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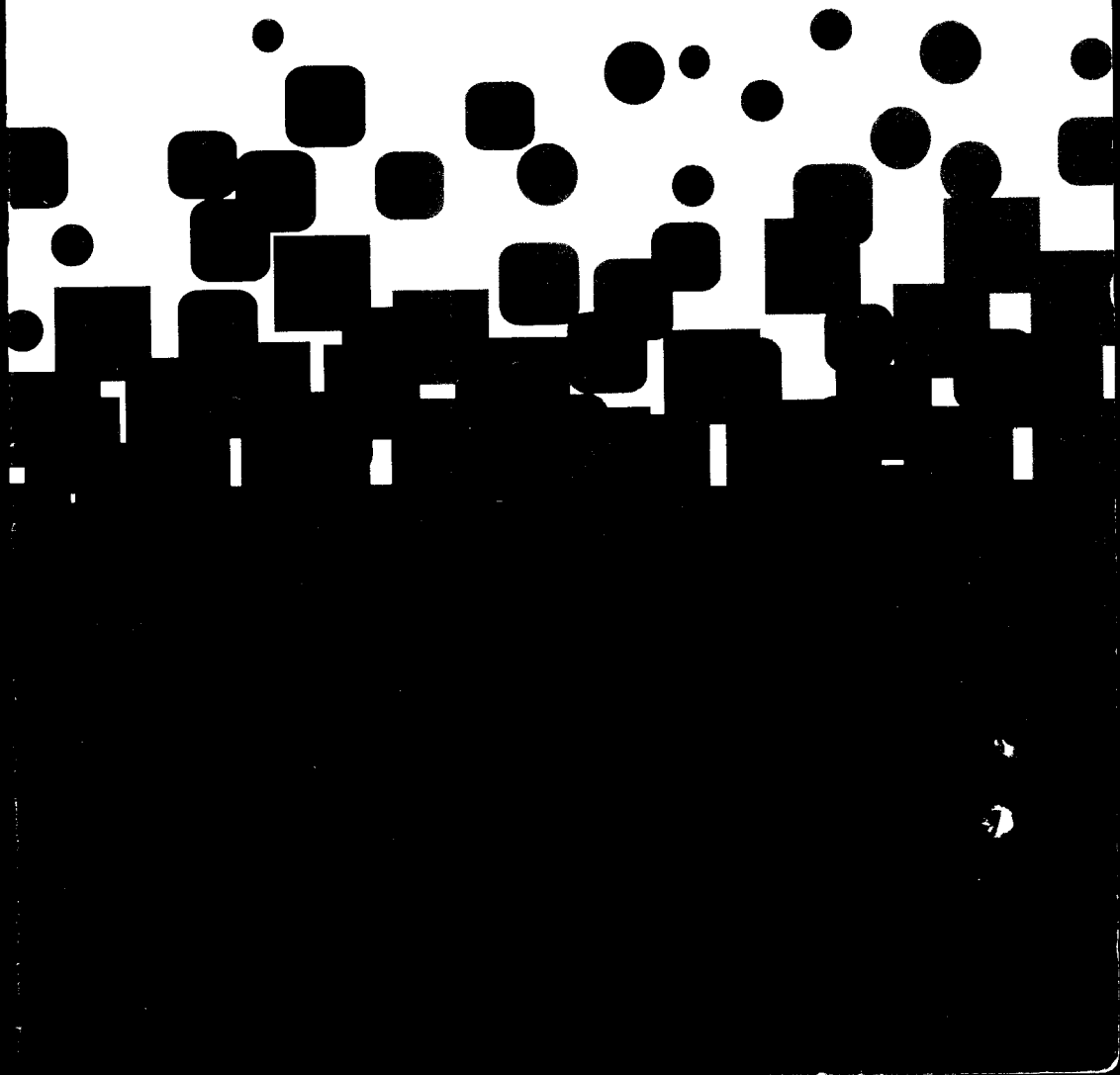
EPA/600/B-94/001
October 1994

Available from: Emergency Response Team (ERT)



Innovative Site Remediation Technology

Thermal Destruction Volume 7



INNOVATIVE SITE REMEDiation TECHNOLOGY THERMAL DESTRUCTION

One of an Eight-Volume Series

Edited by

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1994

Prepared by WASTECH®, a multiorganization cooperative project managed by the American Academy of Environmental Engineers® with grant assistance from the U.S. Environmental Protection Agency, the U.S. Department of Defense, and the U.S. Department of Energy.

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Library of Congress Cataloging in Publication Data

Innovative site remediation technology/ edited by William C. Anderson

128p. 15.24 x 22.86cm.

Includes bibliographic references.

Contents: -- [2] Chemical treatment -- [3] Soil washing/soil flushing
-- [4] Stabilization/solidification -- [6] Thermal desorption -- [7] Thermal destruction

1. Soil remediation. I. Anderson, William, C., 1943-

II. American Academy of Environmental Engineers.

TD878.I55 1994 628.5'5 93-20786

ISBN 1-883767-02-4 (v. 2) ISBN 1-883767-06-7 (v. 6)

ISBN 1-883767-03-2 (v. 3) ISBN 1-883767-07-5 (v. 7)

ISBN 1-883767-04-0 (v. 4)

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Book design by Lori Imhoff

Printed in the United States of America

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The Air & Waste Management Association is a nonprofit technical and educational organization with more than 14,000 members in more than fifty countries. Founded in 1907, the Association provides a neutral forum where all viewpoints of an environmental management issue (technical, scientific, economic, social, political, and public health) receive equal consideration.

This worldwide network represents many disciplines: physical and social sciences, health and medicine, engineering, law, and management. The Association serves its membership by promoting environmental responsibility and providing technical and managerial leadership in the fields of air and waste management. Dedication to these objectives enables the Association to work towards its goal: a cleaner environment.

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Founded in 1880, the American Society of Mechanical Engineers (ASME) is a nonprofit educational and technical organization, having at the date of publication of this document approximately 116,400 members, including 19,200 students. Members work in industry, government, academia, and consulting. The Society has thirty-seven technical divisions, four institutes, and three interdisciplinary programs which conduct more than thirty national and international conferences each year.

This document was reviewed by volunteer members of the Monograph Review Committee of the Solid Waste Processing Division and the Research Committee on Industrial and Municipal Waste, each with technical expertise and interest in the field covered by the document. Although, as indicated on the reverse of the title page of this document, neither ASME nor any of its Divisions or Committees endorses or recommends, or makes any representation or warranty with respect to, this document, those Divisions and Committees which conducted a review believe, based upon such review, that this document and the findings expressed are technically sound.

Hazardous Waste Action Coalition

The Hazardous Waste Action Coalition (HWAC) is an association dedicated to promoting an understanding of the state of the hazardous waste practice and related business issues. Our member firms are engineering and science firms that employ nearly 75,000 of this country's engineers, scientists, geologists, hydrogeologists, toxicologists, chemists, biologists, and others who solve hazardous waste problems as a professional service. HWAC is pleased to endorse the monograph as technically sound.

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ACKNOWLEDGMENTS

The WASTECH® project was conducted under a cooperative agreement between the American Academy of Environmental Engineers® and the Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. The substantial assistance of the staff of the Technology Innovation Office was invaluable.

Financial support was provided by the U.S. Environmental Protection Agency, Department of Defense, Department of Energy, and the American Academy of Environmental Engineers®.

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1

INTRODUCTION

This monograph on thermal destruction is one of a series of eight on innovative site and waste remediation technologies that is the culmination of a multiorganization effort involving more than 100 experts over a two-year period. It provides the experienced, practicing professional guidance on the application of innovative processes considered ready for full-scale application. Other monographs in this series address bioremediation, chemical treatment, solvent/chemical extraction, stabilization/solidification, soil flushing/soil washing, thermal desorption, and vacuum vapor extraction.

This document was originally prepared in 1992 and represents the status of the addressed technologies at that time. For some technologies, additional testing and development has occurred during the two-year peer review and revision process and this additional information is not reflected in this monograph. However, all eight monographs will be periodically reviewed and updated to make them as current as possible.

1.1 Thermal Destruction

Thermal destruction, as considered in this monograph, is an ex situ process that thermally destroys organic contaminants. Generally, thermal destruction is a mature technology employing a variety of combustion chambers, but in waste-site remediation applications, rotary kilns are most common. Innovation in this area has occurred in the form of modifications and improvements to existing systems.

Thermal processes that destroy organic contaminants by oxidation, pyrolysis, hydrogenation, and reduction were considered. Initially twenty-seven candidate technologies were identified from various sources. They

are listed in table 1.1 which also summarizes their final disposition as determined by the Thermal Destruction Task Group. The Huber/Thagard Fluid-Wall Reactor was dropped because it was determined to no longer be an active technology. Three technologies (Infrared Furnace, Rotary Kiln and Wet Air Oxidation) were dropped because it was determined that these were not innovative and were commercially available. Microwave treatment was dropped due to insufficient data.

Several of the other technologies overlapped with one of the other eight monographs and in many cases it was determined by a Steering Committee that it would be more appropriate to address these technologies in these other monographs. UV Oxidation and High Energy Electron Beam were

Table 1.1
Summary of Technologies Considered

	Description	Disposition
1	Huber/Thagard Fluid-Wall Reactor	Dropped, Inactive
2	Infrared Furnace	Dropped, Commercially Available
3	Rotary Kiln	Dropped, Commercially Available
4	Wet Air Oxidation	Dropped, Commercially Available
5	Microwave Treatment	Dropped, Insufficient Data
6	UV Oxidation	Referred to Chemical Treatment
7	High Energy Electron Beam	Referred to Chemical Treatment
8	TACIUK Process	Referred to Thermal Desorption
9	Thermal Dynamics Corp. (TGI)	Referred to Thermal Desorption
10	High Temperature Alloy Drum Dryer	Referred to Thermal Desorption
11	Thermal Augmented Vapor Extraction	Referred to Vacuum Vapor Extraction
12	PYROKIN Thermal Encapsulation Process	Referred to Stabilization/Solidification
13	Vitrification	Referred to Stabilization/Solidification
14	Glassification	Referred to Stabilization/Solidification
15	B&W Cyclone Furnace	Referred to Stabilization/Solidification
16	RETECH PLASMA	Referred to Stabilization/Solidification
17	Soil Detoxification Using Solar Energy	Insufficient Data, Tech to Watch
18	Fluidized Bed Cyclonic Agglomerating Incinerator	Insufficient Data, Tech to Watch
19	Hybrid Fluidized Bed System	Insufficient Data, Tech to Watch
20	Entrained-Bed Gasification	Insufficient Data, Tech to Watch
21	Metallurgical-Based Treatment Process	Insufficient Data, Tech. to Watch
22	Molten Salt Oxidation (MSO) Process	Insufficient Data, Tech to Watch
23	Supercritical Water Oxidation (SCWO)	Insufficient Data, Tech to Watch
24	Catalytic Oxidation	Assessed
25	Rotary Cascading Bed Incineration System	Assessed
26	ECO LOGIC Process	Assessed
27	HRD Flame Reactor Process	Assessed

referred to the Chemical Treatment Task Group and Thermal Augmented Vapor Extraction was referred to the Vacuum Vapor Extraction Task Group.

Many of the thermal-based innovations have been developed for purposes other than destruction. In general, these can be classified as removal (desorption) or immobilization (vitrification) processes. While some destruction of organic contaminants does occur with these systems, destruction is not their primary goal. As a result, three of the candidate technologies (TACIUK Process, Thermal Dynamics Corp. (TGI), and High Temperature Alloy Drum Dryer) were referred to the Thermal Desorption Task Group, and five of the candidate technologies (PYROKIN Thermal Encapsulation Process, Vitrification, Glassification, B&W Cyclone Furnace, and RETECH PLASMA) were referred to the Stabilization/Solidification Task Group.

Several of the candidate technologies were determined to be promising technologies under development that could not be assessed at this time because of insufficient data, but significant testing and evaluation are scheduled in the near future. They may then be seen also as potential candidate remediation technologies. These technologies – Soil Detoxification Using Solar Energy, Fluidized Bed Cyclonic Agglomerating Incinerator, Hybrid Fluidized Bed System, Entrained-Bed Gasification, Metallurgical-Based Treatment Processes, Molten Salt Oxidation Process, and Supercritical Water Oxidation (SCWO) – are not addressed in the text of the monograph, but are briefly described in Appendix A.

The following technologies were judged to be sufficiently developed to warrant inclusion in this monograph:

- Catalytic Oxidation;
- Rotary Cascading Bed Incineration System; and
- ECO LOGIC Process.

In addition, the Horsehead Research Development Company, Inc., (HRD) Flame Reactor Process, a high temperature metal recovery process, is also addressed. While the principal use of this technology is in the processing of materials contaminated with significant recoverable metal constituents, its high processing temperature should be effective also in destroying organic contaminants. Further, the technology is sufficiently developed to be a potential candidate for remediating some sites.

1.2 Development of the Monograph

1.2.1 Background

Acting upon its commitment to develop innovative treatment technologies for the remediation of hazardous waste sites and contaminated soils and ground water, the U.S. Environmental Protection Agency (US EPA) established the Technology Innovation Office (TIO) in the Office of Solid Waste and Emergency Response in March, 1990. The mission assigned TIO was to foster greater use of innovative technologies.

In October of that same year, TIO, in conjunction with the National Advisory Council on Environmental Policy and Technology (NACEPT), convened a workshop for representatives of consulting engineering firms, professional societies, research organizations, and state agencies involved in remediation. The workshop focused on defining the barriers that were impeding the application of innovative technologies in site remediation projects. One of the major impediments identified was the lack of reliable data on the performance, design parameters, and costs of innovative processes.

The need for reliable information led TIO to approach the American Academy of Environmental Engineers®. The Academy is a long-standing, multidisciplinary environmental engineering professional society with wide-ranging affiliations with the remediation and waste treatment professional communities. By June 1991, an agreement in principle (later formalized as a Cooperative Agreement) was reached. The Academy would manage a project to develop monographs describing the state of available innovative remediation technologies. Financial support would be provided by the EPA, U.S. Department of Defense (DOD), U.S. Department of Energy (DOE), and the Academy. The goal of both TIO and the Academy was to develop monographs providing reliable data that would be broadly recognized and accepted by the professional community, thereby eliminating, or at least minimizing, this impediment to the use of innovative technologies.

The Academy's strategy for achieving the goal was founded on a multiorganization effort, WASTECH® (pronounced Waste Tech), which joined in partnership the Air & Waste Management Association, the American Institute of Chemical Engineers, the American Society of Civil Engineers, the American Society of Mechanical Engineers, the Hazardous Waste

Action Coalition, the Society for Industrial Microbiology, and the Water Environment Federation, together with the Academy, EPA, DOD, and DOE. A Steering Committee composed of highly respected representatives of these organizations having expertise in remediation technology formulated the specific project objectives and process for developing the monographs (See page iv. for a listing of Steering Committee members).

By the end of 1991, the Steering Committee had organized the Project. Preparation of the monographs began in earnest in January, 1992.

1.2.2 Process

The Steering Committee decided upon the technologies, or technological areas, to be covered by each monograph, the general scope of the series and the process for development, and appointed a task group composed of five or more experts to write a manuscript for each monograph. The task groups were appointed with a view to balancing the interests of the groups principally concerned with the application of innovative site and waste remediation technologies – industry, consulting engineers, research, academe, and government.

The Steering Committee called upon the task groups to examine and analyze all pertinent information available within the Project's financial and time constraints. This included, but was not limited to, the comprehensive data base on remediation technologies compiled by EPA, the store of information possessed by the task groups' members and that of other experts willing to voluntarily contribute their knowledge, and information supplied by process vendors.

To develop broad, consensus-based monographs, the Steering Committee prescribed a two-fold peer review of the first drafts. One review was conducted by the Steering Committee itself, employing panels consisting of two members of the Committee supplemented by at least four other experts (See *Reviewers*, page iii, for the panel that reviewed this monograph). Simultaneous with the Steering Committee's review, each of the professional and technical organizations represented in the Project reviewed those monographs in which it has substantial interest and competence relating to the technologies being addressed. Aided by a symposium sponsored by the Academy in October 1992, persons having interest in the technologies were encouraged to participate in the organizations' review.

Once both reviews were complete, the Chair of the Steering Committee's review panel organized all the review comments into a integrated document. These review comments were considered by the Task Group, appropriate adjustments were made and a second draft published. The second draft was accepted by the Steering committee and participating organizations. The statements of the organizations that formally reviewed this monograph are presented under *Reviewing Organizations* on page v.

1.3 Purpose

The purpose of this monograph is to further the use of innovative thermal destruction site remediation and waste processing technologies, i.e., technologies not commonly applied, where their use can provide better, more cost-effective performance than conventional methods. To this end, the monograph documents the current state of the technology for a number of innovative thermal destruction processes.

1.4 Objectives

The monograph's principal objective is to furnish guidance for experienced, practicing professionals and users' project managers. The monograph is intended, therefore, not to be prescriptive, but supportive. It is intended to aid experienced professionals in applying their judgment in deciding whether and how to apply the technologies addressed under the particular circumstances confronted.

In addition, the monograph is intended to inform regulatory agency personnel and the public about the conditions under which the processes it addresses are potentially applicable.

1.5 Scope

The monograph addresses innovative thermal destruction technologies which are not yet conventional that have been sufficiently developed so that they can be used in full-scale applications. It addresses all such technologies for which sufficient data were available to the Thermal Destruction Task Group to describe and explain the technology and assess its effectiveness, limitations, and potential applications. Laboratory- and pilot-scale technologies were addressed, as appropriate.

The monograph's primary focus is site remediation and waste treatment. To the extent the information provided can also be applied to production waste streams, it will provide the profession and users this additional benefit. The monograph considers all waste matrices to which thermal destruction processes can be reasonably applied such as soils, liquids, sediments, sludges and gases.

Application of site remediation and waste treatment technology is site specific and involves consideration of a number of matters besides alternative technologies. Among them are the following that are addressed only to the extent essential to understand the applications and limitations of the technologies described:

- site investigations and assessments;
- planning, management, specifications, and procurement; and
- regulatory requirements.

1.6 Limitations

The information presented in this monograph has been prepared in accordance with generally recognized engineering principles and practices and is for general information only. This information should not be used for design or operation evaluations with respect to any specific application.

Readers are cautioned that the information presented is that which was generally available during the period when the monograph was prepared. Development of innovative site remediation and waste treatment technolo-

gies is ongoing. Accordingly, postpublication information may amplify, alter, or render obsolete the information about the processes addressed.

This monograph is not intended to be and should not be construed as a standard of any of the organizations associated with the WASTECH® Project; nor does reference in this publication to any specific method, product, process, or service constitute or imply an endorsement, recommendation, or warranty thereof.

1.7 Organization

This monograph and others in the series are organized under a uniform outline intended to facilitate cross reference among them and comparison of the technologies they address. Chapter 2, Process Summary, provides an overview of all material presented. Chapter 3, Process Identification and Description, provides comprehensive information on the processes addressed. Each process is analyzed in turn. The analysis includes, to the extent information and data are available, a description of the process (what it does and how it does it), its scientific basis, status of development, environmental effects, pre- and posttreatment requirements, health and safety considerations, design data, operational considerations, and comparative cost data. Also addressed are process-unique planning and management requirements and process variations.

Chapter 4, Potential Applications, Chapter 5, Process Evaluation, and Chapter 6, Limitations, provide a synthesis of available information and informed judgments on the processes. Each of these chapters addresses the processes in the same order as they are described in Chapter 3. Technology Prognosis, Chapter 7, identifies aspects of each of the processes needing further research and demonstration before full-scale application can be considered.

2

PROCESS SUMMARY¹.

2.1 *Catalytic Oxidation*

2.1.1 Process Identification and Description

Catalytic oxidation of organic compounds is an established technology that has been employed in industry for decades. However, until recently, oxidation catalysts have been subjected to poisoning by halogens, certain metals, particulates, phosphorus, and sulfur compounds. One effect of this poisoning has been to limit catalytic oxidation applications to non-halogenated contaminated air streams. Recently, new catalysts have been developed which are not poisoned by chlorinated organic compounds and can achieve high destruction efficiencies. These advances have resulted in the design of catalytic oxidation units to treat air flows contaminated with halogenated organic compounds.

Catalytic oxidation units for treatment of halogenated organic compounds (both volatile and semivolatile) typically consist of a preheater (usually gas or electric) to elevate the air-stream temperature to the catalyst temperature, a catalytic reactor, a shell and tube heat exchanger (to recover a portion of the heat in the reactor exit gas), and a scrubber (to remove halogens and hydrogen halides from the oxidation products before their release to the atmosphere). The halogenated organic compounds in the air stream are destroyed by contact with a catalyst maintained at a controlled temperature.

1. This chapter is a summary of Chapters 3.0 through 7.0. Sources are cited, where appropriate, in those chapters — Ed.

In a vapor extraction application, a vacuum pump/compressor draws the well vapor through a manifold and pumps the gas to the catalytic oxidation unit. In a contaminated groundwater application, the groundwater is pumped to the surface, the contaminant is air stripped from the water, and the air and organic contaminated stream is directed through the catalytic oxidation unit.

2.1.2 Potential Applications

Catalytic oxidation has long been used for emission control of organic compounds from a number of industrial sources as well as those removed through soil venting or air stripping from groundwater. It is more economical, in some circumstances, than alternative processes – adsorption of organic compounds on a solid such as activated carbon, selective condensation of organic compounds, and thermal oxidation. Low concentrations and small amounts of contaminant favor carbon adsorption; higher concentrations and larger amounts of contaminant favor catalytic oxidation. Until recently, there were no commercially-available processes for applying catalytic oxidation to control air emissions of halogenated organic compounds.

Field experience with chlorinated organic compounds has been generally positive, although one study showed that a decrease in contaminant destruction efficiency occurred with operating time. The efficiency loss was attributed to the attrition of the fluidized bed of catalyst granules. In another instance, failures of system components resulted in short shutdowns for replacement/repairs. Typical of the component failures was corrosion of the Inconel sheath of a thermocouple that measured the temperature of the vapor in the hydrogen chloride neutralizer following the catalytic reactor.

2.1.3 Process Evaluation

A commercial prototype of the HD CatOx™ system as a unit of a soil vapor extraction system has been operating successfully since mid-1990. The unit has a gas throughput capacity of 7.4 m³/min (260 standard ft³/min) and is designed to handle concentrations as high as 2,500 ppmv trichloroethylene (TCE). The compact system is designed for continuous operation with process and safety controls to maintain conditions that comply with the Permit to Operate.

Operation of the soil vapor extraction system at the design rate of 6 m³/min (200 standard ft³/min) has resulted in a steady decline in the concentration of TCE in the vapor feed to the HD CatOx™ from about 3,500 ppmv to about 500 ppmv after 400 days of on-stream operation. The total amount of TCE removed by vapor extraction during this period is more than 18,150 kg (40,000 lb) demonstrating the commercial applicability of the catalytic oxidation unit for this chemical.

