UNITED STATES and GERMAN BILATERAL AGREEMENT on REMEDIATION of HAZARDOUS WASTE SITES

INTERIM SUMMARY REPORT

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Prepared for:
U.S. ENVIRONMENTAL PROTECTION AGENCY
NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
CINCINNATI, OHIO 45628

Prepared by:
Tetra Tech EM Inc.
591 Camino de la Reina, Suite 640
San Diego, California 92108

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FOREWORD

Environmental contamination is a global situation that requires more reliable, cost-effective cleanup technologies to address common waste problems. Many countries have committed extensive resources to test, develop, and implement technologies to meet complex and ever changing environmental needs. The ongoing challenge for individual countries is how to capitalize on the resources, expertise, and knowledge of other countries that are conducting similar research efforts and effectively transfer the information to those responsible for making decisions and implementing remedial actions.

This research publication is intended to transfer the technological information shared under a bilateral agreement between Germany and the United States. This publication may contribute to finding mutual international solutions for common waste problems.

Over the past 10 years, the U.S. Environmental Protection Agency (EPA) and the German Federal Ministry of Education, and Research (BMBF) have been actively involved in a bilateral agreement on remediation of hazardous waste sites. This collaboration was initiated to better understand each country's approach to remediating hazardous waste sites and to evaluate the effectiveness of innovative technologies being applied at selected sites within each country. Under the bilateral agreement, 20 innovative technologies have been evaluated; 9 in the U.S. and 11 in Germany. Each technology has been evaluated under the political, regulatory, and social conditions of both partner countries.

The purpose of this interim status report is to describe the background of the bilateral agreement; the results of innovative technology demonstrations in the U.S. and Germany; and the benefits, accomplishments, and lessons learned under the agreement through Phase I and II of the agreement. Data for some of the Phase II demonstrations are currently under evaluation; therefore, some results, benefits, and accomplishments for Phase II were not available for inclusion in this report. Final results will be included in the final report.

CONTENTS

CONTENTS (Continued)

Section Page

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

TABLES

FIGURES

FIGURES (Continued)

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AC	Alternating current
AFB	Air Force Base
AOX	Adsorbable organic halides
APEG	Alkaline polyethylene glycol
ArGe	Arbeitsgemeinschaft
ATP	Anaerobic Thermal Processor
B&RE	Brown & Root Environmental
BAI	Billings and Associates, Inc
BEC®	Biological Emission Control
BMBF	German Federal Ministry of Education and Research
BTEX	Benzene, toluene, ethylbenzene, and xylene
CA	Chloroethane
CatOx	Catalytic oxidation
CFM	Chemische Fabrik Marktredwitz Site
cfm	Cubic feet per minute
CFR	Code of Federal Regulations
cm	Centimeter
CRE	Contaminant removal efficiency
CRPAC	Crooksville/Roseville Pottery Area of Concern
DCA	Dichlorethane
DETAD	German Standard Procedure for the Evaluation of Remedial Technologies
DM	Deutschemark
DO	Dissolved oxygen
DRE	Destruction and removal efficiency
dscm	Dry standard cubic meter
EPA	U.S. Environmental Protection Agency
ETI	EnviroMetal Technologies Inc.
FCC	Federal Communications Commission
FS1	Friendship Pottery I
g/m^3	Grams per cubic meter
GC	Gas chromatography
GHM	Gaswerk Hannoversch Munden
GII	Geokinetics International, Inc.
gpm	Gallon per minute
HCl	Hydrogen chloride gas
HDPE	High density polyethylene
hPa	Hectopascals
HSWA	Hazardous and Solid Waste Act
IITRI	IIT Research Institute
ISM	Industrial, scientific, and medical
kg/hr	Kilograms per hour
KSE	KSE Inc.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

kW	Kilowatt
LEL	Lower explosive limit
LNAPL	Light nonaqueous phase liquid
LSW	Lead Site Workshop
µ	Microns
µm	Micron meters
m	Meters
m^2	Square meter
m^3	Cubic meters
m^3/hr	Cubic meters per hour
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
MCL	Maximum contaminant level
MEP	Multiple extraction process
mbar	Millibar
mg	Milligrams
mg/m^3	Milligram per cubic meter
mHz	Megahertz
mm	Millimeter
MPE	Multi phase extraction
MS	Matrix spike
MSD	Matrix spike duplicate
mt	Metric ton
mt/h	Metric tons per hour
mV	Millivolts
NaOH	Sodium hydroxide
NAVBASE	Naval Base
Nm^3	Normal cubic meters
NORDAC	Norddeutsches Altlasten-Sanierungs-Centrum GmbH & Co. KG
O&M	Operations and Maintenance
OMC	Outboard Marine Corporation
PAH	Polynuclear aromatic hydrocarbons
PBET	Physiologically based extraction test
PCB	Polychlorinated biphenyls
PCE	Tetrachlorethene
Plambeck ContraCon	Plambeck ContraCon Bau und Umwelttechnik GmbH
PLC	Programmable logic controller
ppm	Parts per million
Prantner	Prantner & Partner GmbH
PSD	Particle size distribution
psi	Pounds per square inch
PSI	Peroxidation Systems, Inc.
PVC	Polyvinyl chloride
QA	Quality assurance
QAPP	Quality assurance project plan

ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

QA/QC	Quality assurance and quality control
QC	Quality control
RCRA	Resource Conservation and Recovery Act
RF	Radio frequency
RFCA	Rocky Flats Cleanup Agreement
RFETS	Rocky Flats Environmental Technology Site
RFH	Radio Frequency Heating
RMRS	Rocky Mountain Remediation Services, L.L.C.
scfm	Standard cubic foot per minute
SITE	Superfund Innovative Technology Evaluation
SO_2	Sulfur dioxide
STAR	Star Organics, L.L.C.
SVE	Soil vapor extraction
SVOC	Semivolatile organic compound
SVVS®	Subsurface Volatization and Ventilation System
TAT	2,4,6-triaminotoluene
TCA	1,1,1-trichloroethane
TCE	Trichloroethene
TCLP	Toxicity Characteristic Leaching Procedure
Tetra Tech	Tetra Tech EM Inc.
TNT	2,4,6-trinitrotoluene
TOC	Total organic carbon
TOX	Total organic halides
Tph	Total petroleum hydrocarbons
TRPH	Total recoverable petroleum hydrocarbons
TRW	Technical Review Workshop
UCL	Upper confidence limit
U-Nord	Umweltschutz-Nord
UTS	Universal Treatment Standard
UV	Ultraviolet
VC	Vinyl chloride
VCU	Vapor control unit
VFW	American Legion Trailer Park
VOC	Volatile organic compound
yd^3	Cubic yard

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EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) and the German Federal Ministry of Education and Research (BMBF) entered into a Bilateral Agreement in 1990 to study each country's efforts in developing and demonstrating remedial technologies. The overall objective of the Bilateral Agreement is for each partner country to gain a comprehensive understanding of the other's approach to remediating hazardous waste sites and evaluating the effectiveness of innovative technologies being applied at these sites. The specific goals of the Bilateral Agreement are to (1) facilitate an understanding of each country's approach to the remediation of contaminated sites, (2) evaluate innovative remedial technologies according to the standards of both countries, and (3) facilitate international technology exchange.

Activities conducted under the Bilateral Agreement have been implemented in two phases. During Phase I, 10 technologies at sites in the United States and Germany were evaluated. Technology evaluations occurring in the U.S. correspond to EPA Superfund Innovative Technology Evaluation (SITE) demonstrations; those occurring in Germany correspond to full-scale site remediation activities. Technologies demonstrated during Phase I include soil washing, thermal desorption, ex-situ bioremediatio, in-situ radio frequency heating, vacuum distillation, catalytic oxidation, chemical ultraviolet oxidation, and air sparging.

Under Phase II of the Bilateral Agreement, SITE Program quality management protocols were reviewed and used to develop a German equivalent, the German Standard Procedure for the Evaluation of Remedial Technologies (the DETAD). Both the United States and German quality management protocols were then applied to five technology evaluations in the United States and five technology evaluations in Germany. Technologies demonstrated during Phase II include in situ and ex situ bioremediation, reactive barrier, electroheating, photocatalytic reactor, surfactant-enhanced extraction, soil stabilization, biological treatment, and catalytic combustion. The SITE Program and DETAD quality management protocols yielded data of known quality for demonstrations in each respective country.

The Bilateral Agreement will continue to enhance each partner country's cleanup capabilities for hazardous waste sites by sharing information on innovative remedial approaches, promoting development of innovative technologies, improving the quality of technology evaluations, and introducing technology developers to international markets. In addition, international partnering, such as that under the Bilateral Agreement, has and will continue to allow each country to learn about the partner's environmental regulations, policies, and guidelines. This understanding may influence the evolution of remedial regulations in each country and may help to standardize remedial processes on an international level, which would further encourage developers to enter international markets.

1.0 INTRODUCTION

The U.S. Environmental Protection Agency (EPA) and the German Federal Ministry of Education and Research (BMBF) entered into a Bilateral Agreement in 1990 study each country's efforts in developing and demonstrating remedial technologies. The overall objective of the Bilateral Agreement is for each partner country to gain a comprehensive understanding of the other's approach to remediating hazardous waste sites and evaluating the effectiveness of innovative technologies being applied at these sites. The specific goals of the Bilateral Agreement are to (1) facilitate an understanding of each country's approach to the remediation of contaminated sites, (2) evaluate innovative remedial technologies according to the standards of both countries, and (3) facilitate international technology exchange.

This interim summary report outlines the progress of the initiative. The first phase of the Bilateral Agreement has been completed. A summary of the Phase I goals, accomplishments, and results are presented in Section 2. Detailed information on each Phase I technology is presented in Section 4. The second phase is still in progress. Section 5 includes detailed information on each Phase II technology. This report does not include final data for some demonstrations since the analytical data are currently under evaluation and will be summarized in evaluation reports. Once the data and evaluation reports are finalized, a Final Bilateral Summary Report will be issued to include this information. Section 3 will include goals, accomplishments, and results for Phase II once that phase is completed.

1.1 BACKGROUND

Because waste management and the cleanup of contaminated sites present major problems in every industrialized nation, all these countries are searching for innovative solutions to hazardous waste management and site remediation problems. Based on a variety of national and local circumstances, differing standards and techniques have been developed and adopted in various individual countries to solve pressing environmental problems. However, environmental contamination has become an international problem requiring more than a local or national perspective. A broad international awareness and cooperative international programs are required to find solutions to our global environmental problems. By coordinating a joint understanding of environmental situations in different countries, the interactive transfer of technological information may contribute to finding mutual solutions to common environmental problems. This report is part of that international technology transfer initiative.

1.2 PROGRAM PURPOSE

The purpose of the bilateral agreement program is to: (1) gain a comprehensive understanding of the other country's approach to remediating hazardous waste sites and (2) evaluate the effectiveness of innovative technologies being applied at these sites. To achieve these objectives, EPA and the BMBF established to following specific goals for the program:

- Facilitate an understanding of each country's approach to the remediation of contaminated sites
- Evaluate innovative remedial technologies according to the standards of both countries
- Facilitate international technology exchange

The approach to meeting each of these goals involves (1) international technical information exchange, (2) technology demonstrations in each partner country, and (3) publishing technology transfer documents in both German and English.

1.2.1 Facilitate an Understanding of Each Country's Approach to the Remediation of Contaminated Sites

To understand each country's approach to the remediation of contaminated sites, technical meetings were held in each partner country, and site visits were made to contaminated sites undergoing remediation. Additionally, detailed demonstration plans for several innovative technologies were prepared. These plans outlined site-specific technical and regulatory requirements for each technology. Finally, both U.S. and German representatives participated in and presented papers at numerous international conferences on hazardous waste site remediation.

