed soil. Both tracer metals, calcium and zinc, showed significant reductions in leaching properties as a result of treatment.

- The only organic constituents that were found to be leachable from the Demonstration Test feed soil were 2-methylnaphthalene and naphthalene. Although the feed soil was spiked with high levels of hexachlorobenzene (1,000 ppm), it did not leach from the soil. No organic compounds were found to leach from the treated slag.

- For the Demonstration Tests, the mean level of hexachlorobenzene, the Principal Organic Hazardous Constituent (POHC), based on all the feed soil samples was 972 ppm. The 95% confidence interval for the estimated mean was 864 to 1,080 ppm. No hexachlorobenzene was detected in the stack gas, therefore, all DREs determined were based on the detection limit from each of the tests. For the POHC, hexachlorobenzene, the average DRE values ranged from >99.9968% to >99.9999% for all the Demonstration Tests.

- During the three Demonstration Tests, the average DREs determined for 2-methylnaphthalene ranged from >99.9939% to >99.99965%.

- For total xylenes, the DREs associated with the 95% confidence interval for all three Demonstration Tests were >99.9929% to >99.9934%.

- Measured HCl emission rates during the Demonstration Tests ranged from 0.0007 to 0.00173 lb/hr. The HCl removal efficiency of the system was calculated to be at least 98.5%.

- An average of 0.37 grains/dscf of particulate were emitted in the stack gas throughout the Demonstration Tests. This exceeds the RCRA regulatory limit of 0.08 grains/dscf.

- During the Demonstration Tests, NO_x levels were high (5,000 ppm), however, NO_x mass emissions averaged approximately 2.5 lb/hr.

- The most dominant semivolatile organic compound released in the stack gas as a product of incomplete combustion (PIC) during the Demonstration Tests was benzoic acid. Nitrated compounds were also found in the stack gas at low levels (<0.3 ppm). Other oxygenated compounds were detected, but not positively identified in the stack gas.

- The most common volatile organic compound detected (at very low levels) in the Demonstration Test exhaust gas stream was benzene. Other identified volatile compounds (PICs) tended to be chlorinated constituents.

- Copper, iron, lead, potassium, and zinc were in abundance in the solid phase in the stack gas emitted during the Demonstration Tests. The only significant vapor phase metals were calcium and mercury.

- Continuous emission monitoring of the exhaust gases showed only low levels of total hydrocarbons (<4 ppm) and CO (<2 ppm), thus indicating that efficient combustion of the organic contaminants was occurring.

- The Demonstration Test feed soil contained volatile compounds consistent with those associated with diesel fuel. Volatile organic compound analysis was not performed on the treated slag. The semivolatile compounds found most predominantly in the feed soil were the spiked hexachlorobenzene and 2-methylnaphthalene. No semivolatile compounds were detected in the treated soil. The metals found most abundantly in the feed soil were aluminum, calcium, iron, potassium, sodium, and zinc. Zinc was spiked into the feed soil at a nominal level of 22,500 ppm. A high percentage of these elements, except the volatile metals, were retained in the vitrified slag. The volatile metals exited the system mainly in the stack gas.

- During the Demonstration Tests, the only organic compound positively identified at a quantifiable level in the pre-test scrubber liquor was benzoic acid. Additionally, only low levels of inorganic elements were present in the pre-test scrubber liquor. The post-test scrubber liquor did not contain any significant quantities of organic compounds. Nitrated compounds and phthalates were the only compounds present, but at low levels.

Section 2

Introduction

2.1 The SITE Program

In 1986, the EPA's 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 fifth year, SITE 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 three major elements: the Demonstration Program, the Emerging Technologies Program, and the Measurement and Monitoring Technologies Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data on selected technologies. To date, the demonstration projects have not involved funding for technology developers. EPA and developers participating in the program share the cost of the demonstration. Developers are responsible for demonstrating 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 cost. This information will be 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 will also accept proposals at any time when a developer has a treatment project scheduled with Superfund waste. To qualify for the program, a new technology must be at the pilot or full scale 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 wastes suitable for testing the capabilities of the technology. EPA prepares a detailed sampling and analysis plan designed to thoroughly evaluate the technology and to ensure that the resulting data are reliable. The duration of a demonstration varies from a few days to several months, depending on the length of time and quantity of treated waste needed to assess the technology. After the completion of a technology demonstration, EPA prepares two reports, which are explained in more detail below. Ultimately, the Demonstration Program leads to an analysis of the technology's overall applicability to Superfund problems.

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

2.2 SITE Program Reports

The analysis of technologies participating in the Demonstration Program is contained in two documents: the Technology Evaluation Report and the Applications Analysis Report. The Technology Evaluation Report contains a comprehensive description of the demonstration sponsored by the SITE program and its results. It gives a detailed description of the technology, the site and waste used for the demonstration, sampling and analysis during the test, the data generated, and the quality assurance program.

The scope of the Applications Analysis Report is broader and encompasses estimation of the Superfund applications and costs of a technology based on all available data. This report compiles and summarizes the results of the SITE demonstration, the vendor'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 in the Applications Analysis Report, based on available data on pilot- and full-scale applications. The report 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. 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 assure that a technology will be widely applicable or fully developed to the commercial scale. The Applications Analysis Report attempts to synthesize whatever information is available and draw reasonable conclusions. This document will be very useful to those considering the 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 demonstration of the Retech Plasma Centrifugal Reactor technology, please contact:

1. EPA Project Manager concerning the SITE Demonstration:

   Laurel Staley
   U.S. EPA
   Risk Reduction Engineering Laboratory
   26 West Martin Luther King Drive
   Cincinnati, OH 45268
   (513)569-7863

2. Vendor concerning the process:

   Max Schlienger
   Retech, Inc.
   P.O. Box 997
   Ukiah, CA 95482
   (707)462-6522

Section 3

Technology Applications Analysis

3.1 Introduction

This section of the report addresses the applicability of the Retech Plasma Centrifugal Furnace (PCF) to treat various potential soil contaminants and types of soils based primarily upon the results obtained from the SITE demonstration as well as additional tests performed by DOE. Since the results of the Demonstration Tests provide the most extensive data base, conclusions on the technology's effectiveness and applicability to other potential cleanups are based mainly on those results, which are presented in detail in the Technology Evaluation Report. Additional information on the Retech technology, including vendor's claims, a brief process description, a summary of the Demonstration Tests results, and reports on outside sources of data using the Retech technology are provided in Appendices A through D.

Following are the overall conclusions drawn on the Retech technology. The *"Technology Evaluation"* subsection discusses the available data from the Demonstration Test, the Department of Energy (DOE) tests, and Retech provided literature. This subsection also provides more details on the conclusions and applicability of the Retech process.

3.2 Conclusions

The effectiveness of the PCF in encapsulating heavy metals and destroying organic compounds was tested at The Component Development and Integration Facility (CDIF) in Butte, Montana. The CDIF is a DOE facility operated by MSE, Inc. DOE is evaluating the PCF to determine if this technology is suitable for remediation of contaminated soils and sludges at the Idaho National Engineering Laboratory.

In general, this innovative technology is successful in producing a monolithic slag that is non-leachable for inorganic compounds and, in the process, destroying organic compounds by the extreme heat of the process. The limiting factor in the process with the present configuration is the gas treatment system. The scrubber did not remove particulates generated or volatilized metals from the exhaust gas during the treatment process for the Demonstration Tests. However, this shortcoming can be rectified by replacing the existing system with a proven gas treatment system. The overall cost of treatment for this technology is high but it can treat media contaminated with both organic and inorganic compounds.

The conclusions drawn from reviewing data on the Retech PCF are:

- The PCF process can treat media contaminated with both organic and inorganic compounds, producing a slag in which the regulated contaminants are non-leachable.
- The Destruction and Removal Efficiency (DRE) of organic compounds is greater than 99.99% (the regulatory limit).
- Particulate emissions generated by the process, as determined during the Demonstration Tests, exceed 0.08 grains/dscf, the RCRA regulatory limit.
- Although NO_x concentrations in the stack gas are high, emission rates fall within regulatory limits because of the low flow rates of the stack gas.
- The vitreous slag captures and retains a high percentage of the metals from the feed soil. A fraction of the more volatile metals evolves from the feed and passes through the furnace and the gas scrubbing system without being captured.
- The scrubber used for the Demonstration Tests was inadequately designed for effective capture of volatile metal elements and removal of particulates.
- The PCF can treat a wide range of soil and sludge types and contaminants. The feeder selection is dictated by the type of feed. Liquids can be processed by feeding the waste through a liquid injection lance.
- The PCF used during the Demonstration Tests (PCF-6) is not mobile. Retech estimates that setup time for a commercial unit will be approximately 2 months. This time is required for installation, erection, and shakedown of all equipment prior to operation of the system.
- The system, as presently designed and operated, must be erected within an enclosed facility. Onsite support such as adequate power supply (at least 1 MW), cooling water, and cranes for lifting are also required.

- Although the PCF effectively treats soils contaminated with both organic and inorganic compounds, the cost of this remediation technology is high because of the capital cost of the equipment and the labor requirement. The cost per ton for this technology depends greatly on the waste feed rate to the furnace. For a feed rate of 500 lb/hr, and an on-line percentage of 70%, the cost is estimated to be $1,816/ton; for a 2,200 lb/hr feed rate the cost becomes $757/ton.

3.3 Technology Evaluation

The following discussions utilize all available information to provide more detailed conclusions on the process, particularly as related to chemical and operational test results. A summary of the data from the Demonstration Tests is presented in Appendix C; limited data from other tests conducted on this technology may be found in Appendix D, "Case Studies." Detailed estimates regarding the cost of using this technology are presented in a separate section of this report, Section 4, "Economic Analysis."

The furnace evaluated during the Demonstration Tests is a pilot-scale unit designated PCF-6 (the 6 corresponds to the 6-ft diameter of the primary chamber). The feed rate for the PCF-6 during the Demonstration Tests was approximately 120 lb/hr. This unit has been subjected to the most extensive testing. A full-scale system, PCF-8, that is designed to operate at a feed rate of 2,200 lb/hr, is in the process of being permitted in Muttenz, Switzerland. For the purposes of this Applications Analysis Report, only an evaluation of the PCF-6 has been performed.

The feed soil used for the SITE Demonstration Tests was a mixture of metal-bearing soil from the Silver Bow Creek Superfund site and No. 2 diesel oil. These were blended together to provide 10% by weight diesel oil and spiked to provide 28,000 ppm of zinc oxide and 1,000 ppm of hexachlorobenzene. The diesel oil was mixed with the feed soil to show that the process could treat wastes contaminated with high levels of organics. Ten percent (10%) was the maximum level of liquid combustibles that could be fed to the furnace equipped with the type of feeder present at the test site; levels of diesel oil greater than 10% ignite in this feeder because of the heat from the process. It is possible to treat contaminated wastes with a higher percentage of organics using a different feeder configuration assuming that the gas treatment system is sized correctly. Zinc was spiked into the feed soil at the high level to ensure that a metal was leachable from the feed soil in sufficient quantities to allow comparisons with the treated slag leachability. Hexachlorobenzene was spiked as a representative stable (chlorinated) organic compound for the purpose of evaluating the furnace's ability to thermally destroy organic hazardous compounds. The spiking level was chosen to ensure that 99.99% DRE could be positively determined during the Demonstration Tests.

3.3.1 Toxicity Characteristic Leaching Procedure

The PCF is designed to encapsulate inorganic compounds in the vitrified slag and render the treated soil non-leachable. Testing activities have demonstrated that the process can effectively bind inorganic compounds into the treated soil. For the Demonstration Tests, the Toxicity Characteristic Leaching Procedure (TCLP) was performed on both the feed soil and the produced slag. The feed soil was tested to establish initial values for the leachability of organic and inorganic compounds. The vitrified slag underwent TCLP to meet the testing objectives.

For the Demonstration Tests, TCLP analysis of the feed soil for metals shows that the only elements that exhibited significant leachability characteristics were: calcium, sodium, and the spiked zinc (see Table 1). The presence of sodium in the leachate is not unexpected because of its high concentration in the soil and the fact that it is a weakly dissociable metal. This means that sodium, unlike other metals, is readily soluble. If the solution is even slightly acidic (as in the TCLP) this phenomenon is enhanced. None of the eight RCRA characteristic metals found in the feed soil leachate are above the regulatory limit. The evaluation of the leachability of the vitrified slag was based on calcium and zinc. Calcium was chosen, in addition to zinc, because of its tendency to leach from the feed soil. Sodium was not monitored because of its unusual solubility characteristics as explained above.

The TCLP metals analysis of the treated soil is also shown in Table 1. None of the metals, with the exception of sodium, showed any strong characteristic for leaching. Sodium is probably present in the leachate for the reasons stated above and was not considered in this evaluation. Both tracer metals, calcium and zinc, showed significant reductions in leaching properties for the treated soil as compared to the feed. In fact, all of the metals, with the exception of iron and aluminum showed reduced leachability characteristics. The increase in leachability of iron in the treated soil is probably because approximately 100 lb of mild steel was placed in the furnace to aid in initiating the arc of the torch. This considerably increases the iron content of the slag in comparison to the feed soil. The leachability of the aluminum in both feed and treated soil is low and the values reported for the treated soil are only estimates (less than the quantitation limit). Therefore, it is quite probable that the leachability of aluminum from the feed soil as compared to that from the treated soil did not change. TCLP testing on different feed soils by DOE has also shown that the PCF produces a homogeneous non-leachable slag for the metallic elements.

The only organic constituents that were found to be leachable from the feed soil for the Demonstration Tests were 2-methylnaphthalene and naphthalene, as shown in Table 1. Although the feed soil was spiked with a high level of hexachlorobenzene (1,000 ppm), it did not leach from the soil. No organic compounds were found to leach from the treated slag.

The Toxicity Characteristic Leaching Procedure requires samples to be ground into small particles. In this manner, a large amount of surface area is available for leaching. Since the PCF produces a monolithic slag after treatment, the surface area per pound of treated soil is much smaller than that of the feed soil. The TCLP results, therefore, present a conservative assessment of the actual leachability of the monolithic slag.

Table 1. TCLP Results for Demonstration Tests

Compound	Average Feed Soil Leachate Concentration (mg/L)	Treated Soil Leachate Concentration Test 1 (mg/L)	Test 2 (mg/L)	Test 3 (mg/L)	Regulatory Limit* (mg/L)
Metals:					
Aluminum	0.23**	0.45**	0.41**	0.32**	NR
Barium	0.14	0.08	0.08	0.07	100.0
Cadmium	0.07	ND	ND	ND	1.0
Calcium	175	2.1**	2.5**	2.05**	NR
Copper	4.6	0.15	0.35	0.3	NR
Iron	0.06	2.5	2.95	31.1	NR
Magnesium	8.12	ND	ND	ND	NR
Manganese	4.82	0.06	0.06	0.24	NR
Nickel	0.02	ND	0.01**	0.1	NR
Potassium	4.57	ND	ND	ND	NR
Sodium	1,475	1,500	1,400	1,400	NR
Vanadium	0.1	ND	ND	ND	NR
Zinc	982	0.45	0.36	0.3	NR
Semivolatiles:					
Napthalene	0.397	ND	ND	ND	NR
2-Methylnapthalene	0.282	ND	ND	NDS	NR
Hexachlorobenzene	ND	ND	ND	ND	0.13

ND = not detected
NR = Not Regulated
** = 40 CFR (07/01/90 Edition) §261.24, Table 1*
*** Detected at less than the quantitation limit. The quantitation limit is defined as 5 times the instrument detection limit.*

3.3.2 Destruction and Removal Efficiency

The DRE, used to determine organic destruction, is determined by analyzing for the Principal Organic Hazardous Compound (POHC) in the feed soil and the stack gas. DRE may be calculated as follows:

$$\text{DRE (\%)} = \frac{\text{mass in - mass out}}{\text{mass in}} \times 100\%$$

DREs have only been determined for this technology during the SITE Demonstration Tests. For these tests, the POHC was hexachlorobenzene. The mean level of hexachlorobenzene, based on all the feed soil samples for the three Demonstration Tests was 972 ppm. The 95% confidence interval for the estimated mean was 864ppm to 1,080 ppm. No hexachlorobenzene was detected in the stack gas, therefore, all hexachlorobenzene DREs determined are based on the detection limit from the appropriate tests. Table 2 gives these DREs based on the 95% confidence interval of the feed soil and the detection limit for each test.

As can be seen from Table 2, the estimated average DRE values for these tests ranged from >99.9968% to >99.9999% for a highly chlorinated compound, hexachlorobenzene. It can be reasonably assumed that this level of DRE (if measurable) can be achieved for most chlorinated or halogenated compounds.

Analysis of the feed soil indicated that 2-methylnaphthalene, another semivolatile compound, was present at sufficiently high levels in the feed to determine a significant DRE for each test. The 95% confidence interval for 2-methylnaphthalene was 390ppm to 526 ppm. This level of contamination in the feed soil leads to the DREs given in Table 2, again based on detection limits because none of this compound was detected in the stack gas.

Total xylenes, a group of volatile compounds, were also found in sufficient quantities in the feed soil to determine a significant DRE. The 95% confidence interval for the estimated mean of the total xylenes was 128ppm to 139 ppm. The DREs associated with this confidence interval for the three tests were >99.9929% to >99.9934%. Throughout each of the Demonstration Tests, multiple Volatile Organic Sampling Train (VOST) samples were taken. The DREs presented are an average over all three tests based on the 95% confidence interval of xylenes in the feed soil. Averages of all the DREs can be taken because the detection limits obtained are the same for all the VOST samples.

Overall, the PCF appears to be very efficient in destroying both volatile and organic semivolatile compounds when both the primary reaction chamber and the afterburner are operating.

3.3.3 Acid Gas Removal and Particulate Emissions

Measured HCl emission rates for the Demonstration Tests ranged from 0.0007 to 0.0017 lb/hr. The chlorine concentration in the feed soil for Test 1 was 0.066%. This leads to an HCl removal efficiency of 98.5%. Because of the low chlorine input, the regulatory requirement of no greater than the larger of either 4 lb/hr or 99% removal [40 CFR (07/01/90 Edition) §264.343(b)] was met. The removal efficiency may not be

meaningful because of the low chlorine input. However, it appears that, even if the chlorine in the feed had been higher, an HCl removal efficiency of 99% could be achieved.