The developer supplied the following operating data at the design rate of 6 m³/min (200 standard ft³/min): preheater energy requirements, 28KW; catalytic reactor destruction removal efficiency (DRE), 97%; and scrubber performance, >95% hydrogen chloride removal.

Evaluation of a TCE catalytic oxidation unit designed to treat 34 m³/min (1,200 standard ft³/min) at Wurtsmith Air Force Base with a feed stream containing 11 to 12 ppmv TCE stripped from groundwater showed a 97.3 to 99.1% TCE destruction efficiency when it was operated at the vendor-recommended catalyst bed temperature of 370°C (700°F) with ≥19 cm (7.5 in.) depth of catalyst. The unit includes a natural-gas flame preheater to elevate the air-stream temperature to the catalyst bed temperature. Benzene and toluene were the products of incomplete combustion (PICs) most often observed in unit emissions and in the highest concentrations (up to 0.35 ppmv and 0.87 ppmv, respectively).

2.1.4 Limitations

As of mid-1992, catalytic oxidation of halogenated organic compounds had been field-demonstrated on TCE only. Operation appeared to be economical when the feed stream had a relatively high TCE concentration and/or the amount of TCE to be destroyed was large.

With chlorinated organic compounds, it is important to know the daily emission limits for hydrogen chloride. Regulations across the U.S. vary with respect to this acidic gas, and acid-gas neutralization following catalytic oxidation may or may not be required. This factor has a significant impact on the cost-competitiveness of the process.

A potential disadvantage of catalytic oxidizers is that the catalyst may be deactivated, or poisoned, by various volatile materials. For example, chlorinated organic compounds deactivate the platinum-based catalysts commonly used in conjunction with vapor extraction of gasoline-contaminated

soils. It is unclear whether appropriate catalysts are commercially available to treat all chlorinated organic compounds that might be encountered in waste site remediation. Development and selection of suitable catalysts can be time-consuming with uncertain results.

2.1.5 Comparative Cost Data

Catalytic oxidation is cost competitive with other processes, such as carbon adsorption, when there are high concentrations and large amounts of the contaminant. Compared to thermal oxidation, it has lower fuel costs, and generally lower capital costs. However, due to lower operating temperatures, variable feed concentrations, and other factors, materials of construction of associated ducts and vents for catalytic oxidation systems may require special care in selection and operation when compared to thermal oxidation.

Air emission controls can have a significant impact on economic viability when compared to carbon adsorption. The amount of VOCs in the contaminated source and local emissions control limits must be defined, and an appropriate emissions control system must be designed to arrive at the total system cost. Test data for a 6 m³/min (200 standard ft³/min) organic carbon contaminated stream based on TCE removal suggest that catalytic oxidation is more cost-effective, than carbon adsorption when (1) the contaminant is more than 3,630 kg (8,000 lb) and the hydrogen chloride can be vented or (2) the contaminant is more than 7,260 kg (16,000 lb) and the hydrogen chloride must be removed by a neutralizer/scrubber.

2.1.6 Technology Prognosis

Performance and economic results of recent demonstrations have shown the effectiveness of catalytic oxidation in treating selected halogenated organic compounds in soil and groundwater remediation. It is anticipated that development of new catalysts will expand the range of halogenated organic compounds that can be effectively treated by catalytic oxidation.

2.2 Rotary Cascading Bed Incineration (RCBI) System

2.2.1 Process Identification and Description

The Rotary Cascading Bed technology as addressed here is principally that of a mobile high-temperature incineration system. Although there are presently no RCBI systems being used as mobile incinerators, the technology is in operation in fixed systems and should be transferable.

The RCBI system develops highly turbulent gas and solids mixing conditions for the efficient combustion of solid and liquid fuels and wastes. Key to this efficiency are a relatively high rotation speed for the cylindrical combustion chamber, lifters attached to the inside of the chamber, and internal recycling of the bed material at a higher rate from the back end of the chamber to the feed end.

The RCBI rotates at 10 to 15 rev/min, compared to less than 1 rev/min rotation of a typical high-temperature rotary kiln incinerator. The significantly higher rotation rate develops centrifugal forces that result in the bed material being carried up by the lifters (metal plates attached to the RCBI's inner liner parallel to the cylinder axis) above the angle of repose. At some point, the bed material falls off the lifters and cascades through the hot gas space. The degree of cascading for a particular bed material is determined by the rotational speed of the cylinder. Bed recycling is achieved through the use of solids transport chutes forming an Archimedean Spiral that pumps the hot bed solids from the exit end of the RCBI on the outside to the feed end where the hot solids are mixed with the incoming waste solids.

A high degree of turbulence and contact between the solids and the combustion gas, cascading across the entire diameter of the cylinder, is achieved by adjusting the rotational speed of the RCBI. The cascading of the bed material results in a highly turbulent atmosphere in which the waste, the recycled bed material, any liquid or solid auxiliary fuel, combustion air, and combustion gas are intimately mixed. The cascading solids also transfer momentum to the combustion gas, causing a turbulent swirling motion that also induces mixing of the gas. The high degree of turbulence results in the RCBI achieving the Resource Conservation and Recovery Act of 1976 (RCRA) DRE performance standard of 99.99%, at 760° to 870°C (1,400° to 1,600°F) without an afterburner. The reported DRE of 99.99% for the tests

reported on herein (see Subsection 5.2.1) should not be interpreted to imply this performance would result for all conditions.

2.2.2 Potential Applications

The RCBI technology is applicable at sites contaminated with volatile organics and semivolatile organics, sites with lightly contaminated soils and sludges, and complex sites containing organic tars, contaminated soils, sludges, and debris. It can also be used for sites with large quantities of drummed wastes, provided the drums are shredded to less than two inches on a side, if fed to the RCBI, or emptied before the contents are fed to the RCBI. In the latter case, cleaning and compacting the drums will be required, and the resulting drum wash water must be fed to the RCBI or otherwise managed.

2.2.3 Process Evaluation

The RCBI technology, under development since 1981, has been tested at the pilot- and full-scale level on numerous types of fuels and wastes. It has been applied in testing and treating wastes in the following major areas:

- as a waste-to-energy boiler; and
- as a fixed hazardous waste incinerator for low Btu soils, sludges and other wastes.

Table 5.1 (on page 5.6) summarizes data resulting from the first pilot demonstration of the Pedco RCBI. The results of subsequent tests of RCBI systems are detailed in Section 5.2.

The environmental impact of the RCBI will be similar to that of other high-temperature incinerators. Based on test results summarized in Chapter 5.0, the RCBI should meet or exceed all applicable RCRA and air regulatory requirements. The only water usage with a mobile RCBI will be for evaporative cooling of the combustion gas prior to the fabric filter and for treated soil cooling and rehumidification. The process has no aqueous effluents, because the RCBI uses in-bed neutralization, with the introduction of appropriate neutralizing chemicals with the wastefeed, and a dry fabric filter for particulate and metal emission control. There are two solid discharges resulting from the treatment of contaminated soils and sludges requiring land disposal – the treated bottom soil and/or ash from the RCBI and the fabric filter residue.

The RCBI typically will have no major process by-products other than the RCBI and fabric filter ash, and, based on testing with carbon tetrachloride and high sulfur coal, potential operational advantages over other mobile incineration systems are as follows:

- lower capital equipment requirements than for a conventional rotary kiln incinerator because no afterburner is required;
- low fuel usage per unit of soil because of the excellent mixing in the RCBI, and no afterburner fuel requirements;
- neutralization of hydrogen chloride and sulfur dioxide can be accomplished in bed using low cost limestone, without the need for a wet scrubber;
- high in-bed sulfur dioxide removal efficiencies of 90% or higher are achieved based on tests burning high sulfur coal (S at 2.10 to 5.60%); and
- NO_x emission concentrations are low due to lower normal operating temperatures and have been measured in the range of 60 to 100 ppmv for contaminated soils.

2.2.4 Limitations

Because of the RCBI's relatively high rotational speed, it is more complicated and difficult to operate than a standard high-temperature rotary kiln incinerator. Selecting the appropriate rotational speed of the RCBI and the correct amount of bed material for the waste being processed is important to successful operation. Plugging of hot, treated soil recirculation lines is a potential problem. Additional development may reduce the amount of operation attention required for RCBI's comparable to that required for rotary kiln incinerators.

Design of the air pollution control and residue handling equipment must account for a comparatively high degree of entrained soil in the combustion gas created by the highly turbulent, fluidized nature of the RCBI bed material. Also, highly volatile metal emissions such as mercury may present a problem because the RCBI design does not include a wet scrubber. To control emissions of highly volatile mercury, the air pollution control systems would need to be modified.

In waste feed handling, wet, sticky clays are typically the worst problem

as is the case for all treatment technologies. They generally are shredded and/or dried. Extensive reduction of the sizes of soils may be required to optimize heat and mass transfer. The RCBI requires soil pretreatment to a maximum dimension of 5 cm (2 in.), a requirement that is easily met with commercially-available shredding equipment.

2.2.5 Comparative Cost Data

Two estimates of process costs for the RCBI are summarized in table 3.4 (on page 3.16) for an 18.2 tonne/hr (20 ton/hr) RCBI, one at a 9,090 tonne (10,000 ton) site and the other at a 45,450 tonne (50,000 ton) site. Pedco has estimated the capital cost for a mobile RCBI with this capacity to be \$3,000,000 in June, 1992 dollars. Mobilization and demobilization is estimated to cost \$500,000, and operation and maintenance estimated costs are \$26.20/tonne (\$23.82/ton) for the 10,000 ton site and \$19.16/tonne (\$17.42/ton) for the 50,000 ton site.

2.2.6 Technology Prognosis

The RCBI has been under development since 1981 with both pilot- and full-scale tests. The technology could benefit from further development in the following areas:

- exploration of the bed recycle rates as a function of the kind of soil or sludge. Values of 25 to 100 times the feed rate are typically used for coal fuels. High-inert content wastes, such as soils, should be in the range of about 5 to 10 times;
- soil residual and DRE data at different operating conditions for low-vapor pressure constituents, such as polychlorinated biphenyls (PCBs) and dioxins;
- soil entrainment rates and the treated soil distribution between the RCBI bottom ash and the air pollution control (APC) equipment relative to sizing of the soil and ash handling equipment;
- optimal limestone to chlorine ratio to achieve 99% hydrogen chloride removal;
- NO_x emissions at different RCBI temperatures;
- volatile metal emission rates during the treatment of soils; and

- residual organics present in the solids collected by the fabric filter.

2.3 *ECO LOGIC Process*

2.3.1 Process Identification and Description

The ECO LOGIC process, which is particularly suitable for wastes that are primarily aqueous, such as harbor sediments, landfill leachates, and lagoon sludges, is based on the gas-phase thermo-chemical reaction of hydrogen with organic and chlorinated organic compounds at elevated temperatures. At 850°C (1,560°F) or higher, hydrogen reacts with organic compounds to produce smaller, lighter hydrocarbons. In the case of chlorinated organic compounds, such as PCBs, the products of the reaction are primarily methane and hydrogen chloride. This reaction is enhanced by the presence of water.

Seven principal reduction reactions occur simultaneously to varying degrees and at various rates. The most efficient and fastest reactions are the dechlorination of chlorinated organics and the reduction of multi-ring (polynuclear hydrocarbons) structures to form benzene. The reduction of benzene to ethylene and the reduction of ethylene to methane occur at roughly the same rate and conversion efficiency, approximately 99%. The end result is that about 99% of the organic material put into the process is converted to methane.

The ECO LOGIC process uses hydrogen to produce a reducing atmosphere devoid of free oxygen, thus reducing the possibility of dioxin or furan formation. The ECO LOGIC process operates in a hydrogen-rich, oxygen-free environment. Other nonchlorinated hazardous organic contaminants, such as polyaromatic hydrocarbons (PAHs), are also reduced by the ECO LOGIC process to smaller, lighter hydrocarbons, primarily methane and ethylene.

2.3.2 Potential Applications

The process is applicable to contaminated soils, sludges, sediments, water, and oils. Chemical reactions that occur in the hydrogen reduction pro-

cess are enhanced by the presence of water. If water is not in the waste, steam is added to the process. Soil typically has a high enough moisture content to meet the water requirements.

2.3.3 Process Evaluation

ECO LOGIC has conducted destruction tests using a demonstration-scale reactor that is 2 m (2.2 yd) in diameter and 3 m (3.3 yd) in height and is mounted on a 15 m (16.4 yd) drop-deck trailer. A scrubber system and recirculation gas heating system are also mounted on the trailer, as well as the electrical control center. A second trailer holds a propane steam generator and waste preheating vessel. The boiler also accepts a small portion of the scrubbed dechlorinated recirculation gas as fuel. The processing rate for the demonstration unit is 250 to 300 kg/hr (550 to 660 lb/hr) of harbor sediment.

The pilot-scale testing consisted of twelve characterization tests and three performance tests conducted in 1991, processing harbor sediment contaminated with coal tar. The tests are discussed in Section 5.3. Following are highlights of the results, from tests conducted under methods and conditions described in Section 5.3:

- With best-case assumptions, DREs ranged from 99.9999% to 99.99999% and with worst-case assumptions, 99.9% to 99.99%;
- In all twelve characterization tests, the only major organic contaminants measured were naphthalene and chlorobenzene. Both PAH and chlorobenzene emission levels were below ambient air quality guidelines, and blank-correcting would have reduced most of the measured values to zero. Chlorophenols, PCBs, and dioxins were not detected;
- The grit and slag that was produced was virtually free of organic contamination and contained only the inorganic and metallic components of the harbor sediment;
- The decant water from each characterization test was tested for organic compounds and found to be virtually free of organic contamination. In all cases, the decant water was acceptable for disposal at the municipal wastewater treatment plant;
- Although the scrubber sludge (a minor by-product) produced was suitable for landfilling, the analytical costs to prove suitable-

ity make it more economical to recycle this small effluent stream back into the waste input. However, at some point, the increase in mass of the solids will pose a limit to its recycle;

- The emissions of metallic compounds from the stack were higher than the organic emissions and exceeded ambient air quality guidelines. This suggests that a more “state-of-the-art” particulate device may be required; and
- Analysis of the organic emissions during a performance test in which PCB-spiked waste was processed demonstrated that the process is suitable for destruction of PCB-contaminated material. The PCB concentrations (110 to 215 ppm) resulted in a range of DREs of 99.999% to 99.9999%. There were no detectable concentrations of PCBs found in the boiler stack gas, the reactor grit, the scrubber decant water, or the scrubber sludge. Further, there were no detectable stack emissions of other chlorinated compounds, such as dioxins, furans, or chlorophenols.

2.3.4 Limitations

Based upon the demonstration tests, it appears materials handling problems will be the most prevalent problems, including, for example, grit blockages at the reactor bottom exit. An additional concern when decontaminating soils is the preparation of the feed, e.g., screening or crushing the feed to dimensions of <2.5 cm (1 in.).

2.3.5 Comparative Cost Data

To project the processing costs for a full-scale (100 tonne/day (110 ton/day)) unit, the operating costs (Canadian \$) for the pilot-scale destructor processing Hamilton Harbor sediment during the three performance tests were used. Under conditions and assumptions set forth in Section 5.3, the waste destruction is estimated to be approximately \$325/tonne (US \$250/ton) in the first year of operation.

Since the higher the organic and water content the lower the throughput, the cost of destruction is more or less proportional to the throughput. Compared with incineration, processing of wastes having high-Btu (organic) content requires more hydrogen, and, therefore, costs more to process than a watery waste with a low-Btu content.

2.3.6 Technology Prognosis

Material handling problems that surfaced during the Hamilton Harbor demonstration have been addressed and possibly solved. A commercial-scale system has not been built, and additional problems may be encountered during the SITE program demonstration. A full-scale system was to be operational by 1993. (See Appendix C for Technology Contact).

2.4 Horsehead Resource Development Company, Inc., (HRD) Flame Reactor Process

2.4.1 Process Identification and Description

High-temperature metal recovery (HTMR) is becoming an option for treating hazardous materials, including soils. The HTMR processes extract the metal contaminants from the substrate material. The separated metals are typically recovered in a form that can be recycled and then recovered. Metal values will sometimes offset a portion of the treatment costs. The HRD Flame Reactor process is a HTMR technology developed by Horsehead Resource Development Company, Inc., for the treatment of wastes and residues that contain toxic levels of leachable metals.

The Flame Reactor process is based on the use of a two-stage water-jacketed steel reactor vessel divided into a burner stage (fuel combustion) and a reactor stage (oxide reduction). A flow diagram of the HRD's Flame Reactor facility at Monaca, Pennsylvania, is shown in figure 3.8 (on page 3.30). The process is described in Subsection 3.4.1.

Accurate metering of the fuel, combustion air, and feedstock are necessary to maintain sufficient reducing reactor conditions to allow volatile metals, e.g. zinc and cadmium, to be readily extracted from the waste as metallic vapors, while condensable metals, e.g. copper, are separated from the molten slag as a molten alloy.

2.4.2 Potential Applications

The HRD Flame Reactor technology is suited for the treatment of sludges, slags, and metal contaminated soils, and/or recovery of metal contaminants therefrom. This technology, therefore, competes with other high-temperature thermal vitrification processes that encapsulate contaminants, with the potential for material recovery and reuse.

The extremely high-processing temperature makes the Flame Reactor technology suitable for organics destruction and vitrification. The real strength of the technology, however, lies in processing materials with metal constituents that can be recovered in a concentrated form suitable for recycling to the secondary metals market. Even at very low metal concentrations, the Flame Reactor can render a material nonhazardous by immobilizing the metals in a vitrified slag. In order for the metal oxide product to be sufficiently enriched for recycling, however, the total concentration of volatile metals, such as cadmium, lead, and zinc, should be at least 5%. Similarly, condensable metals, such as copper, nickel, and cobalt, should total 5% or more in the feed in order to yield a molten metal alloy product. The slag must be molten at 1,400° to 1,500°C (2,550° to 2,730°F), preferably with a viscosity of 2 poise or less. If necessary, fluxing agents can be blended with the feed prior to processing.

2.4.3 Process Evaluation

Section 5.4 summarizes three large-scale tests conducted to evaluate the HRD Flame Reactor process for treating contaminated soils. The contaminated matrices were secondary lead soda slag, lead-contaminated soil, and electric arc furnace dust spiked with carbon tetrachloride. These tests have demonstrated the ability of the Flame Reactor process to recover metal for recycling, produce a nonhazardous vitrified slag, and destroy organic contaminants.

The tests also revealed that the reactor feed should be fine and dry enough to allow trouble-free pneumatic injection into the reactor. Heat transfer rates and reaction rates are reduced as moisture and particle size increase. Therefore, nominal feed specifications for the Flame Reactor are a particle size distribution of 80% less than 75 μm (200 mesh) and a total water content (including chemically-bound water) of 5%.

2.4.4 Limitations

The major limitations of the HRD Flame Reactor process have to do with the kinds and physical characteristics of the waste, including limits on the feed. For example, at least 5% of the feed should be volatile metals in order that the metal oxide product is sufficiently enriched for recycling, and condensable metals should total 5% or more of the feed in order to yield a molten metal alloy product. Other limitations include crushing of feed to less than 4.75 mm (3/16 in.) and pre-drying for moisture content above 15% (it is desirable that feed moisture be <5%)

2.4.5 Comparative Cost Data

Estimated commercial processing costs, resulting from demonstration tests and assumptions discussed in Section 3.4.3, ranged from \$235/tonne (\$215/ton) for secondary lead soda slag to \$250/tonne (\$228/ton) for contaminated soil.

Sampling, monitoring, and analysis requirements for organic compounds, however, will be higher than those for materials that contain only toxic metals, and the costs of organic analyses could significantly affect processing costs, depending on the compounds involved.

2.4.6 Technology Prognosis

Although the Flame Reactor process is well-suited for the treatment of metal-bearing wastes, the process is unlikely to be economically competitive with lower temperature alternative processes for treatment of organic contaminated soils with low metal content. Horsehead Resource Development Company, Inc., is pursuing opportunities to apply the Flame Reactor technology to treatment of metal-bearing wastes contaminated with organic compounds. Several wastes are under review for process testing. At the present, there are no plans to construct a mobile plant. Although there is considerable interest within HRD and elsewhere, a specific business opportunity must be identified before the large capital investment required can be justified.

3

PROCESS IDENTIFICATION AND DESCRIPTION

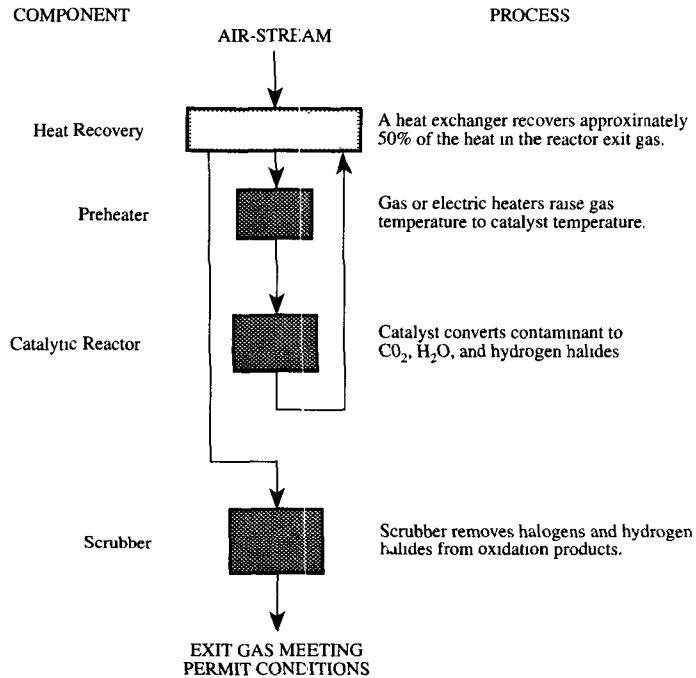
3.1 Catalytic Oxidation

3.1.1 Process Description

Catalytic oxidation is a process that may be used to destroy organic vapors extracted from contaminated soils through soil venting and from contaminated water through air stripping, preventing their discharge into the atmosphere. Soil venting is an effective means for removing volatile organic contaminants (VOCs) from the vadose zone, and air stripping is effective in removing them from groundwater. Most states require the use of an emissions control device, however, to prevent discharge of the extracted vapors into the ambient air. In addition to catalytic oxidation, other treatment processes are selective condensation of organic compounds, adsorption of organic compounds (on a solid such as activated carbon) and thermal oxidation.

Catalytic oxidation units for the destruction of halogenated organic compounds typically consist of a preheater (usually gas or electric) to elevate the air-stream temperature to the catalyst temperature ($<450^{\circ}\text{C}$ (840°F)), a catalytic reactor, a shell and tube heat exchanger to recover a portion (approximately 50%) of the heat in the reactor exit gas, and a scrubber to remove halogens and hydrogen halides from oxidation products before their release to the atmosphere (see figure 3.1 on page 3.2). In the simplest system, only the preheater and catalytic reactor would be necessary; however, the use of the heat exchanger improves treatment economics and the scrub-

Figure 3.1
Catalytic Oxidation Unit Flow Chart



ber may be required to meet regulatory requirements governing acid-gas emissions.