1.2.2 Evaluate Innovative Remedial Technologies According to the Standards of Both Countries

To achieve this goal, a total of 20 innovative technologies were evaluated; nine technologies in the U.S. and 11 technologies in Germany. For each demonstration, a technology evaluation plan was prepared to evaluate each technology as if the demonstrations were conducted in the partner country. Additionally, rigorous quality assurance (QA) oversight was applied to each demonstration to ensure that scientifically-defensible performance data were collected during each demonstration.

1.2.3 Facilitate International Technology Exchange

International technology exchange was facilitated through preparation of a U.S. EPA Innovative Technology Evaluation Report and a German technology evaluation final report for each demonstrated technology. Each report issued under the bilateral agreement underwent rigorous quality assurance (QA) review and endorsement before publication. Throughout the Bilateral Agreement demonstrations, technical information on the various technologies was compiled and transferred to the partner countries. Additionally, numerous papers were presented at innovative technology and hazardous waste site remediation conferences.

1.3 PHASED APPROACH TO COOPERATIVE ACTIVITIES

Activities conducted under the Bilateral Agreement were implemented in two phases. During Phase I, 10 technologies were evaluated at sites in the United States and Germany. Technology evaluations occurring in the United States corresponded to EPA Superfund Innovative Technology Evaluation (SITE) demonstrations; those occurring in Germany corresponded to full-scale site remediation activities. Technologies demonstrated during Phase I included soil washing, thermal desorption, ex situ bioremediation, in-situ radio frequency heating, vacuum distillation, catalytic oxidation, chemical/ultraviolet oxidation, and air sparging. Phase I technology evaluations are complete and evaluation reports have been published.

Under Phase II of the Bilateral Agreement, SITE Program quality management protocols were reviewed and used to develop a German equivalent, the German Standard Procedure for the Evaluation of Remedial Technologies (the DETAD). Both the U.S. and German quality management protocols were then applied to five technology evaluations in the United States and five technology evaluations in Germany. Technologies demonstrated during Phase II include in situ and ex situ bioremediation, reactive barriers, electroheating, photocatalytic reactor, surfactant-enhanced extraction, soil stabilization, biological treatment, and catalytic combustion. Phase II technology evaluations are still in-progress.

2.0 SUMMARY OF BILATERAL AGREEMENT PHASE I GOALS, ACCOMPLISHMENTS, AND BENEFITS

This section summarizes the bilateral agreement Phase I goals and lists the accomplishments or benefits gained by each partner. While the goals were the same for each partner, benefits were realized in different ways. This section also summarizes the lessons learned by each partner.

2.1 GOALS AND ACCOMPLISHMENTS

Tables 1 and 2 list specific U.S. and German accomplishments for each of the four bilateral agreement Phase I goals. Specific accomplishments relating to each goal are discussed in detail below.

2.1.1 Understand Remedial Approaches to Contaminated Sites

German technical representatives studied information from actual site remediation projects to compare the U.S. approach to remedial activities with German procedures. Technical meetings and exchange of regulatory documents and work plans were instrumental in performing this study. After studying the formal, detailed U.S. methods required for every specific remedial project activity, German representatives concluded that the U.S. process takes more time to implement remedial actions. In Germany, the regulators, responsible parties, and contractors work closely to evaluate and select technically feasible, cost-effective remedial solutions in a timely manner. For the purposes of developing German regulations further, German representatives considered streamlining the formalized U.S. processes.

U.S. representatives visited Germany to meet with regulators, survey hazardous waste sites included in the bilateral agreement, and meet with technology developers and technical experts to discuss the implementation of German technology demonstrations. Meetings conducted during these visits allowed U.S. representatives to discuss the intent and scope of activities required to demonstrate an innovative technology according to EPA protocols under conditions in Germany.

Table 1. U.S. Accomplishments Under Phase I

Goals	Accomplishments
Facilitate an understanding of each country's approach to the remediation of contaminated sites	Gained understanding of German remedial approaches by preparing demonstration plans and QA project plans
	Identified current, high-profile German regulatory issues
	Learned how German remedial programs are implemented on a regional basis under state jurisdiction
	Gained an understanding of Germany's capabilities in conducting technology demonstrations
Demonstrate innovative remedial technologies	Completed four technology demonstrations
	Conducted demonstrations as part of full-scale remediation activities
	Developed understanding of German sampling and analysis procedures
Compare QA programs	Implemented German QA programs during demonstrations
	Observed and implemented German analytical procedures
	Disseminated U.S. QA/QC guidelines to Germany
Facilitate technology transfer	Introduced U.S. innovative technologies to Germany
	Participated in international symposia to exchange information on innovative technologies
	Introduced German technology evaluation procedures and environmental regulations to developers

Notes:

QA	Quality Assurance
QA/QC	Quality Assurance/Quality Control

Table 2. German Accomplishments Under Phase I

Goals	Accomplishments
Facilitate an understanding of each country's approach to the remediation of contaminated sites	Gained understanding of U.S. remedial approaches based on exchange of regulatory documents and work plans and through technical meetings
	Gained greater insight into the basis for and substance of EPA regulatory programs for remediation of hazardous waste sites
	Identified the role and jurisdiction of the following remedial project participants: federal and state regulators, responsible parties, and contractors
	Gained an understanding of the role of the cleanup technology developer, contractor, and regulatory agencies during full-scale remediation projects
Demonstrate innovative remedial technologies	Completed six technology demonstrations
	Developed an understanding of U.S. sampling and analysis procedures
	Conducted demonstrations as part of full-scale remediation activities
	Studied regulatory requirements for data collection
Compare QA programs	Implemented U.S. QA programs during demonstrations
	Discussed and evaluated QA/QC issues
	Developed an understanding of U.S. sampling and analysis procedures
	Conducted demonstrations as part of full-scale remediation activities
	Studied regulatory requirements for data collection
Facilitate technology transfer	Introduced German innovative technologies to the U.S.
	Generated parallel performance data to allow an evaluation of U.S. analytical methods
	Promoted innovative technology development by establishing direct lines of international communication
	Participated in international symposia to exchange information on innovative technologies

Notes:

EPA	U.S. Environmental Protection Agency
QA	Quality Assurance
QA/QC	Quality Assurance/Quality Control

2.1.2 Demonstrate Innovative Remedial Technologies

Ten technology demonstrations were completed under Phase I of the bilateral agreement. Of these 10 demonstrations, four were in the U.S. and six were in Germany. The demonstrations have introduced technology developers to foreign regulatory requirements and monitoring techniques, and have introduced the international regulatory, consulting, and industrial community to new technologies. U.S. demonstrations included thermal desorption, air sparging, radio frequency heating, and chemical oxidation by UV light and hydrogen peroxide. German demonstrations included soil vacuum distillation, catalytic oxidation, thermal desorption, and ex-situ bioremediation.

Full-scale remediation demonstrations have provided an opportunity for U.S. and German technical representatives to observe the roles of responsible parties, regulators, developers, and consultants during innovative technology implementation. Understanding the roles and scope of authority of key participants in the remedial process has been instrumental in the efficient performance of bilateral program activities. At times, however, political and cost considerations have hampered demonstration activities, resulting in delays and other difficulties. Many difficulties also resulted from combining a demonstration with full-scale remedial activities. From this, the representatives learned that conducting technology demonstrations as independent treatability studies may be more efficient, albeit in some cases more expensive, than conducting the demonstration in concert with a full-scale site remediation.

Similarities and differences exist between German and U.S. technology monitoring techniques. The differences have been one of the main hurdles to overcome in designing the technology demonstrations. From their experience gained under the bilateral agreement, U.S. representatives have gained an understanding of German monitoring capabilities and have used this knowledge to design plans for German demonstrations. However, implementing each country's monitoring requirements is difficult even under the best circumstances, because most monitoring techniques rely heavily on specialized equipment and the experience of the technical staff in performing the measurements. Even with highly-trained technical staff, learning new techniques and obtaining high quality data are difficult. U.S. representatives have learned that direct communication between technical staff from both countries is the best method to overcome this hurdle.

Table 3 summarizes the 10 technology demonstrations conducted in the United States and Germany as part of Phase I of the Bilateral Agreement.

2.1.3 Compare QA Programs

Demonstrations in Germany and the United States have required implementing QA programs specific to each country's requirements. EPA has prepared a detailed quality assurance project plan (QAPP) that identifies project objectives, QA objectives, and procedures for collecting data of known and documented quality for the evaluation of each demonstrated technology.

These QAPPs served as a primary vehicle for dissemination of the U.S. QA procedures. U.S. representatives have assisted German technical experts in understanding the basis and intent of the U.S. quality assurance/quality control (QA/QC) and analytical method requirements, as well as interpretation of quality control (QC) results. In addition, U.S. representatives held conference calls and attended meetings with German regulators, technology developers, consultants, and analytical laboratories to discuss and evaluate QA/QC requirements associated with technology demonstrations. A large portion of this interaction involved discussing the scope and intent of the rigorous U.S. QA/QC requirements.

In preparing and implementing technology demonstrations, German and U.S. technical representatives observed and implemented each partner's analytical methods. This hands-on experience provided a basis to compare of the similarities and differences of the German analytical techniques and QA/QC procedures with EPA-approved methods. During the demonstrations, two sets of data were generated: one set of data derived by U.S. procedures, and one set derived by German methods. A review of the data could be a potential first step toward achieving performance-based method requirements for international environmental studies.

Prompted in part by U.S. QA/QC procedures disseminated under this program, German technical representatives are currently revising regulatory QA/QC guidelines to provide objective documentation of data quality. Germany's revision of QA/QC guidelines signifies the importance of QA as a key element in technology demonstrations as well as remedial activities in general. U.S. procedures are often

Table 3. Summary of Phase I Results

Technology	Description	Site	Media	Contaminant	Key Results
PHASE I – U.S. Demonstrations					
SoilTech Anaerobic Thermal Processor	Thermal desorption and chemical transformation	Waukegan Harbor Superfund site, Waukegan, Illinois, U.S.	Soil, sediment	PCBs	• Destruction and removal efficiency > 99.99 %
Subsurface Volatilization and Ventilation System (SVVS)®	SVE/air sparging/ in-situ bioremediation	Electro-Voice, Inc. site, Buchanan, Michigan, U.S.	Soil, groundwater	VOCs	• Overall 80.6 % reduction in critical VOCs
perox-pure™	Chemical oxidation	Lawrence Livermore National Laboratory, Tracey, California, U.S.	Water	VOCs	• For spiked groundwater, average removal efficiencies ranged from 81.8 to 99.7 % • For unspiked groundwater, removal efficiencies were: o TCE – 99.9 % o PCE – 99.7 % o TCA – 35 to 84 % • Removal efficiencies: o TOX – 93 to 99 % o AOX – 95 to 99 %
IITRI Radio Frequency Heating	Radio frequency heating	Kelly Air Force Base, San Antonio, Texas, U.S.	Soil	VOCs, SVOCs, petroleum hydrocarbons	• In revised design treatment zone: o TRPH decreased 60 % o 2 noncritical SVOCs decreased o 4 noncritical VOCs increased • In heated zone: o TRPH decreased 95 % o no VOCs or SVOCs significantly changed
PHASE I – German Demonstrations					
NORDAC Soil Washing	Soil washing	NORDAC facility, Hamburg, Germany	Soil	VOCs	• BTEX removal efficiencies ranged from 94.4 to 99.4 %

Table 3. Summary of Phase I Results (Continued)