As shown in Table 3, the particulate emissions during each of the three Demonstration Tests exceeded the regulatory limit of 0.08 grains/dscf [40 CFR (07/01/91) §264.343(c)]. These emission rates have not been corrected for 7% oxygen. The 7% oxygen correction factor is 14/(21-O_2%). The oxygen correction is required by RCRA for all hazardous waste incinerators except those operating under the condition of oxygen enrichment. The purpose for correcting for 7% O_2 in conventional incineration systems is to account for the dilution factor in the stack gas caused by using excess air for combustion. For the Retech process, pure oxygen is fed to the primary chamber through an oxygen lance as soon as feeding of the first batch of soil begins. The O_2 is continually introduced to the furnace throughout the remainder of the treatment process. The O_2 content of the stack gas when no soil is being fed to the furnace (i.e., between feeding cycles, during recharging of the feeder) is in excess of 21%. As stated above, RCRA does not require the 7% O_2 correction factor for hazardous waste incinerators operating under oxygen enrichment [40 CFR (07/01/91) §264.343(c)]. During feeding of the soil to the reactor, the stack gas O_2 level drops to approximately 11%. Therefore, if the correction is to be applied only during the feeding cycle (when presumably the particulates are being generated), then the values given in Table 3 should be increased by a factor of 1.4.

The amount of particulates captured by the air pollution control system was extremely small. This is demonstrated, in part, by the low level of scrubber solids present in the sump. There was less than 0.5% total solids in the scrubber sump tank. The consequence of the high particulate loading during the Demonstration Tests was a substantial build-up of particulate matter in the exhaust blower after the air pollution control system. The pressure differential across the exhaust blower was reduced because of the particulate build-up, and the first two Demonstration Tests were shortened due to this problem. A larger blower was installed for the third Demonstration Test, which was completed as scheduled, but particulate build-up still persisted.

Particulate measurements had not been performed on the PCF by MSE, Inc. prior to the Demonstration Tests. The problem of the high particulate loading in the exhaust blower had been noticed in previous testing, but not to the extent found during the Demonstration Tests. The Silver Bow Creek Superfund Site soil was extremely dry and dusty before it was mixed with the diesel oil. Even after mixing the soil with the diesel oil, it was very free-flowing with no standing liquid. This type of soil had not been treated by the PCF prior to the Demonstration Tests. It is possible that the fines from this feed may not have been retained in the melted soil in the primary reaction chamber and simply passed through the treatment process and the scrubbing unit and into the exhaust blower and stack gas. If the dust did pass through the treatment process, it would be expected that a well-designed wet scrubbing system would be capable of capturing the particulates. If the feed soil does not contain any halogenated compounds, then the process does not require a wet scrubbing system and a baghouse could be used to control the particulate emissions. Judicious selection of the most suitable air pollution control device is necessary before implementation of this technology can be achieved.

3.3.4 Air Emissions

The air emissions during the Demonstration Tests consisted primarily of products of incomplete combustion (PICs) and particulates. For the case of the emitted semivolatile organics, the most dominant compound released in the stack gas was benzoic acid at an average concentration of approximately 4 ppm. The occurrence of benzoic acid in the stack gas is to be expected as both toluene (from the diesel oil) and chlorine (from the hexachlorobenzene) were present in the feed soil. These two compounds, with the addition of heat, readily form benzoic acid as shown in the basic reaction presented below:

$$C_6H_5CH_3 \xrightarrow[\text{heat}]{Cl_2} C_6H_5CCl_3 \xrightarrow{H_2O,\ OH^-} C_6H_5COOH$$

(Toluene) (Benzotrichloride) (Benzoic Acid)

The water and hydroxide required to complete the reaction were provided by the scrubber.

A group of nitrated compounds was found in the stack gas at low levels (< 0.3 ppm). These compounds were formed because of the high levels of NO_x and trace quantities of organic compounds in the stack gas interacting with the scrubber liquor spray. Other compounds such as the phthalate groups and naphthalene were also present but were found in the field blanks as well.

In addition to the target compounds identified by the SW-846 Method 8270 [1] list, the next 20 highest peaks from the chromatograms were investigated for compound identification and semi-quantification. A review of the chromatograms and the spectral data showed that some Tentatively Identified Compounds (TICs) were present in the gas stream. The first Demonstration Test yielded a relatively clean chromatogram that was somewhat comparable to the field blank. No TICs could be positively identified, but it appeared that some of the unknowns contained oxygen somewhere in the molecular structure and some of the unknowns were nitrogen-containing compounds.

Test 2 data appeared to be notably different from the Test 1 data. The chromatogram indicated that several higher molecular weight compounds were detected. The TIC data showed that these compounds were unidentifiable carbonic acids. It should be noted that there were no positive identifications made on the specific type of carbonic acid, but the pattern was present in several of the TICs. Carbonic acids are formed by reacting carbon dioxide with water at high temperature. This may suggest that the torch cooling water leak detected during Test 3 could have developed during Test 2 (see the Technology Evaluation Report for more details). Because of this leak, Test 3 was aborted early and restarted after the leak had been repaired. Compounds that eluted in the early stages of the

Table 2. DRE Results for Demonstration Tests

Compound	Test 1	Test 1 Duplicate	Test 2	Test 3	Regulatory Limit*
Hexachlorobenzene					
Lower 95% Confidence Interval	>99.9964	>99.9982	>99.9990	>99.99989	
Mean	>99.9968	>99.9984	>99.9991	>99.99990	99.99
Upper 95% Confidence Interval	>99.9971	>99.9986	>99.9992	>99.99991	
2-Methylnapthalene					
Lower 95% Confidence Interval	>99.9853	>99.9930	>99.9958	>99.99960	
Mean	>99.9872	>99.9939	>99.9964	>99.99965	99.99
Upper 95% Confidence Interval	>99.9891	>99.9948	>99.9969	>99.99970	

* 40 CFR (07/01/90 Edition) §264.343(a)(1)

chromatogram for the second test contained nitrogen and oxygen within their molecular structure.

The third test data was very similar to the TIC information gathered from Test 1. In general, for the three Demonstration Tests, only low levels of semivolatile organic compounds were identified in the gas stream.

Very low levels of volatile organic compounds were detected in the exhaust gas stream during the Demonstration Tests. The most common of these compounds was benzene at an average concentration of approximately 19 ppbv. DOE testing of inert soils mixed with diesel oil has also resulted in the detection of low levels of benzene in the stack gas. Benzene and substituted benzenes are prevalent in many forms throughout diesel oil and hence benzene is a readily formed PIC. Other identified compounds in the stack gas tended to be very low levels of chlorinated organics which were not identified in the feed soil at the detection limits achieved for the testing and therefore can possibly be PICs.

Sampling and analysis for polychlorodibenzodioxins (PCDDs) and polychlorodibenzofurans (PCDFs) in the exhaust gas stream was accomplished during the Demonstration Tests. The results of these analyses indicated that no PCDDs or PCDFs were formed in the stack gas. Although some PCDDs and PCDFs were detected in some of the samples analyzed, the levels detected were lower than the corresponding blank sample detection limit. For example, a particular isomer of a PCDD was detected with 10 picograms of catch; however, the field blank reported a nondetect with a detection limit of 20 picograms of catch. The variation of the detection limits is a function of the matrix being analyzed and the resolution of the analytical instruments used to quantify the samples.

Table 3. Particulate Results for Demonstration Tests

	Test 1	Test 1 Duplicate	Test 2	Test 3	Regulatory Limit
Particulate Concentration (grains/dscf)	0.34	0.24	0.42	0.41	0.08
Particulate Emissions (lb/hr)	0.34	0.24	0.42	0.42	**

* 40 CFR (07/01/90 Edition) §264.343(c)
** Dependent on stack gas flowrate

Metal emissions during the Demonstration Tests were almost exclusively in the solid phase; very little of the metals were found in the impingers of the sampling trains. The only significant vapor phase metals detected were calcium and mercury. A very volatile metal such as mercury is expected to be found in the vapor phase. Zinc, copper, iron, potassium, arsenic, and lead were in abundance in the stack gas in the solid phase. The presence of iron in the stack gas, at 66 ppm, was a consequence of the high levels of this element in the feed soil and the need for using a mild steel "doughnut" for start-up purposes. The copper in the stack gas is suspected to originate from the throat of the furnace and the torch electrode as copper is not present in high quantities in the feed soil. Lead, at approximately 4 ppm in the stack gas, and arsenic, at 6 ppm, were not retained in the treated soil as they are volatile metals (arsenic sublimates) and most probably evaporated from the soil while it was being treated in the furnace. The high level of zinc in the stack gas, at approximately 125 ppm, was a consequence of the high spiking level of this element and the high volatility of this metal in the temperature range encountered within the furnace. Additionally, the presence of chlorine with the zinc at this temperature range rapidly increases the volatility of zinc. In all cases, (except mercury) the air pollution control system should have captured the metals. As shown later, the scrubber liquor did not contain high levels of metals after each of the tests.

Based on the results from the Demonstration Tests, it appears that not all of the volatile metals are captured in the molten soil at the completion of treatment. If this is the case, then these volatile metals should be captured by the gas treatment system (assuming it is correctly designed). A percentage of the volatile metals originally found in the soil would appear in the scrubber liquor, therefore, possibly requiring treatment of the liquor prior to disposal.

3.3.5 Test Soil and Treated Slag

As stated previously, the feed soil for the Demonstration Tests consisted of a mixture of Silver Bow Creek Superfund Site soil, which is classified as a high metal-bearing soil, and 10% by weight No. 2 diesel oil. Into this mixture, zinc oxide

and hexachlorobenzene were spiked to provide 28,000 and 1,000 ppm, respectively, in the mixed soil. (The corresponding amount of zinc is 22,500 ppm.)

Analysis of the feed soil showed that it contained volatile compounds consistent with those associated with diesel fuel: benzene, toluene, ethyl benzene, and xylene (BTEX). The semivolatile compounds found most predominantly in the feed soil are the spiked hexachlorobenzene and 2-methylnaphthalene. Other diesel-based compounds were also found in the soil but at levels that could not be accurately quantified by SW-846 Method 8270. Gas chromatography/mass spectrometry (GC/MS) analysis also indicated the presence of large numbers of TICs. These TICs were typical of those found in diesel oil and consisted mainly of compounds of naphthalene and benzene. The metals found most abundantly in the feed soil were aluminum, calcium, iron, potassium, sodium, and zinc.

Volatile organic analysis was not performed on the treated soil as no volatile compounds were considered to exist in the slag after it had reached its melting point temperature. The only semivolatile organic compounds found in the treated soil were low levels of two phthalate compounds which were probably sampling or analytical contaminants. This agrees with the TCLP analysis of the slag discussed earlier in which no semivolatile compounds leached from the slag.

For the first Demonstration Test, 480 lb of feed soil were fed to the reactor and a steel "doughnut" weighing 74.5 lb was added. As the feed soil contained 10% organics, which appeared to have been destroyed, a calculated 506.5 lb of slag should have been poured into the collection chamber. The mass of treated soil collected in the slag chamber was 277 lb, the remainder being retained within the reaction chamber to provide a "skull" for the next test. (A skull is a layer of melted material around the interior of the primary chamber which reduces the chamber's volume and acts as an insulator to protect the refractory.) Therefore, a mass balance that yields meaningful results cannot be performed on this technology since a portion of material from each test can potentially remain in the reactor at the end of treatment. It is possible, though, to compare the concentrations of the inorganic elements in the feed soil with that of the collected slag, taking into account the destruction of the 10% organics and assuming that none of the elements are concentrated in the poured slag. Table 4 gives the concentrations of the metals in the slag for all three of the tests. The feed is an average of all feed samples from the three tests. This table shows that a large percentage of the metals from the feed soil are retained within the vitrified slag. Exceptions to this trend are generally the volatile metals: arsenic, lead, mercury, and zinc. These volatile metals, as stated earlier, have been found to be exiting the system through the exhaust stack. In addition, some of these metals can be found in the scrubber liquor.

To evaluate the fate of the feed soil metals, a comparison can be made of the behavior of a non-volatile metal such as aluminum to that of a volatile metal such as zinc. Test 3 provides a good basis for examination since 600 lb of waste were fed into the furnace and 595 lb were poured. The feed soil utilized during Test 3 contained 29.6 lb of aluminum. A total of 26.0 pounds were detected in the treated soil. This represents 88% of the aluminum originally present in the feed soil. Traces of aluminum (0.00340 pounds total) were also detected in the stack gas. A small increase in the aluminum concentration from the pre-test scrubber liquor to the post-test scrubber liquor was also noted. The remainder of the aluminum which has not been accounted for may be due to sampling and analytical variations.

For zinc, 13.9 lb were fed to the furnace in the feed soil during Demonstration Test 3. A total of 5.24 lb (38%) was retained in the treated soil. The stack gas contained 0.332 lb of zinc. A large portion of the zinc plated out as particulate matter in the blower and the long exhaust gas duct. Again, sampling and analytical variation may have contributed, in part, to the apparent discrepancy between the zinc in the feed soil and the zinc in the treated soil and the stack gas.

The increase in iron concentration can be explained by the initial presence of the carbon steel doughnut. The concentrations of both chromium and nickel increase in the treated slag because, prior to the Demonstration Tests, stainless steel had been incorporated into the reactor to form part of the skull. Additionally, the feeder chute used during these tests was fabricated of stainless steel. The increase in the copper concentration is probably because of the melting of portions of the copper throat during treatment. In addition, soil treated prior to the Demonstration Tests, and hence part of the skull, had been high in calcium, manganese, and potassium.

Only the treated soil (not the feed soil) was analyzed for PCDDs and PCDFs during the Demonstration Tests. The levels of PCDDs and PCDFs in the treated soil for the Demonstration Tests were very low. However, as described earlier for the stack gas emissions, the detection limits for the blank samples are higher than the amount of PCDDs and

Table 4. Metals in the Feed Soil and Treated Soil

Element	*Average Feed (ppm)*		*Test 1 (ppm)*		*Test 2 (ppm)*		*Test 3 (ppm)*	
Aluminum	*49,429*	*B*	*51,250*		*46,000*		*43,667*	
Arsenic	*201*		*12*	*	*16*	*	*11*	*
Barium	*508*		*523*		*480*		*453*	
Calcium	*12,500*		*28,750*		*20,500*	*1*	*8,000*	
Chromium	*25*	*	*500*		*510*		*617*	
Copper	*591*		*780*		*1,500*		*827*	
Iron	*36,929*	*B*	*160,000*		*150,000*		*213,333*	
Lead	*426*		*98*	*	*115*	*	*120*	*
Magnesium	*4,650*		*5,725*		*4,600*		*4,667*	
Manganese	*814*		*1,850*		*1,900*		*2,567*	
Mercury	*1*		*ND*	**	*ND*	**	*ND*	**
Nickel	*NA*		*270*		*265*		*287*	
Potassium	*19,357*		*15,500*		*16,000*		*14,667*	
Sodium	*10,171*		*8,175*	*B*	*8,650*		*7,833*	
Vanadium	*80*	*	*60*	*	*60*	*	*50*	*
Zinc	*23,214*		*6,475*		*9,050*		*8,800*	

B indicates that this compound was detected in a blank
NA = Not Analyzed
ND = Not Detected
** = Detected at less than the quantitation limit. The quantitation limit is defined as 5 times the instrument detection limit.*
*** = Instrument detection limit for mercury is 0.133 ppm.*

PCDFs detected in the samples. It is therefore reasonable to conclude that no PCDDs or PCDFs were formed by the treatment process, and if any dioxins/furans were in the feed soil they were destroyed by the intense heat of the process.

3.3.6 Scrubber Liquor

The pre-test scrubber liquor for each of the three Demonstration Tests contained very little in the way of organic compounds. A metals scan on the pre-test scrubber liquor showed that, generally, only low levels of inorganic elements were present. This was expected since, prior to each test, the scrubber sump was flushed and filled with deionized water.

The post-test scrubber liquor did not contain any significant quantities of organic compounds. Nitrated compounds and phthalates were the only compounds present. The nitrated compounds were most likely produced from the high levels of NO_x in the exhaust gas reacting with the water from the scrubber and any organic compounds present. The phthalates and volatile organic compounds probably entered the scrubber sump from the scrubber make-up liquor. The lack of organic compounds in the scrubber liquor and, as stated earlier, the absence of volatile or semivolatile organic compounds in the exhaust gas, indicates that combustion of the organic compounds was complete.

The scrubbing unit is very inefficient in the capture of the inorganic compounds. The scrubber did capture some of the volatile metal elements but not at the levels that would typically be expected from a well-designed system. As stated previously, the exhaust gas contained a variety of metals that should have been captured by the scrubbing unit. The types of metals found in the scrubber liquor were similar to those found in the stack gas; that is, zinc, iron, and arsenic were the elements in abundance. High sodium levels found in the liquor were probably a consequence of the scrubber make-up (sodium hydroxide).

3.3.7 Continuous Emission Monitors

Throughout each of the three Demonstration Tests, CO, CO_2, O_2, NO_x, and total hydrocarbons (THC) were monitored continuously to present a real time image of the combustion process and to determine if regulatory standards were being exceeded. SO_2 was also measured but the data collected was not considered suitable. High levels of NO_x in stack gas are known to interfere with SO_2 meters, and the interference indicates the presence of SO_2 when none is actually present. MSE, Inc. has also monitored the same combustion products for DOE during shakedown tests and other testing of the PCF.

Since the installation of the afterburner in the secondary combustion chamber, the level of total hydrocarbons exiting the system has been low (<4 ppm) even with at least 10% organics in the feed soil. This gives a good indication that effective thermal destruction of the organic compounds is occurring. Another indication of the ability of the process to treat organic contaminated media is the low levels of CO in the exhaust (approximately 1.4 ppm) and the level of CO_2 (approximately 8%). O_2 monitors show significant variation throughout the treatment process as pure O_2 is fed to the primary chamber at approximately 18 scfm while waste is being fed to the furnace.