The feed stream to the catalytic oxidation unit is typically generated by either vacuum extraction or air stripping. In vapor extraction, a vacuum/compressor pump draws the well vapor through the manifold and pumps the gas to the catalytic oxidation unit. In air stripping, contaminated groundwater is pumped to the surface, the contaminant is air-stripped from the water, and the air-contaminant stream is directed toward the catalytic oxidation unit.

3.1.2 Operational Considerations

Field experience with catalytic oxidation units treating trichloroethylene (TCE) has been generally positive, although one study showed that a decrease in contaminant destruction efficiency occurred with operating time. This was attributed to attrition of catalyst granules in the fluidized bed (Hylton 1992). In another instance, a few “learning curve” failures of system components resulted in short shutdowns (Buck, Hauck, and Abdun-Nor 1992). Typical of the component failures was corrosion of the Inconel sheath of a thermocouple that measured the temperature of the vapor in the hydrogen chloride neutralizer following the catalytic reactor. Repairs consisted of a minor redesign of the neutralizer system and substitution of a sheath better able to withstand the corrosive and erosive effects of the two-phase flow of vapor and a liquid condensate containing hydrogen chloride.

3.1.3 Cost Data

The amount (weight) and type of the organic compounds in the contaminated source must be known before the most economical emissions control system can be selected. Other parameters, of course, such as the local emissions control limits, must also be defined. With chlorinated organic compounds, it is important to know the daily emission limits for hydrogen chloride; local regulations across the U.S. vary with respect to this acidic gas. Generally the upper limit is 1.8 kg/hr (4 lb/hr) without acid-gas control; some jurisdictions limit hydrogen chloride emissions to levels set by the best available control technology (BACT). Thus, the catalytic oxidation of chlorinated organic compounds may or may not be required to include acid-gas neutralization. The effect of requiring acid-gas neutralization on the overall economics is large.

Guidelines on economics for three emissions control systems – adsorption by activated carbon, catalytic oxidation without hydrogen chloride neutralization, and catalytic oxidation with hydrogen chloride neutralization – have been presented by Buck, Hauck, and Abdun-Nor (1992) for a catalytic oxidation unit ($5.7 \text{ m}^3/\text{min}$ (200 standard ft^3/min) with a gas-fired preheater). Total emissions control costs included capital, utility costs, and, for systems with hydrogen chloride neutralization, the cost of operating the neutralization system. Favored at sites with small amounts of contaminant because of lower capital costs, carbon adsorption becomes noncompetitive at sites with larger total contaminant volumes.

For TCE, a suggested rule of thumb is that carbon adsorption is favored economically (1) where the contaminant is less than 3,630 kg (8,000 lb) and where hydrogen chloride produced by catalytic oxidation can be vented and (2) where the contaminant volume is up to 7,260 kg (16,000 lb), if the product hydrogen chloride must be removed by a neutralizer/scrubber. If the contaminant reaches 40,000 lb, the project total emissions control costs with carbon adsorption (\$400,000) approximately double that of either catalytic oxidation case (\$150,000 without scrubbing and \$210,000 with a neutralizer/scrubber). Similar economic comparisons may be made for other halogenated organic compounds provided the basic carbon adsorption data, catalysts, and catalytic oxidation kinetics are available.

3.2 Rotary Cascading Bed Incineration System (RCBI)

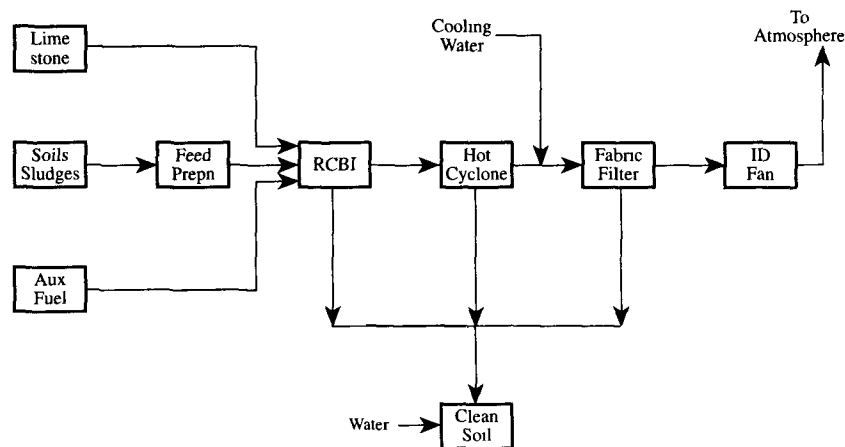
3.2.1 Process Description

The Rotary Cascading Bed Incinerator (RCBI) System is an innovative, high-temperature thermal destruction system that has the capability for high throughput and low-cost in treating low organic-content soils and sludges. The RCBI was developed and patented by Pedco Incorporated (Pedco) of Cincinnati, Ohio. A full-scale RCBI was installed and is being operated as a fixed commercial hazardous waste incinerator in Deer Park, Texas, by Rollins Environmental Services (Falcone 1991). Called the Rollins Rotary Reactor (Rollins RR), the unit was developed under an agreement with Pedco.

The rotary cascading bed technology is addressed here primarily as a mobile, high-temperature incineration system for the treatment of contaminated soils from Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, although there are no RCBI's currently being used as mobile incinerators for the treatment of contaminated soils. Contaminated soils are, however, being treated by the Rollins RR, and the technology should be transferable for use in mobile systems.

The RCBI System uses a rapidly rotating cylindrical chamber to develop highly turbulent gas and solids mixing conditions in order to effect efficient combustion of solid and liquid fuels and wastes. These mixing conditions are obtained by (1) rotating the cylindrical combustion chamber at a high speed, (2) using lifters attached to the inside of the cylinder, and (3) incorporating a high rate of recycling of the bed material from the back end of the RCBI to the feed end. A schematic flow diagram of the RCBI System as it would be used to treat contaminated soils and sludges from CERCLA sites is shown in figure 3.2.

Figure 3.2
Schematic Flow Diagram of the RCBI



Key process design considerations include: rotation, bed recycling, thermal performance, waste feed systems, auxiliary fuels, bed neutralization, air pollution control (APC) equipment, and treated soil handling.

Rotation. The Pedco RCBI rotates at 10 to 15 rev/min, as compared to less than 1 rev/min for a typical high-temperature rotary kiln incinerator. The significantly higher rotational speed develops centrifugal forces that

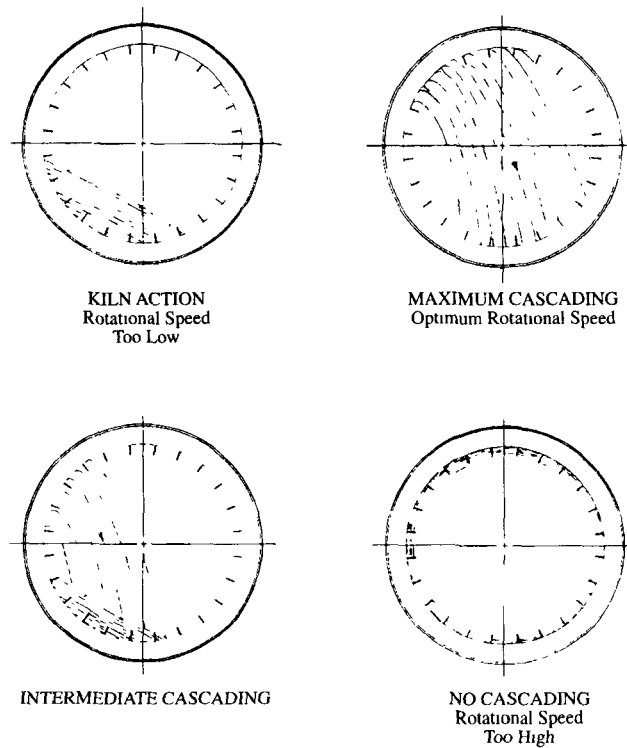
result in bed material being carried up by the lifters above the angle of repose. The lifters are metallic plates attached to the inner liner of the RCBI parallel to the axis of the cylinder. At some point in the rotation, bed material falls off the lifters in a trajectory through the gas space. The degree of cascading of a particular bed material is determined by the rotational speed of the cylinder. In order to obtain optimal contact and turbulence between the solids and the combustion gas, cascading across the entire diameter is effected by adjusting the rotational speed of the RCBI. Figure 3.3 (on page 3.7) depicts the cross-sectional area of an RCBI showing the effect of changes in the speed of rotation on the cascading of bed material (Reed 1984).

The Rollins RR is reported to have a rotational speed of 2 to 5 rev/min, depending on the characteristics of the waste materials being processed (Falcone 1991).

Bed Recycling. The bed is recycled through use of solids transport chutes forming an Archimedean Spiral, which pumps the hot bed solids from the exit end of the RCBI, on the outside of the RCBI to the feed end (Seibel and Long 1990). A diagram of the Pedco RCBI, which includes the solids recirculation chute, is shown in figure 3.4 (on page 3.8) (Reed 1984). The solid-waste feed is dropped onto this hot recycled bed to condition the feed and to transfer heat from the hottest part of the combustion zone to the feed end. This conditioning quickly dries the feed and minimizes sticking of wet soils or sludges on the RCBI walls (Reed 1984). Recycle rates are a function of the waste being fed and may range from 25 to 100 times for high Btu coals, to 5 to 10 times the waste-feed rate for high inert materials, such as contaminated soils (Seibel and Long 1990; Reed 1993).

Thermal Performance. Design features effect a cascading action of the recycled bed material and the waste feed. The cascading bed results in a highly stirred, turbulent atmosphere in the RCBI in which the waste, the recycled bed material, any liquid or solid auxiliary fuel, combustion air, and combustion gases are thoroughly mixed. Cascading solids transfer momentum to the combustion gas, causing a swirling motion that also induces mixing of the gas (Seibel and Long 1991). Approximately 30% of the solids are always suspended in the hot combustion gas (Seibel and Long 1990). This results in a high heat transfer rate to the waste solids similar to that obtained in a pneumatic bubbling fluidized bed incinerator.

Figure 3.3
Stages of Cascading
vs.
RCBI Rotational Speed

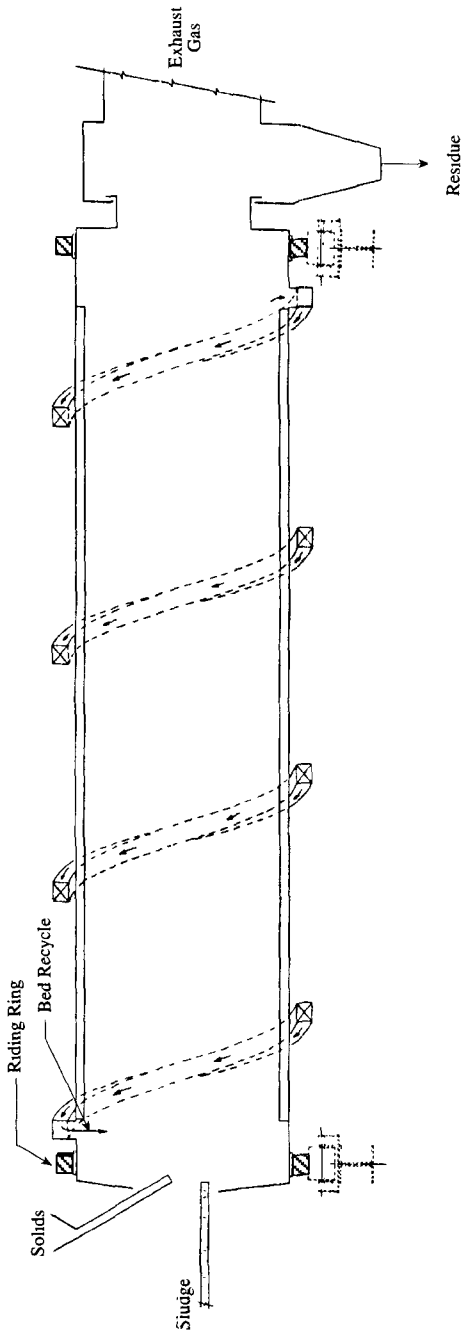


Courtesy Pedco, Inc

The high degree of turbulence results in the Resource, Conservation, and Recovery Act (RCRA) destruction removal efficiency (DRE) standard performance of 99.99% without the use of the burner in the secondary chamber. Efficiencies of >99.998% were obtained without an afterburner for carbon tetrachloride during a trial burn with the Rollins RR (Falcone 1992).

Waste Feed Systems. The soil preparation and feed systems currently used by mobile incineration systems for the feeding of wet sticky clays and

Figure 3.4
Rotary Cascading Bed Incinerator



Courtesy Pedco, Inc

other soils will be also required for feeding the RCBI. Sludge wastes are fed to the Rollins RR through use of a positive displacement pump that discharges to a nonatomizing lance that, in turn, feeds the sludge directly into the combustion chamber (Falcone 1991). Solid wastes are fed by an overhead clamshell crane that discharges the solids to a shredder. The shredded solids are discharged to enclosed screw conveyors that feed the solids directly to the rotary reactor. Liquid wastes are pumped directly to the rotary reactor (Falcone 1991).

Auxiliary Fuels. Because of the highly turbulent action of the cascading bed materials, liquid wastes or fuels do not require atomization. Liquids may be fed through a pipe or a screw feeder (Reed 1984). For low Btu content soils and sludges, low-cost solid fuels such as coal may be used as auxiliary fuels. Rollins uses either natural gas, fuel oil, or shredded wood pallets as auxiliary fuel for the full-scale system. Rollins has also found that the rotary reactor can operate at temperatures as low as 790°C (1,450°F), and low excess air levels while still producing complete thermal destruction and, thereby, save auxiliary fuel (Falcone 1991).

Bed Neutralization. Acid gases, such as hydrogen chloride and sulfur dioxide, generated by the combustion of chlorine and sulfur containing organics, are effectively neutralized by the addition of limestone to the waste feed. Rollins found that the efficiencies of this in-bed neutralization process have been as high as those achieved with traditional wet scrubbing processes (Falcone 1991). Pedco realized similar high efficiencies with a pilot boiler during the combustion of chlorinated materials and high-sulfur coals (sulfur content ranging from 2.10 to 5.60%). Sulfur dioxide removals of 90% were obtained with a calcium-to-sulfur ratio of 1:2 (Seibel and Long 1990). Pedco uses limestone screenings, a low-cost product from the lime industry, for in-bed neutralization.

Air Pollution Control (APC) Equipment. Because of the excellent in-bed neutralization capability, the RCBI can use a relatively simple baghouse for particulate, metals, and acid-gas control. For the treatment of contaminated soils with low concentration levels of chlorinated compounds, this results in a system without any aqueous effluents, since wet scrubbing is not necessary to obtain the 99% hydrogen chloride removal performance standard required by RCRA regulations. The hot, dusty baghouse residue can be mixed with the RCBI bottom ash or treated separately if it has high concentrations of the US EPA regulated metals.

Treated Soil Handling. The treated soil and/or ash leaving the RCBI is hot and dusty and is typically cooled and rehumidified by water sprays or by mixing in a pug mill-type device with water. The baghouse residue can, in some cases, be mixed with the treated soil and/or ash from the RCBI before it is cooled with water.

3.2.2 Application Engineering

The basic concepts underlying the RCBI derive from the fields of low-temperature solids drying, granulation, and calcining (Reed 1984). Rotary dryers have been used for many years in the asphalt industry for the drying of aggregate. These aggregate dryers operate at solids temperatures of about 260° to 315°C (500° to 600°F) and, because of this low temperature, can use rotary dryers fabricated of steel without a refractory lining. They use lifters and a high rotational speed to produce mechanical fluidization and cascade the wet aggregate into the rotating dryer. A burner fires auxiliary fuel through this “veil” of wet aggregate thereby producing a high heat-transfer rate between the wet solids and the hot combustion gas. The innovation of the RCBI System lies in the conversion of the low-temperature aggregate dryer system to a high-temperature incineration system capable of rotating at high speeds and operating at solids temperatures of 425° to 540°C (800° to 1,000°F) higher than the traditional aggregate dryer design.

3.2.3 Status of Development

The rotary cascading bed combustion technology, under development since 1981, has been tested at the pilot- and full-scale level on numerous kinds of fuels and wastes. It has been applied in testing and treating wastes in the following major areas:

- as a waste-to-energy boiler (Seibel and Long 1991), and
- as a fixed, hazardous waste incinerator for low Btu soils, sludges, and other wastes (Falcone 1991, Reed 1984).

Pedco is currently developing the RCBI in the waste-to-energy area (Seibel and Long 1991), and Rollins, in the hazardous waste incineration area. The Rollins RR has been used to incinerate contaminated soils, sludges, wastewater, and liquid wastes (Falcone 1991).

3.2.4 Environmental Impact

The environmental impact of the RCBI on air, water, and land is expected to be similar to that of other high-temperature incinerators.

Air. Test data for the Rollins RR indicates the RCBI should meet or exceed all applicable RCRA and air regulatory requirements. Estimates of the major air emissions of the RCBI based on data from the full-scale Rollins RR (Falcone 1991; Alliance Technologies 1989) are shown in table 3.1. These estimates indicate that the volume of air emissions is expected to be equal to or even lower than emissions from other high-temperature mobile incinerators. The particulate emission data are based on typical fabric filter operation at 22.5 to 45 mg/normal m³ (0.01 to 0.02 grains/dry standard ft³), corrected to 7% oxygen. No specific US EPA regulated metals' emissions data exist for the RCBI.

Table 3.1
Estimated Air Emission Levels From Mobile RCBI System

Emission Parameter	Stack Concentration Range (ppmv-Dry)	Removal Efficiency (Percent)
RCRA DRE (Percent)	—	>99.99
Total Hydrocarbon (As Methane)	5-20	—
Carbon Monoxide	10-45	—
Particulate (gr/dscf @ 7 Percent Oxygen)	0.01-0.02	—
Hydrogen Chloride	5-15	>99
Sulfur Dioxide	5-25	>90
Nitrogen Oxides	60-100	—

Falcone 1991, 1992

Water. The only use of water in a mobile RCBI is for evaporative cooling of the combustion gas (before its passage to the fabric filter), cooling treated soil, and rehumidification. Because the RCBI uses in-bed neutralization and a dry fabric filter for particulate and metal emission control, the

process has no aqueous effluents. Total water usage for an 18.2 tonne/hr (20 ton/hr) mobile RCBI will be about 285 L/min (75 gal/min).

Soils and Sludges. Incident to the treatment of contaminated soils and sludges, two solid discharges require land disposal. One is the treated bottom soil and/or ash from the RCBI, and the other, the fabric filter residue.

During a CERCLA cleanup, specific organic and metal residual requirements would need to be achieved for both of these solid discharges. Data from the full-scale Rollins RR indicate that the RCBI will produce treated soil residual values similar to those of current high-temperature mobile incinerators. The Rollins RR has consistently produced a treated soil with residual organic levels below detection levels.

3.2.5 Pre- and Posttreatment Requirements

Contaminated soil pretreatment generally falls into two areas:

- pretreatment to facilitate waste feed handling; and
- pretreatment to optimize the thermal treatment.

Feed pretreatment to facilitate waste feed handling is required for all mobile incineration systems. Wet, sticky clays typically present the worst problem. They are generally macerated and/or dried.

The feed pretreatment applied to optimize thermal treatment depends on the equipment used. Metal shards from shredded drums, for example, should not typically be fed to a fluidized bed. The need to extensively reduce the size of the feed in order to optimize heat and mass transfer can pose a serious processing problem. The RCBI requires soil pretreatment to maximum dimensions of 5 cm (2 in.) (Long 1989). This is easily done with commercially-available shredding equipment. The full-scale Rollins RR uses a hydraulically-driven, low-speed, high-shear shredder.

The limestone used in the RCBI for in-bed neutralization of acid gases during the combustion of fuels must be crushed to a 1 cm ($<3/8$ in.) particle size (Seibel and Long 1990). Treated soil and/or ash from the RCBI will be hot and dusty and will require the addition of water for cooling and dust control. This is a common procedure for hot, treated soils in the thermal remediation industry.

Table 3.2
RCBI Design Data

RCBI Design	RCBI Value
RCBI SIZING AND CAPACITY	
Soil Capacity	18.2 tonne/hr (20 ton/hr)
Soil Moisture	20 Percent
RCBI DESIGN PARAMETERS	
Temperature Of Operation	Combustion Gas At 815 °C (1,500°F) Soil At 760 - 815°C (1,400-1,500°F)
Excess Air Level	20% Minimum
Rotational Speed	10-16 rpm
AUXILIARY FUEL CANDIDATES	
	Natural Gas Or Propane Fuel Oil Coal Wood Waste Liquids
LIME REQUIREMENT	1.2-1.5 Times Stoichiometric
APC SYSTEM	Hot Cyclone And Fabric Filter
UTILITY USAGE	Fuel-47.5 GJ/hr (45 MM Btu/hr) Electrical-400 kW Water-285 L/min (75 gal/min)
TRANSPORTATION	Three Trailers With RCBI, APC And Control Room

Reed 1992

3.2.6 Special Health and Safety Considerations

Operation of a mobile RCBI will pose the same health and safety considerations as those applicable to mobile incinerators generally. A CERCLA site cleanup always requires a Health and Safety Plan. Handling of hot treated soil, fabric filter residue, and hot rotating equipment are three areas commonly addressed in site cleanup Health and Safety Plans.

3.2.7 Design Data and Unit Sizing

Pedco developed a design for a RCBI with a capacity of 18.2 tonne/hr (20 ton/hr) of contaminated soil containing 20% moisture. The system has an inside diameter of 2.74 m (9.0 ft) and a length of 15.24 m (50.0 ft). The design and sizing parameters are summarized in table 3.2 (Long 1989). A mass-energy balance is shown in table 3.3 (on page 3.14).

Table 3.3
RCBI Calculated Mass-Energy Balance

Mass And Energy into RCBI at 15.6°C (60°F)			
Component	KG/HR	KJ/KG	GJ/HR
Contaminated Soil	18,181.8	181.5	3.300
Auxiliary Fuel	1,095.6	42,706.4	46.789
Combustion Air	19,328.9	0.0	0.000
Air Humidity	174.0	2,460.0	0.428
TOTAL	38,780.2		50.517
Mass And Energy out of RCBI at 815.6°C (1,500°F)			
Component	KG/HR	KJ/KG	GJ/HR
Combustion Gas			
Carbon Dioxide	3,931.5	876.4	3.446
Oxygen	750.6	815.1	0.612
Nitrogen	4,918.0	877.8	13.095
Water Vapor	4,816.5	4,126.5	19.875
Particulate	2,872.7	902.4	2.592
COMBUSTION GAS TOTALS	27,289.3		39.620
Treated Soil	11,490.9	902.4	10.369
Radiation Loss			0.528
TOTAL	38,780.2		50.517

BASIS: 18.2 Metric Tons Per Hour (20 TPH) of Soil At 20% Moisture And 1% Organic, Incinerated At 20% Excess Air
Focus Environmental Mass - Energy Balance Calculations

The Rollins RR has successfully treated soils with moisture contents ranging from 10 to 40% and with heating values from 800 to 5,800 kJ/kg (350 to 2,500 Btu/lb). It has successfully treated sludges with moisture content ranging from 30 to 50% and heating values from 2,300 to 18,600 kJ/kg (1,000 to 8,000 Btu/lb). In addition, the unit successfully incinerated wastewater and organic liquids (Falcone 1991). The Rollins RR has operated at temperatures ranging from 650° to 870°C (1,200° to 1,600°F) and at excess air levels from 20 to 70%.