Technology	Description	Site	Media	Contaminant	Key Results
ZÜBLIN KNV Catalytic Oxidation System	Catalytic oxidation	Entsorgungsbetriebe Duisburg treatment facility, Duisburg-Neumuehl, Nordrhein-Westfalen, Germany	Offgas	BTEX	• Overall removal efficiencies for BTEX ranged from < 99.9 to <94.7 %
RUT TERRA·POR Thermal Desorption Soil Treatment Pilot Plant	Thermal desorption soil treatment	RUT plant, Herten, Nordrhein-Westfalen, Germany	Soil	PAH	• Results varied widely primarily due to low contaminant concentrations in untreated soil
Hochtief Thermal Desporption	Thermal desorption	Hochtief facility, Herne, Germany	Soil	TRPH, PAH, BTEX	• Removal efficiency o TRPH – 99.0 % o PAH – 99.7 % o BTEX – 99.0 %
Harbauer Vacuum Distillation	Soil classification and vacuum distillation	Harbauer facility, Bavaria, Germany	Soil	Mercury	• 97.6 - 98.0 % average removal efficiency for the Harbauer system • 96.6 - 98.7 % average removal efficiency for the vacuum distillation process.
Umweltchutz-Nord TERRANOX	Bioremediation	Haynauerstrasse site, Berlin, Germany	Soil	Hydrocarbons	• The system did not meet demonstration objectives

Notes:

BTEX	Total Benzene, toluene, ethylebenzene, and xylene
PAH	Polynueclear aromatic hydrocarbons
PCB	Polychlorinated biphenyls
SVE	Soil vapor extraction
SVOC	Semivolatile organic compound
TRPH	Total recoverable petroleum hydrocarbons
VOC	Volatile organic compound

consulted as an example for data quality documentation in the international arena. German technical representatives accomplished the following while comparing the programs:

- Implemented U.S. QA programs during demonstrations
- Discussed and evaluated QA/QC issues
- Observed and implemented U.S. analytical procedures
- Generated data by U.S. and German methods to allow a comparison of analytical procedures

Demonstrations in Germany and in the United States have required implementing QA/QC procedures specific to each country's regulatory, technical, and political requirements. Adhering to both countries' QA/QC requirements allows direct use of the demonstration results in the other country; it also allowed the U.S. QA/QC approach to be studied and evaluated under practical conditions. The EPA approach to QA/QC in site remediation may substantially influence the development of new QA/QC policies and guidelines in Germany.

Each country's approach to QA was discussed during conference calls and technical meetings. These direct lines of communication enabled experts to gain insight into the possible advantages and disadvantages of the U.S. procedures. For example, one advantage of U.S. QA/QC requirements is that they provide useful information in determining and documenting data quality.

By implementing the other country's analytical methods, the German Federal Ministry of Education and Research (BMBF) and EPA can compare the effectiveness and cost of various methods while having the full technical support of the partner's laboratory personnel. Although the basic sampling and analysis equipment used in both countries is very similar, difficulties can be encountered in finding laboratories able to perform each partner's analytical methods. Eventually, each partner identified laboratories able to perform the analyses.

By compiling two sets of analytical data, EPA and BMBF will be able to determine the similarities and differences of U.S. and German analytical procedures. The comparison, performed with substantial support from both U.S. and German experts, will enable technology developers and potential clients to gain a better understanding of the international remediation market. This understanding of procedures will be useful to technology developers, analytical laboratories, regulators, and responsible parties in assessing the applicability of foreign technologies in their country.

2.1.4 Facilitate Technology Transfer

U.S. and German regulators, responsible parties, and consultants have been introduced to new, innovative technologies in both countries. This introduction will allow environmental decision makers to select the appropriate technology for site remediation from a broader base of alternatives. Completed demonstrations provide technically sound performance and cost information for comparison of innovative versus traditional technology options.

Participation in international remediation symposia has played a major role in transferring information on technologies demonstrated under the bilateral agreement as well as the overall EPA SITE program. Under the bilateral agreement, U.S. representatives participated in symposia in Berlin, Germany; San Francisco, California; and Budapest, Hungary. Each of these symposia were well attended by the international regulatory and industrial community and provided an opportunity to discuss the technical details of the latest developments in the environmental field. Participation in the various technical sessions and workshops allowed U.S. technical and regulatory representatives to directly discuss pertinent issues with their international counterparts. Participation in these three international symposiums resulted in numerous requests for additional information and yielded interest from international environmental experts.

U.S. and German technology developers have been introduced to each other's technology evaluation approaches, and both countries performed an evaluation of the selected technologies. By including developers in the demonstration process, the developers learned about the performance and cost requirements of the partner country. Understanding these requirements is an important element required to break into international environmental markets. To this end, the bilateral agreement has provided a significant new market opportunity for these technology developers.

German technical representatives accomplished the following to facilitate technology transfer:

- Introduced German innovative technologies to the United States
- Generated parallel performance data to allow an evaluation of U.S. analytical methods
- Promoted innovative technology development by establishing direct lines of international communication
- Participated in international symposia to exchange information on innovative technologies
- Introduced German technology developers to the U.S. remediation technology marketplace.

The technology information and demonstration results have been published for public distribution in the final report of each technology demonstration and at international site remediation conferences.

Parallel sets of performance data have been reported, and the differences in analytical procedures and methods have been evaluated. Information on the similarities and differences in analytical results is of fundamental importance when evaluating the possibility of cooperative marketing and research with the United States.

Innovative technology development was promoted by establishing direct lines of international communication. Understanding remediation requirements is fundamental to sharing technical ideas and distributing experiences for the development of innovative technologies.

German technical representatives participated in numerous international symposia on innovative remedial technologies. At symposia, meetings, and conferences throughout the world, the international community expressed great interest in the status of remedial technology development. Symposia participants were particularly interested in (1) system performance during technology demonstrations and (2) the results of full-scale remediation activities.

2.2 LESSONS LEARNED

Comprehensive demonstration plans and evaluation reports have been written for all 10 of the technology demonstrations. Collecting data using both EPA and German standard monitoring methods during projects in both countries facilitated the exchange of technical information. For demonstrations conducted in Germany, the EPA request for additional measures was compiled after consultation with various technical experts and governmental agencies. However, in some cases, SITE program technology demonstrations conducted in the United States were implemented too rapidly to (1) comprehensively evaluate the U.S. demonstration plans and (2) develop additional measures based on German regulations. The short demonstration timeframe resulted in a reduced level of detail in German requests for additional measures.

BMBF evaluated EPA-approved procedures for collecting and analyzing samples and for monitoring system operating parameters to determine similarities and differences and advantages or disadvantages compared to German procedures. Implementing U.S. methods in field and laboratory work allowed German technical staff to gain experience with U.S. procedures under realistic conditions, while having technical support from U.S. experts. This understanding of U.S. procedures for technology demonstrations will create more efficient future demonstrations.

In Germany, emphasis was placed on implementing and evaluating technologies in full-scale remedial projects. Assessing an innovative technology in a full-scale demonstration allows the technology's capabilities, flexibility, and cost to be evaluated in a competitive situation. However, full-scale demonstrations generally focus on technologies that have already found access to the commercial market. In similar, future technology transfer programs, the standard EPA approach to technology demonstrations with a formal, unbiased framework will likely be incorporated to some degree in German technology demonstration procedures. BMBF's original intention was to demonstrate technologies under competitive marketplace conditions; however, this approach may have complicated the technology demonstrations because of a lack of flexibility during the planning process. Demonstration projects on a pilot or limited commercial scale were generally found to be easier to implement.

German technical personnel reviewed regulatory requirements for collecting data during field implementation. The process of planning, reviewing, and implementing monitoring procedures and the associated elements of a QA program are of special interest to Germany, because it is currently developing a national Soil Protection Act. The evaluation of different approaches allows BMBF representatives to assess the responsibilities of technology developers and regulatory agencies for maintaining data quality.

3.0 SUMMARY OF BILATERAL AGREEMENT PHASE II GOALS, ACCOMPLISHMENTS, AND BENEFITS

Demonstration data for most of the Phase II Bilateral Agreement demonstrations are currently under evaluation. Therefore, a summary of goals, accomplishments, and benefits is not available for inclusion in this interim report. Phase II accomplishments and benefits will be included in the final summary report based on results and conclusions reported in the final evaluation reports for each technology.

4.0 PHASE I DEMONSTRATION ACTIVITIES

Under Phase I of the Bilateral Agreement, 10 technologies were demonstrated and evaluated, including 4 technologies in the U.S. and 6 technologies in Germany. Technology evaluations occurring in the U.S. corresponded to EPA SITE demonstrations; those occuring in Germany corresponded to full-scale site remediation activities.

4.1 RESULTS OF PHASE I U.S. DEMONSTRATION ACTIVITIES

Four technologies were demonstrated and evaluated in the U.S. as part of Phase I of the Bilateral Agreement. This report includes a description of the technology process, summarizes the demonstration objectives, approach, results, and conclusion, and provides vendor contact information for each technology. The following U.S. technologies were evaluated as part of Phase I:

- Soil Tech Anaerobic Thermal Processor
- Subsurface Volatization and Ventilation System ®
- perox-pure™ Chemical Oxidation Technology
- IITRI Radio Frequency Heating

4.1.1 Soil Tech Anaerobic Thermal Processor

The Anaerobic Thermal Processor (ATP) technology developed by SoilTech ATP Systems, Inc. (SoilTech) is a specialized, indirectly heated, rotary kiln system. The system is designed to thermally desorb organic contaminants such as polychlorinated biphenyls (PCB) from soil and sediment. The ATP may be used with alkaline polyethylene glycol (APEG) to provide intimate soil and reagent mixing that, combined with elevated temperature and prolonged residence time, can dechlorinate PCBs in soil and sediment. The ATP technology was demonstrated at the Waukegan Harbor Superfund site in Waukegan, Illinois, in June 1992 (PRC Environmental Management, Inc. [PRC] 1993b).

4.1.1.1 Process Description

The SoilTech ATP system is composed of six main process units (see Figure 1) for a simplified process flow diagram of the ATP's operations). The SoilTech ATP is a proprietary process vessel that uses elevated temperatures to (1) remove volatile and semivolatile contaminants from soil and sediment and