High levels of NO_x are a consequence of this process if air is used as the torch gas. The torch gas passes through the extremely hot arc of the plasma, thus oxides of nitrogen are readily formed. Testing to date has shown that the average concentration of NO_x in the stack gas is approximately 5,000 ppm (uncorrected to 7% O_2 as explained earlier). The oxygen lance operated intermittently rather than continuously during Tests 1 and 3. During Test 2, however, the oxygen was fed at a steady rate over the entire treatment time, so the NO_x values corrected to 7% O_2 may be easily calculated for this test, if desired. This correction is not required by RCRA regulations because the system operates under oxygen enrichment. The average uncorrected NO_x value during Test 2 was 5,467 ppm; the average NO_x value corrected to 7% O_2 was 8,514 ppm.

The uncorrected average NO_x value for testing (5,000 ppm) corresponds to an emission rate of 2.6 lb/hr. The low emission rate is because of the low flowrate of the exhaust gas (approximately 110 scfm). This flowrate is dependent on the size of the torch used. The feed rate of the soil does not influence the level of NO_x in the exhaust assuming the same torch is used for the different feed rates. This is because the torch uses the same amount of torch gas regardless of the feed rate of soil. If a torch larger than that used in the Demonstration Tests is to be employed, then the use of an NO_x reduction technology should be investigated.

3.3.8 Furnace Operation

Since all three Demonstration Tests were designed to be identical in nature, operating conditions during the tests were relatively constant. The feed material was identical in each case, a mixture of Silver Bow Creek soil and 10% by weight No. 2 diesel oil, spiked to provide 28,000 ppm zinc oxide (22,500 ppm zinc) and 1,000 ppm hexachlorobenzene. The feed rate for each test was 120 lb/hr. Although the mass of material to be fed during each test was anticipated to be 960 lb, the actual weight of the feed was 480, 360, and 600 lb for Tests 1, 2, and 3, respectively. The corresponding weight of the treated soil generated during the tests was 277, 265, and 595 lb. The difference between the mass fed and the mass poured during each test can be accounted for by the retention of material inside the chamber as part of the skull as described in Section 3.3.5. As demonstrated by these values, the skull was progressively built up throughout the course of the Demonstration Tests.

The torch power ranged from an average of approximately 410 kW during Test 3 to nearly 460 kW during Tests 1 and 2. The total power consumption of the torch ranged from 3,308 kWh (Test 1) to 4,720 kWh (Test 3). As anticipated, the total power consumption for Test 3 was greater than the other two tests because of the extent of its duration. The torch gas in each case was air with a flowrate of 23 to 24 scfm.

The furnace is operated so that a minimum temperature of 2,100°F is achieved in the primary reaction chamber and a minimum temperature of 1,800°F is reached in the afterburner before feeding of the waste is initiated. The reactor chamber

temperature, once it stabilized, achieved an average value of approximately 2,250°F. The afterburner temperature averaged around 1,800°F (slightly higher during Test 3) once the system reached operating range. The off-gas flowrate was maintained at approximately 110 scfm during all three Demonstration Tests.

The scrubber liquor generated during each of Tests 1 and 2 was close to 150 gal. During Test 3, this value was greatly exceeded due to frequent blowdowns of the scrubber in attempt to reduce particulate loading on the blower downstream. Nearly 800 gal of scrubber liquor were generated during Test 3.

The PCF-6 is a high maintenance process that is subject to frequent stoppage because of equipment failure. During the first Demonstration Test a stoppage occurred when a scrubber sump pump overheated and tripped the system. The test was also shortened because of particulate build-up in the exhaust blower. This same problem caused the second Demonstration Test to be stopped prior to treatment of all the feed. While warming up the primary chamber for the third Demonstration Test, the torch developed a cooling water leak. This led to the furnace being out of operation for approximately 3 hr while the leak was repaired. Experience of operating the PCF-6 has shown that secondary arcing within the primary chamber is the most common form of equipment breakdown. Torch cooling water leaks result when this occurs, and the torch ram need to be welded, plugging these pinhole leaks. With regard to preventive maintenance, torch electrode replacement is the most regular of the procedures that need to be carried out to ensure uninterrupted operation. The electrodes have to be replaced every 60 to 100 hr.

The plasma torch provides a substantial amount of thermal energy to the feed. However, to protect the equipment from being damaged by this heat cooling circuits are utilized. For the PCF-6 the cooling circuits that remove the highest percentage of the heat from the process are the torch cooling circuit (31%), the primary chamber cooling circuit (39%), and the scrubber unit (10%). For optimum operation of the furnace, it would be anticipated that the majority of the heat removed from the system would be from the collection chamber and the scrubbing unit. For the Demonstration Tests, the specific energy consumption was approximately 8 kWh/lb. Physical data indicates that, ideally, a specific energy requirement for the melting of soils is approximately 0.3 kWh/lb. Therefore, there is considerable room for improvement in the design and operation of the PCF system.

3.4 Ranges of Site Characteristics Suitable for the Technology

3.4.1 Site Selection

The selection of sites with potential for utilization of the Retech Plasma Centrifugal Furnace system is not entirely restricted by the geological features of the site as the equipment may be erected within the confines of the contaminated area or placed so that the waste can be transported to the furnace. Obviously, operation is most cost-effective if the furnace is erected on-site. The site should be suitable for construction of a climate controlled building to house the furnace with appropriate access as described below.

3.4.2 Surface, Subsurface, and Clearance Requirements

Surface requirements for the operation of the Retech Plasma Centrifugal Furnace include a level, graded area capable of supporting the equipment and the facility housing this equipment. Foundations are required to support a weight of 65,500 lb of furnace, for the PCF-6, in addition to the weight of the power supply, ancillary equipment, and structural steel. The weight of the PCF-8 furnace including all ancillary equipment except the gas clean-up system is 200,000 lb.

The site must be cleared to allow construction of and access to the facility. Macadam roads are necessary to provide support for oversize and heavy equipment.

3.4.3 Topographical Characteristics

Since the treatment process takes place in an enclosed environment, topographical characteristics of the site need only be suitable for construction of a facility to house the furnace and all the ancillary equipment (oxygen tanks, argon tanks, etc.) In addition, the power requirements for this technology are substantial (see Section 3.4.7), therefore, the supplying of this electricity has to be taken into consideration.

3.4.4 Site Area Requirements

The site requires sufficient space for a 20-ft X 20-ft facility to house the PCF-6 furnace. The PCF-8 furnace requires a 20-ft X 30-ft pad. Additionally, space outside of this facility must be available for storage of any waste generated during the treatment process. If mixing of the feed is necessary prior to treatment, an area onsite for mixing activities is advantageous. The shape of the site is inconsequential to treatment activities as the furnace can be configured into any position, the only requirement being that of 30 ft height for the PCF-6 and 45 ft clearance for the PCF-8. The equipment should be situated in a manner to facilitate convenient access.

3.4.5 Climate Characteristics

Climate characteristics suitable for this treatment technology cover a broad range, since operation takes place in a climate controlled facility. Prolonged periods of freezing conditions may hamper excavation of the contaminated soil. However, this would not affect the operation of the furnace itself.

3.4.6 Geological Characteristics

Major geological constraints that can render a site unsuitable for Plasma Centrifugal Furnace technology include landslide potential, volcanic activity, and fragile geological formations that may be disturbed by heavy loads or vibrational stress.

Generally, any site that can tolerate the construction of a facility to accommodate the furnace is suitable for this technology.

3.4.7 Utility Requirements

The utility requirements include electricity, water, natural gas, and other gases. The basic electrical requirement for accommodating the installation and operation of the furnace is a 1,600-amp, 480-volts, 3-phase power supply for the PCF-6. This requirement is increased to 2,000 amps and 600 volts (3-phase) for the PCF-8. A plant cooling water supply (cooling tower system) is necessary at a flowrate of 350 gpm for the PCF-6 and 450 gpm for the PCF-8. Deionized water is required for the torch cooling circuit and 150 gallons is required for each charge. Five scfm of natural gas are needed for the afterburner. The oxygen lance requires 30 scfm of gaseous oxygen at 92 psia and 25 scfm at 92 psia of gaseous argon is required for seal protection and clearing of viewports.

3.4.8 Size of Operation

The capacity of the Retech Plasma Centrifugal Furnace system utilized during the Demonstration Tests (PCF-6) was 120 lb/hr feed soil input. However, this capacity can be increased to 500 lb/hr using the same torch and furnace if modifications are made to increase the size of the feeder and the slag collection pig. The ability to supply and remove process gases must also be increased to accommodate a higher feed rate. The gas treatment system will also require optimization depending on the organic and water content of the feed. The facility constructed for this pilot-scale furnace was approximately 25 ft by 18 ft by 40 ft, a three tier structure. The two upper tiers housed the soil processing equipment, and the lowest tier housed the gas treatment system.

The Retech process can be retrofitted to a variety of facility sizes according to process design capacity. The equipment layout is restricted by vertical alignment of the reaction chamber, secondary combustion chamber, and the collection chamber. The minimum height requirement for this vertical alignment for the PCF-6 is 30 ft. The gas treatment system may be placed accordingly to meet an optimum facility design plan.

3.5 Applicable Wastes

The Retech furnace can be used to treat wastes containing either hazardous organic or inorganic compounds, or a combination of both. The level of total organics in the feed is not limited. However, the level of organics does influence the choice of furnace feeder. Accordingly, the gas treatment system has to be sized to match the organic content of the waste. Liquid wastes can be fed to the furnace by means of a liquid injection lance. The selection of feeder is also dependent on whether the feed has been containerized or has been excavated and stockpiled.

For the Demonstration Tests on the PCF-6, a screw feeder in which the screw flights were welded to the interior of a rotating drum was used to introduce the soil into the primary reaction chamber. The upper limit of particle size fed to the furnace for this feeder was 4 in. X 4 in. because of the clearance available in the feeder and the torch stand off. The torch and primary chamber themselves are not restricted to this size limitation and may handle larger debris so long as the performance of the torch is not affected (loss of arc).

The operation of the feed system on the PCF-8 is completely different. This unit operates by feeding 55-gal drums to the furnace. The feed system operates as follows: the drum enters from the drum storage area on a conveyor. The first stop is a piercing station where, under a cover of nitrogen with removal of the gases to the furnace, the drum is pierced. A barrel pump is used to remove the major portion of any liquid in the drum. This liquid is pumped directly to the liquid injection lance in the furnace.

Pierced drums can then be placed on the feeder. After 5 drums have been charged to the feeder, the door is closed and the space inside the drum feeder is purged with nitrogen. A water-cooled and refractory-lined gate separates the feeder chamber from the furnace. When it is time to treat a new drum, the gate is raised, the conveyor moves one drum into the furnace and a mechanism at the tip of a drum manipulator pierces and clamps the lid. After the drum is clamped, it is raised a little, the feeder conveyor retracts, and the gate is closed. The manipulator then lowers the drum to a position where the Rototrode® can cut it up. The Rototrode® is a spinning water-cooled copper electrode. An arc between the Rototrode® and the steel drum cuts the drum from the bottom. The operator slices the drum so as to deposit a moderate amount of waste at a time into the furnace. Prior to charging any solids, holes are pierced at several levels of the drum to remove any remaining liquid. After the drum has been cut up, the top part of the drum which remains on the manipulator is pushed off the manipulator. The drum is then melted as part of the feed and becomes part of the slag.

The gas clean-up system must be sized to match the organic content of the feed. The gas scrubbing unit used on the PCF-6 for the Demonstration Tests is described in Appendix A. The air pollution control device used on the PCF-8 utilizes different technologies to meet regulatory standards and reduce disposal costs. The PCF-8 system operates by first mixing the exhaust from the secondary combustion chamber with air to reduce the gas to a temperature of approximately 2,200°F. Downstream of the mixer is a heat exchanger which recovers heat for use later in the process. The exhaust gases then pass through a quench where water is added to reduce the gas temperature to below 194°F. Beyond the quench is a prewash and 2-stage ionizing wet scrubber. Both particulate and acid gases are designed to be removed by the water in the quench and ionizing wet scrubber. An exhaust blower forces the gases to the section where NO_x are removed. A heat exchanger, which uses oil as the heat transfer medium between the hot gas heat exchanger and the heat exchanger utilized to remove NO_x, raises the temperature of the gas from approximately 85°F to approximately 575°F. Ammonia is added to a catalyst bed to reduce the NO_x to design levels of below 50 ppm.

Materials handling requirements for operation of a Retech furnace include containerization and transport to the process feed, and disposal of the vitrified slag and scrubber liquor. Retech, Inc. anticipates that the treated soil will meet delisting requirements and that the slag can be buried in existing landfills or used as a product (roadfill, ballast, etc.).

3.6 Regulatory Requirements

Operation of the Retech Plasma Centrifugal Furnace for treatment of contaminated soil requires compliance with certain Federal, state, and local regulatory standards and guidelines. Section 121 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) requires that, subject to specified exceptions, remedial actions must be undertaken in compliance with Applicable or Relevant and Appropriate Requirements (ARARs), Federal laws, and more stringent promulgated state laws (in response to releases or threats of releases of hazardous substances, pollutants, or contaminants) as necessary to protect human health and the environment.

The ARARs which must be followed in treating Superfund waste onsite are outlined in the Interim Guidance on Compliance with ARARs, Federal Register, Vol. 52, pp. 32496 et seq. These are:

- Performance, Design, or Action-Specific Requirements. Examples include RCRA incineration standards and Clean Water Act 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 complied with.
- Locational Requirements. These set restrictions on activities because of site location and environs.

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

- Federal EPA air and water pollution regulations,
- state air and water pollution regulations, and
- local regulations, particularly Air Quality Management District (AQMD) requirements

These regulations govern the operation of all technologies. Other Federal, state, and local regulations are discussed in detail below as they apply to the performance, emissions, and residues evaluated from measurements taken during the Demonstration Tests.

3.6.1 Federal EPA Regulations

3.6.1.1 Clean Air Act

The Clean Air Act (CAA) establishes primary and secondary ambient air quality standards for protection of public health, and emission limitations for certain hazardous air pollutants. Permitting requirements under the Clean Air Act are administered by each state as part of State Implementation Plans developed to bring each state into compliance with National Ambient Air Quality Standards (NAAQS). The ambient air quality standards listed for specific pollutants are applicable to operation of the Retech system due to its potential emissions, notably CO and NO_x. Other regulated emissions may also be produced, depending on the waste feed. It is likely, then, that a PCF built in any state will be required to obtain an air permit. The allowable emissions will be established on a case-by-case basis depending upon whether or not the site is in attainment of the NAAQS. If the area is in attainment, the allowable emission limits may still be curtailed by the available increments under Prevention of Significant Deterioration (PSD) regulations. This can only be determined on a site-by-site basis.

3.6.1.2 Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 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, entitled 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 which must be addressed by CERCLA remedial actions are:

- long-term effectiveness and permanence,
- short-term effectiveness,
- implementability, and
- cost.

The Retech system has demonstrated that organic contaminants in the feed stream can be destroyed with at least 99.99% DRE. This illustrates both long- and short-term effectiveness with respect to organic compounds. The Plasma Centrifugal Furnace also demonstrated that heavy metals are immobilized in a non-leaching vitrified slag based on toxicity characteristic leaching procedure analyses performed on the treated soil. The long-term effectiveness and permanence of the Retech treatment system will not be evaluated by subsequent analyses because this is not in the scope of work for this project. It is anticipated, however, that the components in treated soil will remain stable in the vitrified slag indefinitely.

The short-term effectiveness of the Retech system may be evaluated by examining analytical data obtained from the stack gas and the scrubber liquor. These data indicate that the Plasma Centrifugal Furnace is effective with respect to some, but not all, regulated emissions and that the scrubbing system is not very effective.

The implementability of the system appears favorable. The assembled system is, however, relatively permanent. This lack of mobility indicates that the system is better suited for facilities where ongoing treatment is required rather than for

facilities where short-term or small-scale treatment is required.

Based on the Economic Analysis of the Retech PCF system (see Section 4), the cost of this technology is comparatively high with respect to alternative incineration methods. However, certain types of waste which are not remediable by other techniques (i.e., metal and organic contamination, dioxin-containing, radioactive) may possibly be rendered nonhazardous by this technology. Additional testing is required to evaluate this potential.

3.6.1.3 Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) is the primary Federal legislation governing hazardous waste activities. Subtitle "C" of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste, most of which are also applicable to CERCLA activities.

Depending on the waste feed and the effectiveness of the treatment process, the Retech system generates two potentially hazardous waste streams: the scrubber liquor and the treated slag. For this treatment process with a suitably designed scrubbing system, the scrubber liquor constitutes the primary hazardous waste stream. The scrubber liquor contains any metal contaminants which were volatilized during the treatment process along with particulate matter removed from the gas stream.

For generation of any hazardous waste, the site responsible party must obtain an EPA generator identification number and comply with accumulation and storage requirements for generators under 40 CFR 262 or have a Part B Treatment, Storage, and Disposal (TSD) permit of interim status. Compliance with RCRA TSD requirements is required for CERCLA sites. A hazardous waste manifest must accompany offsite shipment of waste. Transport must comply with Federal Department of Transportation (DOT) hazardous waste transportation regulations. The receiving TSD facility must be permitted and in compliance with RCRA standards.

Technology or treatment standards have been established for many hazardous wastes; those appropriate for the Retech process will be determined by the type of waste generated. The RCRA land disposal restrictions, 40 CFR 268, mandate that hazardous wastes which do not meet the required treatment standards receive treatment after removal from a contaminated site and prior to land disposal, unless a variance is granted. If either the scrubber liquor or the vitrified slag is a hazardous waste which does not meet its pertinent treatment standard, additional treatment will be required prior to land disposal. Incineration may be the Best Demonstrated Available Treatment (BDAT) prior to disposal of any solid residue in a certified landfill. Precipitation and/or carbon adsorption may be necessary for any waste scrubber liquor.

3.6.1.4 Clean Water Act

The Clean Water Act (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. Typical operation of the Retech system does generate liquid discharge streams. Occasionally, the system cooling water circuits are flushed. It is anticipated that this cooling water will be discharged into the sanitary sewer. 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. The cooling water may contain rust inhibitor or other water conditioners at unregulated levels.