3.2.8 Operational Requirements and Considerations

The mobile RCBI will require two operators per shift and will operate continuously for 24 hours per day, 7 days per week. Continuous operation

will require four labor shifts or 8 people. Soil feed preparation and handling and treated soil handling will require two more operators per shift.

Operation of an RCBI designed to process a contaminated soil having a moisture content of 20% would have to operate at about 50% of rated throughput capacity to process a contaminated soil with moisture content of 50%.

3.2.9 Unique Planning and Management Needs

The RCBI, used as a mobile incinerator for CERCLA site remediation, would have no unique planning and management needs. Planning and management needs would be essentially the same as those required for mobile rotary kilns and fluidized bed incinerators. The use of lime for in-bed neutralization of acid gases would require special lime storage and handling facilities.

3.2.10 Comparative Cost Data – Process Costs

Two estimates of process costs were made for the 18.2 tonne/hr (20 ton/hr) RCBI. One is for operations at a 9,090 tonne (10,000 ton) site and the other, for operations at a 45,450 tonne (50,000 ton) site. For these estimates, the soil at each site is assumed to contain 20% moisture and to be contaminated with 1% organic constituents having an average chlorine content of 50% by weight.

Estimates of operating costs are presented in table 3.4 (on page 3.16). Elements of those costs and estimated capital cost are discussed below. (Nonprocess cost elements are set forth in Section 3.2.11.)

Labor. The estimate covers the cost of one skilled and one unskilled operator per shift required for direct operations. Other labor costs, for soil feed preparation and handling, hot treated soil handling, and analytical services, were not included. For a four-shift operation, 8 operators at an average cost of \$30,000/yr/person and one supervisor at \$60,000/year, the total labor cost will be \$300,000/year with an operating factor of 80%. Assuming one month each for mobilization and demobilization, the 18.2 tonne/hr (20 ton/hr) RCBI would process a 9,090 tonne (10,000 ton) site in about 2.9 months at a labor cost of about \$71,400. The estimated processing time and labor cost for the 45,450 tonne (50,000 ton) site is 6.3 months and about \$157,000.

Table 3.4
Process Cost Estimates for the RCBI

Process Cost Estimate for a 9,090 Tonne (10,000 Ton) Site			
Capital Cost (1992) \$3,000,000			
Process Operating Costs	Cost in \$	\$/Tonne	\$/Ton
Labor	71,400	7.85	7.14
Auxiliary Fuel	110,900	12.20	11.09
Power	12,500	1.38	1.25
Neutralization	550	0.06	0.06
Maintenance	42,850	4.71	4.28
OPERATING COSTS-SUB TOTAL	238,200	26.20	23.82
Capital Recovery	130,300	14.33	13.03
Mobilization/Demobilization	500,000	55.00	50.00
TOTAL PROCESS COSTS	868,500	96.00	87.00

Process Cost Estimate for a 45,450 Tonne (50,000 Ton) Site			
Capital Cost (1992) \$3,000,000			
Process Operating Costs	Cost in \$	\$/Tonne	\$/Ton
Labor	157,000	3.45	3.14
Auxiliary Fuel	554,400	12.20	11.09
Power	62,500	1.38	1.25
Neutralization	2,750	0.06	0.06
Maintenance	94,200	2.07	1.88
OPERATING COSTS-SUB TOTAL	870,850	19.16	17.42
Capital Recovery	286,550	6.30	5.73
Mobilization/Demobilization	500,000	11.00	10.00
TOTAL PROCESS COSTS	1,657,400	36.00	33.00

Reference see Section 3.2.10 of text

Auxiliary Fuel. The amount and cost of auxiliary fuel will depend on the kind of fuel used and the heat content of the contaminated soil. For a soil with 20% moisture and 1% organic contamination, the RCBI will generate about 46.8 Gj/hr (44.4 MM Btu/hr) using auxiliary fuel. For natural gas costing \$4.74/Gj (\$5/MM Btu), the RCBI auxiliary fuel cost, based on the mass and energy balance calculations summarized in table 3.3 (on page 3.14), will be \$110,900 for the smaller site and \$554,400 for the larger site.

Electrical Power. Pedco has estimated that the RCBI requires 400 kw (Long 1989). At \$.05/kw hr, the estimated cost of electricity for the RCBI

is \$12,500 for the 9,090 tonne (10,000 ton) site and \$62,500 for the 45,450 tonne (50,000 ton) site.

Neutralization. For a contaminated soil containing 1% of organic material that is 50% organic chlorine, it is estimated that an 18.2 tonne/hr (20 ton/hr) RCBI will need 5.5 kg (11 lb) of limestone/tonne of soil at 40% excess limestone for in-bed neutralization. At \$11/tonne (\$10/ton) for limestone screenings, the estimated cost for neutralization of the smaller site will be \$550 and, about \$2,750 for the larger.

Maintenance. In the chemical industry, the annual cost of maintenance of process equipment is typically about 4% of the equipment capital cost. Because of its high rotational speed and innovative nature, however, annual cost of maintenance of the RCBI has been estimated to be 6% of capital cost. This results in an estimated maintenance cost of \$42,900 at the smaller site and, \$94,200 at the larger.

Capital Recovery. The basis for the estimate of capital recovery is a 12% interest cost and a 10-year equipment life. This results in a capital recovery factor of 18.25%/yr, or a cost of \$130,300 for the smaller site and, \$286,600 for the larger.

Mobilization and Demobilization. The estimated cost to mobilize and start-up the RCBI and to demobilize the unit is about \$500,000.

Capital Cost. Pedco estimated the capital cost for a mobile RCBI with a capacity of 18.2 tonne/hr (20 ton/hr) to be \$3,000,000 in June, 1992 dollars (Reed 1992). The estimate contemplates a unit consisting of the following components (Long 1989):

- A trailer-mounted RCBI with hydraulic drive system, feeding chutes, gas burner for start-up and for supplemental fueling, rear breeching, cooling system, built-in traveling supports, alignment provisions for the trunnions, ash removal, and recycling system. The RCBI will be supplied with the instrumentation required for control and for monitoring, including thermocouples, pressure sensors, sampling tubes and tachometers;
- A trailer-mounted fabric filter with induced draft fan; dust collection, removal, and recycling system; and stack. The fabric filter and stack will be equipped with appropriate instrumentation for control and monitoring;

- A trailer-mounted, winterized control and monitoring room equipped with instrumentation that controls the RCBI, the fabric filter, the induced draft fan, and the evaporative cooling system. It will include a control panel equipped with recorders with alarms to keep a permanent record of all major operating parameters. This trailer will also contain the monitoring rack with continuous monitors for carbon monoxide, carbon dioxide, hydrocarbons, hydrogen chloride, O₂, NO_x, and sulfur dioxide. Sampling ports will be provided for sampling the gas stream for the presence of other contaminants; and
- A truck or trailer to handle the ducting for connecting the RCBI to the fabric filter, the piping required for the cooling system, feeder chutes, the stack, spare parts, the electrical cabling, instrumentation wiring, and other necessary parts required to set up and operate the unit.

The Pedco capital estimate also includes the following engineering and permitting-related costs (Long 1989):

- three persons for 4 months' start-up and training;
- ten sets of RCBI operating manuals; and
- one person for permitting support for the RCBI's first project.

Additional field and consulting engineering costs are included in the amount of \$675/day plus expenses for each person.

The estimate does not include the following capital items:

- office trailers;
- diesel generator to supply electricity to the system if power is not available;
- shredder pretreatment and feed system for the contaminated soil;
- cooling system for the hot treated soil and fabric filter residue;
- treated soil and ash storage and handling;
- lime or limestone storage and feed handling system; and
- decontamination facilities.

Although additional costs accrue (see Section 3.2.11), the technology-dependent process cost estimates for the RCBI presented here can be used

in comparing the cost of its operation with that of other systems. The comparisons, of course, must address the same kinds of wastes at sites of similar size under the same cost basis.

3.2.11 Nonprocess Cost Elements

Following are nonprocess cost elements, not included in the estimates set forth in Section 3.2.10, that commonly accrue in a Superfund remediation project:

- site preparation;
- soil excavation and pretreatment;
- treated soil and process residues disposition;
- *nonprocess labor* – clerks, soil excavation and health and safety personnel, site supervisors, etc.;
- contractor profit;
- treated soil and process-related analyses; and
- demonstration tests for state and federal regulatory agencies.

These costs are basically independent of the technology, and in many cases their total will be significantly higher than the process costs. For example, a typical Superfund project may require 50 people on site, with only 8 operators and one supervisor being directly related to the operation of the process. Soil excavation, pretreatment, and disposition after treatment can be expensive, particularly for wet soils and sediments that require mechanical dewatering and/or drying.

3.3 ECO LOGIC Process

3.3.1 Process Description

The ECO LOGIC process is suitable for treating many kinds of wastes and hazardous waste matrices, including contaminated soil. It is particularly suitable for wastes that are primarily aqueous, such as harbor sediments, landfill leachates, and lagoon sludges.

The presence of water in the waste acts to prevent Cl_2 formation and aids in the destruction process, since water itself can act as a reducing agent to help dismantle the contaminant molecules. For example, water contaminated with 0.1% (1,000 mg/L) polychlorinated biphenyls (PCBs) can be readily processed.

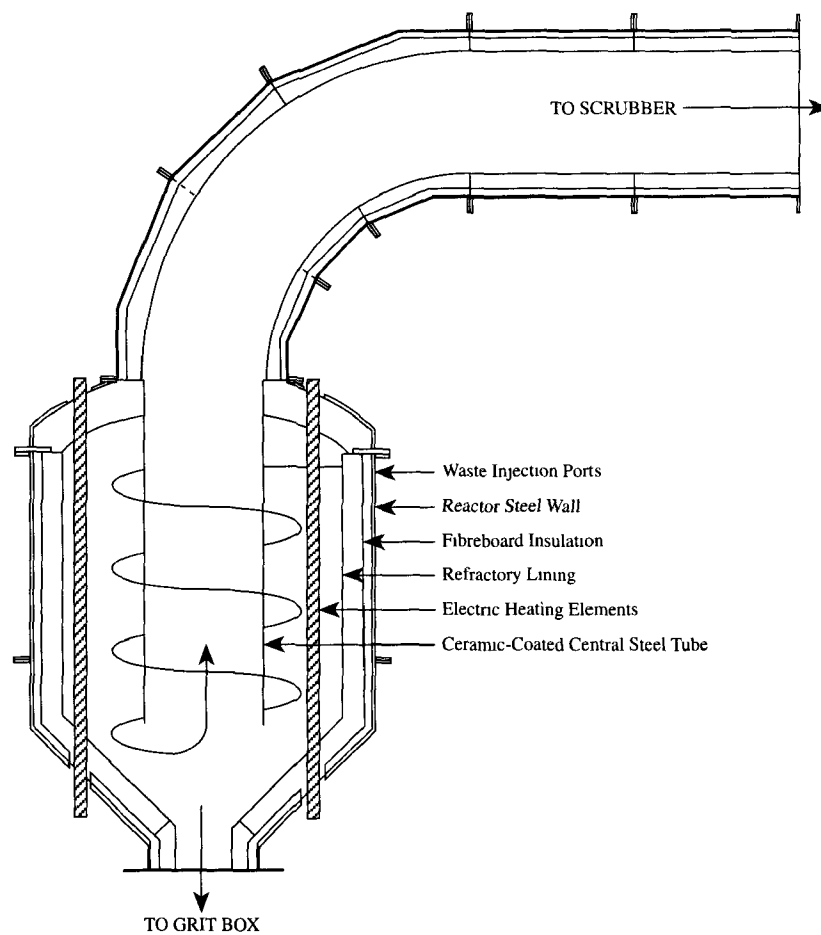
Research and development has focused on bench-scale testing of surrogate compounds, development of a larger lab-scale destructor (1 kg/hr (2.2 lb/hr)) for testing actual waste samples, and construction of a mobile full-scale unit (250 to 300 kg/hr (550 to 660 lb/hr)) for materials and component testing.

ECO LOGIC set up a demonstration facility for processing polyaromatic hydrocarbons (PAHs) and PCB-contaminated harbor sediments in Hamilton, Ontario, and conducted destruction tests during the spring of 1991. The demonstration-scale reactor, 2 m (6.6 ft) in diameter and 3 m (9.8 ft) in height, is mounted on a 15 m (49 ft) drop-deck trailer. A scrubber system and recirculation gas heating system are also mounted on the trailer, as well as the electrical control center. A second trailer holds a propane-fired steam generator and waste preheating vessel. The boiler accepts a small portion of the scrubbed dechlorinated recirculation gas as fuel. The processing rate for the demonstration unit is 250 to 300 kg/hr (550 to 660 lb/hr).

Figure 3.5 (on page 3.21) is a schematic of the reactor where the destruction of the waste occurs. The various input streams are injected through several ports mounted tangentially near the top of the reactor. Special nozzles are used to atomize liquid wastes in order to accelerate liquid vaporization. The gas mixture swirls around a central ceramic-coated steel tube, and is heated by 18 vertical silicon carbide electric heating elements. By the time it reaches the bottom of the reactor, the gas mixture has reached a temperature of at least 850°C ($1,560^\circ\text{F}$). Some particulate initially present in the waste drops out of the reactor bottom and is collected in a grit box. Finer particulate entrained in the gas stream flows up the ceramic tube, into the exit elbow and through the retention zone. The process reactions take place from the bottom of the ceramic tube upwards, and take less than one second to complete.

Figure 3.6 (on page 3.22) is a process schematic of the entire pilot-scale system, including the reactor. Most of the components of the pilot-scale system are mounted on two standard drop-deck highway trailers. Hydrogen

Figure 3.5
Thermo-Chemical Reduction Reactor

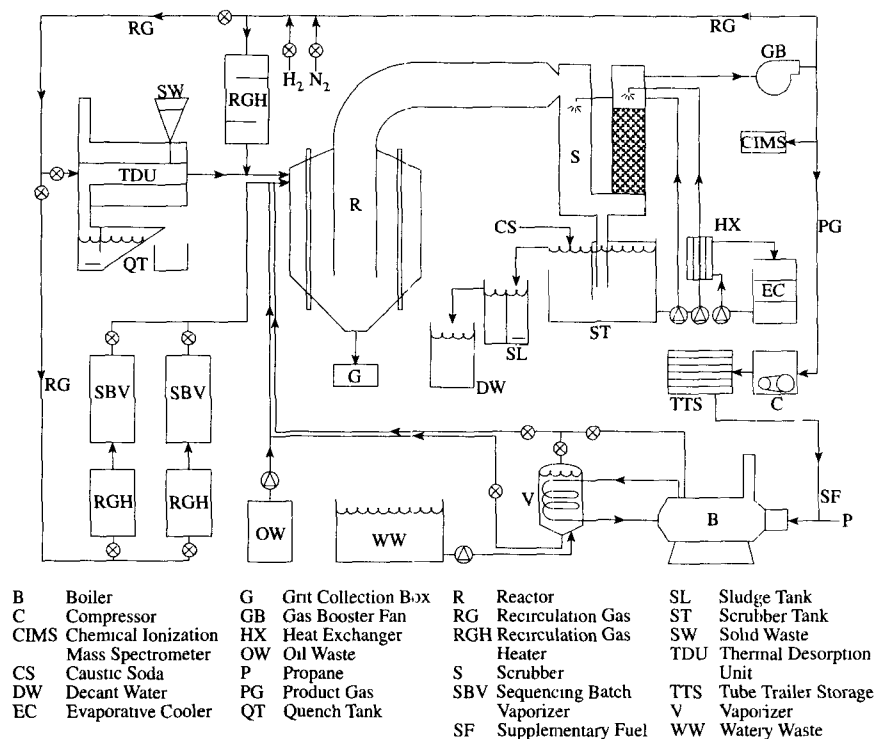


Courtesy ECO LOGIC

and recirculated product gas are preheated in the recirculation gas heater, which consists of two propane-fired single-ended radiant tube heaters. The recirculation gas flowrate varies with the waste type and concentration, up to a maximum of 95% of the product gas. Nitrogen is used to purge the entire assembly prior to waste processing and following the discontinuation of processing.

Several feed systems are available for various types of wastes, depending on whether watery waste, oil waste, or solid waste is being processed. Wa-

Figure 3.6
Process Schematic



Courtesy ECO LOGIC

tery waste is preheated in a vaporizer using steam from a boiler. The contaminated steam from the vaporizer is metered into the reactor at a rate determined by the process control system. Hot contaminated liquid exits the bottom of the vaporizer at a controlled flowrate and enters the reactor through an atomizing nozzle. Oil waste can be metered directly from drums into the same line using a peristaltic pump.

Solid wastes such as soil or decanted sediment are decontaminated in a thermal desorption unit (TDU) with the contaminants being sent to the reactor through a separate port. The internal workings of the TDU are designed to vaporize all water and organic contaminants in the waste soil/sediment while mechanically working the solids into as fine a mixture as possible. The water vapor and organic contaminants are swept into the reactor by a sidestream of scrubbed recirculation gas.

Solids, such as contaminated electrical equipment, can be thoroughly desorbed using the sequencing batch vaporizer (SBV) chambers. These chambers take advantage of the reheated recirculation gas stream to heat the equipment and carry contaminants into the reactor. The hydrogen atmosphere is nonreactive with most metals, minimizing potential problems of metal oxide formation.

The SBV can also be used for vaporization of drummed solid chemical wastes, such as hexachlorobenzene. Significant stockpiles of "hex wastes" exist and are still being generated as byproducts of chlorinated solvent production. Advantages of vaporizing hex wastes directly from the drum include decreases in worker exposures and fugitive emissions from drum transfer operations, cleaning of the drums in place, and segregation of inorganic contaminants into the existing drums. The SBV has been tested at lab-scale with hex waste samples and PCB-contaminated electrical equipment.

The product gas leaving the reactor is scrubbed in a caustic scrubber to remove water, heat, fine particulates, and hydrogen chloride. The scrubber water is recirculated from the scrubber tank to sprayers in the first leg of the scrubber and to a polypropylene media bed in the second leg. Sodium hydroxide is added periodically to maintain a scrubber water pH of 9. The heat adsorbed by the scrubber water is removed by a plate-plate heat exchanger and evaporative cooler. By the end of the second leg, the product gas temperature has been cooled to approximately 35°C (95°F). It is drawn out of the scrubber by a gas booster fan.

The dirty scrubber water from the two scrubber legs returns to the scrubber through a drop-tube that extends well below the water surface. This acts as a seal against air infiltration and as an emergency pressure relief mechanism. One-half of the scrubber tank is partitioned and covered to prevent any gas release if a short-term pressure surge forces gas out of the bottom of this tube. A check valve allows the gas to re-enter the system once the pressure returns to normal. The system normally operates within 10 inches water gauge (0.36 psi) of atmospheric pressure.

As waste is processed through the system, water condenses in the scrubber tank and overflows to a sludge settling tank and then to a decant water tank. The scrubber tank is agitated with a mixer to prevent sludge sedimentation. Decant water is the only liquid effluent, and, after pH balancing, has been found suitable for sewer disposal where pilot testing has been conducted. The amount of effluent is equal to the amount of water in the incoming waste stream, so on-site waste water treatment is not a costly option if required. The minor amount of sludge produced can be diverted to the solid waste stream being processed through the TDU which would result in a slight increase in the decontaminated solids discharged from the TDU.

The cooled and scrubbed product gas is a clean, dry mixture of hydrogen, methane, carbon monoxide, and other light hydrocarbons. As indicated earlier, most of the gas is reheated and recirculated back into the reactor, in order to maintain a high concentration of hydrogen in the reactor. A sidestream is drawn off for on-line sampling. Sidestreams can also go to the TDU as a sweep gas, to the SBV as sweep gas, or to a compressor for storage in a tube trailer. Storage of the product gas under pressure permits the analysis of large batches of gas prior to using the gas as fuel and allows the operation of the system in a "stackless" mode. Potential applications for the stored product gas include heating the TDU, steam reformation for optimum hydrogen recovery, and steam/electricity generation.

Throughout waste processing operations, the product gas is sampled continuously using the chemical ionization mass spectrometer (CIMS). This analyzer is capable of accurately monitoring up to 10 organic compounds every few seconds at concentrations ranging from percent levels down to ppb levels. It is used as part of the ECO LOGIC Process to monitor the concentrations of certain compounds indicative of the process destruction efficiency. The compounds selected for monitoring depend on the waste being processed. For example, during PCB processing,

monochlorobenzene is typically monitored as an indicator of destruction efficiency. Low levels of this volatile compound indicate that destruction of the PCBs is proceeding to completion. An increase in the monochlorobenzene concentration triggers an alarm in the process control system, and the exceedance of a preset threshold is used to automatically curtail waste input. The CIMS also provides a continuous record of the quality of the product gas being compressed and stored.

The process equipment described above was installed at Hamilton Harbor on two 15-m (39 ft) drop-deck trailers. A process control trailer containing the on-line mass spectrometer, process control system, and other analysis equipment was located near the two process trailers. The footprint for the entire process was only 20 m by 60 m (66 ft by 195 ft). The equipment was completely self-contained with its own power generator and water supply.

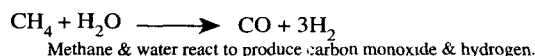
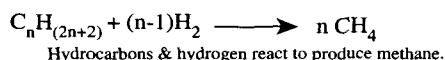
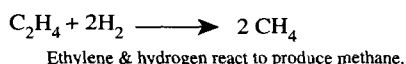
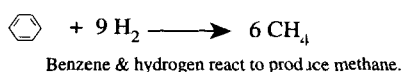
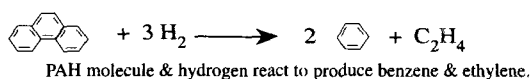
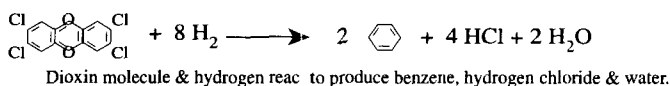
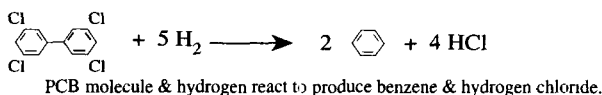
3.3.2 Scientific Basis

The ECO LOGIC process is based on the gas-phase, thermo-chemical reaction of hydrogen with organic and chlorinated organic compounds at elevated temperatures. At 850°C (1,560°F) or higher, hydrogen reacts with organic compounds in a process known as *reduction* to produce smaller, lighter hydrocarbons. In the case of chlorinated organic compounds, such as PCBs, the products of the reaction are primarily methane and hydrogen chloride. This reaction is enhanced by the presence of water.