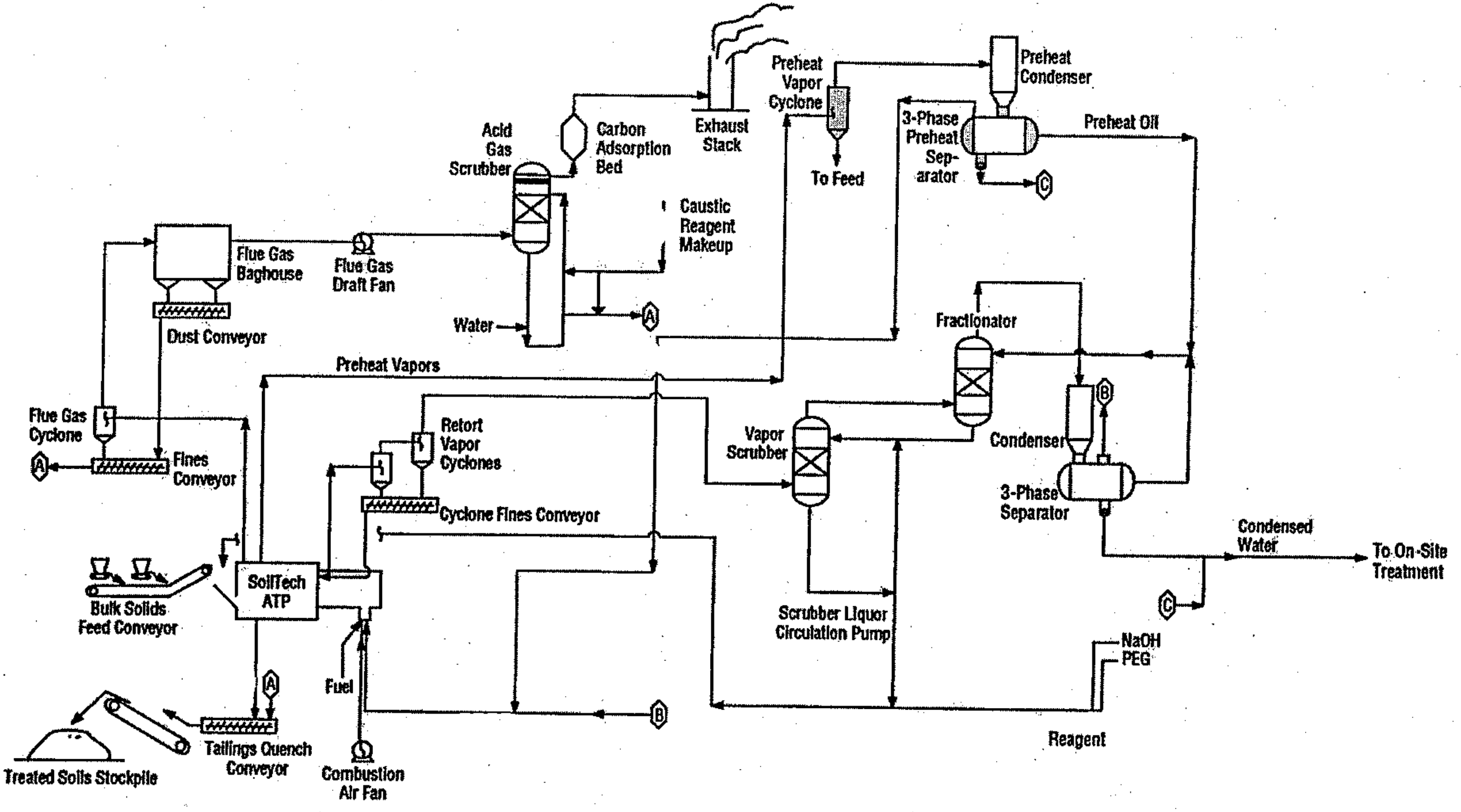


FIGURE 1
ATP SIMPLIFIED PROCESS FLOW DIAGRAM INCLUDING OPTIONAL APEG MODULE

(2) isolate and concentrate the contaminants in a liquid phase in the vapor recovery system for appropriate and permanent disposal. The ATP is a horizontal, rotating kiln that contains four separate internal sections: the preheat, retort, combustion, and cooling zones. Figure 2 is a simplified sectional diagram showing the four internal zones.

The feed enters the ATP through the preheat zone. The preheat zone heats and mixes the feed at temperatures (400 to 600 °F) high enough to vaporize materials with relatively low boiling points, such as water, volatile organics, and some semivolatile organics. The remaining hot solids pass through a proprietary sand seal that continuously conducts them into the retort zone while almost totally preventing vapor flow. The retort zone operates at a temperature (about 1,100 °F) high enough to vaporize heavy oils. Thermal cracking of hydrocarbons also takes place in the retort zone, resulting in the formation of coke and gases of low molecular weight. The coked and decontaminated solids pass through a second sand seal into the combustion zone. The vapors and gases from the preheat and retort zones are extracted from the ATP under a slight vacuum (0.1 inch of water column) and enter condensing systems (the two independent condenser trains shown in Figure 1). Most (by mass) of the vapor and gas streams are condensed to liquid water and oils, which are cooled to about 120 °F. The residual vapors, mainly noncondensable gases, are transported out of the condensing systems and into the combustion zone of the ATP through the stationary end frame.

Auxiliary burners number 1 and 2 are mounted in the stationary end frame of the ATP. These burners are fired with natural gas and any combustible vapors in the remaining noncondensable off-gas stream to provide process heat.

The elevated temperature in the retort zone is achieved by recycling a portion of the hot, decontaminated solids from the combustion zone to the retort zone via a dedicated recycle channel. Conductive heat transfer through the wall of the inner kiln also contributes to a minor portion of the heat in the zone.

The sand seals at both ends of the retort zone maintain a nearly oxygen-free environment that prevents hydrocarbons and coke in this zone. The residence time for the solids in the preheat zone is typically about 30 minutes. The residence time for the solids in the retort zone is 4 to 7 minutes, which is usually long enough to ensure complete volatilization of the hydrocarbons. The residence time can be increased by decreasing the waste feed rate.

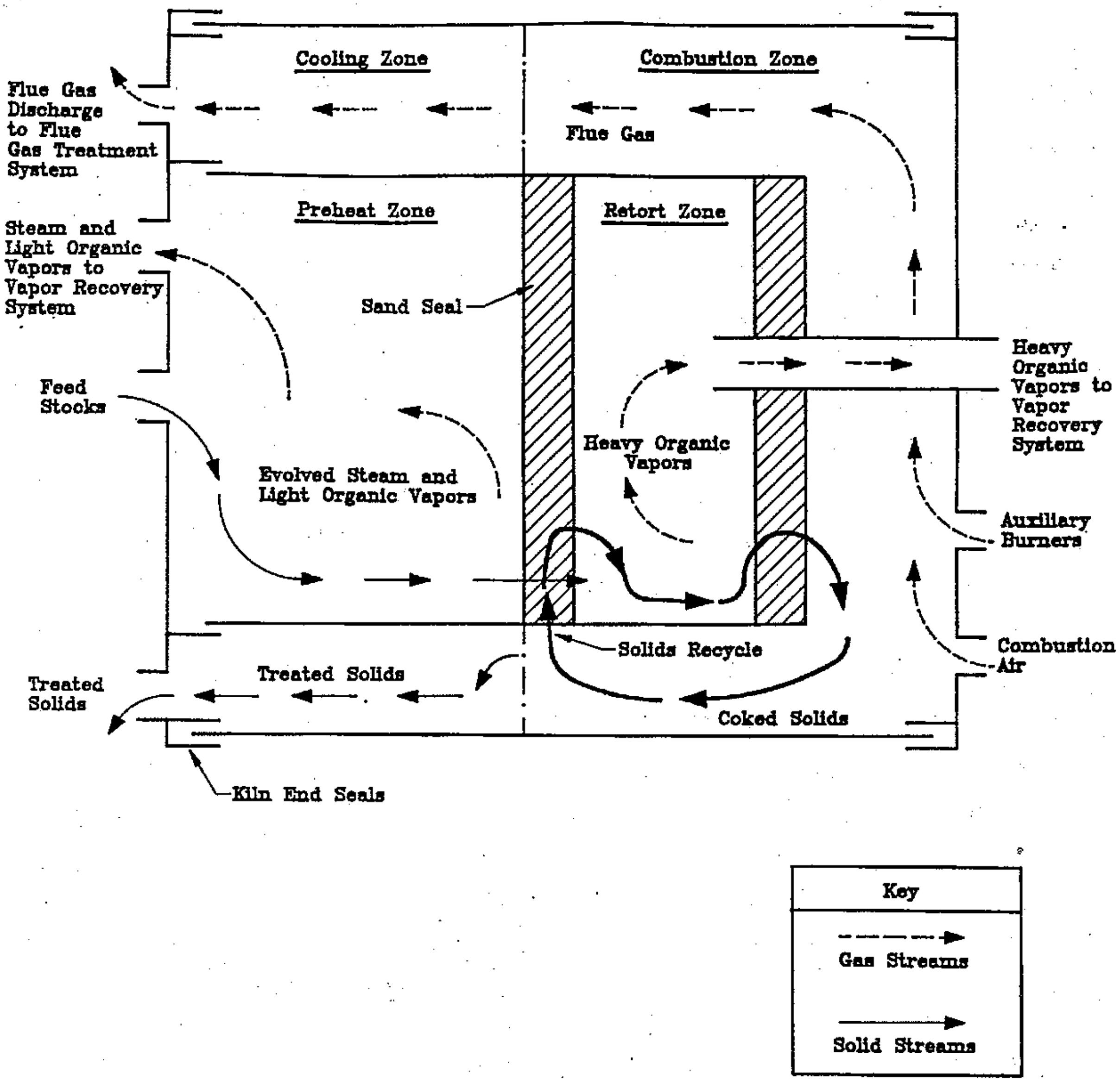


FIGURE 2

SIMPLIFIED SECTIONAL DIAGRAM
SHOWING THE FOUR INTERNAL ZONES

The combustion zone contains a large number of "lifters" in rows around the inner lining of the outer shell. These lifters serve to lift the coked solids and discharge them in sheets that drop vertically through the horizontally moving air and flue gas stream. These falling solids are turbulently exposed to any oxygen present in the air stream, thus allowing the simultaneous combustion of the coke and the makeup fuels. The combustion zone temperature is maintained at about 1,300 °F.

The solids in the combustion zone that are not diverted for recycling enter the cooling zone. Here they are lifted and distributed to the exterior of the kiln's inner shell to provide conductive heat transfer to the feed in the preheat zone. The treated solids are cooled to an exit temperature of 500 to 600 °F. Finally, the treated solids drop from the ATP annulus into a screw conveyor beneath the sealed, stationary, feed-end plenum. The flue gases exit the top of the plenum and enter the flue gas treatment system.

The vapor recovery system cools and condenses water and contaminant vapors that are removed from the preheat and retort zones of the ATP. The vapors from the preheat zone are withdrawn under a vacuum to a preheat vapor cooling system consisting of a cyclone, condenser, and three-phase separator. The fines collected in the preheat vapor cyclone are returned to the contaminated feed stream just before it enters the ATP.

The vapor stream from the retort zone first passes through a pair of cyclones to remove entrained particles; these particles, consisting of dusts and fines, are sent to the combustion zone via a screw conveyor. The vapor is then cooled by oil circulating in two packed columns, the vapor scrubber and the fractionator. These columns act as a two-stage, direct-contact condenser for compounds with relatively high boiling points. For feed that contains little or no heavy oil fraction, a charge of diesel or fuel oil may be added to provide the direct-contact, condensing medium. On startup, oils are added to the vapor recovery system to provide circulation and reflux oils.

The vapor stream from the preheat zone and the uncondensed retort vapors are cooled to near-ambient temperatures in separate, water-cooled condensers. The three immiscible phases exiting each condenser are segregated in a gas-oil-water separator. The final noncondensable gas phase, consisting of light hydrocarbons (mostly butane and lighter compounds) and some inert gases (including carbon dioxide and nitrogen), is recycled to the combustion zone, where the hydrocarbons are oxidized. The liquid hydrocarbon phase in each separator is combined with the condensate from the packed columns. Bottom oil is periodically discharged to a waste oil storage tank. Condensed water is pumped directly to an on-site wastewater treatment system.

4.1.1.2 Demonstration Objectives and Approach

There were four primary objectives and five secondary objectives in evaluating the SoilTech ATP technology (PRC 1992).

Primary Objectives:

- Assess the technology's ability to remove PCBs from soil and sediment at the Outboard Marine Corporation (OMC) site.
- Determine whether dioxins or furans are produced in the system.
- Document the operating conditions of the SoilTech ATP.
- Develop capital and operating costs for the SoilTech ATP technology that can be readily used in the Superfund decision-making process.

Secondary Objectives:

- Characterize the feed waste and treated solids so that the results of this demonstration can be used as part of Superfund decision-making processes at other sites.
- Evaluate disposal options for the treated solids and treated condensate.
- Determine what semivolatile organic degradation products exist in the treated solids and exhaust gas.
- Determine the stack gas PCB, dioxin/furan, semivolatile organic compound (SVOC), and volatile organic compound (VOC) concentrations.
- Characterize the preheat and retort off-gas PCB, SVOC, and VOC concentrations and mass flowrates.

Data to assess the demonstration objectives were collected over four test runs: three test runs, each of which lasted at least 8 hours and one test-run, which lasted at least 4 hours. QA/QC procedures were followed as specified in the approved QAPP.

4.1.1.3 Results and Conclusions

Based on the results of the SITE demonstration tests and other tests performed by SoilTech, a number of conclusions have been drawn regarding the applicability of the ATP technology. The most extensive data were obtained during the SITE demonstration tests; data from other tests have been evaluated in relation to SITE program objectives. The conclusions are presented below.