3.6.1.5 Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) establishes primary and secondary national drinking water standards. Provisions of the Safe Drinking Water Act apply to remediation of Superfund sites. CERCLA Sections 121(d)(2)(A) and (B) explicitly mention three kinds of surface water or groundwater standards with which compliance is potentially required - Maximum Contaminant Level Goals (MCLGs), Federal Water Quality Criteria (FWQC), and Alternate Concentration Limits (ACLs) where human exposure is to be limited. CERCLA describes those requirements and how they may be applied to Superfund remedial actions. The guidance is based on Federal requirements and policies; more stringent, promulgated state requirements may result in application of even stricter standards than those specified in Federal regulations.

3.6.2 State and Local Regulations

Compliance with ARARs may require meeting state standards that are more stringent than Federal standards or may be the controlling standards in the case of non-CERCLA treatment activities. Several types of state and local regulations which may affect operation of the Retech system are cited below:

- permitting requirements for construction/operation,
- prohibitions on emission levels, and
- nuisance rules.

3.7 Personnel Issues

3.7.1 Operator Training

Training required for an operator of the Retech system includes that required by all hazardous waste incinerator operators plus training specific to the Retech plasma furnace.

The training required of all hazardous waste incinerator operators is detailed in 40 CFR 264 Subpart B, Section 264.16, Subpart C on preparedness and prevention, as well as Subpart D on contingency plans and emergency procedures that also present issues central to personnel training.

Additional operator training, specific to the Retech system, is also required. This is necessary in order to develop a safe and effective operating technique for this unique treatment operation. Use of the plasma torch and high voltage also demand special operator training.

3.7.2 Health and Safety

The health and safety issues involved in using the Retech system for waste immobilization are generally the same as those that apply to all hazardous waste treatment facilities as detailed in 40 CFR 264 Subparts B through G, and Subpart X. Specific issues including high temperature operation induced by the plasma torch and high voltage must also be taken into consideration.

3.7.3 Emergency Response

The emergency response training for using the Retech system is the same general training required for operating a treatment, storage and disposal (TSD) facility as detailed in 40 CFR 264 Subpart D. Training must address fire and containment-related issues such as extinguisher operation, hoses, sprinklers, hydrants, smoke detectors and alarm systems, self-contained breathing apparatus use, hazardous material spill control and decontamination equipment use, evacuation, emergency response planning, and coordination with outside emergency personnel (e.g., fire/ambulance).

3.8 Summary

The Retech, Inc. Plasma Centrifugal Furnace is an innovative thermal technology that can treat wastes contaminated with both organic and inorganic compounds. For this reason, this technology may be useful in the treatment of Superfund site wastes.

The main disadvantages of this system are high particulate emissions, high NO_x concentrations in the stack gas, and the cost of remediation. The problem of the high particulate emissions can easily be rectified by means of a more efficient gas scrubbing system. The high NO_x levels in the stack gas result from the use of air as the torch and purge gases. Alternate torch and purge gases may negate or substantially reduce NO_x emissions. This will be investigated as part of DOE portion of these studies. The NO_x levels in the exhaust stream may be of concern with state and regional regulatory agencies. Many states have more stringent requirements than that of the Federal Government. Federal requirements state that the NO_x emission rate must be less than 9.2 lb/hr (40 tons/yr based on operation 365 days/yr, 24 hr/day). In some severely polluted areas of the country, this may be reduced to 2.2 lb/hr (10 tons/yr per based on operation 365 days/yr, 24 hr/day.) The PCF-6 does not exceed this 9.2-lb/hr standard, but the concentration in the stack gas is high. Many state and regional authorities are basing the NO_x level requirements on concentration not emission rates. These stringent requirements will necessitate the installation of expensive NO_x control devices for the PCF, further increasing the cost of remediation. A full discussion of the costs of this technology is presented in Section 4.

Section 4

Economic Analysis

4.1 Introduction

The primary purpose of this economic analysis is to estimate costs (not including profits) for a commercial-size treatment utilizing the Retech Plasma Centrifugal Furnace (PCF) system. The PCF-6 used during the Demonstration Test is a pilot-scale treatment technology (feed rate of 120 to 200 lb/hr) and may not be as cost efficient as a full-scale unit (PCF-8, feed rate of 2,200 lb/hr). The costs associated with the PCF, 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, forming the basis for the estimated cost analysis presented in Tables 5 and 6. The costs presented are based upon installing and operating the PCF at a fixed facility and treating a total of 2,000 tons of contaminated waste.

The actual Demonstration Test treated approximately 1,440 lb of contaminated soil at a feed rate of 120 lb/hr and a weekly prorated on-line percentage of 70% (prorated based on 2 startups/wk and operating 24 hr/day, 5 days/wk). Typical on-line conditions of the PCF range from 50% to 70%. With the feed system used during the Demonstration Tests, the PCF-6 has reached a maximum feed rate of approximately 200 lb/hr. By utilizing an improved feed system (such as a continuous hopper system), a feed rate of 500 lb/hr is expected. With such a feeder system, along with a new power supply and torch, the PCF-6 may reach a feed rate of 1,000 lb/hr. Since the PCF-6 used during the Demonstration Tests was pilot-scale, and therefore was probably not as cost effective as a full-scale unit, cost calculations were performed for 120, 500, and 1,000 lb/hr configurations of the pilot-scale PCF-6. Costs were also estimated for a full-scale PCF-8 (2,200 lb/hr). The costs presented in Table 5 are based on:

- a feed rate of 500 lb/hr,
- an operating time of 24 hr/day, 5 days/wk, 50 wk/yr,
- two starts of the PCF-6 per wk,
- 50%, 60%, and 70% on-line percentages,
- operation of the PCF at a fixed facility, and
- treating a total volume of 2,000 tons of waste.

The on-line percentage takes into account startup time and periodic shutdowns to respond to maintenance or operational problems.

Table 6 shows the costs for a PCF-6 operating with feed rates of 120, 500, and 1,000 lb/hr and 50%, 60%, and 70% on-line conditions. Table 6 also lists the estimated cost of a full-scale PCF-8 operating at a feed rate of 2,200 lb/hr and on-line conditions of 50%, 60%, and 70%. The cost estimates presented in Table 6 are based on:

- an operating time of 24 hr/day, 5 days/wk, 50 wk/ yr,
- two starts of the PCF per wk,
- operating the PCF at a fixed facility, and
- treating a total of 2,000 tons of contaminated waste.

Costs which 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 (—) on Tables 5 and 6. Categories with no costs associated with this technology are indicated by a zero (0) on Tables 5 and 6.

Important assumptions regarding operating conditions and task responsibilities that could significantly impact the cost estimate results are presented below:

- The cost estimates presented in this analysis are representative of charges typically assessed to the client by the vendor and do not include profit. Costs such as preliminary site preparation, permits and regulatory requirements, initiation of monitoring programs, waste disposal, sampling and analyses, and site cleanup and restoration are considered to be the responsible party's (or site owner's) obligation and are not included in the estimate presented. These costs tend to be site specific and are left to the reader to perform the calculations relevant to each specific case. Whenever possible, applicable information is provided on these topics so that the reader may perform the calculations to obtain relevant economic data.

- For hypothetical 100% on-line conditions, the treatment rate is the same as the feed rate of the PCF-6 during the SITE Demonstration Tests; 120 lb/hr. Two factors limit the treatment rate: the feed rate and the on-line percentage. Increasing the feed rate and the on-line percentage or both greatly reduces the cost per ton.

Table 5. Estimated Costs in $/Ton of the PCF-6[a]

Factor Feed Rate of 500 lb/hr, Treating a total of 2,000 Tons	On-Line Factor 50%	60%	70%
Residuals & Waste Shipping, Handling & Transport Costs			
Preparation	—	—	—
Waste disposal	—	—	—
Total Residuals & Waste Shipping, Handling & Transport Costs	—	—	—
Analytical Costs			
Operations	0	0	0
Environmental monitoring	—	—	—
Total Analytical Costs	0	0	0
Facility Modification, Repair, & Replacement Costs			
Design adjustments	0	0	0
Facility modifications	0	0	0
Scheduled maintenance (materials)	82	68	58
Equipment replacement	0	0	0
Total Facility Modification, Repair, & Replacement Costs	82	68	58
Site Restoration Costs			
Site cleanup and restoration	—	—	—
Permanent storage	0	0	0
Total Site Restoration Costs	0	0	0
Total Operating Costs($/Ton)	2,447	2,079	1,816

[a] Cost for treating a total of 2,000 tons of contaminated soil.
[b] This cost is reported in "$", not "$/ton". It is not used directly, but is used for estimating other costs (ie., annualized equipment cost, insurance and taxes, scheduled maintenance, and contingency).
[c] This cost is estimated at less than one dollar per ton of waste treated.

Table 6. Summary of Estimated Costs in $/Ton for Various Feed Rates and On-line Operating Conditions

Treatment of 2,000 Tons of Contaminated Soil	PCF-6 120 Lb/Hr On-line Factor			PCF-6 500 Lb/Hr On-line Factor			PCF-6 1,000 Lb/Hr On-line Factor			PCF-8 2,200 Lb/Hr On-line Factor		
	50%	60%	70%	50%	60%	70%	50%	60%	70%	50%	60%	70%
Site Preparation Costs	179	154	137	66	61	56	49	46	44	39	38	37
Permitting and Regulatory Costs	—	—	—	—	—	—	—	—	—	—	—	—
Equipment Costs	998	831	713	252	210	180	141	118	101	140	117	100
Startup and Fixed Costs	2,167	1,808	1,552	559	468	405	323	273	239	331	282	250
Labor Costs	5,334	4,444	3,809	1,280	1,066	914	640	534	458	291	242	208
Supplies Costs	20	20	20	20	20	20	20	20	20	20	20	20
Consumables Costs	590	581	575	188	186	183	123	121	120	112	111	110
Effluent Treatment and Disposal Costs	0	0	0	0	0	0	0	0	0	0	0	0
Residuals & Waste Shipping, Handling & Transport Costs	—	—	—	—	—	—	—	—	—	—	—	—
Analytical Costs	0	0	0	0	0	0	0	0	0	0	0	0
Facility Modification, Repair, & Replacement Costs	323	269	231	82	68	58	46	38	33	45	38	32
Site Demobilization Costs	0	0	0	0	0	0	0	0	0	0	0	0
Total Operating Costs($/Ton)	9,611	8,107	7,037	2,447	2,079	1,816	1,342	1,150	1,015	978	848	757

- In order for the PCF-6 to operate at a fixed facility, the facility must have a secondary cooling water system of 350 gpm; an indoor structure to operate the furnace with a minimum vertical height of 30 ft; and 1,600 A, 480 V, 3-phase electrical power for the main furnace. The PCF-8 requires at least a 450 gpm secondary cooling water system; a 45 ft high indoor facility; and 2,000 A, 600 V, 3-phase electrical power. For these cost calculations it is assumed that the fixed facility will support all of these requirements of the PCF. The cost of preparing a facility to meet these requirements can be very high.

- Operations are assumed to be 24 hr/day (3 shifts), 5 days/wk, and 50 wk/yr. Based on an expected 60-hr average lifetime of the torch electrode, there will be 2 cold startups per week: 1 startup at the beginning of the week and the other to replace the torch electrode. Site preparation and initial equipment testing operations are assumed to be 12 hr/day, 5 days/wk. Excavation activities for site preparation will take place concurrent with treatment. Waste-specific equipment testing will take place before treatment is begun and is assumed to be one week long. These cost calculations are based on treating a total of 2,000 tons of waste.

- Transportation costs of the waste feed from a contaminant waste site to a fixed facility of the PCF are site- and waste-specific, and have not been included in these cost calculations.

- Operations for a typical shift require five workers: two feed operators, one maintenance operator, and two system operators. Each shift is assumed to be eight hours.

- Capital costs for equipment are not used directly, and are limited to the cost of the furnace and any additional equipment such as a feeder, a torch, a power supply, and a scrubber. Percentages of the total equipment cost are used for estimating purposes.

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

4.2 Results of Economic Analysis

Data gathered during the Demonstration Test indicates that a weekly prorated on-line factor of approximately 70% most closely represents the operating conditions during this period of time. The furnace was off-line to respond to operational problems and to bring the temperature of the furnace up to operating temperatures. This on-line percentage is prorated for one week operating 24 hr/day, 5 days/wk, and with 2 startups. Typical on-line percentages of the PCF range from 50% to 70%, thus cost calculations were performed for 50%, 60%, and 70% on-line conditions. The feed rate during the Demonstration Test was approximately 120 lb/hr. For this feed rate, and a total treatment volume of 2,000 tons of contaminated waste, the results of the analysis show a cost-per-ton range from $7,037 to $9,611 for 70% and 50% on-line conditions, respectively. These costs are considered to be order-of-magnitude estimates as defined by the American Association of Cost Engineers, with an expected accuracy within +50% and -30%; however, because this is a new technology, the range may actually be wider. Since the PCF-6 is currently at the pilot-scale level, the cost per ton of soil treated is very high. If the PCF-6 is adapted to operate at a 500 lb/hr or 1,000 lb/hr feed rate, and with on-line conditions from 50% to 70%, the cost-per-ton range is far less; from $1,816 to $2,447 and from $1,015 to $1,342, respectively. For the full-scale unit (PCF-8), the cost-per-ton ranges from $757 to $978 for 70% and 50% on-line conditions, respectively. A PCF operating at 120, 500, 1,000, and 2,200 lb/hr will take approximately 9.4, 2.4, 1.1, and 0.5 years to cleanup 2,000 tons of waste, respectively.

Figure 1 presents a breakdown of the costs for each of the twelve cost categories for a feed rate of 500 lb/hr. Figure 2 presents the relative treatment cost of a PCF operating at a feed rate of 120 to 2,200 lb/hr and on-line conditions of 50%, 60%, and 70%. Both Figures 1 and 2 are based on treating a total of 2,000 tons of contaminated waste. The results show that, for a feed rate of 500 lb/hr, the technology is labor-intensive with approximately 52% of the total cost attributed to labor. For higher treatment rates of the PCF-6, the percentage of labor cost contributing to the total cost decreases, but the technology is still labor-intensive. The startup and fixed costs of the PCF-8, operating at 2,200 lb/hr, make up approximately 33% of the total cost, while labor makes up approximately 29%. Together labor and startup and fixed costs make up 77%, 74%, 70%, and 62% of the total operating cost of a PCF operating at 120, 500, 1,000, and 2,200 lb/hr, respectively. These costs can be reduced by increasing the on-line percentage and feed rate, thus increasing the actual treatment rate and decreasing the treatment time required.

4.3 Basis for Economic Analysis

The cost analysis was prepared by breaking down the overall cost into 12 categories:

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

The 12 cost factors examined as they apply to the Plasma Centrifugal Furnace process, along with the assumptions employed, are described in detail below. Except where specified, the same assumptions were made for the costs of operating a PCF at 120, 500, 1,000, and 2,200 lb/hr.

4.3.1 Site and Facility Preparation Costs

For the purposes of these cost calculations "site" refers to the location of the contaminated waste and "facility" refers to the fixed location where the PCF is operated. The contaminant waste must be transported from the site to the fixed facility of the PCF.

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 estimate.

Additional site preparation requirements peculiar to the plasma centrifugal reactor are assumed to be performed by the prime contractor (Retech). These site preparation activities include excavation of hazardous waste from the contaminated site and storing the waste in sealed containers prior to treatment by the furnace.

Cost estimates for site preparation are based on operated heavy equipment rental costs, labor charges and equipment fuel costs. It is assumed, to achieve an excavation rate of approximately nine tons/hr, the minimum rental equipment required is: three excavators, one box dump truck, and one backhoe. An excavator is available for $1,260/wk, a box dump truck is available for $525/wk, and a backhoe is available for $585/wk. The minimum labor required is one supervisor at $40/hr, three excavator operators at $30/hr each, one box dump truck operator at $30/hr, and one backhoe operator at $30/hr. Diesel fuel consumption is estimated at three gal/hr/excavator, two gal/hr/box dump truck, and three gal/hr/backhoe. Diesel fuel prices fluctuate with supply and demand and current market prices, however, for these calculations it is assumed to be $1/gal. It is assumed that excavation activities will operate on a 12 hr/day and a 5 day/wk basis.

Transportation costs of the contaminated waste from the site to the fixed facility of the PCF are very site- and waste-specific and have not been included in these cost calculations.

For the purposes of these cost calculations installation costs are limited to transportation and assembly costs of the PCF. The installation cost has been annualized based on a 15-year life of the equipment and a 6% annual interest rate. The annualized installation cost is based upon the writeoff of the total installation cost, using the following equation:

$$\text{Annualized Installation Cost} = (V)\ \frac{i\,(1+i)^n}{(1+i)^n - 1}$$

Where V is the cost of installation (assumed to be limited to transportation and assembly costs),
n is the equipment life (15 years), and
i is the annual interest rate (6%).

Transportation costs are limited to trucking costs. Trucking charges include drivers and are based on a 40,000 lb, 48-ft long, 8-ft high legal load. Five tractor/trailers are required to transport the PCF-6 and six trailers are required to transport the PCF-8. A 1,000 mile basis is assumed at a rate of $1.65/mile/legal load.

Assembly consists of unloading the PCF from the trailers, assembling the furnace, and shakedown testing of the PCF to check out each of the furnace subsystems individually. Assembly costs include laying foundations, installation of structural steel, piping, wiring, and instrumentation, as well as other miscellaneous installation tasks. Assembly costs are assumed to be $250,000. This assumption is based on the assembly of the PCF-6 at the Component Development and Integration Facility (CDIF) during spring of 1989.

Utility connections and auxiliary buildings required for the PCF to operate at a fixed facility can be very expensive. These costs depend on the fixed facility where the PCF is installed, and must be considered in site-specific cost calculations.

4.3.2 Permitting and Regulatory Costs

Permitting and regulatory costs are generally the obligation of the responsible party (or site owner), not that of the vendor. These costs may include actual permit costs, system monitoring requirements, and the development of monitoring and analytical protocols. Permitting and regulatory costs can vary greatly because they are site- and waste-specific. No permitting costs are included in this analysis, however depending on the treatment site, this may be a significant factor since permitting activities can be very expensive and time-consuming.

4.3.3 Equipment Costs

Equipment costs include major pieces of equipment (the plasma centrifugal furnace), purchased support equipment (a small mobile crane), and rental equipment (none). Support equipment refers to pieces of purchased equipment necessary for operation.