Figure 3.7 (on page 3.26) shows seven principal reduction reactions that are reported to occur in the ECO LOGIC process. The first is the dechlorination and dismantling of a PCB molecule to produce hydrogen chloride and benzene. The second reaction is the dechlorination of the dioxin molecule. The third reaction is the reduction of a PAH compound, phenanthrene, to produce benzene and ethylene. The fourth is the reduction of a benzene molecule to produce methane, and the fifth is the reduction of ethylene to produce methane. The sixth reaction is the reduction of straight-chain hydrocarbons to produce methane. The seventh reaction is a “water shift reaction” and is not a reduction reaction, although it occurs only in a reducing atmosphere. In this reaction, methane and water combine to form carbon monoxide and hydrogen.

Figure 3.7

Thermo-Chemical Reduction Reactions



Courtesy ECO LOGIC

All of these reactions occur simultaneously in the ECO LOGIC process, although to varying degrees and at various rates. The most efficient and fastest reactions are the dechlorination of chlorinated organics and the reduction of multi-ring structures to form benzene. The reduction of benzene to ethylene and the reduction of ethylene to methane occur at roughly the same rate and conversion efficiency, approximately 99%. Straight-chain compounds convert to methane at a higher rate. The result is that about 99% of the organic material input to the process is converted to methane.

The back reaction from methane in combination with water to form carbon monoxide and hydrogen is much less efficient (20 to 30%), but, nonetheless, very useful. Since hydrogen is one of the main costs of operation,

reactions that generate hydrogen help reduce the overall cost of the process. Unfortunately, this reaction and the conversion of ethylene to methane are both endothermic, so there is an increased energy cost, which partially offsets the savings on hydrogen. Another hydrogen-producing reaction is the breakdown of methane to form carbon and hydrogen. This occurs to a limited extent, depending on the amount of excess hydrogen in the reducing atmosphere and the reaction temperature.

The ECO LOGIC process uses hydrogen to produce a reducing atmosphere devoid of free oxygen, thus reducing the possibility of dioxin or furan formation. Other nonchlorinated hazardous organic contaminants, such as PAHs, are also reduced by the ECO LOGIC process to smaller, lighter hydrocarbons, primarily methane and ethylene.

The process lends itself to continuous monitoring of the destruction efficiency, because of the tendency of the reaction to produce lighter, more volatile gases. An on-line mass spectrometer process gas analyzer system can measure key organic compounds on a continuous basis and be integrated into the process control system. Specifically, destruction efficiencies can be measured very quickly by continuously monitoring chemical intermediate products such as chlorobenzene and benzene concentrations. The information from the mass spectrometer is sent to the process controller so that an increase in chlorobenzene or benzene concentration (signaling a decrease in PCB or PAH destruction efficiency) halts the input of waste and alerts the operator.

3.3.3 Operational Considerations

Throughout the demonstration testing phase of the Hamilton Harbor Project, modifications were made in an effort to increase the throughput and reliability of the system. The majority of problems encountered were related to materials handling, including:

- plugging problems at the bottom of the waste vaporizer vessel and at the Turbotak nozzle at the reactor inlet;
- erosion in the piping system, flow measurement and flow control elements;
- pressure control problems in the reactor;
- process gas release due to reactor overpressure;

- grit exiting the reactor plugging the system; and
- build-up slag material around the glo-bar (silicon carbide heating element) causing glo-bar breakage during cooling.

Most of these problems have been recognized and addressed. In addition, the hydrogen chloride produced may cause corrosion problems in long term operation.

3.3.4 Cost Data

The cost of destruction of wastes, discussed in the Hamilton Harbor report, is based on actual test conditions and measurements and their projection to commercial scale (ELI ECO LOGIC International, Inc. 1992). For watery wastes, such as those processed at Hamilton Harbor, the cost was approximately \$275 (Canadian) /tonne (US \$250/ton). The developers estimate the cost for processing contaminated soils would approach \$210 (Canadian)/tonne (US \$190/ton). The details of these cost estimates are covered in the evaluation of the process in Section 5.3.

3.4 Horsehead Research Development Company, Inc., (HRD) Flame Reactor Process

3.4.1 Process Description

High temperature metal recovery (HTMR) is becoming an option for treating hazardous materials, including soils. The HTMR process extracts the metal contaminants from the substrate material. The separated metals are typically recovered in a form that can be recycled, and the value of the recovered metal sometimes offset a portion of the treatment costs.

The HRD Flame Reactor Process is a HTMR technology developed by Horsehead Resource Development Company, Inc., for the treatment of wastes and residues that contain toxic levels of leachable metals. Since its installation in 1984, HRD's Flame Reactor facility in Monaca, Pennsylvania (18,145 tonne/yr (20,000 ton/yr)) has demonstrated its capability to

process a wide variety of metal-bearing wastes and residues, e.g., steel mill electric arc furnace (EAF) dust, zinc plate residues, and lead smelter residues. Recently, the application of Flame Reactor technology has been extended to soil remediation in a series of process tests that included a treatability study on lead-contaminated soil from the C&R Battery Superfund site in Richmond, Virginia. The results of these studies are reported in Sections 5.4.1 through 5.4.3.

The company is currently building a 27,215 tonne/yr (30,000 ton/yr) Flame Reactor facility to treat steel mill EAF dust. The plant is located on the site of the North Star Steel minimill in Beaumont, Texas. Roughly 5,450 tonne/yr (6,000 ton/yr) of metal will be recovered for recycling instead of being landfilled. The plant start-up was scheduled for the first quarter of 1993. (See Appendix C for Technology Contact).

The Flame Reactor Process is based on the use of a water-jacketed steel reactor vessel that is divided into two stages: a burner stage (fuel combustion) and a reactor stage (oxide reduction). A flow diagram of the Monaca Flame Reactor facility is shown in figure 3.8 (on page 3.30). In the first, or burner stage, fuel in the form of pulverized coal or coke, or natural gas, is combusted with oxygen-enriched air (40 to 80% O₂) under fuel-rich conditions to produce a high-temperature (2,200° to 2,500°C (3,990° to 4,530°F)) reducing atmosphere. In the second, or reactor stage, fine dry soil is pneumatically injected into the hot reducing gases, causing the temperature to decrease rapidly. The average reactor temperature is between 1,400° and 1,800°C (2,550° and 3,270°F), depending on the desired operating conditions, and total gas residence time in the reactor is 100 to 500 milliseconds.

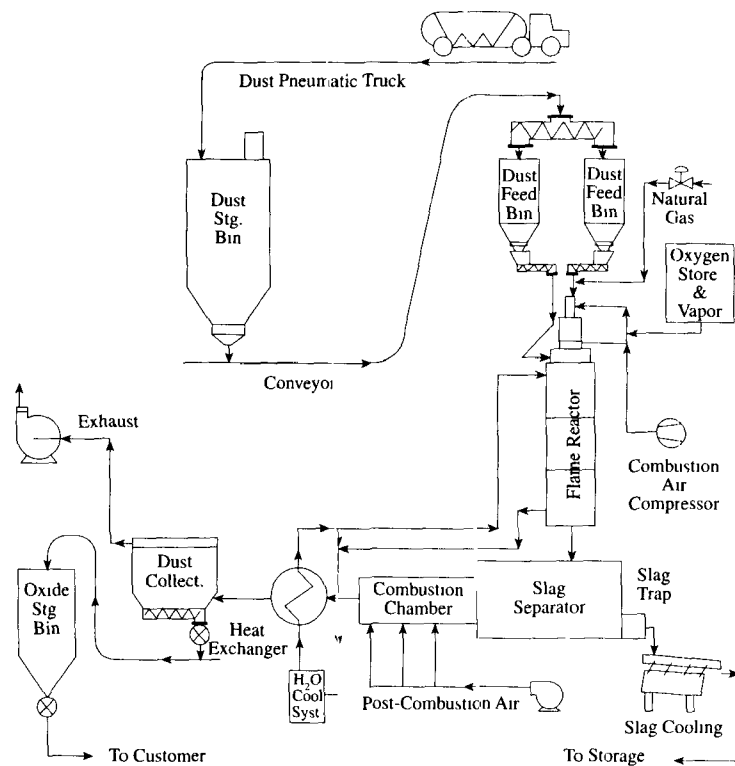
Less volatile metals, such as copper, nickel, and cobalt coalesce as a molten alloy. The remaining components of the waste, including silicates and metal oxides such as those of iron, form a molten slag. The reactor feeds directly into a slag separator, or horizontal cyclone, where the process gases and volatile compounds are separated from the molten materials. If a molten metal alloy is formed, it is separated from the slag in a quiescent holding unit before the slag is tapped. The slag is continuously tapped and solidified on a noncontact, water-cooled, vibrating conveyor. The conveyor transports the slag to a temporary collection bin, from which it is transferred to storage.

The molten slag must be fluid enough to be readily tapped from the slag separator. Therefore, the slag must be molten at 1,400° to 1,500°C (2,550°

to 2,730°F), preferably with a viscosity of 2 Poise, or less. Soils, because of their siliceous composition, generally require fluxing agents to effect proper slag fluidity. The flux can be blended with the feed prior to processing.

Volatile metals, such as zinc, lead, arsenic, and cadmium are vaporized from the waste along with volatile alkali and halide compounds. The process gases are drawn from the slag separator through the offgas system where the metal vapors are postcombusted with ambient air and condensed as metal oxides. The remaining H_2 and CO are combusted to water vapor

Figure 3.8
HRD Flame Reactor Gas Fired Process Flow Diagram



Courtesy Horsehead Resource Development Company Inc

and carbon dioxide. The gases are subsequently cooled, and the mixed metal oxide particulate is collected in a pulse-jet baghouse. The offgas is discharged to the atmosphere.

The HRD two-stage reactor design separates the two major sets of oxide smelting reactions. The exothermic carbon-oxygen reactions take place in the first stage, while the endothermic metal oxide-carbon monoxide reactions occur in the second stage.

3.4.2 Operational Considerations (Zagrocki 1992a)

Accurate metering of the fuel, combustion air, and feedstock is necessary in order to maintain the reactor conditions sufficiently reducing to ensure metallic zinc, cadmium, copper, etc., are formed, while leaving iron as a reduced oxide. This control of the reducing atmosphere is essential to allow volatile metals, e.g., zinc and cadmium, to be readily extracted from the waste as metallic vapors, while condensable metals, e.g., copper, are separated from the molten slag as a molten alloy. Iron is partially reduced to FeO, which improves slag fluidity and reduces iron contamination in the metal alloy.

The extremely high processing temperature makes the HRD Flame Reactor technology suitable for organics destruction and vitrification. The real strength of the technology, however, lies in its capacity for processing materials with metal constituents that can be recovered in a concentrated form for recycling to the secondary metals market. The Flame Reactor process does not require a minimum metal concentration in the feed for effective treatment. Even at very low metal concentrations, the Flame Reactor can render a material nonhazardous by immobilizing the non-volatile metals in a vitrified slag. In order for the metal oxide product to be sufficiently enriched for recycling, however, the total concentration of volatile metals, e.g., cadmium, lead, and zinc, should be at least 5%. Likewise, condensable metals, such as copper, nickel, and cobalt should equal 5% or more in the feed in order to yield a molten metal alloy product.

At a minimum, the feed should be fine and dry enough to allow trouble-free pneumatic injection into the reactor. Moisture and particle size also affect reactor performance, heat transfer rates and reaction rates being reduced as moisture and particle size increase. For this reason, a nominal feed specification for the Flame Reactor is a particle size distribution of

80% less than 75 μm (200 mesh) and a total water content (including chemically-bound water) of 5%. The Flame Reactor, however, has successfully processed material which was 80% < 1,000 μm with 15% total water.

3.4.3 Cost Data

Estimated cost data for the commercial processing of secondary lead soda (SLS) slag have been developed based on the results of demonstration tests and key assumptions. These estimates are presented in Section 5.4.1.

4

POTENTIAL APPLICATIONS

4.1 Catalytic Oxidation

Catalytic oxidation is effective and potentially more economic than traditional carbon adsorption for controlling the emissions of halogenated organic compounds removed by vapor extraction from the vadose zone or by air stripping from contaminated groundwater. The key to the economical difference is the concentration and total amount of contaminant to be treated. Low concentrations and small amounts of contaminant favor carbon adsorption; high concentrations and large amounts of contaminant favor catalytic oxidation. At very high concentrations thermal oxidation is favored.

In most cases, both the concentration and the boiling point of the organic compounds removed through soil venting and air stripping are so low that condensation is economically impractical because of high capital and operating costs. The process of adsorption of the organic compounds on granular activated carbon is often used because of low capital requirements and operating simplicity. When the quantity of the contaminant is large, however, or the organic compounds have low adsorption factors on the carbon, the operating cost of the adsorption process makes it noncompetitive with oxidation.

Under many conditions, thermal oxidation is the process of choice. There is a need, however, to heat the mixture of organic compounds and air to a temperature of about 800°C (1,500°F), and, therefore the cost of the auxiliary fuel to sustain the desired operating temperature can be substantial. Energy savings can be realized by product gas-to-feed heat exchangers, but their use raises capital costs, and maintenance costs are likely to be higher. Any corrosive substances in the oxidation products will make selec-

tion of proper materials of construction for heat exchangers more critical. With chlorinated organic compounds, a combustion product is hydrogen chloride, a strongly acidic and potentially corrosive gas. Consequently, thermal oxidation has been infrequently employed at soil vapor extraction projects that recover chlorinated organic compounds.

Catalytic oxidizers have long been used for emissions control of air/organic compound mixtures. An advantage of catalytic oxidation is that it occurs at a lower temperature than thermal oxidation. Compared with thermal oxidation, energy costs are lower for two reasons, one thermodynamic and the other, engineering. First, less fuel is required to preheat the air/organic compound mixture to the reaction temperature, and second, it is easier and cheaper to build a product-to-feed heat exchanger for the lower operating temperature of about 450°C (840°F), typical of catalytic reactors. A potential disadvantage of catalytic oxidizers, however, is that the catalyst may be deactivated, or poisoned, by various volatile materials. For example, chlorinated organic compounds deactivate the platinum-based catalysts commonly used in conjunction with vapor extraction of gasoline-contaminated soils. Thus, until recently, there were no commercially-available catalysts for applying the nominally better catalytic oxidation process to control air emissions of halogenated organic compounds (Lester 1989).

4.2 Rotary Cascading Bed Incinerator (RCBI) System

The RCBI technology is applicable to almost any kind of organically contaminated Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) site where mobile rotary kilns, rotary dryers, fluidized beds, or infra-red conveyor furnaces have been used in thermal remediations. This would include CERCLA sites contaminated with volatile organics and semivolatile organics. The RCBI would be applicable to sites with lightly-contaminated soils and sludges and to complex sites containing organic tars, contaminated soils, sludges, and debris. For drum sites with large quantities of drummed wastes, it might be necessary to shred the drums to pieces less than 5 cm (2 in.) on a side, if they are to be fed to the RCBI. An option would be to empty the drums, feed the separated wastes

to the RCBI, clean and compact the drums, and feed the drum wash water to the RCBI.

4.3 ECO LOGIC Process

The ECO LOGIC Process is applicable to contaminated soils, sludges, sediments, water, and oils. The feed rates depend on the kind of waste and the waste characteristics. The chemical reactions that occur in the hydrogen reduction process are enhanced by the presence of water, and if water is not available in the waste, steam is added to the process. Soil typically has sufficient moisture content to meet the water requirements. At the Hamilton Harbor demonstration, slurried sediments that were 90 to 95% water, with 5 to 10% solids, of which about 30% was organic material, primarily coal tar, were processed. Currently, a desorption module is being tested at the front end of the reactor. Its function is to desorb organic compounds from soil so that only the soil organic content and the soil moisture are processed through the reactor and only the inorganics pass through the soil desorption module. This system has been tested at pilot-scale in Bay City, Michigan, during a US EPA Superfund Innovative Technology Evaluation (SITE) Program demonstration in the fall of 1992, with the following matrices and throughputs:

- contaminated soil (1000 ppm polychlorinated biphenyls (PCBs)) 1.8 to 6.4 tonne/day (2 to 7 ton/day);
- contaminated water and oil 4.5 tonne/day (5 ton/day) (4000 ppm PCBs); and
- contaminated oil (20% PCBs) and water 1.8 tonne/day (2 ton/day).

Since the higher the organic and water contents, the lower the throughput, the cost of destruction is more or less proportional to the throughput. Compared with incineration, processing of wastes having high-Btu (organic) content requires more hydrogen, and therefore, costs more to process than a watery waste with a low-Btu content. Methods of conserving and producing hydrogen that may offset this are under investigation.

Table 4.1
Examples of Metal Industry Wastes Amenable
to FLAME REACTOR Processing

Type of Waste or Residue	Industry Affected	Areas of Impact	Solution Provided by Flame Reactor
Air Pollution Control Dusts	<ul style="list-style-type: none"> ■ primary metal ■ secondary metal ■ metal casting ■ metal finishing 	<ul style="list-style-type: none"> ■ carbon steel electric arc furnace dusts - Pb, Cd, Cr ■ copper converter flue dusts - Pb, Cd, As ■ foundry dusts - Pb, Cd ■ grinding dusts - Pb 	<ul style="list-style-type: none"> ■ Cd, Pb, and/or As are recovered with Zn as a recyclable mixed oxide ■ Cu is recovered as an alloy with Ni, Pb ■ Cr and Ni encapsulated in slag
Solution Purification Solids	<ul style="list-style-type: none"> ■ primary metal electrowinning ■ electrorefining ■ electroplating 	<ul style="list-style-type: none"> ■ jarosite - Pb, Cd ■ goethite - Pb, Cd ■ cementation wastes - Pb, Cd 	<ul style="list-style-type: none"> ■ Cd, and/or Pb are recovered with Zn as a recyclable mixed oxide ■ Cu is recovered as an alloy with Ni, Pb
Electrolysis Sludges	<ul style="list-style-type: none"> ■ primary metal electrowinning ■ electrorefining ■ electroplating 	<ul style="list-style-type: none"> ■ electroplating sludges - Cr, Pb, Cd ■ anode sludges - Pb 	<ul style="list-style-type: none"> ■ Cd, Pb, and/or As are recovered with Zn as a recyclable mixed oxide ■ Cu is recovered as an alloy with Ni, Pb ■ Cr and Ni encapsulated in slag
Slags	<ul style="list-style-type: none"> ■ primary metal 	<ul style="list-style-type: none"> ■ lead blast furnace slag - Pb 	<ul style="list-style-type: none"> ■ Cd and Pb are recovered with Zn as a recyclable mixed oxide
Leach Residues	<ul style="list-style-type: none"> ■ primary metal 	<ul style="list-style-type: none"> ■ neutral leach residue - Cd, Pb 	<ul style="list-style-type: none"> ■ Cd and Pb are recovered with Zn and Ag as a recyclable mixed oxide
Soils	<ul style="list-style-type: none"> ■ primary metal ■ secondary metal ■ metal casting ■ metal finishing 	<ul style="list-style-type: none"> ■ landfills - various ■ site remediation - various 	<ul style="list-style-type: none"> ■ toxic metals are encapsulated in a vitrified slag ■ recovery of metals for recycling when present in sufficient quantities

Courtesy Horsehead Resource Development Company, Inc

4.4 Horsehead Research Development Company, Inc., (HRD) Flame Reactor System

The HRD Flame Reactor technology is suited to the treatment and/or recovery and recycling of metal contaminants in sludges, slags, and soils. This technology competes with other high-temperature thermal vitrification processes that encapsulate contaminants with the potential for material recovery and reuse. Table 4.1 lists examples of metal industry wastes amenable to Flame Reactor processing (Zagrocki 1992a).

5

PROCESS EVALUATION

5.1 Catalytic Oxidation

5.1.1 HD CatOx™

The Industrial Catalyst Group of Allied-Signal, Inc. announced the development and commercial availability of a “Halohydrocarbon Destruction Catalyst” (HDC) in 1989. The HDC is designed to tolerate chlorine and other halogens and is very effective in promoting the oxidation of halohydrocarbons at temperatures $<450^{\circ}\text{C}$ (840°F). Allied-Signal published data on the HDC performance with a variety of halogenated solvents at various space velocities and temperatures (Lester 1989). Using this information, King, Buck/Catalytic designed and constructed a commercial HD CatOx™ system for treating gases from a soil vapor extraction process. The prototype has been operating successfully since mid-1990 in southern California. The unit has a capacity of $7.4\text{ m}^3/\text{min}$ ($260\text{ standard ft}^3/\text{min}$) and is designed to handle 2,500 ppmv trichloroethylene (TCE). The system was packaged so that it would occupy one parking space on the top floor of a multi-story parking garage. It consists of a vacuum pump/compressor, heat exchanger, process heater, fixed-bed catalytic reactor, neutralizing scrubber, and self-contained cooling system. It is designed for continuous operation with process and safety controls to maintain conditions that comply with the Permit to Operate.

Operation of the soil vapor extraction system at the design rate of $5.7\text{ m}^3/\text{min}$ ($200\text{ standard ft}^3/\text{min}$) has resulted in a steady decline in the concentration of TCE in the vapor feed to the HD CatOx™, from about 3,500 ppmv to about 500 ppmv after 400 days of on-stream operation. The total amount

of TCE removed by vapor extraction during this period is more than 18,140 kg (40,000 lb).

A permit for construction of the system was issued by the South Coast Air Quality Management District (SCAQMD). Operating results have met the conditions listed in the operating permit. Minimal operating data for the unit have been made available. Data supplied by the developer, however, indicates the following: preheater energy requirements, 28kw; catalytic reactor Destruction Removal Efficiency (DRE), 97%; and, scrubber performance, 95+% hydrogen chloride removal. The prototype is priced at approximately \$150,000 and is designed to treat about 115 kg (250 lb) of TCE/day. Daily operating costs for utilities and the caustic for hydrogen chloride neutralization are about \$200. This compares favorably with a carbon adsorption system which had an estimated cost of \$2,000/day for regeneration charges alone (Buck, Hauck, and Abdun-Nor 1992).

5.1.2 ARI International (Hylton 1992)

Building 5000 at Wurtsmith Air Force Base (AFB) is the site of an effort to remove volatile organic compounds (VOCs), chiefly TCE, from groundwater by air stripping with emissions control. The Air Force Engineering and Services Center at Tyndall AFB contracted the Oak Ridge National Laboratory (ORNL) to analyze and evaluate a full-scale catalytic oxidation unit. Elements of the evaluation included obtaining data on the destruction efficiency of the preheater and the catalytic reactor, determining whether there were any products of incomplete combustion (PICs) in the effluent of the preheater or the catalytic reactor, and collecting accurate utility costs for operation of the catalytic system.

Air stripping with a catalytic oxidation system began in October 1987. The contaminated groundwater was pumped to the surface and contacted countercurrently with air in two packed columns in series to transfer the VOCs from the water to the air. The air stripping system was designed to treat 833 L/min (220 gal/min) of water; however, the system was usually operated in the range of 568 to 643 L/min (150 to 170 gal/min).