- The ATP technology can treat media contaminated with VOCs and SVOCs, including PCBs, polynuclear aromatic hydrocarbons (PAH), and total petroleum hydrocarbons (TPH). The ATP does not remove metals from wastes.
- The ATP can be used to dechlorinate PCBs by adding APEG. The destruction and removal efficiency (DRE) of the ATP for PCBs is greater than 99.9999 percent.
- Most contaminants removed from the waste are accumulated in the vapor scrubber oils in the vapor recovery system. Treatment residuals are not destroyed on site and require off-site treatment. The long-term effectiveness of the ATP system ultimately depends on the methods used to treat and dispose of these residuals.
- The concentration of contaminants in the ATP's internal process streams, including fines from air pollution control equipment, vapor scrubber oils, and condensed water, are higher than the concentration of contaminants in the treated solids.
- Contaminant removal mechanisms include thermal desorption and chemical transformation (i.e., dehalogenation).
- The ATP can treat a variety of soil and sediment types, including soils classified as silt/loam and sand. Wastes containing greater than 20 percent moisture will benefit from pretreatment (dewatering).
- The flue gas treatment system, as it was operated at the completion of the Waukegan Harbor Superfund site remediation, can effectively treat flue gas to meet stack gas emission standards for particulates and organic compounds.
- Low concentrations of dioxins and furans may be present in the ATP's process effluents and internal waste streams. The source of the dioxins and furans may be (1) dioxins and furans in the untreated waste or carrier oil (if the ATP is used with dehalogenation), or (2) thermal transformation of contaminants in the untreated waste. Treatability studies are recommended when treating wastes that contain dioxin or furan precursors.
- As a result of the full-scale remediation activities at the Waukegan Harbor Superfund site, SoilTech has improved the ATP system's reliability by (1) improving the internal sections of the ATP and (2) upgrading the flue gas treatment system. These improvements resulted in an on-line percentage reported to be 85 percent.
- A treatability study is recommended, before full-scale application of the ATP, to determine the anticipated residual contaminant concentrations in the treated solids and to obtain preliminary process operational data.

- For the Waukegan Harbor remediation project, soil treatment costs were approximately $155 per ton. The regulatory support, mobilization, startup, and demobilization costs for SoilTech's 10-ton-per-hour (tph) unit totalled about $1,400,000 for the site. A 5-tph, truck-mounted ATP unit is also available. For the 5-tph unit, fixed costs are expected to be lower, but soil treatment costs would be higher.

4.1.1.4 Vendor Contacts

Mr. John Noland
SoilTech ATP Systems, Inc.
500 N. Gulph Road, Suite 315
King of Prussia, Pennsylvania 19406
(205) 992-0800

Mr. Joseph Hutton
SoilTech ATP Systems, Inc.
800 Canonie Drive
Porter, Indiana 46304
(219) 926-8651

4.1.2 Subsurface Volatilization and Ventilation System®

The Subsurface Volatilization and Ventilation System (SVVS) ® process is an integrated technology that utilizes the benefits of soil vapor extraction/air sparging and in-situ bioremediation for the treatment of subsurface organic contamination in soil and groundwater. The SVVS® process evaluated under the EPA SITE Program was developed and designed by Billings and Associates, Inc. (BAI) and operated by Brown & Root Environmental (B&RE) (formerly Halliburton NUS Environmental Corporation). (In this report, BAI and B&RE are referred to as the developer and operator, respectively). The SVVS® process uses (1) vapor extraction to remove the easily-strippable volatile contaminants and (2) biostimulation to remove the less volatile, more tightly sorbed contaminants. Vapor extraction is the more dominant removal mechanism during the early phases of treatment, while biostimulation processes dominate in later phases.

The SVVS® technology was tested in 1993 at the Electro-Voice, Inc. site in Buchanan, Michigan to assess the developer's claim that the system would reduce the average contamination of seven target contaminants in the vadose zone by 30 percent after one year of system operation (EPA 1995b). The 1-year timeframe was chosen for testing purposes only, and does not reflect the limits of the technology.

4.1.2.1 Process Description

The SVVS®, developed and designed by BAI, and operated by B&RE under a licensing agreement, integrates the benefits of both vapor extraction and bioremediation, removing and destroying all phases of organic contamination from the subsurface. Vapor extraction removes the easily-strippable volatile compounds from the soil, and appears to be the dominant mechanism during the early phases of remediation. Bioremediation, more specifically biostimulation, processes are more dominant in the later phases of a remediation and are used to accelerate the in-situ destruction of organic compounds in the soil and groundwater. The combined application of the technologies results in remediation that is more rapid than using biostimulation alone, while generating lower quantities of volatile organics than conventional vapor extraction technologies. An additional benefit is the remediation of contaminants that would not normally be remediated by vapor extraction alone (contaminants with lower volatilities or that are more tightly sorbed). The result is an integrated technology that results in lower costs and faster remediation.

A typical SVVS® is comprised of a network of air injection and vacuum extraction wells designed to circulate air below the ground to:

- Volatilize and remove volatile organic contaminants from the groundwater and soil
- Increase the flow of oxygen in the soil to enhance the rate of in-situ transformation and destruction of organic contaminants by indigenous soil microbes

An SVVS® is custom-tailored to address specific site conditions. A typical SVVS® consists of alternating air injection and vacuum extraction wells aligned together in rows referred to as reactor lines. The number and spacing of the wells depends upon modeling results using a design parameter matrix, as well as the physical, chemical, and biological characteristics of the site. The reactor lines are linked together and plumbed to a central vapor control unit (VCU) that is used to house air injection and vacuum pumps, gauges, control valves, and other process control hardware. The VCU may also house an emission treatment system. One or more vacuum pumps are used to create negative pressure to extract contaminant vapors and control vapor migration, while an air compressor simultaneously creates positive pressure across the treatment area. Vacuum extraction wells are generally placed above the water table and are typically screened in the zone of maximum contamination to better focus remedial stresses. Air injection wells are screened below the groundwater table. The exact depth of the injection wells and screened intervals are site-specific design considerations. Depending on groundwater depths and fluctuation, horizontal vacuum screens, "stubbed" screens, or multiple-depth completions may be an option. Solar panels or passive heated air injection may also enhance subsurface volatilization, particularly in the winter months. Additional valves may be placed on individual reactor lines or on the individual wells for better control of air flow and pressure. The SVVS® design allows positive and negative air flow to be shifted to different locations within the treatment plot in order to concentrate remedial stress on those areas requiring it.

The SVVS® at the Electro-Voice site is comprised of three separately-valved reactor lines. Figure 3 presents a schematic diagram of the SVVS® configuration at the Electro-Voice facility. The Electro-Voice design consists of 11 vacuum extraction wells and nine air injection wells, each separately valved for optimum system flexibility and air flow control. The air injection wells are installed into the water table with a 1 foot screened interval positioned approximately 10 feet beneath the water table in the dry well area (water table in the dry well area is approximately 50 feet below grade). The extraction wells were installed such that a 5-foot section of screen is set to intersect the "sludge layer." The extraction wells were also installed with a 5-foot blank with a drain port attached to the bottom of the screen to control condensation. A number of sand chimneys were installed to better facilitate vertical air circulation throughout the plot. The injection and vacuum air supply lines of each reactor line are manifolded to a single injection and vacuum line inside the VCU Building. The pumps used during the SITE demonstration are BAI V5, capable of 85 cubic feet per minute (cfm) reverse pressure air flow, and BAI A5, capable of delivering 120 cfm air flow. Typically, the positive (injection) pressure pump flow rate is maintained at approximately 80 percent of the vacuum pump flow rate. In addition to the various technology control systems, the VCU contained the Biological Emission Control (BEC)® units to further reduce levels of VOCs in the extracted air stream prior to release to the atmosphere.

The soil vapor extraction element of the process operates by pumping clean air into the injection wells to percolate upward through the saturated and unsaturated zone, making contact with volatile organic contaminants. The continuous circulation of clean air encourages the mass transfer of bulk liquid, dissolved, and sorbed phase contamination to the vapor phase. Vacuum extraction wells installed in the vadose zone (1) pull the percolated air through the soil under vacuum, further enhancing the mass transfer or stripping of contaminants and (2) control the migration of contaminated vapors.

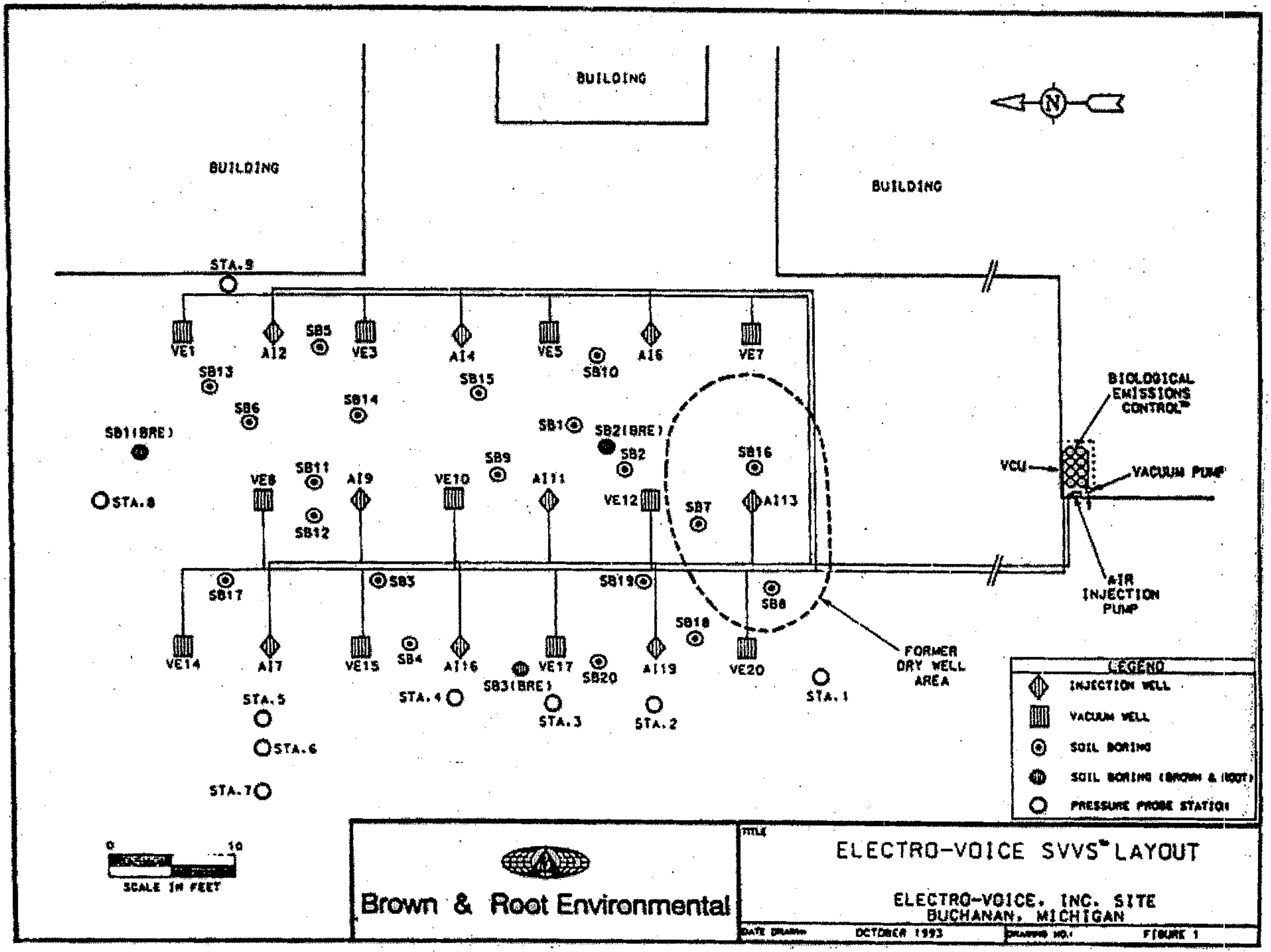


FIGURE 3
CONFIGURATION OF THE SVVS® AT THE ELECTRO-VOICE SITE

The increased circulation of air (specifically oxygen) in the groundwater and soil also stimulates and accelerates natural biodegradation. A steady supply of oxygen allows those microbes that respire aerobically to utilize the organic contaminants as a food source, thus converting these organic substrates to cell material and energy for metabolic processes. By-products of these metabolic reactions are carbon dioxide and water. As long as oxygen is supplied and a food source remains, the microbial populations proliferate and biodegradation rates increase.