The plasma furnace used during the Demonstration Tests is a pilot- scale unit, with a maximum feed rate of about 200 lb/hr. The equipment cost of this PCF-6 is $1,538,000. Replacement of the current scrubber with an improved version, in order to reduce the volume of scrubber effluent, would add approximately $400,000 to the equipment cost. To increase the feed rate to approximately 500 lb/hr a new feeder would be required. The cost of a larger capacity feeder (500 lb/hr), with a hopper for loading waste would be approximately $100,000. With this new feeder and a new power supply and torch, it is estimated that the PCF-6 could reach a feed rate of 1,000 lb/hr. The cost of a new power supply and torch would be approximately $250,000. For the purposes of these cost calculations, it is assumed that an improved scrubber is in place, thus making the cost of a PCF-6 operating at 120, 500, and 1,000 lb/hr a total of $1,938,000, $2,038,000, and $2,288,000, respectively. Retech has already developed a larger furnace that has an estimated feed rate of 2,200 lb/hr (PCF-8), and an approximate equipment cost of $5,000,000.

The annualized equipment cost is based on a 15-yr life of the equipment and a 6% annual interest rate. The annualized equipment cost is based upon the writeoff of the total initial capital equipment cost and scrap value [2,3] (assumed to be 10% of the original equipment cost) using the following equation:

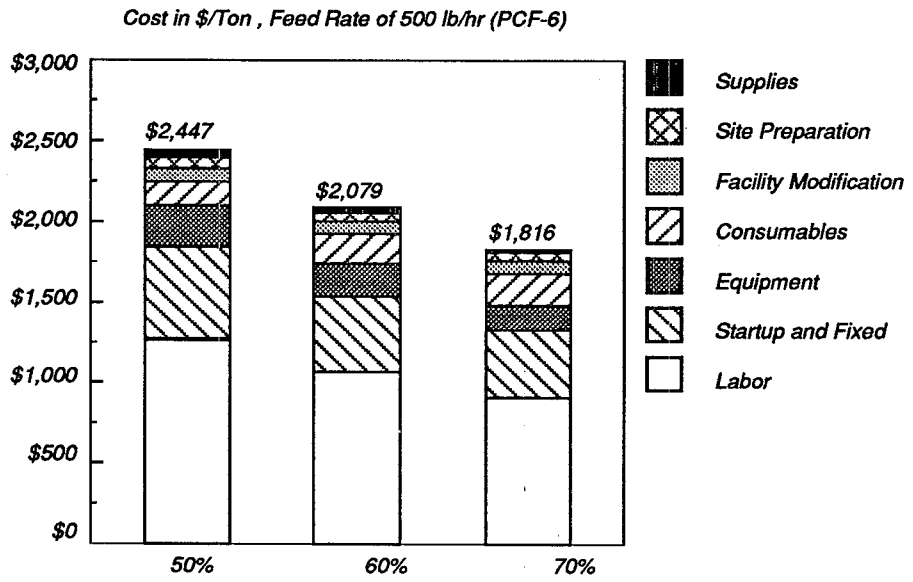

Figure 1. Summary of cost breakdown for 12 cost categories.

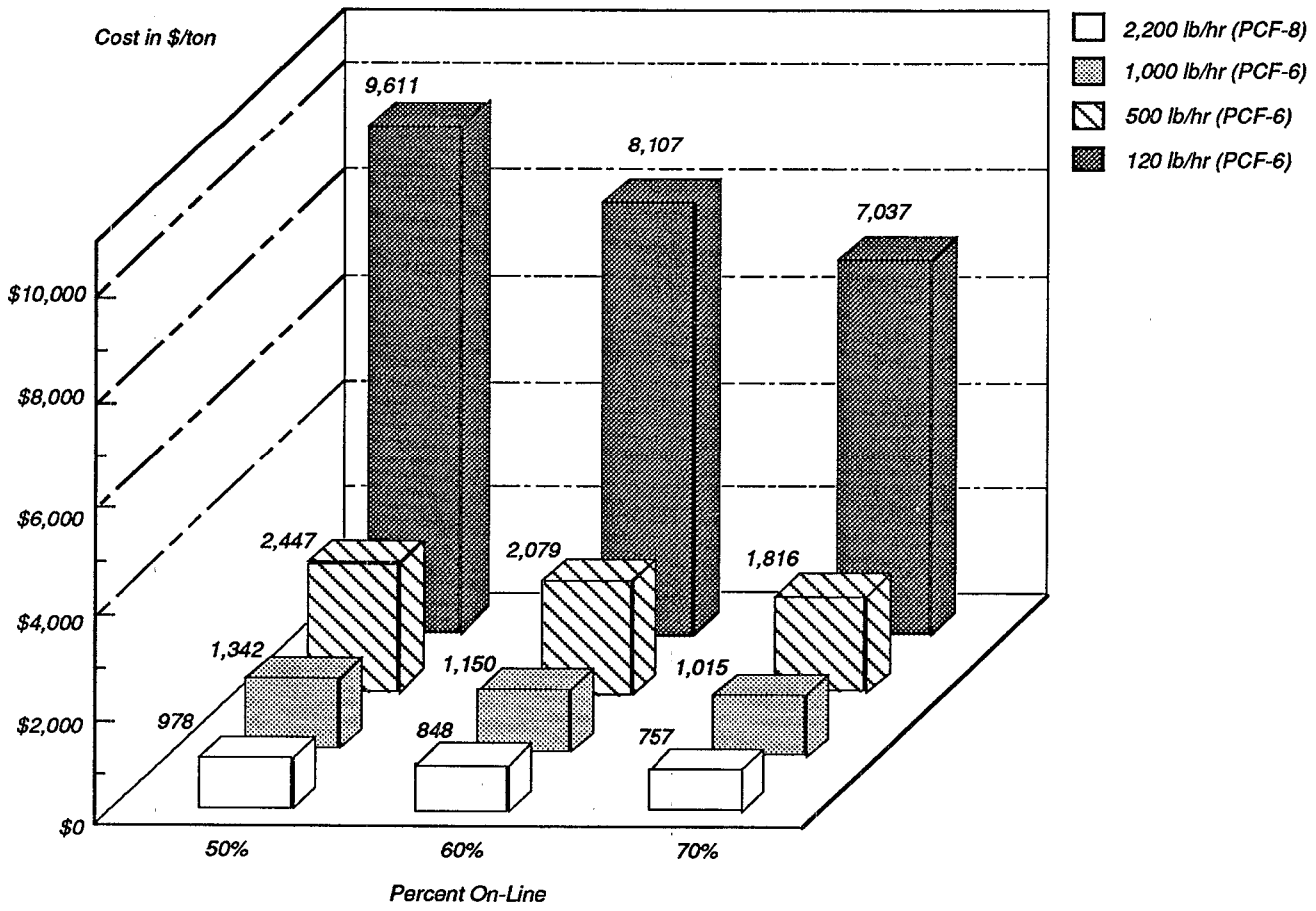

Figure 2. Summary of overall treatment costs of a PCF-6 and a PCF-8.

$$\text{Capital Recovery} = (V - Vs)\ \frac{i\,(1+i)^n}{(1+i)^n - 1}$$

Where V is the cost of the original equipment,
Vs is the salvage value of the equipment,
n is the equipment life (15 years), and
i is the annual interest rate (6%) [2,3].

4.3.4 Startup and Fixed Costs

For each project the PCF is commissioned (prior to the commencement of treatment) a period of one week is required for waste-specific testing of the furnace. This includes checking out each of the systems individually for the particular waste to be treated, prior to starting up the entire PCF. Seven workers are required for 12 hr/day, 5 days/wk during the waste-specific equipment testing. Costs of initial equipment tests is limited to labor charges at a rate of $40/hr.

Working capital is based on the amount of money currently invested in supplies and consumables. The working capital costs of supplies and consumables is based on maintaining a one-month inventory of these items. (See "Supplies Cost" and "Consumables Cost" for the specific amount of supplies and consumables required for the operation of the PCF. These quantities were used to determine the amount of supplies and consumables required to maintain a one-month inventory of these items.)

Insurance and taxes are usually approximately 1% and 2 to 4% of the total equipment capital costs, respectively. The cost of insurance of a hazardous waste process can be several times more than this. Insurance and taxes together are assumed for the purposes of this estimate to be 10% of the equipment capital costs [3].

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

A contingency cost of 10% of the equipment capital costs is allowed for any unforeseen or unpredictable cost conditions, such as strikes, storms, floods, and price variations [3,4].

4.3.5 Labor Costs

Labor costs are limited to salaries. Personnel required per shift is estimated at: 2 feed operators at $25/hr, 2 system operators at $40/hr and one maintenance operator at $30/hr. Rates include overhead and administrative costs. It is assumed that personnel will work an average of 40 hr/wk, thus there will be 3 shifts for a 24-hr 5-day/wk operation. Table 7 shows the labor costs for operating a PCF-6 with feed rates of 120, 500, and 1,000 lb/hr and a PCF-8 with a feed rate of 2,200 lb/hr.

4.3.6 Supplies Costs

Based on data from previous operations, over a period that reflects operating conditions similar to those experienced during the Demonstration Tests, the costs for chemicals, spare parts, and office/general supplies that are actually used to treat each ton of waste are estimated at $20. Chemicals consist of caustic soda for the neutralization of the scrubber liquor and flocculent for water treatment.

4.3.7 Consumables Costs

Natural gas is required at approximately 4 scfm during startup and while the PCF-6 is on-line. The cost of natural gas for these cost estimates is assumed to be $5.00/million BTU, with no monthly fee. The PCF-6 also requires 16 scfm of oxygen and 11 scfm of argon. The cost of oxygen and argon is estimated at $0.252/100 cf and $0.435/100 cf, respectively.

The full-scale PCF-8 operating at 2,200 lb/hr does not require this 4 scfm of natural gas, but requires supplementary fuel to startup the furnace and oxygen to promote combustion, both available for an estimated cost of $40/ton of waste treated.

The cooling water systems utilized by the PCF are all assumed to be closed, therefore the only water required is for the initial charge to the cooling water systems. With the scrubber system used during the Demonstration Test, it is estimated that 250 gal of scrubber wastewater per ton of waste treated will be generated. With a new scrubber in place, it is estimated that nearly all of the scrubber water will be recycled back into the scrubber sump. For these cost estimates it is assumed that an improved scrubber is in operation and the PCF will require 50 gal of water per ton of waste treated.

For the purposes of these cost calculations the following water rates, available for commercial use in Butte, MT are used:

- first 1,000 cf $1.47/100 cf
- next 4,000 cf $1.38/100 cf
- next 5,000 cf $1.17/100 cf
- next 60,000 cf $1.10/100 cf
- next 930,000 cf $0.89/100 cf

The electricity required for the PCF is limited to the electricity utilized by the plasma torch. During the Demonstration Test the torch used approximately 430 kW of electricity. These cost estimates assume that the PCF will require:

- 430 kW for 120 lb/hr feed rate;
- 600 kW for 500 lb/hr feed rate;
- 800 kW for 1,000 lb/hr feed rate; and
- 1,200 kW for 2,200 lb/hr feed rate.

These cost estimates assume a flat rate of $0.06/kWh and no monthly charge.

4.3.8 *Effluent Treatment and Disposal Costs*

One effluent stream is anticipated from the Plasma Centrifugal Furnace process. This is the wastewater generated from the scrubber system. The slag generated by the PCF process is assumed to be a residual; see "Residuals and Waste Shipping, Handling and Transport Costs". Assuming the implementation of an improved scrubber it is estimated that 4 lb of scrubber discharge (a sludge) per ton of soil treated will be generated.

Onsite facility costs are restricted to onsite storage of the wastewater or sludge and assumed to be the obligation of the site owner or responsible party. It is assumed that the wastewater or sludge will be stored in approved 55-gal drums.

Off-site facility costs consist of wastewater disposal fees and are assumed to be the obligation of the responsible party (or site owner), not Retech. The disposal fee of both scrubber water or sludge is estimated at $100/55 gal drum. The volume of scrubber effluent generated will be less with a new and more efficient scrubber, thus lowering the disposal cost; however the capital cost and other costs dependent upon the capital cost will be higher. At a feed rate of 120 lb/hr and 50% on-line condition the overall treatment cost (including disposal cost) of the PCF-6 varies little whether it is configured with the scrubber used during the Demonstration Tests or a new improved scrubber in operation. At higher feed rates and higher on-line percentages, replacing the scrubber with a more efficient scrubber produces a significant cost savings over operating the PCF-6 with the old scrubber (if disposal costs are included in the overall treatment costs). The PCF-8 already has a more efficient scrubber system than the one used in the PCF-6 system during the Demonstration Tests.

Disposal cost of the scrubber effluent with the scrubber used in the Demonstration Tests in place are estimated at $455/ton of waste treated. With the new scrubber (discussed above) in place the disposal cost of scrubber effluent is estimated at $1/ton of waste treated. These are only estimates. Disposal costs are highly dependent upon the type and volume of hazardous waste generated.

4.3.9 *Residuals and Waste Shipping, Handling and Transport Costs*

Waste disposal costs include storage, transportation and treatment costs and are assumed to be the obligation of the responsible party (or site owner). It is assumed that the only residual or solid wastes generated from this process is the slag. Landfill is the anticipated disposal method for this material.

The slag generated by the furnace is anticipated to be non- leachable. If the slag can be delisted, it is assumed that it may be disposed of for $10/ton of slag. Delisting costs are highly dependant upon the type of waste being treated. If the slag can not be delisted, it will be considered a hazardous waste, and disposal cost may be much higher (dependant upon the type of waste).

4.3.10 *Analytical Costs*

No analytical costs during operations are included in this cost estimate. Standard operating procedures for Retech do not require planned sampling and analytical activities. Periodic spot checks may be executed at Retech's discretion to verify that equipment is performing properly and that cleanup criteria are being met, but costs incurred from these actions are not assessed to the client. The client may elect, or may be required by local authorities, to initiate a sampling and analytical program at their own expense.

The analytical costs associated with environmental monitoring have not been included in this estimate due to the fact that monitoring programs are not typically initiated by Retech. Local authorities may, however, impose specific sampling and monitoring criteria whose analytical requirements could contribute significantly to the cost of the project.

4.3.11 *Facility Modification, Repair and Replacement Costs*

Maintenance costs are assumed to consist of maintenance labor and maintenance materials. Maintenance labor and ma-

Table 7. Summary of Estimated Labor Costs in $/Ton for Various Feed Rates and On-line Operating Conditions

Treatment of 2,000 tons of Contaminated Soil

			PCF-6 120 Lb/Hr On-line Factor			PCF-6 500 Lb/Hr On-line Factor			PCF-6 1,000 Lb/Hr On-line Factor			PCF-8 2,200 Lb/Hr On-line Factor		
Operators	# of oper. per shift	Rates ($/hr)	50%	60%	70%	50%	60%	70%	50%	60%	70%	50%	60%	70%
			Labor Cost ($/ton)			Labor Cost ($/ton)			Labor Cost ($/ton)			Labor Cost ($/ton)		
Feed Operators	2	25	1,667	1,389	1,190	400	333	286	200	167	143	91	76	65
Maintenance Operators	1	30	1,000	833	714	240	200	171	120	100	86	55	45	39
System Operators	2	40	2,667	2,222	1,905	640	533	457	320	267	229	145	121	104
Total			5,334	4,444	3,809	1,280	1,066	914	640	534	458	291	242	208

terials costs vary with the nature of the waste and the performance of the equipment. Maintenance labor has previously been accounted for under "Labor Costs". For estimating purposes the annual maintenance materials cost is assumed to be 3% of equipment capital costs. Costs for design adjustments, facility modifications, and equipment replacements are included in the maintenance costs.

4.3.12 Site Restoration Costs

Site cleanup and restoration is limited to the removal of all excavation equipment from the site. Filling, grading or recompaction requirements of the soil will vary depending on the future use of the site and are assumed to be the obligation of the responsible party.

4.4 Future Development of a Transportable PCF

Retech plans to develop a transportable PCF that will be able to treat hazardous waste onsite, rather than having to transport the contaminated waste from a hazardous waste site to the fixed facility of the PCF. The PCF-6 and the PCF-8 are expected to fit on 5 and 6 transportable trailers, respectively. This will replace the installation cost of a fixed PCF and the transportation cost of the waste feed from the site to the fixed facility of the PCF with: transportation; reassembly; and disassembly costs of the PCF at each site the furnace is commissioned to treat contaminated waste. Labor costs for a transportable PCF would have to include both salaries and living expenses. Living expenses depend upon several factors: the duration of the project, the number of local workers hired, and the geographical location of the project. Depending on the length of the project, Retech may elect to hire local personnel and train them to operate the furnace, thus eliminating living expenses.

The cost of operating a PCF as a transportable technology would be approximately 30% higher than the cost of operating the PCF at a fixed facility (if only the costs calculated in this report are considered). This is an approximate estimate, based on treating a total volume of 2,000 tons of waste and a per diem of $60/day/operator.

References

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Appendix A

Process Description

A.1 Introduction

The Plasma Centrifugal Furnace (PCF), developed by Retech, uses heat generated from a plasma torch to melt and vitrify solid feed material. Organic components are vaporized and decomposed by the intense heat of the plasma and are oxidized by the air used as the plasma gas, before passing to the off-gas treatment system. Metal-bearing solids are vitrified into a monolithic nonleachable mass.

The Retech PCF system is comprised of a thermal treatment system and an exhaust gas treatment system, shown conceptually in Figure A-1. The thermal treatment system consists of:

- a feeder;
- a primary chamber;
- a plasma torch;
- an afterburner;
- a secondary chamber; and
- a collection chamber.

The exhaust gas treatment system consists of:

- a quench tank;
- a jet scrubber;
- a packed-bed scrubber;
- a demister; and
- a stack blower.

A.2 The Thermal Treatment System

Hazardous waste is initially loaded manually, from sealed containers, into a spiral feeder. The waste is fed uniformly and continuously into the centrifugal reactor through a chute connecting the feeder to the primary chamber, which is a rotating tub with a central orifice, or copper throat.