The catalytic oxidation unit was fabricated by ARI International (ARI). It destroys the VOCs in the air stream by bringing air in contact with a fluidized bed of catalyst granules at a controlled temperature. The catalytic oxidation unit includes a natural gas flame preheater to elevate the air

stream temperature to the catalyst bed temperature. The unit was designed to treat 34.2 m³/min (1,200 standard ft³/min), and Wurtsmith personnel normally operated the unit at the ARI-recommended catalyst bed temperature of 370°C (700°F). The estimated concentration of TCE in the feed stream to the unit was 11 to 12 ppmv. The catalyst granules in the fluidized bed oxidation unit are composed of an aluminum oxide support impregnated with chromium. The catalyst is normally attrited because of the constant grating of the granules against each other and so the catalyst must be periodically replenished. The depth of a full load of catalyst for this unit is approximately 20 cm (8 in.), and the catalyst bed chamber is approximately 0.8 m² (1 yd²) in cross section. The pressure drop across the catalyst bed is directly proportional to the depth of the bed. According to a manufacturer's representative, 2.5 cm (1 in.) of water pressure drop corresponds to approximately a 2.5 cm (1 in.) depth of catalyst in the bed. The pressure drop across the catalyst bed was observed to decrease approximately 124 Pascal (0.5 in. of water) in four months operating time because of the catalyst attrition.

Four series of samples were collected from the catalytic oxidation unit in October 1989, February 1990, August 1990, and May 1991. Samples were collected simultaneously from the feed, preheater effluent, and stack effluent while the unit was operated at catalyst bed temperatures ranging from 315 to 480°C (600 to 900°F).

The major emphasis of the project was the collection of samples of VOCs. A volatile organic sampling train (VOST) was used for collecting these samples. (The VOST is the US EPA) Method 30 for the collection of volatile principal organic hazardous constituents from the stack gas effluents of hazardous waste incinerators.) The sampling procedure was specified to allow the catalytic oxidation unit to attain steady-state conditions when it was necessary to change the catalyst bed temperature. The unit was allowed to operate one hour after reaching the desired catalyst bed temperature prior to initiating sample collection.

The results of this study indicate that the TCE catalytic oxidation unit at Wurtsmith AFB destroys TCE with 97.3 to 99.1% destruction efficiency, with TCE feed ranging from 13.5 to 7.8 ppmv, when operated at the vendor-recommended, catalyst bed temperature of 370°C (700°F) and the unit contains ≥ 19 cm (7.5 in.) depth of catalyst, as indicated by the pressure drop across the catalyst bed (Hylton 1992). Benzene and toluene were the

PICs observed most often and in the highest concentrations (up to 0.35 ppmv and 0.87 ppmv, respectively). The results indicate that the formation of these compounds was not due to the oxidation of the TCE, although the mechanism responsible for their formation was not identified. One possible explanation offered was that methane in the natural gas reacted to form ethyne (acetylene) which reacted to form benzene. Other PICs observed included 1,2-dichloroethylene (DCE), 2-butanone, 1,1,1-trichloroethane, ethylbenzene, chloroform, xylenes, styrenes, trichloro-fluoromethane, and dichlorodifluoromethane. Periodic water samples taken by Wurtsmith personnel indicated that DCE was also a contaminant in the feed water to the air strippers. Some of the compounds measured as PICs, e.g., 2-butanone and trichlorofluoromethane, were identified in field blank samples indicating that the presence of these compounds may have been caused by contamination while installing and removing the VOST traps. Another concern about this testing was the lack of a mass balance for the chlorine atoms.

As to costs, the capital cost of an ARI fluidized bed oxidation unit with features similar to those of the oxidation unit in Building 5000 at the Wurtsmith AFB is approximately \$83,000 for the equipment and \$15,000 for installation. Wurtsmith personnel routinely monitor the monthly electrical and natural gas usage in Building 5000; however, these costs are for the whole building rather than for the catalytic oxidation unit. The building's sole purpose is to house the air stripping columns, the oxidation unit, and the associated equipment. The four main electrical power users in the building are the (1) air stripper blowers, (2) air stripper water pumps, (3) oxidation unit blower, and (4) air compressor to operate the pneumatic controls. The power requirements for the air stripper blowers and water pumps probably overshadow the latter two users. There are two major users of natural gas in the building. The catalytic oxidation unit uses natural gas to preheat the feed stream to the catalyst bed temperature and the building is heated with natural gas as needed. For the purposes of estimating costs, the total cost of electrical and natural gas is used to determine the utility costs for the oxidation unit, with recognition that this will result in a conservative estimate.

Data were obtained from Wurtsmith personnel regarding the quantity of water treated by the air strippers at this location during the same period. Using these data and the utility cost data, the utility cost may be expressed with respect to the quantity of water treated. The average utility cost per

3,800 L (1,000 gal) of water treated during this program was estimated to range from \$0.48 (FY 1989) to \$0.36 (FY 1991).

5.2 Rotary Cascading Bed Incinerator (RCBI) System

5.2.1 System Performance

The first pilot demonstration of the Pedco RCBI was conducted from mid-1984 through 1985 at the Rollins incineration facility in Bridgeport, New Jersey. The pilot RCBI had an inside diameter of 0.71 m (2 ft 4 in.) and length of 5.5 m (18 ft). Tests were conducted on a high-sulfur Ohio coal and five wastes, an emulsion sludge, an acrylic emulsion, a chlorinated aromatic liquid waste, a floor wax, and a clarifier sludge. The coal contained 4.3% sulfur. The wastes and coal were fired separately in each run at rates from 0.17 to 1.11 GJ/hr (165,000 to 1,050,000 Btu/hr). Destruction Removal Efficiency testing was not conducted. Table 5.1 (on page 5.6) summarizes the pilot test results (Seibel and Long 1990).

After the pilot demonstration, Pedco designed a larger rotary cascading bed combustor (RCBC) boiler. This unit, designed for generation of 2,270 kg (5,000 lb) of steam per hour, was installed at the Hudepohl Brewing Company in Cincinnati, Ohio. The boiler is similar to the RCBI design. Incorporated in it are an internal close-coupled tube bundle for heat exchange followed by an external superheater, evaporator, and an economizer (Seibel and Long 1991). The RCBC boiler has an internal diameter of 1.7 m (5.5 ft), a length of 7.6 m (25 ft), a rotational speed of 16 rev/min, and a maximum operating temperature of 900°C (1,650°F). The unit was operated for 1,400 hours on high-sulfur coal (sulfur content ranging from 2.10 to 5.65%), and much testing was conducted on the in-bed neutralization of sulfur dioxide. During the testing it was found that a calcium-to-sulfur ratio of 1:2 was sufficient to reduce sulfur dioxide emissions by 90%. The relatively low temperature of the RCBC boiler resulted in average NO_x emission rates of about 0.09 kg (0.2 lb) of NO_x per MM Btu while using coal as a fuel (Seibel and Long 1990).

Table 5.1
RCBI Pilot Test Results

Waste Feed	Feed Rate kg/hr (lb/hr)	Temp °C (°F)	Stack Gas Constituents*	Conc ppmv
Emulsion Sludge	41 (90)	870 (1600)	CO THC	2 <1
Acrylic Emulsion	96 (210)	840 (1550)	CO	2-40
Chlorinated Aromatics	7 (15)	860 (1575)	HCL	13
Floor Wax	71 (157)	870 (1600)	CO THC	33-50 <17
Clarifier Sludge	46 (100)	870 (1600)	CO	5-10
Ohio Coal	18 (40)	860 (1575)	SO ₂	5

*CO-Carbon Monoxide
THC-Total Hydrocarbons
HCL-Hydrogen Chloride
SO₂-Sulfur Dioxide

Excerpted from "Development and Operating Data for the Pedco Rotary Combustion System" by W.H. Long and R.V. Seibel, In Power — Volume 9, the proceedings of the 1990 Industrial Conference, St. Louis Copyright 1990 American Society of Mechanical Engineers With permission

Pedco performed another pilot program using a 4,550 kg (10,000 lb) of steam per hour pilot unit at the North American Rayon plant in Elizabethton, Tennessee. The unit was tested on 23 different fuels and wastes (Seibel and Long 1991).

The pilot work at the Rollins Bridgeport facility was carried out to develop the RCBI concept, gather data for use in designing a full-scale commercial unit, and to develop waste feed and ash handling designs. It was after this development program that Rollins installed the first full-scale commercial Rollins RR at Deer Park, Texas, in 1988 (Falcone 1991).

The Rollins RR at Deer Park is configured in parallel with a 4.4 m (14.4 ft) slagging rotary kiln. Both the slagging kiln and the RR are connected to a joint afterburner chamber and a common air pollution control (APC) system (Falcone 1991). The Rollins RR was tested without the afterburner in October 1989. During this program, 8 tests were performed using carbon tetrachloride contaminated soil. The average carbon tetrachloride DRE was >99.998%, and the DRE range was 99.997 to >99.9991% at a combustion temperature of about 790°C (1,450°F). Waste feed rates ranged from 2.7 to 3.8 tonne/hr (3 to 4.2 ton/hr) (Alliance Technologies Corporation 1989; Falcone 1992).

Estimated emission levels from the Rollins RR of carbon monoxide, THC, hydrogen chloride, and sulfur dioxide are shown in table 3.1 (on page 3.11) (Falcone 1991). The Rollins RR has consistently achieved nondetectable organic levels in the treated soil (using EPA test method 8270) during 4 years of operation (Falcone 1992). The detection level of EPA method 8270 is about 1 ppm.

5.2.2 Process By-products

The RCBI generally will have no major process by-products. In some cases, volatile metals such as lead, cadmium, or arsenic could concentrate in the fabric filter residue. The residue, in some instances, could be hazardous because of the presence of these metals. This is not unique to the RCBI, however, but could occur also in other mobile high-temperature incinerators.

5.2.3 Key Operational Aspects

The RCBI, *taking full credit for test data from testing with carbon tetrachloride and high sulfur coals*, has potential operational advantages over other mobile incineration systems in the following key operational aspects:

- lower capital equipment requirements than for a conventional rotary kiln incinerator because no afterburner is required;
- low fuel usage per unit of soil because of the excellent mixing in the RCBI, and no afterburner fuel requirements;
- in-bed neutralization of hydrogen chloride and sulfur dioxide using low-cost limestone, without the need for a wet scrubber;
- high in-bed sulfur dioxide removal efficiencies of 90% or higher are achieved based on tests burning high-sulfur coal; and
- low NO_x emission concentrations, measured in the range of 60 to 100 ppm due to lower normal operating temperatures.

5.3 **ECO LOGIC Process**

In the pilot-scale demonstration testing of the ECO LOGIC hazardous waste destruction process at Hamilton Harbor, in Hamilton, Ontario, Canada, twelve characterization tests and three performance tests were carried out in May, June, and July, 1991, processing harbor sediment contaminated with coal tar. Funding for the program was provided by ECO LOGIC, Environment Canada, and Environment Ontario.

After installation and system integrity tests, a surrogate waste of clean water and diesel fuel was processed under a variety of conditions with good results. The characterization tests were intended to test the operation of the system within the design parameters with various feed rates and sediment concentrations. During these short (2 to 4 hr) tests, stack emission testing on the boiler stack was conducted to determine emission rates of organic compounds. Concentrations of the target compounds in the waste feed and process effluents are given in table 5.2 (on page 5.9) (ELI ECO LOGIC International, Inc. 1992).

The polyaromatic hydrocarbons (PAHs) input to the process was calculated by two methods to arrive at a best-case and worst-case calculation of DRE. Samples of the waste influent were analyzed for the standard priority PAHs as well as for total organic content. The waste influent concentration is listed as a range of ppm concentrations of PAHs and the lower end of each range corresponds to the PAHs analyzed. The upper end of the range represents the total organic content of the influent and is based upon the assumption that the coal-tar contamination of the sediment was all PAHs, but that most of the PAHs were larger molecules that are not on the standard priority list. These PAHs would be broken down into smaller ones as they are reduced and, at some point, would pass through the priority list phase on the way to being reduced to methane. Based on a visual inspection of the sediment, the coal-tar contamination was much higher than the low-ppm concentrations of priority PAHs. The sediment had a gooey, oily texture and appearance and smelled like fresh asphalt. Use of the total organic content as the PAH influent concentration provides a best-case assumption of DRE, ranging from 99.9999% to 99.99999%. The worst-case assumption, that the priority PAHs were the only ones destroyed, gives DREs ranging from 99.9% to 99.99%.

Table 5.2
Analytical Results Summary

Run	Target Analysis	Waste Influent Conc.* (mg/L)	Decant Water Conc. (µg/L)	Grit Conc (mg/L)	Sludge Conc. (mg/L)	Stack Gas Conc. (µg/m ³)	Destruction Removal Efficiency** (%)
C1	PAHs	6.6 - 15,000	24	0.04	1.06	1.00	99.96 - 99.99998
C2	PAHs	6.6 - 15,000	13	0.06	0.77	1.00	99.92 - 99.99996
C3	PAHs	3.1 - 15,000	26	0.04	0.49	0.26	99.97 - 99.99999
C4	PAHs	5.0 - 14,000	8	0.70	0.49	1.00	99.98 - 99.99998
C5	PAHs	3.5 - 19,200	31	0.07	0.40	0.14	99.98 - 99.99999
C6	PAHs	3.5 - 19,200	33	0.16	0.66	0.46	99.95 - 99.99999
C7	PAHs	12.1 - 25,200	18	4.03	0.07	0.19	99.99 - 99.99999
C8	PAHs	11.7 - 22,400	18	9.87	0.54	0.62	99.97 - 99.99999
C9	PAHs	11.7 - 22,400	39	3.08	1.43	0.16	99.99 - 99.99999
C10	PAHs	11.1 - 22,400	39	0.98	0.68	0.25	99.99 - 99.99999
C11	PAHs	4.3 - 26,100	87	6.77	1.25	0.28	99.98 - 99.99999
C12	PAHs	3.3 - 19,200	124	4.68	18.0	0.37	99.98 - 99.99999
P1	PAHs	6.1 - 21,000	483	1.67	32.8	0.27	99.99 - 99.99999
P2	PAHs	7.3 - 30,000	680	7.76	56.1	0.23	99.99 - 99.99999
P3	PAHs	3.1 - 30,000	423	0.37	4.3	0.14	99.98 - 99.99999
P3	PCBs#	110 - 215	ND	ND	ND	ND	99.999 - 99.9999##

* Low end of range is concentration of priority pollutant PAHs, high end of range is total organic concentration
DREs correspond to these input concentrations

** $DRE = [(Total\ Input - Stack\ Emissions) / (Total\ Input)] \times 100$

Range of PCB concentration is due to variation in analyses DREs correspond to these input concentrations

Based on detection limits - no PCBs detected

Courtesy ECO LOGIC

The effluents consisted of boiler stack gas, reactor grit and slag, scrubber decant water, and scrubber sludge. For each characterization test, a number of samples were analyzed for a variety of compounds. The MM5 stack sampling trains, which were used to measure air emissions, were analyzed most extensively, including analysis for PAHs, polychlorinated biphenyls (PCBs), chlorobenzenes, chlorophenols, dioxins, and furans. The grit, decant water, and scrubber sludge were each analyzed for PAHs, PCBs, and metals. The waste was analyzed for solids content, total organic content, PAHs, PCBs, and metals. Other samples, such as lab blanks, blank train rinsings, and prerun scrubber water, were also analyzed for quality assurance/quality control (QA/QC) purposes. In all twelve characterization tests, the only major organic contaminants measured were naphthalene and chlo-

robenzene. Chlorophenols, PCBs, and dioxins were not detected. Detection limits for these tests were as follows:

PCBs in stack gas	D.L. = 120 ng/DSm ³
PCBs in grit	D.L. = 20 ng/g
PCBs in decant water	D.L. = 70 ng/L
PCBs in sludge	D.L. = 50 µg/L
Dioxins in stack gas	D.L. = <u>0.34</u> ng DSm ³
Furans in stack gas	D.L. = <u>0.15</u> ng DSm ³
CPs in stack gas	D.L. = 0.88 µg/DSm ³

Both PAH and chlorobenzene emission levels were below ambient air quality guidelines, and blank-correcting would have reduced most of the measured values to zero.

The grit and slag was virtually free of organic contamination and contained only the inorganic and metallic components of the harbor sediment. Depending upon the metals content of the waste being processed, the grit produced may be recyclable or suitable for landfilling.

The decant water from each characterization test was held in batches for analysis and subsequent disposal. It was tested for organic compounds and metals and, in all cases, was virtually free of organic contamination. In addition, the inorganic contamination of the decant water was very low because most of the metals in the sediment remained with the grit after processing. The decant water represented the largest volume of effluent, equivalent to the amount of water processed with the sediment. In each test, the decant water was acceptable for disposal at municipal wastewater treatment plants.

The scrubber sludge, consisting primarily of lime, carbon, fine particulate, and water, was a minor by-product. The sludge resulted from the scrubber water being recirculated over and over through the scrubber, and some organic contamination of the sludge did occur. As experience with the scrubber operation was gained, certain parameters were changed to minimize the amount of sludge produced. Although the sludge produced was suitable for a landfill, the analytical cost to prove this makes it more economical to recycle this small effluent stream back into the waste input.

Table 5.3 provides mass balance data derived from bench-scale test data. The mass balance is performed around the reactor only.

The performance tests were conducted in order to demonstrate the capability of the system to operate for longer periods (days) and to measure a wider range of emissions during longer sampling periods. In order to test the destruction efficiency of the process with PCB-contaminated material, the sediment waste liquid was spiked with PCB oil in the third performance test.

The emission measurements from the boiler stack during the performance testing demonstrated the destruction removal efficiency of the ECO LOGIC Process. The stack emission sampling was more extensive for the

Table 5.3
Mass Balance Data*

	Kg/min	lb/hr
MASS INPUT		
Organics	0.03	3.96
Inorganics	0.07	9.24
Water	0.90	118.8
Hydrogen	0.003	0.38
Lime	0.005	0.66
Total	1.008	133.04
MASS OUTPUTS		
Product Gas		
CO	0.0018	0.238
H ₂	0.0061	0.806
CH ₄	0.0027	0.357
H ₂ O	0.0038	0.502
Subtotal	0.0144	1.903
Decant Water		
H ₂ O	0.876	115.63
Metals & Lime	0.0005	0.07
Grit Solids	0.099	13.07
Scrubber Sludge	0.020	2.64
Total	1.010	133.31

* From Bench Scale Tests
Courtesy ECO LOGIC

performance tests than for the characterization tests. Three stack sampling trains were used for each test, measuring semivolatile trace organic compounds, volatile organic compounds, and metals. The semivolatile (MM5) train samples were analyzed for PAHs, PCBs, chlorobenzenes, chlorophenols, dioxins, and furans. The volatile (VOST) train samples were analyzed for 31 volatile compounds, and the metals train for 25 elements. In addition, continuous analyzers sampled the stack gas for oxygen, carbon dioxide, carbon monoxide, total hydrocarbons, water vapor, sulfur dioxide, and nitrogen oxides.

The concentrations of organic contaminants, primarily naphthalene and chlorobenzene, in the stack gas were lower than ambient air quality guidelines, for both the semivolatile and volatile compounds tested. The emissions of metallic compounds from the stack were somewhat higher than the organic emissions and exceeded ambient air quality guidelines.

The effluents were similar to those produced during characterization tests. The scrubber decant water could be disposed of through the sewers, and the scrubber sludge was suitable for landfilling. The volume of sludge produced was about 1% of the volume of sediment processed, which makes diverting the sludge back to the waste input stream a reasonable option.

The organic emissions during the third performance test, when the PCB-spiked waste was processed, demonstrated, for these conditions, that the process is suitable for destruction of PCB-contaminated material. The analysis of the liquid influent PCB concentration was 110 ppm total PCBs. Based on a PCB analysis of the oil used to spike the liquid influent, however, the overall input concentration (including steam) should have been 215 ppm. The difference is probably due to inadequate mixing before sampling. These concentrations result in a range of DRE for PCBs of 99.999% to 99.9999%. There were no detectable concentrations of PCBs in the boiler stack gas, the reactor grit, the scrubber decant water, or the scrubber sludge. Nor were there detectable stack emissions of other chlorinated compounds, such as dioxins, furans, or chlorophenols.

To project the processing costs for a full-scale (100 tonne/day (110 ton/day)) unit, the operating costs (all Canadian dollars except where US dollars are indicated (all are September, 1992 dollars)) for the Hamilton Harbor Project pilot-scale destructor processing Hamilton Harbor sediment during the three performance tests are used. These costs include the actual destruction costs (energy and hydrogen) and costs, such as propane, consumables,

and labor. Costs for analyses are included in labor and consumables, and site security costs are included in the labor and equipment capital costs. Costs for setting up and demobilization are not included. At Hamilton Harbor, the electricity was supplied by a mobile generator burning diesel fuel. The energy costs are therefore quoted as diesel fuel costs.

The three performance tests processed an average of 0.6 tonne (0.66 ton) of waste over a 6 hour period. Approximately 20 m³ (26 yd³) of hydrogen, 250 L (265 gal) of diesel fuel, and one bag of lime were consumed for each performance test. These costs are directly related to the actual destruction of the organic waste and can be linearly scaled to the waste throughput.

The resulting variable costs are:

Diesel fuel	\$160/tonne (US \$120/ton)
Hydrogen	\$35/tonne (US \$25/ton)
Caustic	\$5/tonne (US \$3.75/ton)
TOTAL	\$200/tonne (US \$150/ton)

Fixed costs are defined here as the costs required to operate the destructor (manpower, etc.) and are independent of the waste throughput. The labor requirements for a 100 tonne/day (110 ton/day) unit should not be any different than for the pilot-scale unit at Hamilton Harbor. It is assumed that one engineer and a crew of 5 trained operators are required for a cost of \$3,600/day (US \$2,960/day). Electricity required to run units such as pumps, heaters, process equipment, and instrumentation would be generated from diesel fuel and is estimated to be approximately double the cost of the Hamilton Harbor project for a 100 tonne/day (110 ton/day) unit. Other costs, such as those for propane, water, and sewerage, are also assumed to be doubled. The parts and supplies listed are for maintenance items, such as glo-bars. The \$1,000/day (US \$822/day) cost is based on the cost of parts and maintenance borne during the Hamilton Harbor project.

The resulting fixed costs for a 100 tonne/day (110 ton/day) unit would be:

	\$/day	US \$/day
Labor	3,600	2,960
Per diem for 6	600	495
Diesel fuel	100	82

Propane	300	247
Parts, Supplies	1,000	822
Water	100	82
Sewer	<u>100</u>	<u>82</u>
TOTAL:	\$5,800	\$4,770

The capital cost of a 100 tonne/day (110 ton/day) unit is estimated to be \$2,000,000 (US \$1,645,000). If this capital cost is depreciated over a 3 year period, the cost is \$1,830/day (US \$1,505/day). Estimated general insurance costs are based on the capital equipment cost and are \$1.25/\$100/yr (US \$1.03/100/yr), or \$68/day (US \$55/day). Pollution liability insurance could cost an additional \$300/day (US \$247/day). For a 100 tonne/day (110 ton/day) unit, the total depreciation and insurance costs would be approximately \$20/tonne (US \$15/ton).