During the early stages of an SVVS® operation, the overall rate of contaminant transfer to the vapor phase may exceed the biodegradation rates. This phase, according to the developer, may last anywhere from 2 weeks to a few months. The extracted vapors may need to be treated above ground before being released to the atmosphere. The amount of treatment will decrease steadily over this period until biodegradation rates surpass the net transfer rate of contaminant mass into the circulating air. When this point is reached, the vapor extraction off-gas will consist predominantly of carbon dioxide and water, and treatment of the exhausted air stream should no longer be necessary.

4.1.2.2 Demonstration Objectives and Approach

There was one primary objective and eight secondary objectives in evaluating the SVVS® technology.

Primary Objective:

- Evaluate the developer's claim of a 30 percent reduction in the sum of the concentrations of seven VOCs (benzene, toluene, ethylbenzene, xylenes, tetrachloroethene, trichloroethene, and 1,1-dechlorethene) in vadose zone soils over a 12-month period of operation

Secondary Objectives:

- Monitor the reduction of VOCs in the saturated soil and groundwater within the treatment plot
- Monitor the impact of the technology on groundwater outside the immediate treatment area
- Qualitatively determine the magnitude of contaminant reduction due to vapor extraction versus in-situ biodegradation by performing a baseline soil gas test and three shut-down soil gas monitoring tests
- Determine the magnitude of reduction of individual contaminants within vadose zone soils of the dry well area

- Monitor general soil conditions that might inhibit or promote the systems effectiveness
- Monitor the effectiveness of the biofilter in reducing VOC contamination in the extracted air stream
- Monitor the extracted air stream to qualitatively assess biodegradation in the treatment plot over the course of the demonstration
- Develop an estimate of operating costs for remediating VOC contamination

Data to assess the demonstration objectives were collected over a 1-year period. Pre- and post-treatment samples as well as periodic groundwater samples were collected. QA/QC procedures were followed as specified in the approved QAPP.

4.1.2.3 Results and Conclusions

The SVVS® achieved an overall 80.6 percent reduction of the seven critical VOCs in the vadose zone after 1 year of system operation. This level of reduction greatly exceeded the developer's claim, which promised a 30 percent reduction over a 1-year timeframe. The average concentrations of the sum of the seven critical analytes (benzene, toluene, ethylbenzene, xylenes, trichloroethene, tetrachloroethene, and 1, 1-dichloroethene) in the study area before and after 1 year of operation were 341.5 mg/kg and 66.2 mg/kg, respectively. Reductions for each subsurface horizon revealed an 81.5 percent reduction for the "sludge layer," the most contaminated horizon throughout the treatment plot, and 97.8 to 99.8 percent for all other vadose zone horizons. When evaluating system performance by comparing VOC concentrations in paired boreholes before and after 1 year of treatment, contaminant reductions ranged from 71 to 99 percent. This indicated that the system operated relatively uniformly over the entire vadose zone of the treatment plot, and no significant untreated areas were encountered, regardless of initial VOC concentration or lithology.

The studies conducted by the SITE program also suggest the following conclusions regarding the technology's performance at the Electro-Voice site. These conclusions were based upon secondary project objectives and are presented as follows:

- An analysis of individual VOC contaminants in the vadose zone before and after treatment revealed reductions that ranged from 78 to 92 percent. Xylenes, the most prevalent contaminant, (comprising 60 percent) of the VOCs in the treatment plot, were reduced by 78 percent, whereas tetrachloroethene, which represented 1.6 percent of the total VOC concentration in the vadose zone, exhibited a 92 percent reduction. The relative distribution of individual compounds in vadose zone soils was similar before and after treatment, suggesting that the technology at this site did not appear to selectively remove or destroy one component over another.

- The technology was evaluated for its ability to reduce VOC contamination in groundwater within the treatment plot. The lack of detectable levels of contamination in the groundwater during system operation precluded any meaningful evaluation of the systems performance on groundwater within the physical boundaries of the treatment plot.

- A comparison of VOC contamination before and after 1 year of treatment revealed a 99.3 percent reduction in saturated zone soils. Although no claims were made regarding expected percent reductions in the saturated zone, the reduction achieved was comparable to those observed in the vadose zone horizons.

- Soil sampling conducted during pre-treatment and post-treatment events did not reveal any compounds present at concentrations that might inhibit biodegradation (i.e., heavy metals). In addition, general soil analyses revealed that there were sufficient quantities of soil nutrients available to biodegrade the entire mass of contamination in the vadose zone of the treatment plot.

- Bimonthly monitoring of the extracted air stream indicated that mass removal rates of VOCs were highest at the beginning of the treatment when soil VOC concentrations were elevated and transfer to the vapor phase occurred easily. As the concentration in the soil decreased, mass removal rates also decreased and stabilized in spite of elevated flow rates. Vapor flow rates observed during the demonstration fell within the range of conventional SVE systems that rely solely on vapor extraction as the primary mechanism for contaminant removal. The SVVS® also exhibited the same pattern observed in conventional SVE systems, which is characterized by high removal rates during the initial operation of the unit followed by an asymptotic decrease in removal rates over time.

- The results of three system shut-down tests indicate that biodegradation was occurring across the treatment plot, especially along the southern portion of the treatment plot where the highest levels of soil contamination were measured. The correlation between high biological activity and contaminant occurrence suggests that the technology was able to stimulate biodegradation of contaminants. The results of three shut-down tests suggest a progressive decrease in biological activity over time. The decrease in the rate of biodegradation, however, was significantly less than the rate of decrease of vapor phase contaminants in the vacuum extraction line. This observation would support the developer's claim that biological processes play an increasingly important role, relative to vapor extraction, as the remediation proceeds.

- The performance of the BEC® system could not be evaluated since it was taken off-line a few months into the demonstration when the exhaust off-gasses met the discharge criteria for the site.

- The system was initially installed and operated in a large portion of the site not impacted by dry well contamination. Subsequent to this discovery, the system operation was shifted to that portion of the treatment plot containing subsurface contamination. The fact that a major portion of the system was installed over an uncontaminated area did not affect overall system performance; however, it did have some impact on cost.

- The cost for a full-scale remediation of soils at the Electro-Voice site, assuming that the total volume of contaminated soil to be remediated is 21,300 cubic yards (yd^3), was estimated at \$221,000 or \$10.40/yd^3 . The largest cost component of the technology appears to be site preparation (28 percent), followed by analytical services (27 percent) and residuals/waste shipping, handling, and storage (13 percent).

4.1.2.4 Vendor Contacts

Steve Thompson
Project Manager
Brown & Root Environmental
4641 Willoughby Road
Holt, Michigan 48842
(517) 694-6200

Jeff Billings
President
Billings and Associates, Inc.
3816 Academy Parkway, N-NE
Albuquerque, New Mexico 87109
(505) 345-1116

4.1.3 perox-pure™ Chemical Oxidation Technology

The perox-pure™ chemical oxidation technology, developed by Peroxidation Systems, Inc. (PSI), was evaluated at Lawrence Livermore National Laboratory Site 300 in Tracy, California, over a 3-week period in September 1992 (EPA 1993). The perox-pure™ chemical oxidation technology is designed to destroy dissolved organic contaminants in water. The technology uses UV radiation and hydrogen peroxide to oxidize organic compounds present in water at parts per million (ppm) levels or less. This treatment technology produces no air emissions and generates no sludge or spent media that require further processing, handling, or disposal. Ideally, end products are water, carbon dioxide, halides (for example, chloride), and in some cases, organic acids.

4.1.3.1 Process Description

The perox-pure™ chemical oxidation treatment system was developed by PSI to destroy dissolved organic contaminants in water. Using UV radiation and hydrogen peroxide to oxidize organic compounds. In broad terms, oxidation is a chemical change in which electrons are lost by an atom or a group of atoms. Oxidation of an atom or group of atoms is always accompanied by the reduction of another atom or group of atoms. Reduction is a chemical change in which electrons are gained by an atom or group of atoms. An atom or group of atoms that has lost electrons has been oxidized, and an atom or group of atoms that has gained electrons has been reduced. Oxidation and reduction always occur simultaneously, and the total number of electrons lost in the oxidation must equal the number of electrons gained in the reduction. In the perox-pure™ technology, organic contaminants in water are oxidized by hydroxyl radicals, a powerful oxidant produced by UV radiation and hydrogen peroxide. Subsequently, the organic contaminants are broken down into carbon dioxide, water, halides, and in some cases, organic acids.

A variety of organic contaminants can be effectively oxidized by combining (1) UV radiation and hydrogen peroxide, (2) UV radiation and ozone, or (3) ozone and hydrogen peroxide. The principal oxidants in the perox-pure™ system, hydroxyl radicals, are produced by direct UV photolysis of the hydrogen peroxide added to contaminated water. The perox-pure™ system generates UV radiation by using medium-pressure, mercury-vapor lamps.

In principle, the most direct way to generate hydroxyl radicals (OH•) is to cleave hydrogen peroxide (H_20_2) through photolysis. The photolysis of hydrogen peroxide occurs when UV radiation (hν) is applied, as shown in the following reaction:

$$H_20_2 + h\nu \rightarrow 2\ OH\bullet$$

Thus, photolysis of hydrogen peroxide results in a quantum yield of two hydroxyl radicals (OH•) formed per quantum of radiation absorbed. This ratio of hydroxyl radicals generated from the photolysis of hydrogen peroxide is high. Unfortunately, at 253.7 nanometers (nm), the dominant emission wavelength of low-pressure mercury-vapor lamps, the absorptivity (or molar extinction coefficient) of hydrogen peroxide is only 19.6 liters per mole-centimeter. This absorptivity is relatively low for a primary absorber in a photochemical process. Because of the low absorptivity value for hydrogen peroxide, a high concentration of residual hydrogen peroxide must be present in the treatment medium to generate a sufficient concentration of hydroxyl radicals. According to PSI, the perox-pure™ system overcomes this limitation by using medium-pressure UV lamps.

The hydroxyl radicals formed by photolysis react rapidly with organic compounds, with rate constants on the order of 10^8 to 10^{10} liters per mole-second; they also have a relatively low selectivity in their reactions. However, naturally occurring water components, such as carbonate ion, bicarbonate ion, and some oxidizable species, act as free radical scavengers that consume hydroxyl radicals. Free radical scavengers are compounds that consume any species possessing at least one unpaired electron. In addition, excess hydrogen peroxide can itself act as a free radical scavenger, decreasing the hydroxyl radical concentration. Reactions with hydroxyl radicals are not the only removal pathway possible in the perox-pure™ system; direct photolysis by UV radiation of organic compounds also provides a removal pathway for contaminants. With these factors affecting the reaction, the proportion of oxidants required for optimum removal is difficult to predetermine. Instead, the proportion for optimum removal must be determined experimentally for each waste.