The copper throat, at the bottom of the primary chamber, is used to strike the arc of the plasma torch. The torch is then moved slowly up and down the side of the primary chamber during heat up. Feeding of the waste material begins once the primary chamber's temperature is greater than 2,000°F and

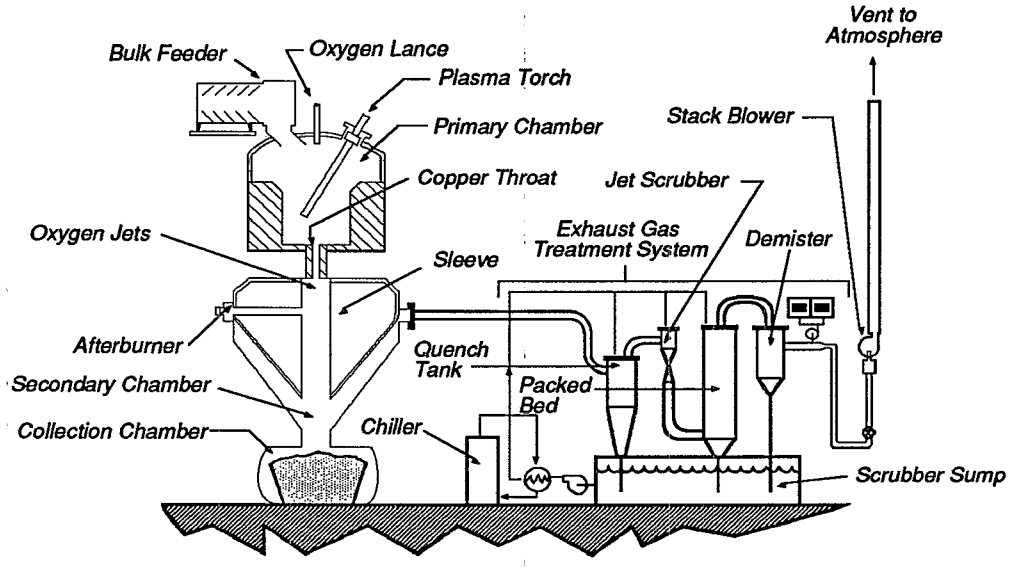

Figure A-1. Schematic of the Plasma Centrifugal Furnace

the secondary chamber's temperature is greater than 1,800°F. Solid material is retained in the tub by centrifugal force. The primary chamber walls have an inner shell with a water jacket welded between. A water/rust inhibitor cooling stream circulates between the shell and the jacket. At the copper throat, an area of high heat flux, the cooling water/rust inhibitor flow area is reduced to increase the cooling in this area.

The plasma torch uses electrical discharges to add energy to plasma torch gases in order to increase the gas temperature beyond that normally attainable by chemical reaction. The plasma torch produces a transferred arc that directly contacts a conducting portion (copper throat) of the centrifugal reactor. The heat generated by the plasma torch brings the waste material to temperatures sufficient to melt soil (typically on the order of 3,000°F). The waste is melted by this extreme heat, incorporating any inorganic and metal components into a stable material. Organic components are volatilized by the heat of the plasma and oxidized by the air used as the plasma gas. Oxygen may also be added from an oxygen lance in the primary chamber to enhance combustion of organics.

For this application, the torch uses approximately 20 scfm of air for plasma gas and is rated at 500 kW. It runs on direct current provided by a power supply that uses 3-phase input. The torch is cooled by a high velocity flow of distilled water.

After the feed material adjacent to the copper throat is heated to the conducting temperature, the torch is moved slowly to heat more of the soil on the bottom of the reactor and eventually the sidewall. As the torch is moved away from the center of the reactor, the reactor rotation is slowed to allow the molten soil to run towards the center of the reactor, where it begins to solidify. This is continued until the entire primary chamber has been treated by the torch.

Once the complete primary chamber has been treated, the torch is then used to melt the mass of soil at the copper throat. When the mass is melted, the reactor spin rate is slowed to allow the pool to move inward and the melted soil to pour out of the bottom of the reactor through the throat, past a natural gas afterburner. The afterburner does not operate during the pouring process.

The afterburner, located just downstream of the primary chamber, provides an additional heat input (beyond that supplied by the plasma torch) to combust products of incomplete combustion (PICs). The afterburner operates on a natural gas flame. The organics that are volatilized and oxidized are drawn off to the gas treatment system.

A camera port in the secondary chamber allows observation of the gases and slag exiting the throat. If needed, oxygen may be added from oxygen jets located in the secondary chamber to enhance combustion of organics. The secondary chamber walls have three inches of refractory lining to abate heat loss and protect the steel walls. These walls also form a jacketed vessel with cooling water circulating between them to maintain a safe operating temperature.

The molten mass falls from the secondary chamber into a heavy pig mold located in the collection chamber. The collection chamber is a cylindrically shaped, water-cooled, jacketed vessel. One end is closed off and the other end has a hinged door, where the pig molds are loaded and unloaded. Each mold can hold approximately 1,000 lb of vitrified slag.

A.3 Exhaust Gas Treatment System

Effluent gas treatment equipment is designed to suit requirements of the feed material. A typical gas treatment system may consist of: a quench tank, a jet scrubber, a packed-bed scrubber, and a demister.

A mildly caustic scrubber solution (pH maintained at 8.5) is used in the quench tank, jet scrubber, and packed-bed scrubber. The scrubber sump is equipped with a 50-ton chiller to cool the scrubber water circulating through the exhaust gas treatment equipment, so that all the moisture can be removed from the exhaust gases. The chilled scrubber water proceeds first to the quench tank, where it cools the exhaust gas stream from approximately 1,000 to 40 °F. From the quench tank, the scrubber water passes to a jet scrubber, which is designed to remove particulates and acid gases. A counter-flow packed-bed scrubber provides additional removal of acid gases. A demister then removes moisture droplets entrained in the flow.

The clean gases are emitted to the atmosphere through an exhaust stack. A stack blower at the exhaust stack maintains a negative pressure in the reactor system, preventing any leakage.

Appendix B

Vendor's Claims

This appendix summarizes the claims made by the developer, Retech, Inc., regarding the Plasma Centrifugal Furnace, the technology under consideration. This appendix was generated and written solely by Retech, Inc., and the statements presented herein represent the vendor's point of view. Publication here does not represent EPA's approval or endorsement of the statements made in this section; EPA's point of view is discussed in the body of this report.

Retech, Incorporated (Retech), the developer of the Plasma Centrifugal Furnace (PCF), states that the PCF system offers three advantages over conventional rotary kiln incineration in treating wastes. These are:

- The PCF process produces slag that meets the requirements for delisting and effectively destroys toxic organic compounds.
- The combination of vacuum-tight seals, sub-atmospheric operation, leach-resistant product and high DRE in the PCF process aids in obtaining community acceptance.
- Although PCF treatment costs are high ($600 to $1200/ton), the ability to obtain a final solution for a wide range of feedstocks makes this process cheaper in many cases than the total costs of other treatments.

Discussion of these claims is presented in the three sections following: B.1 Treatment Effectiveness, B.2 Community Acceptance, and B.3 Comparative Economics.

B.1 Treatment Effectiveness

Conventional incinerator ash frequently has identifiable metallic residues, and the proximate analysis of kiln bottom ash typically shows unburned carbon in the range of hundreds to thousands of parts per million. However, in the PCF process the mixing and intimate contact of unburned materials with the metal oxides in the slag eliminates all fixed carbon from the slag through carbon monoxide formation (the CO subsequently reacts to CO_2).

After cooling, the slag product from the PCF may be glassy (non-crystalline) or crystalline, or a mixture of the two. The degree of crystallinity is primarily determined by the nature and proportions of the various metal oxides present in the glass. The slag samples from the three SITE test runs reported herein all had a fairly uniform mix and had similar degrees of crystallinity. As noted in Section 3, all samples satisfied the TCLP criteria. Retech has done leach tests on PCF slag having different elemental compositions, resulting in a wide range of crystallinity; in all cases, the leach resistance of the slag formed was excellent.

To be delistable, solids must not represent a hazard to health or the environment due to their form or properties. Thus, the solids must not only pass TCLP tests in the form produced, but adverse treatment reasonably expectable should not result in so much deterioration that the material would then fail the tests. In one set of tests performed for Retech to assess the effect of particle size on leach resistance, slag crushed to -100 mesh met standards, but that crushed to -400 mesh had one metal in the leachate at an unsatisfactory level.

The SITE tests also evaluated the ability of the PCF-6 to destroy hazardous organics. Hexachlorobenzene was chosen as the additive to constitute a Principal Organic Hazardous Constituent (POHC) because it is high on the list of compounds hard to destroy, it contains chlorine, and it has a ring structure.

The quantity of hexachlorobenzene surviving was below the detection limit in every sample taken during the three tests. The sensitivity of the test was highest in the third SITE Demonstration Test, sufficient to show the DRE was at least "six 9's", i.e., >99.9999%. Furthermore, no Product of Incomplete Combustion (PIC) was found at a concentration higher than permissible. The total hydrocarbon content of the gas was congruent with this observation, well under 10 ppm.

The effluent stream in the Butte SITE tests was unsatisfactory in one respect - dust. This was a result of inadequate filtering. A production-size unit at Muttenz, Switzerland, was measured in a government-supervised trial burn to have an effluent dust load of 0.014, 0.0004, 0.0004, and 0.0004 grains per dry standard cubic foot (converted from metric measurement values of 14.0, 0.9, 0.9, and 0.9 mg/N°m³). Other measurements in the trial burn showed NO_x levels of 19 to 23 ppm at the stack (downstream of NO_x removal equipment). All the government requirements on effluent were met in this test.

The data from the Swiss tests show that the slag product meets the requirements for delisting, and that toxic organic compounds are destroyed effectively. SITE demonstration testing data also support this claim (see Appendix C).

B.2 Community Acceptance

One of the problems associated with conventional thermal treatment of hazardous wastes (i.e., rotary kilns) is that pressure excursions (alias "puffs") occur occasionally. Emitted fumes can contain incompletely burned, and thus potentially hazardous, substances.

The gas seals on rotary kilns operate at high temperatures, and essentially limit the flow to a quantity proportional to the square root of the pressure difference between the kiln interior and the outside atmosphere. The pressure difference at usual operating conditions is typically a few inches of water (4 in. of water column corresponds to 10 millibars or 1/100 of standard atmospheric pressure). Any pressure surges more than 10 millibars then result in leakage outward through the hot seal.

The PCF furnace chamber, in contrast, has gas-tight seals that do not permit untreated gas to escape, even at excess pressures of 1,000 millibars (14.7 psig) or more. Thus the risk of worker and community exposure is markedly reduced.

Retech's experience in locating its SITE test program is quite concordant with the statement above. After initial presentation of the concept to community leaders in August of 1988, newspaper stories described plans, and a media information day was organized in mid-November which started a public comment period. No significant adverse reaction was recorded.

A larger-scale plant (PCF-8) has been permitted in Muttenz, Switzerland, again with no significant community objection. In contrast, a plan by public authorities for siting a regional rotary kiln incinerator encountered so much resistance that the plan has been shelved.

As the developer, we believe the inherent features of the PCF process will help prospective users of the technology obtain the consent of local communities for siting a PCF facility.

B.3 Comparative Economics

The cost per ton of material fed into the PCF depends not only on the nature of the feed, but on the scale of the equipment and the circumstances of the treatment (e.g., short or long program at a Superfund site, or permanent installation). The sections below discuss the effects of scale, treatment costs with the PCF-8 (a larger unit than the pilot-scale PCF-6 used for the SITE Demonstration) and the costs of alternative treatments for the wastes for which PCF treatment is appropriate.

B.3.1 Effects of Scale

Retech's first PCF had a tub diameter of only 18 in. (i.e., a PCF-1.5, since the number in the furnace designation refers to the tub diameter measured in feet). We first operated it in September 1987 and learned quickly that a very leach-resistant slag was made when contaminated soils were placed in the furnace. A large number of tests have been made in the PCF-1.5 since then. The feeder system was improved to enable more uniform feeding of solids. Operating with air at about 150 kW, we found we could feed about 40 lb/hr of dirt. The specific energy consumption is then 3.8 kWh/per pound melted.

With the pilot-size PCF-6, operators at Butte found, in a series of shakedown runs, that they could melt about 500 lb/hr of soil with a torch power of 500 to 600 kW. The specific energy consumption at 500 kW and 500 lb/hr is then 1.0 kWh/lb. The SITE Demonstration tests were run at a significantly lower feed rate (only 120 lb/hr) to be compatible with a longer run time (8 hr) for demonstrating operability. (Total feed for the three replicate runs was limited to about 3,000 lb, in order to retain enough material for a fourth run (if one of the first three was found to be unusable.) The specific energy consumption during the three SITE runs, at 500 kW and 120 lb/hr., is 4.2 kWh/lb. With the PCF-8 in Muttenz, the feed rate with 1200 kW of torch power is one metric tonne per hour (2,200 lb/hr). At this size, the specific energy consumption is 0.55 kWh/lb.

It is clearly desirable to consider whether substantial further improvements are still possible. For this, we use two pieces of information. Large-scale *in situ* vitrification tests conducted by Battelle's Pacific Northwest Laboratories and a successor organization, Geosafe, resulted in a specific energy requirement of 0.7 kWh/kg or 0.32 kWh/lb. This is close to the value of about 1,000 Btu/lb. (0.29 kWh/lb) obtained from thermochemical data on typical soil constituents.

Table B-1 summarizes the above data and calculations. Considering the losses inherent in a water-cooled wall furnace, only modest further improvements in specific energy requirement can be expected at sizes larger than the PCF-8.

Because the feed rate with the PCF-8 is four times as high as the present configuration of the PCF-6, remediation times would be much more acceptable with the PCF-8. We believe it appropriate to use cost data for the PCF-8 when comparing PCF economics with alternatives.

B.3.2 Treatment Costs with the PCF-8

The PCF technology is useful both for onsite remediation and offsite treatment at a permanent location. The cost-per-ton treatment is a function of the quantity treated per setup for

Table B-1. Specific Energy Data for Various Types of Equipment

Equipment Type	*Melt Diameter (ft)*	*Specific Energy (kWh/lb)*
PCF-1.5	*1.2*	*3.8*
PCF-6	*4.5*	*1.0*
PCF-8	*7*	*0.55*
ISV	*30-40*	*0.32*
Theory	*Infinite*	*0.29*

onsite remediation. A brief cost analysis for treating the same hypothesized waste at a permanent location, at a Superfund site with 10,000 tons to treat, and at a Superfund site with 2,000 tons to treat is presented in the paragraphs below. The waste is assumed to average about 10% of contained organic by weight.

Assumptions: feed rate is 1 metric tonne/hr (1.1 short tons/hr), available operating time is six 24-hr days/wk for 50 wk/yr, material treated during 75% of the available operating time. Power consumption is assumed to be 1,500 kW, 1,200 kW as torch power and 300 kW for auxiliary equipment. Operations in Switzerland with the PCF-8 indicate that torch electrodes should be changed at the end of each one week run.

Then, per operating day:

Amount treated - 1.1 X 24 X 0.75 = 19.8 ton	
Power at 8/kWh - 1500 X $0.08 X 24 X 0.75 =	$2,160
Parts & chemicals - $20 X 24 X 0.75 =	360
Suppl. fuel & oxygen - $40 X 24 X 0.75 =	720
Labor (incl. maint.) at $40/hr - 5 X $40 X 24 =	4,800
Material handling @ $40/ton =	790
	$8,830
$/ton	$446

Capital cost is estimated at $8 X 10^6 for 5 yr. Payback, treating each year 19.8 tons X 50 X 6 = 5,940 TPY; the 5 year output would be 29,700 tons. Thus, for a permanent installation, the treatment cost would be $446 plus $269 cost of capital or $715/ton.

To treat 10,000 tons would take 505 operating days or about 84 weeks. The time to demobilize, transport and reinstall a transportable unit (on 6 or 7 trailers) is estimated at 9 weeks with a dollar outlay of about $300,000. Then the total cost per ton becomes:

Operating	$446
Capital $8 X 10^6 X (84 + 9)/(250 X 10,000)	298
Setup $300,000/10,000	30
	$774

To treat 2,000 tons would only take 101 operating days or about 17 weeks. The cost is then estimated as:

Operating	$446
Capital $8 X 10^6 X (17 + 9)/(250 X 2,000)	416
Setup $300,000/2,000	150
	$1,002

The above calculations assume that the capital cost for a permanent location are comparable with the costs of making the equipment transportable.

B.3.3 Costs for Hazardous Landfill

As of fall 1991, there still existed at least one landfill accepting hazardous waste at $800/ton (not including transportation). This might be economically preferred to PCF treatment for quantities less than 2,000 tons, unless one were to take into account the risk of having to remove and treat at some time in the future. If one were to assume the risk to be as low as 10% and the cost of removal and treatment as $2,000/ton, the comparative cost would be $1,002 for PCF at 2,000 tons versus $1,100 for hazardous landfill ($800 fee + $100 transportation to fill location + $200 for potential retreatment).

B.3.4 Costs for Shredding Plus Kiln Burning Plus Ash Stabilization

The PCF-8 can treat drummed waste (which most sites have a significant amount of), while acceptable kiln treatment would require shredding. For wastes where the kiln ash does not pass TCLP requirements, stabilization (making into concrete) can be done to meet the requirements, but the stabilized ash weighs more than the original ash (perhaps twice) and must still go into a landfill (however at considerably lower cost than the untreated material). The costs for such a transportable system are rather conjectural. We assume $200/ton for a shredder cost, $400/ton for the incineration cost and $150/ton of ash stabilized for stabilization cost. We assume the cost of admitting the stabilized material to a landfill is $100/ton of stabilized material (=$200/ton of original ash). Then the total cost for the alternative treatment would range from the value for 20% ash (200 + 400 + 0.2 X 350) = $670 to a value for 80% ash (200 + 400 + 0.8 X 350) = $880.

B.3.5 Summary Statement

The PCF system is least costly only when the subject material is difficult to treat or when many different types of material need to be treated by one process. The analysis above shows that when conventional methods do not provide a final solution in a one-step process, the PCF system can be less expensive.

The above statement is in accord with Retech's customer contacts. The greatest interest is shown by companies whose waste problems involve: a) both heavy metals and hard-to-destroy toxic organics, b) radioactive metals and organics together, or c) a wide variety of wastes to be treated in one facility.

Appendix C

SITE Demonstration Results

This section summarizes the results of the SITE demonstration of the Retech Plasma Centrifugal Furnace (PCF) system as they pertain to the evaluation of the developer's claims. These results are further discussed in Section 3 of this report. A more detailed account of the demonstration is found in the companion Technology Evaluation Report.