The resulting cost of destruction of Hamilton Harbor type sediment, therefore, is approximately \$280/tonne (US \$210/ton) if the unit operates continuously for 365 days/yr. In the first year of operation, it is estimated that the unit will be down approximately 30% of the time for maintenance and design improvements. Using this figure for process availability, 25,550 tonne (28,105 ton) can be processed in one year. The resultant annual costs are:

Variable costs	= 25,550 tonne (28,100 ton) x \$200/tonne
	= \$5,110,000 (US \$4,200,000)
Fixed costs	= 365 days x \$5,800/day
	= \$2,117,000 (US \$1,739,900)
Depreciation/	= 365 x \$2,198/day
Insurance	= \$802,300 (US \$659,400)
TOTAL	= \$8,029,300 (US \$6,600,000)

The cost per tonne is calculated as \$8,029,300 (US \$6,600,000) divided by 25,550 tonne (28,165 ton) which equals approximately \$315/tonne (US \$230/ton). Therefore, in the first year of operation, the waste destruction cost for Hamilton Harbor type sediments is estimated to be approximately \$315/tonne (US \$230/ton). Design improvements currently being tested may lower this cost somewhat.

The cost of soil processing with the thermal desorption unit as a front-end predestruction processor is estimated to be as low as \$255/tonne (US \$190/ton). This estimate is based on the processing of soil with a moisture content of 30% and a total organic content of 10%. The loading to the reactor would then be 40% of the soil weight processed, at a cost of \$134/tonne (US \$100/ton). The remaining \$120/tonne (US \$90/ton) cost is made up of \$107/tonne (US \$80/ton) for energy and \$13/tonne (US \$10/ton) for capital cost depreciation.

5.4 Horsehead Research Development Company, Inc., (HRD) Flame Reactor System

Three large-scale tests have been conducted to evaluate the HRD Flame Reactor process for treating contaminated soils and solids. Contaminated matrices included secondary lead soda (SLS) slag, lead-contaminated soil, and electric arc furnace (EAF) dust spiked with carbon tetrachloride. Summary descriptions of the test, test results, and cost estimates for these cases follow.

5.4.1 US EPA Superfund Innovative Technology Evaluation (SITE) Program with Secondary Lead Soda Slag

Test Description. In the period March 20 to 23, 1991, a US EPA SITE demonstration test was performed to evaluate the Flame Reactor process for hazardous waste treatment. The work was done within the guidelines defined by the US EPA SITE Program with specific objectives established by the SITE Program Managers. Complete details of the test appear in the Applications Analysis Report and the Technical Evaluation Report (US EPA 1992a; US EPA 1992b).

Secondary lead soda slag is a residue from the National Lead (NL) Industries soda slag process for lead battery recycling. The Flame Reactor test lot of 65 tonne (72 ton) was obtained from a stockpile of 270 to 320 tonne (300 to 350 ton) in Atlanta, Georgia. This SLS slag was generated at a plant in Pedricktown, New Jersey, where a stockpile of 4,535 to 13,067

tonne (5,000 to 15,000 ton) of SLS slag is located. Both the Atlanta and Pedricktown locations are Superfund sites.

As received at the test site, the SLS slag averaged about 9.7% moisture and was very coarse as shown by the particle size distribution data in table 5.4. Chunks of material larger than about 4 in., some of which were over 2 feet in cross-section, were excluded from the sample used for the data in table 5.4. Prior to Flame Reactor processing, the SLS slag was dried to 2 to 7% moisture and crushed in a hammermill to 4.75 mm (<3/16 in). Roughly 60 tonne (65 ton) of dried and crushed SLS slag were prepared from the initial 65 tonne (72 ton). The prepared material is characterized in table 5.5 (on page 5.17). In addition to the demonstration test, a series of shakedown runs were conducted to determine the operating conditions for the demonstration test and several runs with flux additions (silica flour) were performed to improve slag characteristics.

Table 5.4
Particle Size Distribution of Secondary Lead Soda Slag

Mesh size	% Passing
2 inch	64.8
1.5 inch	59.1
1 inch	54.0
0.625 inch	48.3
0.25 inch	39.2
0.111 inch	32.0

US EPA 1992a

X-ray diffraction indicated that the principal lead, iron, and sodium compounds were caracolite ($\text{Na}_3\text{Pb}_2(\text{SO}_4)_3\text{Cl}$), hydrous iron oxides, and sodium sulfate, respectively. Metallic iron, metallic lead, and carbon particles were also present as artifacts of the soda slag process. Throughout the tests, the prepared SLS slag handled well in the Flame Reactor feed system.

Table 5.5
Characterization of Prepared Secondary Lead Soda Slag

Parameter	Percent
Moisture (weight loss at 110°C)	5.2
Passing 60 mesh	50.9
Passing 100 mesh	36.4
Passing 200 mesh	22.9
Passing 325 mesh	15.2

US EPA 1992a

A split of the samples taken by the US EPA subcontractors during the demonstration tests were also analyzed by HRD. The carbon analyses were done on a Leco carbon analyzer, chloride was determined by Volhard titration, and fluoride analysis involved distillation followed by determination via specific ion electrode. All other analyses were done by inductively coupled plasma spectroscopy (ICP) using a dissolution procedure modified from a U.S. Bureau of Mines method which uses a mixture of mineral acids to dissolve the entire sample. This method does not meet the US EPA QA/QC requirements.

The dissolution method that the US EPA chose for their ICP analyses was Method 3050. Method 3050 did not dissolve the entire sample and is known to cause a low bias for silicon and chromium. The relative merits of the ICP dissolution methods used by HRD and the US EPA are discussed in considerable detail in the Technical Evaluation Report for this project. The averages of both sets of chemical analyses appear in table 5.6 (on page 5.18).

Results. Partitioning of the major elements to the slag and oxide products was calculated using a statistical-based material balance program. By evaluating the interrelation of the data and the quality of the data points, the material balance program calculates an internally consistent balance of the process streams and their components (Zagrocki 1992b). The recoveries of major elements to the oxide or slag product, as presented in table 5.7 (on page 5.19), were taken from this material balance calculation.

The product slag consistently passed Toxicity Characteristic Leachate Procedure (TCLP) testing for leachable metals. The average TCLP results are presented in table 5.8 (on page 5.20).

A site-specific risk analysis is required to assess the effect of the HRD Flame Reactor stack emissions. Based on limited data, the atmospheric emissions of metals could be a concern. Because of data limitations, however, no conclusions could be reached on metal emissions. In particular, the

Table 5.6
EPA SITE Demonstration With Secondary Lead Soda
Slag Average Composition of Solids as Analyzed by HRD and EPA
(weight %)

Element	SLS Slag		Product Slag		Product Oxide	
	EPA	HRD	EPA	HRD	EPA	HRD
Aluminum	0.60	0.69	1.53	1.64	0.062	0.080
Antimony	0.037	NA	0.036	NA	0.12	NA
Arsenic	0.52	NA	0.026	NA	0.11	NA
Barium	0.086	NA	0.16	NA	0.028	NA
Beryllium	0.0001	NA	0.0001	NA	0.0001	NA
Cadmium	0.041	0.043	0.0004	<0.001	0.14	0.15
Calcium	0.65	0.72	1.30	1.57	0.23	0.21
Carbon	15.0	14.7	NA	1.09	NA	<0.1
Chloride	2.46	2.64	NA	0.37	NA	2.95
Chromium	0.0088	0.024	0.0089	0.040	0.031	0.034
Copper	0.19	0.17	0.34	0.37	0.17	0.19
Fluoride	0.013	0.031	NA	0.016	NA	0.033
Iron	10.3	10.8	20.5	22.7	3.18	4.12
Lead	5.41	6.10	0.55	1.12	18.0	19.1
Magnesium	0.23	0.26	0.54	0.63	0.035	0.045
Manganese	0.075	0.074	0.18	0.18	0.028	0.32
Mercury	0.00007	NA	0.00001	NA	0.00001	NA
Potassium	0.24	0.23	0.24	0.27	0.74	0.74
Selenium	0.0073	NA	0.0034	NA	0.0066	NA
Silicon	0.28	8.10	0.33	10.2	0.11	10.5
Silver	0.0003	NA	0.0004	NA	0.0027	NA
Sodium	12.2	12.2	15.5	15.3	16.8	15.6
Sulfur	5.25	8.4	NA	5.6	NA	14.7
Thallium	0.025	NA	0.069	NA	0.0071	NA
Tin	0.28	NA	0.080	NA	0.69	NA
Zinc	0.42	0.44	0.16	0.12	1.62	2.19

US EPA 1992a

Table 5.7
Recovery Rates for EPA SITE Demonstration Test

Element	Percent Recovery	
	Slag	Oxide
Lead	8	92
Sodium	64	36
Sulfur	30	44
Iron	91	9
Silicon	63	37

US EPA 1992a

HRD Flame Reactor emitted lead, chromium, and arsenic at rates above the Tier II screening limits during the SITE demonstration.

Costs. The HRD Flame Reactor system processed the SLS slag at a cost of \$1,035/tonne (\$932/ton). A preliminary operating cost estimate (\$240/tonne (\$215/ton)) was developed for processing the remaining Pedricktown SLS slag stockpile at the Monaca Flame Reactor facility. The estimate is based upon the results of the SLS slag tests and the following assumptions:

- Processing would be performed at the Monaca Flame Reactor facility;
- De-stocking and transportation costs to Monaca would not be included;
- The SLS slag would be crushed to 80% minus 200 mesh and dried to <2% free moisture;
- A 25% addition of silica flux would be used to improve slag integrity;
- The SLS slag would be fed at 2.4 tonne/hr (2.7 ton/hr) or about 3 tonne/hr (3.4 ton/hr) with flux;
- The costs would be presented on a \$/tonne (\$/ton) basis for processing a 10,890/tonne (12,000 ton) lot of material; and
- Offgas scrubbing for hydrogen chloride or sulfur dioxide would not be required.

Table 5.8
Average TCLP Results for EPA SITE Demonstration Test

TCLP Metal	mg/L	Regulatory Value mg/L
Arsenic	0.474	5.0
Barium	0.175	100.0
Cadmium	<0.050	1.0
Chromium	<0.060	5.0
Lead	<0.330	5.0
Mercury	<0.010	0.2
Selenium	0.033	1.0
Silver	<0.050	5.0

US EPA 1992a

The estimated operating costs are summarized in table 5.9 (on page 5.21). Pretreatment labor and utility costs are included with the Flame Reactor cost. Overall staffing, including supervision, would number twelve people. The pretreatment circuit would be run by a single operator 2 shifts per day, 5 days per week. The Flame Reactor would operate 24 hours per day, 7 days per week. Two Flame Reactor operators would be required for each of the four shifts, with one daylight mechanic and one supervisor for a Flame Reactor complement of ten. Three days are estimated to be required for start-up and shutdown of the Flame Reactor and feed preparation circuit. Including the mechanic and supervisor, this adds up to 30 man-days. The capital cost estimate is based on the assumption of financing at 12% interest over ten years. It is assumed that the slag would be marketed at a value equivalent to handling and shipping costs for no net profit or loss.

5.4.2 Soil Treatment Tests

Test Description. On November 5, 1991, 6,540 kg (14,420 lb) of lead-contaminated soil were excavated from the C&R Battery Superfund site in Richmond, Virginia, and transported to the Monaca Flame Reactor facility for a treatability test. The test was directed by the US EPA through its prime contractor, Versar, Inc. The purpose of the test was to evaluate high-temperature metal recovery (HTMR) for soil remediation.

Table 5.9
Processing Fee for Flame Reactor Processing of Secondary Lead Soda Slag

Cost Factors	Units	\$/Unit	Units/ton	Cost/ton \$
Natural gas	MCF	3.50	8.62	30.15
Oxygen	100 scf	0.25	189.3	47.31
Labor	Man-hrs	20.00	1.41	28.16
Electricity	kwh	0.05	305.	15.25
Flux	tons	36.00	0.25	9.00
Materials & supplies				17.28
Direct costs				147.15
Indirect costs				10.00
Capital & taxes				58.06
SUBTOTAL				215.21
Product oxide shipping & recycling				—
Product slag handling & marketing				—
NET PROCESSING FEE				\$215.21

US EPA 1992a

The C&R Battery soil averaged about 13.2% moisture content. The soil was screened to remove battery case pieces, plants, and other items larger than about 5 cm (2 in.), dried to 0.44% moisture content in a Holoflute dryer, and crushed to 2.4 mm (<3/32 in.) in a hammermill. The quantity of soil prepared for the Flame Reactor process treatability test totaled 4,830 kg (10,640 lb). The particle size distribution of the prepared soil is given in table 5.10 (on page 5.22).

Early in the crushing operation, it was discovered that the hammermill screen had several large holes and was, therefore, passing coarse material. This soil, about 1,000 kg (2,200 lb), was put aside as a backup lot and was used near the end of the test program. This coarse soil did not perform well in the Flame Reactor.

The sampling and analysis plan called for six composite samples of soil, slag, and oxide to be collected from steady-state operation. Because of the very limited quantity of soil available for the test, a test matrix could not be run to investigate a range of operating parameters. After start-up, operating conditions were changed rapidly until reasonable lead extraction and slag

Table 5.10
Particle Size Distribution of Dried and Crushed Soil

Mesh Opening μm	Percent Passing
1180	93.7
600	85.2
250	68.1
150	56.0
75	38.7
45	25.9

Courtesy Horsehead Resource Development Company, Inc.

fluidity were achieved. The Flame Reactor operating conditions for the test are summarized in table 5.11.

Results. Summaries of the chemical analysis of the major constituents in the soil, the product oxide, and the product slag appear in table 5.12 (on page 5.23). The distribution of the major elemental species between the oxide and slag is shown in table 5.13 (on page 5.24). The average TCLP leachate analyses for five of the six slag samples taken are shown in table 5.14 (on page 5.25). The sample collected when the coarse soil was being processed yielded a TCLP lead result of 30.3 mg/L. Because the soil was

Table 5.11
Soil Test Operating Conditions

Parameter	SITE Demonstration
Soil feedrate, tons per hour	0.6
Flux addition, % of soil	80
Natural gas, MCF per ton of soil	37.1
Oxygen, 100 scf per ton of soil	421
Combustion air, % oxygen	75

Courtesy Horsehead Resource Development Company, Inc.

Table 5.12
Treatability Test on Lead-Contaminated Soil from C&R Battery
Average Composition of Solids as Analyzed by HRD and EPA
(weight %)

Element	SLS Slag		Product Slag		Product Oxide	
	EPA	HRD	EPA	HRD	EPA	HRD
Aluminum	0.61	3.35	1.51	2.9	0.77	0.96
Antimony	0.036	NA	<0.01	NA	0.093	NA
Arsenic	0.0086	NA	0.0007	NA	0.051	NA
Barium	0.012	NA	0.018	NA	0.012	NA
Beryllium	<0.0001	NA	<0.0002	NA	<0.0005	NA
Cadmium	0.0075	<0.010	<0.0005	<0.005	0.086	0.10
Calcium	1.21	1.72	10.4	15.8	12.7	16.2
Carbon	NA	11.9	NA	NA	NA	NA
Chloride	NA	NA	NA	NA	NA	2.24
Chromium	0.005	<0.010	0.0091	0.017	0.011	0.013
Cobalt	0.012	NA	0.010	NA	0.011	NA
Copper	0.042	0.034	0.030	0.042	0.12	0.12
Fluoride	NA	NA	NA	NA	NA	0.42
Iron	2.04	2.08	7.16	11.1	3.56	3.20
Lead	6.94	11.8	0.15	0.35	9.27	21.3
Magnesium	0.14	0.25	0.30	0.46	0.26	0.29
Manganese	0.060	0.048	0.12	0.16	0.11	0.096
Mercury	0.00002	NA	<0.00001	NA	0.0001	NA
Nickel	0.0098	NA	0.0076	NA	0.0072	NA
Potassium	<0.10	1.03	<0.10	0.67	<0.50	0.90
Selenium	0.0004	NA	<0.001	NA	0.0036	NA
Silicon	NA	17.8	NA	22.0	NA	5.36
Silver	<0.001	NA	<0.0004	NA	0.0068	NA
Sodium	0.19	0.54	0.29	0.57	0.68	0.63
Sulfur	NA	1.2	NA	<0.2	NA	5.9
Thallium	0.00002	NA	<0.00001	NA	0.0006	NA
Vanadium	0.0019	NA	0.0017	NA	0.0059	NA
Zinc	0.74	0.087	0.22	0.30	9.5	9.0

Courtesy Horsehead Resource Development Company, Inc

inadequately prepared, this result is not considered representative of Flame Reactor performance. All other TCLP metal analyses for the sixth sample were comparable to those listed in table 5.14 (on page 5.25). For comparison, TCLP analyses of the untreated soil were 122.0 to 27.0 mg/L lead and 3.04 to 2.28 mg/L cadmium.

Table 5.13
Recovery Rates for Soil Treatability Test

Element	Percent Recovery	
	Slag	Oxide
Lead	20	80
Calcium	67	33
Iron	86	14
Silicon	79	21

Courtesy Horsehead Resource Development Company, Inc

Costs. An order-of-magnitude capital and operating cost estimate was developed for a 30,000 tonne/yr (33,000 ton/yr) Flame Reactor facility to treat contaminated soil (table 5.15 on page 5.26). For this estimate, fine and dry soil would be provided to the Flame Reactor from a soil washing process operated at the site. The resulting \$7.2 million capital and \$250/tonne (\$228/ton) operating cost estimates are based on the following assumptions:

- The soil pretreatment and long-term storage costs are not included;
- A flux rate of 50% is assumed. The flux is a 3:1 mixture of quicklime and hematite;
- Flame Reactor slag will be back-filled on the site;
- Credits for recovered metal revenues are not included;
- Utilities are available at the plant boundary line; and
- Offgas scrubbing for hydrogen chloride or sulfur dioxide is not required.

The commercial consumption of natural gas and oxygen for SLS and soil differ from the test values because:

- Feed preparation would be better in commercial operations;
- Quicklime is used in place of hydrated lime;

- Processing rates are increased; and
- Operating parameters are slightly different.

The biggest reason for the differences between the commercial and test consumptions is the quantity of water fed to the reactor. Drying the waste feed to lower levels of moisture in a commercial plant will significantly reduce the Flame Reactor fuel consumption. For soil, using quicklime instead of hydrated lime further reduces water input. While drying (or calcining in the case of lime) requires the same theoretical energy whether performed in the Flame Reactor or a drier, the water is heated to a much higher temperature in the Flame Reactor and the energy efficiency is lower, i.e., heat losses are higher.

Improved particle size reduction in a commercial facility also translates into reduced consumption, since the reaction rate improves with smaller feed particle size. Thus, the Flame Reactor can be operated under slightly less intensive conditions to achieve the same level of treatment.

Table 5.14
Average TCLP Results for Soil Treatability Test

Metal	Result mg/L	Regulatory Values mg/L
Antimony	0.16	—
Arsenic	<0.06	5.0
Barium	0.14	100.0
Beryllium	<0.001	—
Cadmium	<0.005	1.0
Chromium	<0.006	5.0
Cobalt	0.096	—
Copper	<0.5	—
Lead	1.5	5.0
Mercury	<0.0002	0.2
Nickel	0.25	—
Selenium	<0.010	1.0
Silver	<0.004	5.0
Thallium	<0.001	—
Vanadium	<0.007	—
Zinc	3.1	—

Courtesy Horsehead Resource Development Company, Inc

Table 5.15
Processing Fee for Flame Reactor Processing of
Lead-Contaminated Soil

Cost Factors	Units	\$/Unit	Units/ton	Cost/ton \$
Natural gas	MCF	3.50	8.35	29.22
Oxygen	100 scf	0.25	133.00	33.25
Labor	Man-hrs	20.00	1.01	20.20
Electricity	kwh	0.05	200.	10.00
Flux	tons	36.00	0.5	18.00
Materials & supplies				17.45
Direct costs				128.12
Indirect costs				10.00
Capital & taxes				90.29
SUBTOTAL				228.41
Product oxide shipping & recycling				—
Product slag handling & marketing				—
NET PROCESSING FEE				\$228.41

Courtesy Horsehead Resource Development Company, Inc

The higher processing rates in commercial operations reduce the unit consumption because of proportionally lower heat losses at higher throughputs. For a particular waste feed, the heat flux depends mainly upon the operating temperature. Therefore, for a given reactor size, the energy (fuel) per mass of waste consumed to offset heat losses decreases at higher feed rates. In addition, as the reactor size is increased to accommodate even larger feed rates in commercial plants, the wall surface area increases more slowly than the reactor volume, thereby reducing the impact of heat losses.

Finally, there are some small differences in the commercial soil treatment scenario. First, the flux addition is 65% instead of 80%, as used in the treatability test. Second, the level of volatile metals, lead and zinc, is over an order-of-magnitude lower than in the test run, requiring less fuel for reduction. In addition, the commercial plant is based on 65% oxygen enrichment compared with 80% in the test.

5.4.3 Destruction Removal Efficiency Test with Carbon Tetrachloride

Test Description. In a test, conducted in March, 1990, carbon tetrachloride was fed into a Flame Reactor simultaneously with steel mill EAF dust in order to simulate a metal-bearing waste contaminated with hazardous organic compounds. The purpose of the test was to demonstrate the ability of the Flame Reactor process to destroy hazardous organic contaminants in conjunction with the treatment of metal-bearing wastes.

The carbon tetrachloride was injected separately of the EAF dust to avoid fouling with the pneumatic injection system. The carbon tetrachloride was introduced at the same point in the process, but through a port offset from the solid feed by 90 degrees. The carbon tetrachloride was fed at a rate equivalent to 5% of the total feed.

Results. The average DRE was 99.9986% and no carbon tetrachloride was detected in either the slag or oxide products.

6

LIMITATIONS

6.1 Catalytic Oxidation

Catalytic oxidation of halogenated volatile organic compounds (VOCs) has only been field-demonstrated on trichloroethylene (TCE). Performance results indicate that this technology can successfully destroy over 97% of the feed stream TCE. Economics seem to be favorable when the feed stream has a relatively high TCE concentration and/or the amount of TCE to be destroyed is large. The application of catalytic oxidation to treat other halogenated organic compounds and mixtures of organic compounds that are candidates for vapor extraction or air stripping is dependent upon the identification and commercial availability of appropriate catalysts.

6.2 Rotary Cascading Bed Incinerator (RCBI) System

6.2.1 Reliability of Performance

Because of the RCBI's relatively high rotational speed, it is more complicated than a standard high temperature rotary kiln incinerator. Pedco has found that rotation of the rotary cascading bed at the appropriate speed with the correct amount of bed material introduces important maintenance considerations. The RCBI may require additional development before it can be run at operating factors (availability) equivalent to the availabilities expected from traditional low rev/min, high-temperature rotary kiln incinerators.

6.2.2 Waste Matrix

Large pieces of shredded drums and heavy pieces of contaminated debris should not be fed to the RCBI.