The principal operating parameters for the perox-pure™ technology are hydrogen peroxide dose, influent pH, and flow rate (which determines hydraulic retention time). Typically, during treatability studies, initial target values for these parameters are selected based on (1) the technology developer's experience and (2) the anticipated effects of the operating parameters on the treatment system's performance. These operating parameters are discussed briefly below.

Hydrogen peroxide dose is selected based on treatment unit configuration, contaminated water chemistry, and contaminant oxidation rates. Because hydrogen peroxide is a hydroxyl radical scavenger, excess hydrogen peroxide can result in a net decrease in treatment efficiency. However, if the hydrogen peroxide dose is low, hydroxyl radical formation will also be low, decreasing treatment efficiency. Therefore, a balance must be maintained between excess and low levels of hydrogen peroxide.

Influent pH level controls the carbonate chemistry, which can affect treatment efficiency. Because carbonate and bicarbonate ions will scavenge hydroxyl radicals, groundwater pH may need to be adjusted before treatment to shift the carbonate equilibrium to carbonic acid, which is not a scavenger.

Flow rate through the treatment system will determine hydraulic retention time. Increasing or decreasing the flow rate will affect treatment efficiency by changing the time available for hydroxyl radical formation and contaminant destruction.

4.1.3.2 Demonstration Objectives and Approach

There were three primary objectives and one secondary objective in evaluating the perox-pure™ chemical oxidation technology.

Primary Objectives:

- Assess the technology's ability to destroy VOCs from groundwater at the demonstration site under different operating conditions
- Determine whether the treated water meets applicable disposal requirements at the 95 percent confidence level
- Obtain information required to estimate the operating costs for the treatment system, such as electrical power consumption and chemical doses

Secondary Objective:

- Obtain preliminary information on the presence and types of by-products formed during treatment

The demonstration was conducted in three phases. Phase 1 consisted of eight test runs using raw groundwater; Phase 2 consisted of four runs using groundwater spiked with 1,1-dichloroethane (DCA), 1,1,1-trichloroethane (TCA), and chloroform; and Phase 3 consisted of two runs using spiked groundwater to evaluate the effectiveness of quartz tube cleaning.

4.1.3.3 Results and Conclusions

Key findings of the demonstration are as follows:

- For the spiked groundwater, PSI determined the following preferred operating conditions: (1) influent hydrogen peroxide level of 40 mg/L, (2) hydrogen peroxide level of 25 mg/L in the influent to reactors 2 through 6, (3) an influent pH of 5.0, and a flow rate of 10 gallons per minute. At these conditions, the effluent trichloroethene (TCE), tetrachlorethene (PCE), and DCA levels were generally below the detection limit (5 micrograms per liter [µg/L]) and effluent chloroform and TCA levels ranged from 15 to 30 µg/L. The average overall removal efficiencies for TCE, PCE, chloroform, DCA, and TCA were 99.7, 97.1, 93.1, 98.3, and 81.8 percent, respectively.
- For the unspiked groundwater, the effluent TCE and PCE levels were generally below the detection limit (1 µg/L), with corresponding removal efficiencies of 99.9 and 99.7 percent. The effluent TCA levels ranged from 1.4 to 6.7 µg/L, with removal efficiencies ranging from 35 to 84 percent.
- The perox-pure™ system effluent met California drinking water action levels and federal drinking water maximum contaminant levels for TCE, PCE, chloroform, DCA, and TCA at the 95 percent confidence level.

- The quartz tube wipers were effective in keeping the tubes clean and appeared to reduce the effect scaling has on contaminant removal efficiencies.

- Total organic halides (TOX) removal efficiencies ranged from 93 to 99 percent. Adsorbable organic halides (AOX), A German technology evaluation parameter, removal efficiencies ranged from 95 to 99 percent.

- Analysis of influent and effluent samples for VOCs indicated that no new target VOCs or tentatively identified compounds were formed during treatment.

Using information obtained from the SITE demonstration, an economic analysis was performed to examine costs for treating 260 million gallons of contaminated groundwater. This analysis examined two cases based on groundwater characteristics. In Case 1, the groundwater was assumed to have five contaminants, two of which are easy to oxidize (TCE and PCE) and the remaining three are difficult to oxidize (chloroform, DCA, and TCA). In Case 2, the groundwater was assumed to have only two contaminants that are easy to oxidize (TCE and PCE). For each case, costs for a 50 gallon per minute flow rate scenario are summarized below.

Case 1 (5 contaminants)

- Capital costs are estimated to be approximately $906,000, of which the perox-pure™ system direct capital cost is $185,000

- Annual operation and maintenance costs are estimated to be about $188,000, of which the perox-pure™ system direct O&M costs are $125,000

- Groundwater remediation costs are estimated to be $11 per 1,000 gallons of contaminated water, of which perox-pure™ system direct treatment costs are $5

Case 2 (TCE and PCE only)

- Capital costs are estimated to be about $776,000, of which the perox-pure™ system direct capital cost is $55,000

- Annual O&M costs are estimated to be about $111,000, of which perox-pure™ system direct O&M costs are $61,000

- Groundwater remediation costs are estimated to be $7 per 1,000 gallons, of which perox-pure™ system direct treatment costs are $3

4.1.3.4 Vendor Contact

Chris Giggy

Process Engineering Manager
Peroxidation Systems, Inc.
5151 East Broadway, Suite 600
Tucson, Arizona 85711
(602) 790-8383

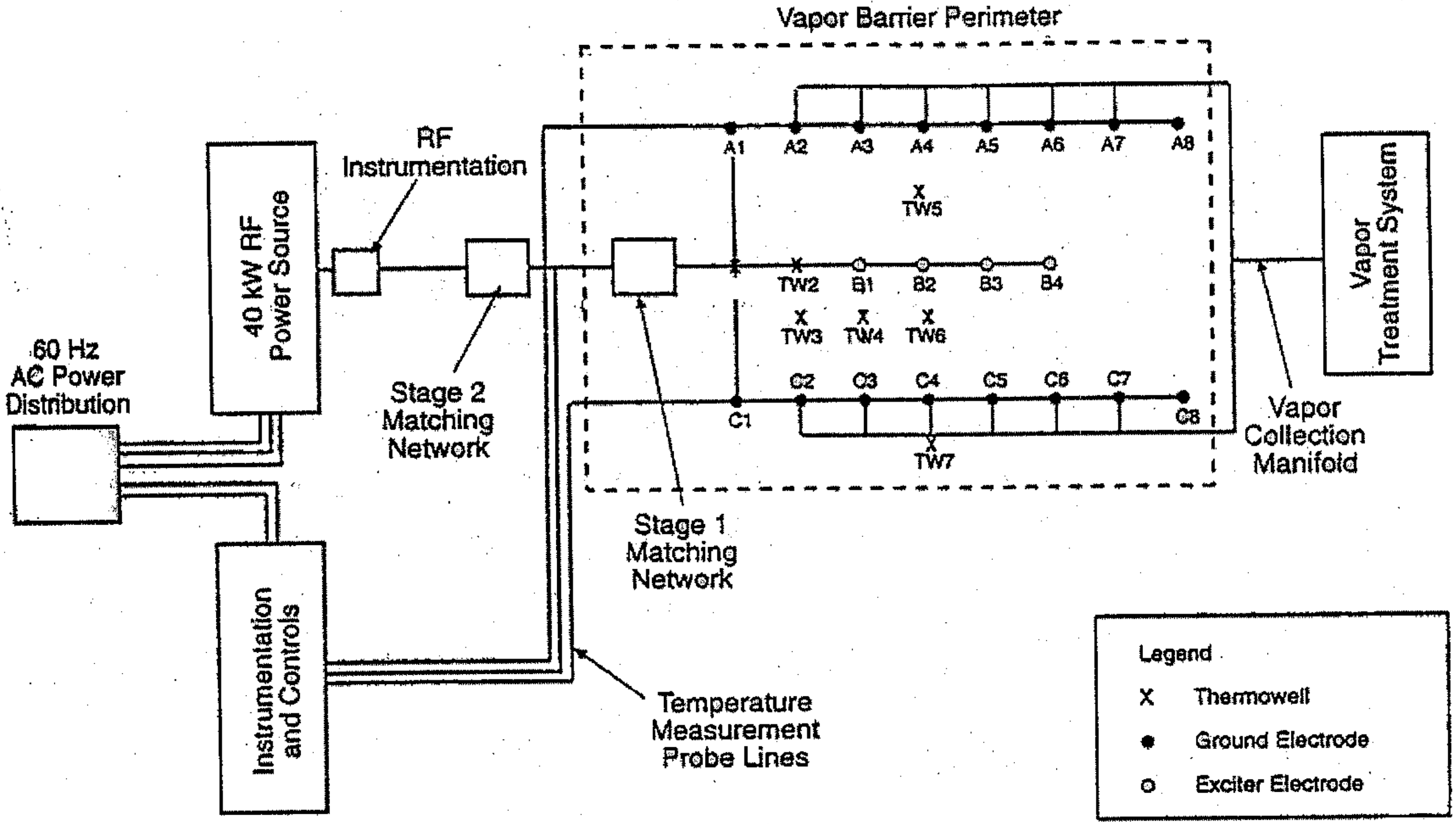
4.1.4 IIT Research Institute Radio Frequency Heating

A demonstration of IIT Research Institute's (IITRI) in situ Radio Frequency Heating (RFH) system was conducted from January 1993 to August 1993 at Site S-1 at Kelly Air Force Base in San Antonio, Texas (EPA 1995a). IITRI's RFH system applies radio frequency (RF) energy to soil through exciter electrodes, thereby heating the soil along with water and contaminants contained within the soil. The IITRI RFH technology has two primary functions: (1) to heat the soil by transmitting RF energy into it and (2) to collect vapors from the volatilized contaminants in the heated soil.

4.1.4.1 Process Description

IITRI claims that the RFH technology remediates contaminated soil in situ by heating the soil and volatilizing the contaminants, thus potentially enhancing the performance of standard SVE technologies. Moisture present in the soil is also volatilized and may provide a steam sweep within the treatment zone, thus further enhancing the removal of organic contaminants. Steam and contaminant vapors are collected by vapor extraction wells and channeled to the vapor treatment system. The vapor treatment system is site- and contaminant-specific, and therefore, is not included in this evaluation. A basic schematic for the IITRI RFH system used during the SITE demonstration is shown in Figure 4.

The RFH technology is potentially capable of remediating unsaturated soils contaminated with VOCs and SVOCs. RFH is believed to be best suited to remediating soils containing a high fraction of sand and other coarse materials. In soils containing a high fraction of silt or clay, contaminants tend to be strongly sorbed to the soil particles. Therefore, removing the contaminants may become much more difficult since these soils often have insufficient air permeability for adequate removal of vaporized contaminants. The developer claims that the technology is applicable to clayey soils because the permeability of such soils will increase as they dry; this claim needs to be substantiated by conducting further tests with the technology.



Not to Scale

FIGURE 4
BASIC SCHEMATIC OF THE IITRI RFH SYSTEM

The primary components of IITRI's RFH system include:

- RF -generator - The RF generator converts alternating current (AC) electricity to the desired frequency radio wave. The 40-kilowatt (kW) generator used during the SITE demonstration can provide a continuous RF wave at a frequency of 6.78 megahertz (MHz). Operating on a frequency band allocated for industrial, scientific, and medical (ISM) equipment minimizes Federal Communications Commission (FCC) operating requirements. The frequencies allocated for ISM equipment are 6.78 MHz, 13.56 MHz, 27.12 MHz, 40.68 MHz, and seven higher frequencies.

- Matching network - RF energy from the generator flows to the matching network, which is used to adjust the electrical characteristics of the RF energy being transmitted into the soil. Continuous monitoring and adjustment are required because the dielectric characteristics of the soil change as it is heated. The matching network allows the RFH system to compensate for these changes. Proper operation of the matching network maximizes the fraction of the power from the RF generator that is absorbed by the soil. This is important for two reasons. First, the higher the fraction of power absorbed by the soil, the more energy-efficient the system. Second, power that is not absorbed by the soil is reflected back to the generator and other electrical components. Excessive reflected power will cause the electrical components to overheat.