The demonstration activities consisted of three separate tests using the same feed soil throughout. Sampling of all process input and output streams was carried out in accordance with the Demonstration Plan [1].

These test results focus primarily on the leachability characteristics of the waste along with the Destruction and Removal Efficiency (DRE) achieved by the technology. Acid gas removal and particulate emissions, air emissions, continuous emission monitoring, test soil and treated soil characterization, and scrubber liquor characterization are also addressed.

C.1 Toxicity Characteristic Leaching Procedure

The Toxicity Characteristic Leaching Procedure (TCLP) was performed on both the feed soil and the produced slag. These results are discussed in detail in Section 3 of this report and summarized in Table 1. Testing activities indicated that the process effectively bound inorganic compounds into the treated soil. TCLP analysis of the feed soil for metals shows that the only elements exhibiting significant leachability characteristics during the Demonstration Tests were calcium and the spiked zinc; therefore, these compounds were selected as tracer compounds. (Sodium was present, but was not selected as a tracer compound because it does not behave in the same manner as other regulated metals.) None of the TCLP characteristic metals found in the feed soil leachate were above the regulatory limits.

Both tracer metals, calcium and zinc, showed significant reduction in leaching properties for the treated soil as compared to the feed. In fact, all of the metals, with the exception of aluminum, iron, and sodium showed reduced leachability characteristics. It is likely that the leachability of aluminum did not actually change, since the concentration in the leachate from both the feed and treated soil is low, and the values reported for the treated soil are only estimates (less than 5 times the quantitation limit). The increase in leachability of iron in the treated soil was due to the utilization of supplementary steel to aid in the start-up procedures, increasing the iron content of the feed considerably. Sodium leachability is discussed in greater detail in Section 3.

Although the feed soil was spiked with high levels of hexachlorobenzene (1,000 ppm), the only organic constituents that were found to be leachable from the feed soil were naphthalene and 2-methylnaphthalene. No organic compounds were found to leach from the treated slag.

C.2 Destruction and Removal Efficiency

Hexachlorobenzene was spiked into the feed soil at a level of 1,000 ppm. The DRE (used to determine organic destruction) was calculated for hexachlorobenzene, the Principal Organic Hazardous Compound (POHC), by analyzing the feed soil and the stack gas for this compound. The estimated mean level of hexachlorobenzene, based on all the feed soil samples for the three tests, was 972 ppm. The 95% confidence interval for the estimated mean was 864 to 1,080 ppm. Hexachlorobenzene was not detected at all in the stack gas. DRE calculations were, therefore, based on the stack gas detection limits from each of the tests.

DREs were also determined for 2-methylnaphthalene, a semivolatile contaminant, and total xylenes, a group of volatile compounds present in the feed soil. In both cases, DRE determinations were again based on detection limits since the compounds were not detected in the stack gas. The estimated mean level of 2-methylnapthalene in the feed soil was 458 ppm with a 95% confidence interval of 390 to 526 ppm.

For the Demonstration Tests, the estimated average DRE values for hexachlorobenzene ranged from >99.9968% to >99.9999%. Table 2 (Section 3) summarizes the DREs for each test based on the confidence interval of the feed soil and the detection limit for that particular test. For 2-methylnaphthalene, estimated average DREs ranging from >99.9872% to >99.9996% were attained during the Demonstration Tests. Total xylenes were present in the feed soil at an estimated mean level of 134 ppm (95% confidence limit of 128 to 139 ppm). The DREs determined for total xylenes were thus >99.9929% to >99.9934%. This range represents an average over all three Demonstration Tests since the detection limit

for the Volatile Organic Sampling Train (VOST) is identical in each case. These results are summarized and discussed in Section 3, Table 2.

C.3 Acid Gas Removal and Particulate Emissions

Measured HCl emission rates ranged from 0.0007 to 0.0017 lb/hr with an average emission rate of 0.0009 lb/hr. The chlorine concentration in the feed soil, as determined during Test 1, was low, 0.066%. The regulatory requirement of less than 4 lb/hr was met. The HCl removal efficiency was 98.5%.

As shown in Table 3 in the body of this report, particulate emissions during the three tests range from 0.24 to 0.42 grains/dscf (uncorrected for 7% O_2) with an average of 0.374 grains/dscf. This exceeds the RCRA regulatory limit of 0.08 grains/dscf. Even higher values are expected when correcting the results for 7% O_2 (see Section 3). The poor efficiency of the scrubber with respect to particulate removal is demonstrated by the fact that there was less than 0.5% total solids in the scrubber sump tank, an amount insufficient for sampling and analysis.

C.4 Air Emissions

The air emissions were chiefly comprised of products of incomplete combustion (PICs) and particulates. Table C-1 presents a summary of the semivolatile organic compounds emitted in the stack gas. The most dominant semivolatile organic compound released in the stack gas was benzoic acid at an average concentration of approximately 4 ppm. A group of nitrated compounds was detected at levels less than 0.3 ppm. Other compounds such as the phthalate groups and naphthalene were also present, but were found in the field blanks as well. Some Tentatively Identified Compounds (TICs) were present in the gas stream. No TICS could be positively identified for Test 1, but it appears that some of the unknowns contained oxygen somewhere in the molecular structure and some of the unknowns are nitrogen-containing compounds. In Test 2, several higher molecular weight compounds were detected. The TIC data indicates that these compounds were unidentifiable carbonic acids. Compounds

Table C-1. Stack Gas Composition

	Test 1				Test 2				Test 3			
	lb/100 lb feed		ppm		lb/100 lb feed		ppm		lb/100 lb feed		ppm	
Semivolatiles:												
Acetaophenone	<2.15E-06		<0.38		4.63E-06	J	0.71	J	2.30E-O6		0.031	
Benzoic Acid	3.77E-04		6.7		3.29E-04		4.9		1.98E-04		2.6	
Benzyl Alcohol	<4.95E-07		<0.0099		<1.65E-07		<0.0033		3.76E-07	J	0.0056	J
Butylbenzylphthalate	<3.28E-07		<0.0023		<1.09E-07		<0.00079		3.76E-07	J	0.0056	J
Dibutylphthalate	<9.93E-07	B	<0.0077	B	4.48E-06	JB	0.030	JB	1.15E-06	B	0.0067	B
Diethlyphthalate	<5.41E-05	B	<0.70	B	2.54E-05	B	0.28	B	2.50E-05	B	0.24	B
2,4-Dinitrolphenol	2.13E-05	J	0.25	J	1.27E-05	J	0.13	J	5.74E-06		0.050	
bis(2-Ethlyhexyl)phthalate	7.36E-05	B	0.41	B	5.08E-05	B	0.24	B	4.69E-06	B	0.019	B
Naphthalene	1.68E-05	B	0.26	B	8.96E-06	B	0.12	B	1.15E-05	B	0.134	B
Nitrobenzene	<3.13E-07	J	<0.0055	J	2.84E-06	J	0.042	J	1.56E-06		0.021	
2-Nitrophenol	<8.56E-06	J	<0.13	J	2.09E-06	J	0.028	J	1.36E-05		0.16	
4-Nitrophenol	1.15E-05	J	0.1849	J	<1.43E-05		<0.22		1.01E-05		0.12	
Metals:												
Aluminum	5.02E-04	B	1.339	B	9.56E-04	B	2.097	B	5.67E-04	B	1.139	B
Antimony	1.18E-05		0.031		4.16E-05		0.091		2.62E-05		0.053	
Arsenic	1.88E-03	B	5.020	B	2.98E-03	B	6.538	B	2.47E-03	B	4.966	B
Barium	4.26E-05	B	0.114	B	8.09E-05	B	0.177	B	6.11E-05	B	0.123	B
Beryllium	1.63E-07		0.000		3.58E-07		0.001		2.91E-07		0.001	
Cadmium	1.76E-05		0.047		3.99E-05		0.088		2.76E-05		0.056	
Calcium	8.41E-04	B	2.510	B	1.74E-03	B	3.807	B	9.60E-04	B	1.928	B
Chromium	3.39E-04	B	0.904	B	6.57E-04	B	1.441	B	7.27E-04	B	1.461	B
Copper	1.63E-03	B	4.351	B	4.71E-03	B	10.320	B	2.04E-03	B	4.090	B
Iron	1.51E-02	B	40.162	B	3.01E-02	B	66.125	B	4.51E-02	B	90.559	B
Lead	9.28E-04	B	2.477	B	2.29E-03	B	5.021	B	1.60E-03	B	3.213	B
Magnesium	2.01E-04	B	0.535	B	3.26E-04	B	0.716	B	2.47E-04	B	0.497	B
Manganese	1.14E-04	B	0.305	B	2.48E-04	B	0.544	B	3.20E-04	B	0.643	B
Mercury	1.38E-06	B	0.004	B	2.92E-06	B	0.006	B	5.09E-06	B	0.010	B
Nickel	6.65E-05	B	0.177	B	1.10E-04	B	0.372	B	1.74E-04	B	0.351	B
Potassium	3.76E-03		10.041		7.11E-03		15.586		6.69E-03		13.438	
Selenium	5.02E-06		0.013		1.11E-05		0.024		6.40E-06		0.013	
Silver	2.88E-06		0.008		6.32E-06		0.014		4.65E-06		0.009	
Sodium	2.26E-03	B	6.024	B	4.26E-03	B	9.351	B	3.78E-03	B	7.595	B
Thallium	5.52E-06		0.015		1.35E-05		0.030		1.25E-05		0.025	
Vanadium	2.76E-05		0.074		6.57E-05		0.144		4.51E-05		0.091	
Zinc	3.01E-02		80.325		8.36E-02	B	183.248	B	5.53E-02	B	111.008	B

B Indicates that this compound was detected in a blank.
J Estimated result. Indicates that result is less than the quantitation limit. Quantitation limit is five times the instrument detection limit.
< Not detected at or above the detection limit.

that eluted in the early stages of the chromatogram contained nitrogen and oxygen within their molecular structures. Test 3 data was very similar to that of Test 1. Generally, only low levels of semivolatile organic compounds were identified in the gas stream.

Very low levels of volatile organic compounds were detected in the exhaust gas stream. The most common of these compounds was benzene. Other identified compounds tended to be chlorinated organics which were not present in the feed soil and therefore can positively be identified as PICs.

No polychlorodibenzodioxins (PCDDs) or polychlorodibenzofurans (PCDFs) were detected above the blank sample detection limits. This indicates that PCDDs and PCDFs are not formed by the process when treating a highly chlorinated feed material. The detection limits for the blank samples were well within the levels defined by the SW-846 Method 8290.

The metals emissions in the stack gas were almost exclusively in the solid phase. Table C-1 summarizes these results. The only metals present in significant amounts in the vapor phase were calcium and mercury. Arsenic, copper, iron, lead, potassium, and zinc were in abundance in the solid phase in the stack gas. The air emission data shows that the air pollution control system did not capture the metals with any degree of efficiency. This is further displayed by the analysis of the scrubber water which did not contain high levels of metals at the conclusion of the tests.

C.5 Test Soil and Treated Slag

The feed soil consisted of a mixture of Silver Bow Creek Superfund Site soil (a heavy metal-bearing soil) and 10% by weight No. 2 diesel oil. One thousand ppm of hexachlorobenzene and 28,000 ppm of zinc oxide (corresponding to 22,500 ppm zinc) were spiked into this mixture. The estimated means of the organic constituents of the feed are presented in Table C-2 and are based on all three Demonstration Tests since the feed soil was homogenized prior to testing. Metals concentration in the feed soil for all three Demonstration Tests is presented in Table 4 in Section 3.

Table C-2. Organic Compounds in the Feed Soil

Compound	*lb/100 lb feed*	*ppm*
Volatiles:*		
Benzene	*9.91E-05*	*0.99*
Ethyl Benzene	*2.84E-03*	*28*
Toluene	*1.81E-03*	*18*
Xylene	*1.34E-02*	*134*
*Semivolatiles**:*		
Hexachlorobenzene	*9.72E-05*	*972*
2-Methylnaphthalene	*4.58E-05*	*458*
Naphthalene	*1.52E-05*	*150*
Phenanthrene	*6.62E-06*	*66*

B Indicates that this compound was detected in a blank.
** 1,2-Dichloroethane and methyl ethyl ketone were both detected in small amounts, but not in all sets.*
*** Other compounds were detected at low levels, but not in all sets.*

Volatile organic analysis was not performed on the treated soil as no volatile compounds were considered to exist in the slag after it had reached its melting point temperature. The only semivolatile organic compounds found in the treated soil were low levels of two phthalate compounds. These compounds were likely sampling or analytical contaminants. This corresponds with the TCLP analysis of the slag discussed earlier in which no semivolatile compounds leached from the slag. Table 4 (Section 3) presents the concentration of the metals in the slag for all three tests. Comparison of these data to the pre-treatment data show that a large percentage of the metals from the feed soil were retained within the vitrified slag. Exceptions to this trend are generally the volatile metals: arsenic, lead, mercury, and zinc. These volatile metals have been shown to be exiting the system through the stack gas. In addition, some of these metals can be found in the scrubber liquor as shown by Table C-3.

The treated slag (but not the feed soil) was sampled and analyzed for PCDDs and PCDFs using SW-846 Method 8290. Again, no PCDDs or PCDFs were found at levels above those found in the blank samples. It is likely that if all the feed soil had reached molten temperatures in the furnace, then any dioxins/furans present in the feed soil would have been thermally destroyed.

C.6 Scrubber Liquor

The pre-test scrubber liquor for each of the three Demonstration Tests contained only small amounts of organic compounds. A metals scan of the pre-test scrubber liquor indicated only low levels of metals as well. Table C-3 summarizes this information. The only organic compound identified and accurately quantified was benzoic acid in one of the samples from Test 2. Other compounds can be identified, but are present at less than five times the detection limit.

Table C-3 Results of Scrubber Liquor Analysis for Metals

Compound	*Pre-Test mg/L*	*Post-Test mg/L*
Aluminum	*0.89*	*1.9*
Antimony	*<0.30*	*<0.30*
Arsenic	*2.4*	*3.8*
Barium	*0.45*	*0.13*
Beryllium	*<0.00050*	*<0.0050*
Cadmium	*0.38*	*0.076*
Calcium	*7.1*	*8.6*
Chromium	*1.1*	*1.1*
Copper	*2.3*	*4.1*
Iron	*29*	*35*
Lead	*0.98*	*2.3*
Magnesium	*1.4*	*1.8*
Manganese	*0.32*	*0.53*
Mercury	*0.0075*	*0.064*
Nickel	*0.48*	*0.38*
Potassium	*11*	*23*
Selenium	*0.014*	*0.075*
Silver	*0.026*	*0.044*
Sodium	*580*	*2400*
Thallium	*<0.0016*	*<0.0016*
Vanadium	*0.056*	*0.011*
Zinc	*31*	*100*

< Not detected at or above the detection limit.

The post-test scrubber liquor did not contain any significant quantities of organic compounds. Only nitrated compounds and phthalates were present. The scrubbing unit was very inefficient in the capture of the inorganic compounds. Table C-3 shows that the scrubber did capture some of the metal elements, but not near the expected levels for a well-designed system. The distribution of metals in the scrubber liquor is similar to that found in the stack gas. This is a clear indication of the poor ability of the scrubbing system to remove the inorganic contaminants from the exhaust gas stream. The sodium is a consequence of the scrubber make-up (sodium hydroxide) and the silicon is most likely from the sandy nature of the soil.

C.7 Continuous Emission Monitoring

Throughout each of the Demonstration Tests, emissions including CO, CO_2, O_2, NO_x, and total hydrocarbons (THC) were continuously monitored. SO_2 was also monitored, but the data collected was not considered valid (see Section 3).

The THC level exiting the system was low (<4 ppm) during the Demonstration Tests. This indicates that thermal destruction of the organic compounds was occurring effectively. Other indicators of this include the low levels of CO and CO_2 in the exhaust gas (approximately 1.4 ppm and 8%, respectively.) O_2 levels demonstrated wide fluctuations corresponding to the inlet of pure O_2 during feeding of the test soil. High levels of NO_x (approximately 5,000 ppm uncorrected to 7% O_2, see Section 3) were observed during these tests since air was utilized as the torch gas. Because of the low flowrate of the exhaust gas, the corresponding emission rate is 2.6 lb/hr.

Appendix D

Case Studies

D.1 Preliminary Testing

D.1.1 Description

Prior to the Demonstration Tests, a series of Preliminary Tests were conducted by SAIC, as part of the SITE program, to assess the performance of Retech's Plasma Centrifugal Furnace (PCF) [1]. Three tests were originally scheduled, however, Preliminary Test 2 was only partially completed due to equipment failure. Preliminary Test 1 utilized 550 lb of unspiked synthetic soil matrix (SSM) prepared by EPA. Preliminary Test 3 utilized 200 lb of SSM spiked with the following compounds:

Volatiles:
- 1,200 ppm tetrachloroethylene (TCE)

Semivolatiles:
- 1,800 ppm anthracene
  4,000 ppm bis(2-ethylhexyl)phthalate

Metals:
- 1,000 ppm chromium
  16,000 ppm zinc.

The Preliminary Testing activities included sampling and analysis of the feed soil, the treated soil, the scrubber liquor, and the stack gas. The stack gas was also monitored throughout the tests using Continuous Emission Monitors (CEMs).

D.1.2 Testing Protocol

Test 1 was conducted to evaluate background contamination levels of phthalates in the feed soil, scrubber discharge, and stack gas, so as to allow accurate determination of bis(2-ethylhexyl)phthalate in these matrices during subsequent tests. This was necessary since phthalate contamination is prevalent from a wide variety of sources. In addition, the stack gas was monitored for emissions of CO, CO_2, O_2, NO_x, and THC.

In Test 3, the feed soil samples, treated soil samples, scrubber makeup samples, and scrubber liquor samples were analyzed for organics, metals, EP Toxicity (except scrubber makeup and liquor), and ash fusion temperature (feed soil only). The stack gas was sampled for organics, metals, particulates, and moisture, and was continuously monitored for CO, CO_2, O_2, NO_x, and THC.