6.2.3 Soil Carry-Over

Because of the highly turbulent, fluidized nature of the RCBI bed material, there will be a high degree of entrained soil in the combustion gas. It is likely that 20% or more of the soil fed will exit the RCBI as entrained particulate. This relatively high soil carryover, compared to a high temperature rotary kiln, will need to be considered during the design of the air pollution control and residue handling equipment.

6.2.4 Volatile Metal Emissions

Because the RCBI design does not include a wet scrubber, mercury emissions are a potential problem. In order to control emissions of highly volatile mercury, if present in the soil being treated, the RCBI air pollution control systems would have to be modified. This modification might involve a wet scrubber following the system fan or dry injection of carbon in front of the fabric filter to capture the mercury. Other volatile metals such as arsenic, zinc, lead, and cadmium, are a potential problem which may require application of suitable APC equipment or capacity restrictions.

6.2.5 Risk Considerations

The greatest potential risk with using of the RCBI as a mobile unit for the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) soils lies in the need for and uncertainty about the cost and time required for needed development work. Rollins has shown that the technology can be made to work effectively, but has kept the cost and time frame required to develop the Rollins Rotary Reactor as a commercial unit confidential. Pedco believes that a mobile RCBI could be built and operational within a period of one year (Reed 1992).

6.2.6 Process Needs

The process, as described by Pedco, appears to be appropriate for the treatment of contaminated soils. A possible modification might be to posi-

tion a hot cyclone between the RCBI and the fabric filter to remove the coarse fraction of the entrained soil before it reaches the fabric filter.

6.3 *ECO LOGIC Process*

Materials handling will probably present the most problems during operations, as it did in the tests at Hamilton Harbor. Specific problems encountered were:

- grit blockages at the reactor bottom exit that caused interruptions in processing of 6 to 8 hr. Modifications to correct this problem have been completed;
- breakage of the glo-bar (silicon carbide electric heating) elements in the reactor during cooling. A new design is expected to correct this problem; and
- small scrubber sludge recycle stream. But it is anticipated that no problems will arise when recycling this stream even at 90 tonne/day (100 ton/day) commercial size.

Additional concerns when decontaminating soils are:

- Certain types of soils may be more difficult to decontaminate than others;
- Feed soils must be screened or crushed to <2.5 cm (1 in.); and
- the operation of the soil desorption module.

Finally, storage and handling of hydrogen gas presents unique potential fire and explosion hazards.

6.4 Horsehead Research Development Company, Inc., (HRD) Flame Reactor System

The major limitations of the Flame Reactor process have to do with the kinds of wastes and their physical characteristics. Specifically, the following factors may pose limitations:

- Waste must be suitable for gravity and pneumatic transport;
- Feed preparation requirements for soil include screening at 5 cm (2 in.) to remove large rocks and plant debris, crushing to 3 mm (<1/8 in.) with D50 <100 μ m, and drying to <5% moisture;
- Flux additions may be necessary to produce a fluid slag;
- Wastes containing mercury present a problem;
- The offgas/oxide collection system must remain above the dew point. Other effects of corrosive by-products are not known;
- Volatile metals should be at least 5% of the feed in order that the metal oxide product is sufficiently enriched for recycling;
- Condensable metals should total 5% or more in the feed to yield a molten metal alloy product; and
- Test facility restrictions limit hazardous organic compounds to <500 ppm and prohibit the processing of mercury wastes.

High-Btu wastes are balanced against fuel requirements and, therefore, are not a problem.

7

TECHNOLOGY PROGNOSIS

7.1 Catalytic Oxidation

The commercial treatment of halogenated organic compounds from soil or groundwater remediation by catalytic oxidation is relatively new. Performance in and economic results from recent demonstrations, discussed in chapter 5.0, have shown the effectiveness of this technology. Catalytic Oxidation offers a significant economic advantage over granular activated carbon treatment in many cases. In addition, it offers the potential for hot-gas reinjection to accelerate the contaminant removal process. It is anticipated that new catalyst development will expand the range of halogenated organic compounds treated by catalytic oxidation.

7.2 Rotary Cascading Bed Incinerator (RCBI) System

Rollins has shown that the RCBI can be developed into an effective mobile soil treatment system (Falcone 1991). Although the Pedco RCBI technology is close to commercialization for soil treatment, the following aspects of the technology may need further development and demonstration for full-scale operations:

- Internal recirculation rate as a function of the type of soil or sludge needs to be explored. Pedco believes that a recirculation of about 5 to 10 times would be appropriate for high-inert content feed materials such as soils (Reed 1993);

- Soil residual and destruction removal efficiency (DRE) data at different operating conditions for low-vapor pressure constituents such as polychlorinated biphenyls (PCBs) and dioxins;
- Soil entrainment rates and the treated soil distribution between the RCBI bottom ash and the air pollution control (APC) equipment relative to sizing of the soil and ash handling equipment;
- Optimal limestone-to-chlorine ratio to achieve 99% hydrogen chloride removal;
- NO_x emissions at different RCBI temperatures;
- Volatile metal emission rates during the treatment of soils; and
- Residual organics present in solids collected by the fabric filter.

Some of the data needed can probably be realistically estimated by Pedco based on the extensive pilot data from the rotating cascading bed (RCB) boiler program (Seibel and Long 1991). The Pedco RCBI appears to hold the promise of being an efficient, cost-effective innovative technology for the thermal treatment of contaminated soils.

7.3 ECO LOGIC Process

The ECO LOGIC process seems to be sufficiently developed to undertake full-scale remediation projects, assuming that material handling problems that surfaced during the Hamilton Harbor demonstration (which have been addressed) are solved. A commercial-scale system has not been built and additional problems may be encountered during the Superfund Innovative Technology Evaluation (SITE) Program demonstration.

7.4 Horsehead Research Development Company, Inc., (HRD) Flame Reactor System

The Flame Reactor process is well-suited to the treatment of metal-bearing wastes. Most of the metals of value are recovered in a recyclable form, and hazardous organic compounds are destroyed. The process is unlikely to be economically competitive with lower-temperature alternative processes for treatment of organic contaminated soils with low-metal content.

Continuous, commercial scale (1.1 to 2.7 tonne/hr (1.2 to 3.0 ton/hr) waste feed) demonstration plant operation has been performed at the Monaca Flame Reactor facility since 1985. Total testing time is close to 4,000 hours with about 5,445 tonne (6,000 ton) of material processed. The materials tested include:

- Steel mill electric arc furnace (EAF) dust – about 10 sources;
- Zinc plant residues – 4 sources, 5 types;
- Lead smelter residues – 1 source, 2 types;
- Superfund wastes – 2;
- Soil – 2 sources; and
- Destruction removal efficiency test – carbon tetrachloride surrogate test.

A Part B permit application for K061 (EAF dust) processing at the Monaca Flame Reactor plant was filed in December 1988. After the Part B permit is approved, HRD will seek permit modifications to process other wastes as might be relevant to commercial treatment opportunities.

These test programs have demonstrated the ability of the Flame Reactor process to recover metal for recycling, produce a non-hazardous vitrified slag, and destroy organic contaminants. The sampling, monitoring, and analysis requirements for organic compounds, however, will be greater than for materials that contain only toxic metals. The capital costs should not be much higher than for similar materials without organic compounds. Organic analyses could significantly impact processing costs, however, depending on the compounds involved. HRD is pursuing opportunities to apply the Flame Reactor technology to treatment of metal-bearing wastes

contaminated with organic compounds. Several wastes are under review for process testing.

The Flame Reactor technology is ready for use in commercial processing and remediation. An 18,150 tonne/yr (20,000 ton/yr) demonstration facility has operated at Monaca, Pennsylvania, since 1983. A 27,200 tonne/yr (30,000 ton/yr) facility for EAF dust processing is being constructed in Beaumont Texas, with start-up scheduled for the first quarter of 1993. At the present time, there are no plans to construct a mobile plant. Although there is considerable interest within HRD and elsewhere, a specific business opportunity must be identified before such a capital investment can be justified.



APPENDIX A

Other Promising Technologies

Following is a discussion of other promising technologies that are under development, but could not be assessed at this time because of insufficient data. Significant testing and evaluation are scheduled in the near future that will likely generate adequate data for assessment, and these technologies may also become candidates for remediation.

Supercritical Water Oxidation

Supercritical Water Oxidation (SCWO) is the oxidation of organics, with air or oxygen, in the presence of a high concentration of water under temperatures and pressures above the critical-point values of water: 374°C and 22 MPa (705°F and 218 atm). Above the critical temperature and pressure, the properties of water are quite different from those of the normal liquid or atmospheric stream. For example, organic substances are completely soluble (i.e., miscible in all proportions) in water under some supercritical conditions, while salts are almost insoluble under others.

Supercritical water oxidation has been under development since 1980. Over the past twelve years, the oxidation efficiency of SCWO for many chemicals and some wastes has been studied at the laboratory and bench scale (Tester et al. 1991). As an oxidation process, its efficiency can be measured as the degree of destruction of organic feed materials (e.g. destruction removal efficiency (DRE)) or as the degree of conversion of organic carbon to carbon dioxide (e.g. DE). The DEs and DREs of SCWO have been reported to range from 99.9% at 400° to 450°C (752° to 842°F) with a residence time of 5 min to 99.9999% at 600° to 650°C (1,112° to 1,200°F) with a residence time of less than 1 min. Beyond the laboratory scale, a trailer-mounted pilot plant was built by Modar and tested twice in the field (Staszak, Malinowski, and Killiea 1987; Johnson et al. 1988). That

pilot plant could not effectively remove solids. One of the major technical barriers was the plugging of reactors by inorganic solids under supercritical conditions (Stone and Webster Engineering Corporation 1989). In 1989, MODEC devised a new reactor designed to avoid plugging by inorganics. The design has been demonstrated successfully by continuous operation at the bench scale (Modell 1992). To date, no commercial SCWO units have been built.

The SCWO process produces aqueous, solid and gaseous effluents. The aqueous effluent is primarily water with some dissolved alkali salts. The gas is primarily carbon dioxide (95 to 99.95% carbon dioxide, 100 ppm N₂, 50 ppm carbon monoxide, and the balance, O₂). The solid is primarily oxides and insoluble salts of metals (if present in the feed). Potential advantages claimed for SCWO are: less expensive than incineration for treating aqueous wastes; the process can be rapidly bottled up by emergency shut-down procedures so as to avoid discharge of contaminated effluents during an upset or off-specification operation; and gaseous effluents can be virtually eliminated through condensation of the carbon dioxide offgas.

There are various applications of the SCWO process under research and development. Specifically, studies are underway to assess the process for use in the chemical demilitarization program and a facility is being designed and built for managing nonhazardous petrochemical wastes. (See Appendix C for Technology Contact).

Soil Detoxification Using Solar Energy

It has been proposed that remediation of contaminated soil could be carried out by a combination of conventional and solar technologies. This might involve removing the contaminants from the soil using conventional thermal desorption extraction methods and exposing them to a concentrated solar flux. A concentrated solar flux on the order of 100 W/cm² (645 W/in.²) can readily be created in a solar furnace or a dish concentrator (Glatzmaier, Mehos, and Nix 1990). Volatile contaminants from the soil could be entrained in a carrier gas stream or condensed to a liquid and exposed to the solar flux in a windowed reactor placed near the focus of the furnace or concentrator. Semivolatile components could also be injected directly into the solar reactor as a liquid.

The Department of Energy (DOE) has been studying solar detoxification since 1986. The DOE-sponsored laboratory and field testing has indicated

that photons in the ultraviolet portion of the solar spectrum significantly increase rates of contaminant oxidation and allow high rates of destruction with minimal products of incomplete combustion at relatively low temperatures. Since FY 90, the United States Environmental Protection Agency's (US EPA) budget has included a line item for cooperative work with DOE in investigating the use of this technology to treat various waste streams. In FY 91, the Department of Defense's (DOD) budget included a line item providing \$5,000,000 to research, develop, test, and evaluate a fully functional solar unit.

The US Army Toxic and Hazardous Materials Agency (USATHAMA), DOE, and the US EPA are collaborating to evaluate this solar technology. The US EPA's Risk Reduction Engineering Laboratory (RREL) in Cincinnati is supporting this evaluation by conducting fundamental studies and carrying out a "Mini-Pilot" Testing Program at the site of the Solar Energy High-Flux Facility of the DOE National Renewable Energy Laboratory (NERL) in Golden, Colorado. This will generate data needed for the design of a field demonstration-scale Solar Reactor System. This tri-agency effort will culminate in a DOD field demonstration project at a DOD site expected to be in operation by 1995. (See Appendix C for Technology Contact).

Fluidized Bed Cyclonic Agglomerating Incinerator

This two-stage system is a combination of two technologies developed by the Institute of Gas Technology (IGT) over the past several years (US EPA 1991; Mensinger et al. 1991). The first stage is based on IGT's sloping grid, fluidized-bed (SGFB) technology, which was developed as a part of a coal gasification process. The bulk of the bed operates at a temperature of 816° to 1,093°C (1,500° to 2,000°F), while the central spout operates at a sufficiently higher temperature to agglomerate the ash. The mobility of inorganic contaminants, such as metals, is reduced because of their incorporation into this glassy matrix. Additional destruction of gaseous products leaving the first stage is achieved in a cyclonic combustor.

A 0.91-m (3 ft) diameter unit employing the SGFB technology was tested with coal (over 10,000 hours of operation) and demonstrated that agglomerated ash can be produced. These agglomerates were tested by the Extraction Procedure (EP) Toxicity Test and were not hazardous waste under the applicable definition. The same unit was tested with a spent foundry sand and spent blast abrasive feeds (approximately 454 to 907 kg/

hr (1,000 to 2,000 lb/hr)), both of which were contaminated with 1 to 2% organics. In the test with the spent blast abrasive feed, it was determined that the organic destruction exceeded 99.99% for the contaminant tributyl tin oxide, and the reclaimed blast abrasive was suitable for reuse under US Navy specifications. The test with the foundry sand feed produced similar favorable results. Bench-scale (15.2-cm diameter unit at 9.1 kg/hr (6 in.-diameter unit at 20 lb/hr)) tests of the first stage have been successful in determining the operating conditions necessary to achieve soil agglomeration. The leaching characteristics of the soil agglomerates were also determined.

In separate testing, the cyclonic combustor has been evaluated in a 0.84 GJ/hr (0.8 MM Btu/hr) unit at a feed rate of 13.6 to 27.2 kg/hr (30 to 60 lb/hr) of synthetic waste feed and achieved over 99.9999% DRE for CCl_4 .

This technology was accepted into the Superfund Innovative Technology Evaluation (SITE) Emerging Technologies Program in July, 1990. As mentioned above, bench-scale tests have been conducted and agglomerated soil samples have been produced at several operating conditions. A 5.4 tonne/day (6 ton/day) pilot plant is being built and will be used to test two soils in a series of twelve tests. The unit was planned to be operational in 1993. (See Appendix C for Technology Contact).

Hybrid Fluidized Bed System

The Hybrid Fluidized Bed System is a three-stage system designed to treat soils and sludges contaminated with organic and volatile inorganic contaminants (US EPA 1991). The first stage consists of a spouted bed that operates with an inlet velocity of 45.7 m/sec (50 yd/sec) and a temperature of 816° to 927°C (1,500° to 1,700°F). Large particles are retained in this stage until they are reduced in size through abrasion and grinding. System advantages based on calculations include better heat transfer for large clumps of dirt as compared to conventional rotary kilns and less pressure drop as compared to a conventional fluidized bed. Fine particles, volatile metals, and organic compounds pass to the second stage, the fluidized bed afterburner, where the organic compounds are further destroyed. In addition, this bed contains materials that absorb metal vapors, capture fine particles, and promote the formation of less mobile metal compounds. Processed soil is removed in the third stage, hot cyclone. Offgases are quenched and treated in a conventional baghouse for particulate and metal control.

Bench-scale tests were conducted in 1989 to determine the ability of the fluidized bed materials to capture metals (Energy & Environmental Research Corp. 1992; Taylor 1992). Capture rates of the volatile metals of 85 to 95% were achieved. A 30.5-cm (12 in.) diameter pilot-scale unit was constructed and tested in 1991 under a Small Business Innovative Research (SBIR) grant. This system was operated in a batch mode (2.3 kg/5 min (5 lb/5 min)) and fed soil spiked with organics and metals. Greater than 99.9% removal of contaminants was achieved.

This technology was accepted into the SITE Emerging Technologies Program in July, 1990. A Process Development Unit (61-cm diameter/continuous at 227 kg/hr (24-in. diameter/continuous at 500 lb/hr)) was built and mechanically tested with soil feed. The system was then modified to convert the spouted bed from an oxidation to a gasification system and to add an afterburner after the fabric filter. It was then tested with auto shredder residue feed. A US EPA Bulletin summarizing results of this test was planned for publication in 1993. (See Appendix C for Technology Contact).

Entrained-Bed Gasification

The treatment of waste by the Entrained-Bed Gasification system is an extension of Texaco's conventional gasification technology in which organic compounds are partially oxidized to a synthesis gas containing mainly carbon monoxide and hydrogen (US EPA 1991). It is expected that inorganic components of the feed, such as metals, would be captured in a glass-like slag. Solids in the feed must be ground and pumped in a slurry form containing 30 to 60% liquid by weight. The slurried feed, oxygen, and auxiliary fuel are fed to a refractory-lined pressure vessel that operates above 20.2×10^5 Pa (20 atm) and between 1,204° and 1,538°C (2,200° and 2,800°F). The slag and synthesis gas are then cooled and separated. The synthesis gas is further cooled and cleaned by a scrubbing system and may be used to produce other chemicals or burned as a fuel.

Texaco's conventional gasification technology has been operated commercially for over 30 years with feedstocks such as natural gas, heavy oil, coal, and petroleum coke. In December 1988, under a grant from the California Department of Health Services, Texaco demonstrated this system using low-heating-value petroleum tank bottoms. During a 40-hr pilot run, this material was used as a supplemental feed to a coal-fired gasifier. Car-

bon conversion in the waste was over 99%, and solid residues from the process were found to be nonhazardous based on California Assessment Manual limits for total and leachable materials. All residue streams were determined to be free of trace organics and US EPA priority pollutants.

This technology was accepted into the SITE Demonstration program in July, 1991. A demonstration with Superfund hazardous waste was planned for mid-1993 at Texaco's Montebello Research Laboratory. (See Appendix C for Technology Contact).

Metallurgical-Based Treatment Processes

This general class of waste treatment technologies is based on steel-making and related metallurgical processes. The basic system configuration is a refractory reactor containing a melt into which waste materials are introduced and broken down. The bath can operate from about 800° to 1,800°C (1,470° to 3,270°F). The metallic constituents can be reduced to the metal state and be poured off or tapped periodically and recovered. The nonmetallic inorganic constituents form a slag which can also be tapped and withdrawn separately from the metals. The more volatile metals, such as lead, leave the reactor in the fume going overhead and can be collected, after cooling, in a baghouse or other air pollution control device. This characteristic is of particular interest with respect to the treatment of municipal solid waste and contaminated soils that may have volatile heavy metals present. The organic matter in the feed is broken down and reacts at the high temperatures in the bath. The composition of the flue gases depends on the oxidative conditions in the melt. Fugitive emissions from the furnace can be controlled through tight seals. These processes are quite versatile and can handle a large variety of wastes. The inorganic content of soils and other wastes would end up primarily as a stable slag or aggregate. The developers of these systems maintain that the slag would be nonhazardous, implying that it would pass the Toxicity Characteristic Leachate Procedure (TCLP) or other regulatory tests.

One version of this type of process is called Sirosmelt, which has been commercialized by an Australian company, Ausmelt, Pty. Ltd. The original technology was invented by Dr. John Floyd in the early 1970's. The key to the Sirosmelt technology is a patented lance that is submerged in a bath of molten materials. Some 18 plants using the Ausmelt technology have been designed, installed, and operated. The Ausmelt system has been tested in

pilot- or full-scale runs on a variety of wastes, for example, tin slag reduction, lead residues, and flue dust.

The Ausmelt process has been fully demonstrated for several feedstocks to at least a scale of about 5 tonne/hr (5.5 ton/hr). A facility to process 120,000 tonne/yr (132,280 ton/yr) of zinc plant residues being constructed in Korea for Korea Zinc was scheduled to start up in 1993. Data on the processing of a wide variety of waste and other feedstocks (approximately 30 different materials) have been generated in the Ausmelt pilot plant of approximately 200 kg/hr (440 lb/hr). The company is completing a pilot-scale plant in Colorado and plans to run tests on soil in the near future.

A recently formed US company, Molten Metal Technology, Inc., Cambridge, Mass., is currently developing a set of waste management systems also based on steel-making and related processes. The company is constructing a pilot facility in New Bedford, Mass., and has been carrying out tests at a L'Air Liquide research facility near Paris, France. The company has formed alliances with a number of firms, including DuPont, L'Air Liquide, Rollins Environmental Services, Inc., and AM-RE SERVICES, Inc. (See Appendix C for Technology Contact).

Molten Salt Oxidation (MSO) Process

The MSO process utilizes a combination of chemical reactions and thermal treatment to destroy waste materials. The reactor melt is composed of ordinary salts, such as sodium carbonate, or of mixtures including potassium carbonate or sodium chloride. Operating temperatures are commonly held to $950^{\circ} \pm 50^{\circ}\text{C}$ ($1,740^{\circ} \pm 120^{\circ}\text{F}$), but may be controlled throughout the range 700° to $1,200^{\circ}\text{C}$ ($1,290^{\circ}$ to $2,190^{\circ}\text{F}$). At operating temperature the molten salt has a viscosity similar to water. The waste streams introduced in the MSO process can be gaseous, liquid, solid, or slurry phase feed stocks; however, the maximum particle size must be controlled to 3 mm (1/8 in.) for pneumatic conveying. In general, most waste materials that are recommended for treatment by MSO have sufficient heat release to keep the salt bath hot and molten. A few waste streams might require the addition of supplemental fuel, such as gas or oil.

Rockwell International has evaluated the feasibility of this process on specific wastes, including perchloroethylene bottoms, hexachlorobenzene, chlordane, polychlorinated biphenyls (PCBs) and simulated radioactive

wastes. The tests were performed either at bench-scale (0.5 to 5 kg/hr (1 to 10 lb/hr)) or pilot-scale (50 to 910 kg/hr (100 to 2,000 lb/hr)) systems. Wastes that exhibit the most compatible thermal, physical, and chemical properties for the MSO process are offgases from other treatment systems, energetic liquids, nonenergetic liquids, and toxic chemicals such as pesticides, herbicides, PCBs, infectious waste, and chemical warfare agents. As the fraction of inert material (ash) increases in the waste stream, the potential for using the MSO process drops. Molten salt oxidation is not viable for inert solids such as soil, asbestos, concrete, grout, and most D & D rubble.

The DOE may be interested in MSO as an effective treatment process for mixed and hazardous waste; however, there are technical and implementation factors that need to be resolved before successful commercialization. (See Appendix C for Technology Contact).

B

APPENDIX B

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