D.1.3 Major Conclusions Based on Preliminary Testing

Based on the sampling and analysis results obtained during the tests, most of the metals detected were more abundant in the treated soil than in any other sample matrix. Particulate emissions were well below the RCRA limit of 0.08 grains per dscf. However, the performance of the Retech PCF did not meet other treatment protocols as described below.

The treated slag was leachable and contaminated with unacceptable levels of organic compounds. It is possible that the organics in the treated soil were high as a result of raw feed that inadvertently fell through the reaction chamber into the slag receiver. Leachability characteristic tests performed on the waste feed and treated soil samples revealed chromium to be nonleachable in either the waste feed or the treated soil and zinc (unregulated) to be leachable in both soil matrices.

The Destruction and Removal Efficiency (DRE) criterion of 99.99% was not achieved for two of the three TCE samples. Although 99.99% DRE was achieved for anthracene and bis(2-ethylhexyl)phthalate, residual concentrations in the treated soil were greater than 1% of their respective concentrations in the feed for these compounds. A significant number of organic compounds that were not present in the feed were generated during treatment due to incomplete combustion of the feed soil contaminants and detected in the stack gas.

The CEM data indicated that process emissions were promptly affected by disturbances from steady state operation. Periods of feeding caused CO, CO_2, O_2, and THC to rise. During torch outages, the oxygen concentration in the exhaust gas dropped while all other constituents rose dramatically. Pouring of the slag also caused the NO_x and CO levels to rise in every case.

A significant amount of copper was detected in all sample matrices, even though copper was not a spiked compound in the surrogate waste feed. The abundance of copper found may be due to breakdown of the plasma torch's copper electrodes and from the copper throat of the reactor.

Acceptable treatment results were not obtained during the Preliminary Tests. Inadequate power input to the system may have contributed to this. Additional work to address these problems and develop solutions has been undertaken to deter-

mine the potential for the technology to adequately treat hazardous waste. Other systems have been configured to include a greater power supply.

D.1.4 Data Summary

Tables D-1 and D-2 summarize the important results obtained from the Preliminary Tests. Information is also provided regarding regulatory limits and restrictions.

The average levels of the contaminants detected in the treated soil are presented in Table D-1. These contaminants include those compounds spiked into the feed soil and copper (likely from torch electrodes or the furnace throat, as stated previously). The levels of organic contaminants in the treated soil may be higher than anticipated due to the presence of untreated soil within the treated slag. Leachability characteristic testing revealed that the amount of zinc that leached from the treated soil was approximately 0.6% of the total zinc in the test soil. The chromium values were determined to be insignificant. The relevance of the low chromium values in the treated soil leachate is diminished by the fact that chromium was not found to be leachable in the feed soil either.

The post-treatment scrubber liquor and solids were analyzed together since insufficient scrubber solids were obtained for independent analysis. Copper and zinc were the most abundant elements detected. Copper was detected at 720 mg/L in the post-test liquor, compared to 350 mg/L in the pre-test liquor, while chromium was reported as 3.7 mg/L in the pre-test and 9.1 mg/L in the post-test. Similarly, zinc was 280 mg/L in the post-test liquor and 160 mg/L in the pre-test. Both TCE and bis(2-ethylhexyl)phthalate were detected in the scrubber liquor, but the amounts were each less than their respective quantitation limit (5 times the detection limit).

The emissions from the stack were analyzed for volatiles, semivolatiles, metals, particulates, and moisture. For Test 3, the DREs calculated for the TCE samples were <99.57%, <99.93%, and 99.9995%. The DREs for the semivolatile compounds [anthracene and bis(2-ethylhexyl)phthalate] and particulate concentrations in the stack gas were within federal regulations (see Table D-2). The most abundant metals in the stack gas were copper and zinc.

D.2 MSE Plasma Arc Furnace Experiment

D.2.1 Description

During July 1991, prior to the SITE Demonstration Tests, MSE, Inc. conducted a series of Afterburner Commissioning Tests (ACTs) as part of their Plasma Arc Furnace Experiment (PAFE) on Retech's PCF to evaluate the operation of the newly installed afterburner and associated chiller [2]. Four ACTs were planned using identical operating conditions, with the exception that the feed rate for ACT-1 and ACT-2 was 100 to 300 lb/hr and the feed rate for ACT-3 and ACT-4 was 120 lb/hr. The feed utilized for these tests was soil obtained from Idaho National Engineering Laboratories (INEL) mixed with 10% by weight No. 2 diesel fuel. Testing objectives included:

- Monitor upper and lower baffle temperatures to determine optimum operating conditions (with the upper baffle thermocouple port and throat camera port plugged with refractory for ACT-3 and ACT-4.)
- Check out afterburner and chiller under actual operating conditions (and determine automatic controller setpoints for ACT-3 and ACT-4.)
- Personnel training.
- Develop operating techniques.

Table D-1. Summary of Test Results and Land Disposal Restrictions*

	Scrubber Liquor (mg/L)		Treated Soil Leachate** (mg/L)		Treated Soil*** (mg/kg)	
Parameter	*Average Measured Value*	*Regulatory Limit*	*Average Measured Value*	*Regulatory Limit*	*Average Measured Value*	*Regulatory Limit*
Volatiles:						
Tetrachloroethylene	*ND*	*0.056*	—	*NR*	*0.001*	*5.6*
Semivolatiles:						
Anthracene	*ND*	*0.059*	—	*NR*	*103*	*4.0*
Bis(2-ethylhexyl)phthalate	*0.018*	*0.28*	—	*NR*	*117*	*28*
Metals:						
Chromium	*9.1*	*5.0*	*ND*	*5.0*	*252*	*NR*
Copper	*720*	*1.3*	*315*	*NR*	*315*	*NR*
Zinc	*280*	*NR*	*21.5*	*NR*	*893*	*NR*

* *Land disposal restrictions taken from 40 CFR 268.41 and 40 CFR 268.43, November 7, 1986 with documented Federal Register changes through June 8, 1989.*

** *During the Preliminary Tests, EP Toxicity analysis was used rather than TCLP analysis. Average measured values reported for Treated Soil Leachate are EP Toxicity values. Compounds with no reported values are not included in the standard EP Toxicity analysis.*

*** *Levels reported are the total concentrations of analytes based on a complete digestion of the treated soil.*

ND Not Detected

NR Not Regulated

Table D-2. Summary of Stack Gas Results and Regulatory Limits

Parameter	Average Measured Value	Regulatory Limit
Volatiles:		
Tetrachloroethylene DRE (%)		
Sample 1	*<99.57**	*99.99*
Sample 2	*<99.93**	*99.99*
Sample 3	*99.9995*	*99.99*
Semivolatiles:		
Anthracene DRE (%)	*>99.999***	*99.99*
Bis(2-ethylhexyl)phthalate DRE (%)	*99.998***	*99.99*
Emissions:		
Particulate (gr/dscf, corrected to 7% O2)	*0.041*	*0.080*
Hydrogen Chloride Exiting Stack (lb/hr)	*<0.0005*	*4.0*
Nitrogen Oxides Exiting Stack (lb/hr)	*1.22****	*NR*
Nitrogen Oxides Exiting Stack (lb/hr, corrected to 7% O_2)	*4.27*****	*9.2*

* *The tetrachloroethylene DREs for Samples 1 and 2 were determined from stack gas emission rate values that exceeded the saturation level of the analyses. These values are qualified with a "less than" symbol.*

** *Concentrations of these compounds in the treated soil were greater than 1% of the concentrations in the feed soil.*

*** *The concentration of NO_x in the stack gas averaged approximately 6,500 ppm.*

**** *The concentration of NO_x in the stack gas (corrected to 7% O_2) averaged approximately 19,250 ppm.*

NR *Not Regulated. Regulations apply to emissions corrected to 7% O_2.*

Testing objectives were met for each test.

D.2.2 Testing Protocol

During the Afterburner Commissioning Tests, sampling and analysis did not take place. Instead, parameters were monitored periodically by the Data Acquisition System (DAS) to provide information regarding system operation. CEMs were also utilized to trace the behavior of the system exhaust gas. A number of parameters were calculated by the DAS throughout the tests to provide additional operating information. During ACT-3 and ACT-4, the upper baffle thermocouple port and the throat camera port were plugged with refractory to assist in raising the secondary combustion chamber temperature. Material was not fed during ACT-3 because of the unavailability of oxygen, however, testing was conducted to determine the temperatures that could be achieved in the secondary chamber.

D.2.3 Major Conclusions Based on PAFE ACTs

During ACT-1, ACT-2, and ACT-4, the afterburner was utilized to provide additional combustion gas flow. Because of this, the blower operated at approximately maximum capacity throughout these three tests. Peak primary chamber temperatures ranged from 2,287 to 2,334 °F, and peak secondary chamber temperatures ranged from 1,778 to 2,241 °F during ACT-1, ACT-2, and ACT-4. Peak primary chamber temperature was 2,244°F, and peak secondary chamber temperature was 1,919°F during ACT-3.

D.2.4 Data Summary

Figure D-1 shows a typical plot of total hydrocarbons (THC) during these testing operations. The notable peaks present represent instances of torch flameout (loss of arc) and restart. Figure D-2 shows a typical plot of carbon monoxide (CO). Here again, the peak near the end of treatment coincides with flameout and restart conditions. Both of these plots demonstrate low values throughout treatment and effective combustion of organic compounds.

D.3 Plasmox® Waste Treatment Facility

D.3.1 Description

A hazardous waste treatment facility utilizing a PCF designed by Retech, Inc. has been constructed in Muttenz, Switzerland [3]. The facility is devised to treat drummed waste in a manner minimizing potential exposure to the waste and to any incompletely burned products, while turning solid components, including the drum itself into a non-leaching slag. The Plasmox® facility is owned and operated by MGC Plasma, Ltd.

The furnace is designated PCF-8 (plasma centrifugal furnace with an 8-ft diameter primary chamber). The basic treatment concept is similar to that employed by the PCF-6 during the Demonstration Tests and uses an electric arc in a sealed, sub-atmospheric environment to vitrify solid constituents of the feed while organic components are partly burned in a spinning reaction chamber. The combustibles finish burning in a secondary combustion chamber. The effluent is cleaned in a comprehensive gas treatment system, while vitrified material is periodically tapped into a mold.

The system throughput is about 1 metric ton/hr (usually 4 to 5 drums). Two plasma torches are used for heat input. The main power is provided with an RP-600T, which uses a power supply rated at 2,000 amps and 600 volts. This torch is used to vitrify solid material charged to the rotating tub. A smaller torch, the RP-250T, is directed at the edge of the throat. It ensures that no glass is left on the surface of the copper rim of the throat after material is discharged and adds plasma heat to the gases entering the secondary combustion chamber.

The burning is accomplished in both the primary chamber and the secondary chamber. Oxygen is added to the primary chamber through an oxygen lance. Additional air and/or oxygen is added between the throat and the secondary combustion chamber to facilitate complete combustion. A temperature of at least 2,200°F is achieved in the secondary combustion chamber. Residence time at full flow conditions is about 2.5 seconds.

The reaction chamber also possesses two liquid injection lances. During the preheat period, fuel oil is burned to raise the furnace temperature to 2,200°F before initiating toxic feed.

A separate building has a comprehensive water treatment system for cleaning, purifying, and recycling the water which is used in the quench and ionizing wet scrubbers. At typical

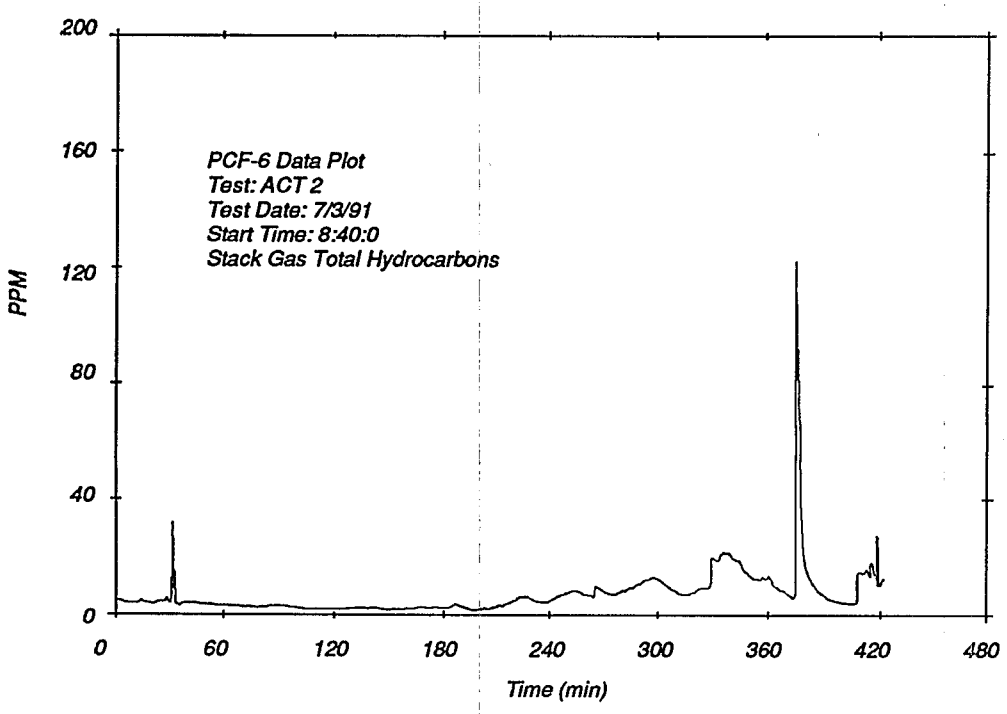

Figure D-1. Typical THC and CO Plot during ACTs.

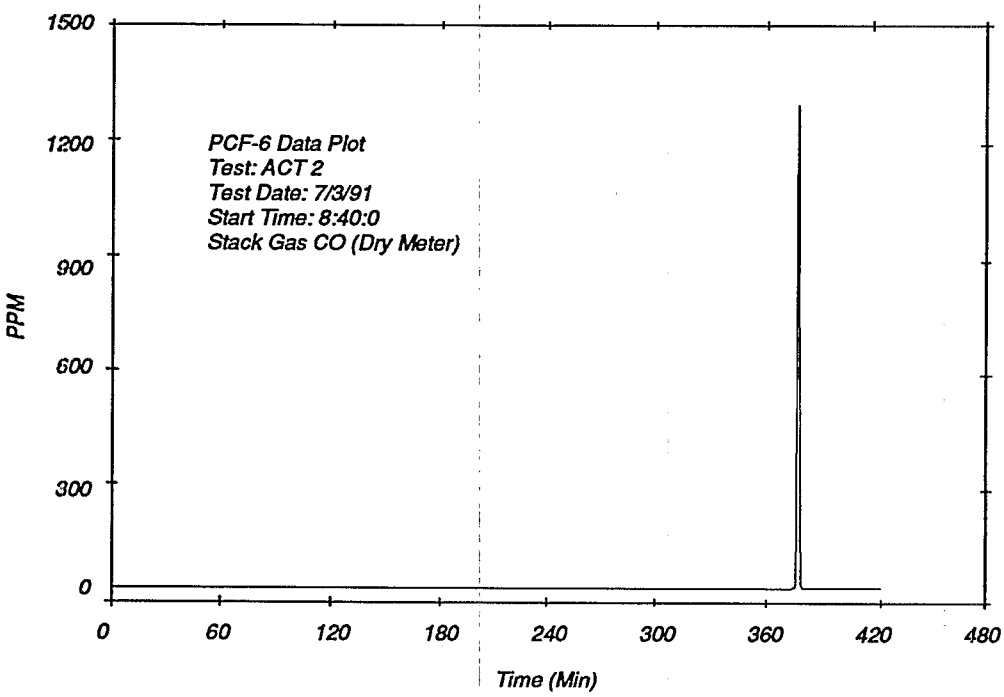

Figure D-2. Typical CO Plot during ACTs.

operating conditions, the waste water cleaning plant produces about 18 kg/hr of filter cake and 4 m^3/hr of purified water. The purified water meets all Swiss standards for discharge into streams.

D.3.2 Testing Protocol

In order to measure the capacity of the slag to tie up heavy metals in a non-leaching form, tests were conducted on March 7, 1991 in which four metals were spiked into the waste feed. The waste feed was comprised of approximately 175 kg of dirt and 35 kg of steel. The spiked metals included chromium (17.1 kg), lead (1.9 kg), nickel (0.9 kg), and zinc (4.0 kg). Operating current in the furnace was 2,000 amps at 600 to 700 volts. Off-gas dust samples were not taken during this test. The slag generated during this test was chipped from the furnace and subsequently tested for leach resistance. The Swiss standard leach test uses carbon dioxide as the primary active agent, in contrast to the U.S. TCLP test which uses acetic acid. The MGC plasma X-ray fluorescence instrument was used to measure elemental concentrations in the slag.

D.3.3 Major Conclusions Based on Plasmox® Treatment Facility

The opacity of the off-gas was well under the Swiss requirement, and emitted NO_x averaged about 40 ppm. The NO_x upstream of the deNO_x unit ranged from 750 to 900 ppm. The Swiss requirements for off-gas composition were all met. The leachability characteristics of the slag with respect to the spiked metals were all within the Swiss regulatory limits.

D.3.4 Data Summary

Table D-3 summarizes the results of the analysis of the slag for the metals spiked into the feed. The Swiss regulatory limits for these compounds are also provided in this table. Off-gas composition data collected during these tests was not available.

Table D-3. Swiss Leach Test Results

Compound	*Test 1 (mg/L)*	*Test 2 (mg/L)*	*Swiss Regulatory Limit (mg/L)*
Chromium	*<0.05*	*<0.05*	*0.05*
Lead	*<0.1*	*<0.1*	*0.1*
Nickel	*<0.1*	*<0.1*	*0.2*
Zinc	*<0.05*	*0.07*	*0.5*

References for Appendices

1. Science Applications International Corporation. July 11, 1991. "Demonstration Plan for Centrifugal Plasma Reactor Technology."

2. MSE, Inc. July, 1991. "Afterburner Commissioning Tests, Tests Number ACT-1 through ACT-4."

3. Fünfschilling, M. R., W. Bernhard, and R. C. Eschenbach, "Test Results with the Plasma Centrifugal Furnace at Muttenz, Switzerland." Presented at the 1991 Incineration Conference in Knoxville, Tennessee May 14-16, 1991.

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