- Exciter electrodes - Energy from the RF generator flows through the matching network and coaxial cables and onto the exciter electrodes, which convey the energy into the soil. The exciter electrodes extend vertically from just above the ground surface to near the bottom of the treatment zone. The exciter electrodes used during the SITE demonstration were fabricated from 2.5-inch (0.064 meters) and 4-inch (0. 10 meters) copper pipe and were installed in 10-inch (0.25 meters) boreholes to a depth of 19.5 feet (5.94 meters) below the surface. The boreholes were backfilled around the electrodes using a material similar to the surrounding soil. The revised design treatment zone contained one row of four exciter electrodes spaced 2.5 feet (0.76 meters) apart .

- Ground electrodes - Two rows of eight ground electrodes each were installed parallel to and on either side of the exciter electrode row. The ground electrodes were fabricated from 2-inch (0.05-meter) diameter aluminum pipe and were 29 feet (8.8 meters) in length. The electrode configuration was designed to direct the flow of RF energy through the soil and contain the energy within the treatment zone. The outer casing of the ground electrodes was perforated on the side facing the treatment zone to permit the collection of vapors from the soil. They were perforated in a uniform pattern over the full length of the electrode with the exception of the four corner electrodes, which were not perforated. Each perforated ground electrode was connected to a manifold, which led to the vapor treatment system. Two additional perforated vapor extraction pipes were installed parallel to the ground surface to prevent vapors from building up below the vapor barrier.

- Thermowells - Thermowells are Teflon® tubes sealed at the bottom with approximately 1 to 2 inches (0.03 to 0.05 meters) of silicon oil in their bottoms. Each thermowell was designed to hold either six thermocouples or one fiber optic probe. The SITE demonstration used seven thermowells.

- Fiber optic probes - Fiber optic probes were inserted into those thermowells that were between the two ground electrode rows (Thermowells 1 through 6). The probes went all the way to the bottoms of the thermowells and contained four tips each to take four temperature readings. Readings were taken every 24 hours and could be taken with the RF power on. Toward the end of the project, the excessive heat caused several tips of the fiber optic probes to break off; all were replaced with thermocouples.

- Thermocouples - The temperature of the soil is monitored by thermocouples positioned throughout the treatment zone. During the SITE demonstration, the thermocouples were placed in the thermowells and on the inner walls of the ground or exciter electrodes. Thermocouples were located at depths of 1, 12, 24, and 29 feet (0.3, 3.7, 7.3, and 8.8 m) on the inner walls of the ground electrodes. On the exciter electrodes, thermocouples were located at depths of 1, 10, and 19 feet (0.3, 3.0, and 5.8 m). Thermocouples were also located at depths of 1, 12, 24, 29, 31, and 34 feet (0.3, 3.7, 7.3, 8.8, 9.4, and 10 m) in Thermowell 7 at the start of the demonstration. Due to the malfunction of the fiber optic probes previously explained, thermocouples were used in Thermowells 1 through 6 at the end of the demonstration.

- Aboveground vapor collection pipes - These perforated pipes collect any vapors that rise to the surface of the treatment zone.

- Vapor collection manifold - The ground electrodes and the aboveground vapor collection pipes feed the manifold, which gathers the vapors together and channels them into the vapor treatment system.

- Blower - The blower provides a vacuum throughout the treatment zone by pulling the contaminated air stream through the vapor collection manifold and vapor collection pipes.

- Vapor barrier - The vapor barrier is fabricated from three layers of material: a fiberglass-reinforced silicone sheet; a 3-inch (0.08-m) thick layer of fiberglass insulation; and a polyethylene (or other plastic) sheet. The heat-resistant silicone sheet is the layer nearest to the ground surface. This layer prevents the release of volatilized contaminants, helps maintain a vacuum in the treatment zone, and protects one side of the insulation. The layer of insulation reduces heat loss from the treatment zone. The top sheet of plastic protects the other side of the insulation and keeps air out of the treatment zone.

- RF shield - A corrugated aluminum arch with flat aluminum covers the same area as the vapor barrier and serves as an RF shield. The arch is designed to limit the amount of RF energy that escapes the system. An airtight weather cover protects the RF shield.

- Extended ground plane - An extended ground plane made of wire cloth connects the RF shield to the ground electrodes. The extended ground plane helps contain the RF energy within the treatment zone.

- Expanded metal shield - An expanded metal shield lies on top of the vapor barrier and extends 10 feet (3.0 m) beyond each side of the treatment zone. The expanded metal shield helps contain the RF energy within the treatment zone, minimizes or prevents interference from radio broadcasts, and provides a safe working environment for the workers.

Although not a component of IITRI's RFH technology, the vapor treatment system is crucial to the overall process. During the SITE demonstration, vapors that condensed in the vapor collection system piping were collected as liquids. The uncondensed portion of the vapor stream was incinerated in a propane-fueled flare. Other sites may require more complex vapor treatment systems.

4.1.4.2 Demonstration Objectives and Approach

The main objective of the demonstration test is to show that the in situ contaminant removal process can achieve the developer's goals in the field. The developer claimed that at a soil temperature of 150 °C, the radio frequency heating technology can remove 90 percent of the petroleum hydrocarbons and 95 percent of the VOCs. The removal efficiency will be determined by comparing the analyses of soil samples taken before and after the test.

Based on these goals and the contaminant concentrations present at the site, there were three primary objectives and two secondary objectives in evaluating the IITRI RFH technology.

Primary Objectives:

- Determine whether the technology removes more than 90 percent of the petroleum hydrocarbons
- Determine whether the technology obtains a greater than 90 percent removal efficiency from the soil for the following six critical SVOCs – 2-methyinaphthalene, naphthalene, 2,4,6-trichlorophenol, and 2-methylphenol
- Determine whether the technology obtains a greater than 95 percent removal efficiency from the soil for the following four critical volatile organic compounds – benzene, toluene, ethylbenzene, and chlorobenzene

Secondary Objectives:

- Measure the degree of removal of other contaminants feasible under the conditions of the test
- Determine the outward lateral migration, if any, of contaminants into a zone outside of the treatment area

Pre- and post-treatment samples were collected so assess the objectives. QA/QC procedures were followed as specified in the approved QAPP.

4.1.4.3 Results and Conclusions

The following results were observed for total recoverable petroleum hydrocarbons (TRPH) and SVOCs within the revised design treatment zone:

- There was a statistically significant decrease in TRPH concentration at the 95 percent confidence level; the estimated decrease in the mean concentration was 60 percent.
- None of the five critical SVOCs achieved a statistically significant change during the preliminary evaluation and, therefore, were not evaluated for the smaller revised design treatment zone.
- Pyrene and bis(2-ethylhexyl)phthalate were the only noncritical SVOCs that exhibited changes in the preliminary and final statistical evaluations. They exhibited a change in concentration at the 97.5 percent confidence level; estimated decreases in the mean concentrations were 87 and 48 percent, respectively.

The decreases in TRPH and SVOCs were likely due to some combination of the RF energy and SVE applied to the soil. RFH increased the temperature of the soil, along with water and contaminants contained within the soil, thereby volatilizing (to varying degrees) SVOCs and certain components of TRPH. SVE, which was used to remove the volatilized contaminants, also enhances vaporization. Decreases in TRPH and SVOC may also have been caused by the degradation of these compounds from soil temperatures reaching greater than 1,300 °C (2,372 °F) near the exciter electrodes. Decreases from migration outside the treatment zone are unlikely, since the configuration of the SVE system limits this type of migration.

For the VOCs within the revised design treatment zone, the following results were observed:

- Chlorobenzene was the only critical VOC that achieved a statistically significant concentration change in the preliminary statistical evaluation; it did not achieve a statistically significant change in the final statistical evaluation. No plausible theories have been developed to explain the fact that chlorobenzene did not exhibit a statistically significant decrease in the revised design treatment zone.
- There were statistically significant increases in the concentrations of four noncritical VOCs (all ketones) at the 99 percent confidence level; estimated increases in the mean concentrations were 457 percent for 2-hexanone; 263 percent for 4-methyl-2-pentanone 1,073 percent for acetone, and 683 percent for methyl ethyl ketone.

The ketones may have been formed by the degradation and subsequent oxidation of TRPH near the exciter electrodes, where soil temperatures were highest. A possible degradation pathway may be the pyrolytic conversion of TRPH to unsaturated hydrocarbons. In the presence of a catalyst (e.g., silica in the soil), the RF energy may convert these hydrocarbons into ketones. Alternatively, the increase in ketones may also have been caused by inward migration from sources such as groundwater and the soil beyond the sampled area. There are insufficient data to confirm or disprove either of these hypotheses.

Outside the revised design treatment zone, only TRPH showed a statistically significant change at the 95 percent confidence level, with an estimated 88 percent mean concentration increase. Because the SVE system created a vacuum in the treatment area, the TRPH increase may have been caused by inward migration; it is not likely to be due to outward migration.

The following results were observed within the heated zone:

- There was a statistically significant decrease in TRPH concentration at the 97.5 percent confidence level; the estimated decrease in the mean concentration was 95 percent.
- None of the critical or noncritical SVOCs exhibited a statistically significant change in the final evaluation.
- None of the critical or noncritical VOCs exhibited a statistically significant change in the preliminary or final evaluations.

The TRPH decrease may be caused from the SVE system pulling the volatilized contaminants out of the heated zone into vacuum wells. As in the revised design treatment zone, this decrease may also have been caused by the degradation of these compounds from the elevated temperatures of the RFH system.

Outside of the heated zone, there was a statistically significant decrease in the concentration of bis(2-ethylhexyl) phthalate at the 90 percent confidence level; the estimated decrease in the mean concentration was 37 percent. This decrease may also have resulted from the same combination of contaminants being volatilized and collected by the SVE system. There were also statistically significant increases at the 99 percent confidence level in the concentrations of four noncritical VOCs (all ketones) outside the heated zone. The estimated mean increases for these four ketones were 423 percent for 2-hexanone; 249 percent for 4-methyl-2-pentanone; 1,347 percent for acetone; and 1,049 percent for methyl ethyl ketone. As previously discussed, these ketones (1) may have been formed by the degradation and subsequent oxidation of TRPH or (2) may have migrated inward from the groundwater or surrounding soil.

4.1.4.4 Vendor Contacts

Harsh Dev
IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616
(312) 567-4257

4.2 RESULTS OF PHASE I GERMAN DEMONSTRATION ACTIVITIES

Six technologies were demonstrated and evaluated in Germany. as part of Phase I of the Bilateral Agreement (see Figure 5). This report describes the technology process; summarizes the demonstration objectives, results, and conclusion; and provides vendor contact information for each technology. The following German technologies were evaluated as part of Phase I:

- NORDAC Soil Washing
- Entsorgungsbetriebe Duisburg/ZÜBLIN Catalytic Oxidation
- RUT TERRA • POR Low Temperature Thermal Desorption
- Hochtief Thermal Desorption
- Harbauer Vacuum Distillation
- Umweltchutz-Nord TERRANOX

4.2.1 NORDAC Soil Washing

The NORDAC soil washing technology was developed by Norddeutsches Altlasten-Sanierungs-Centrum GmbH & Co. KG (NORDAC), Hamburg, Germany. The NORDAC system is a full-scale commercial treatment technology developed to remove contaminants, including VOCs, from soil and to reduce the volume of soil requiring additional treatment in order to meet applicable cleanup requirements. Through a multi-step treatment approach, the system washes VOCs from soil and separates out fine-grained soil from coarser-grained soil. The NORDAC technology was demonstrated on May 20 and 21, 1996, at the

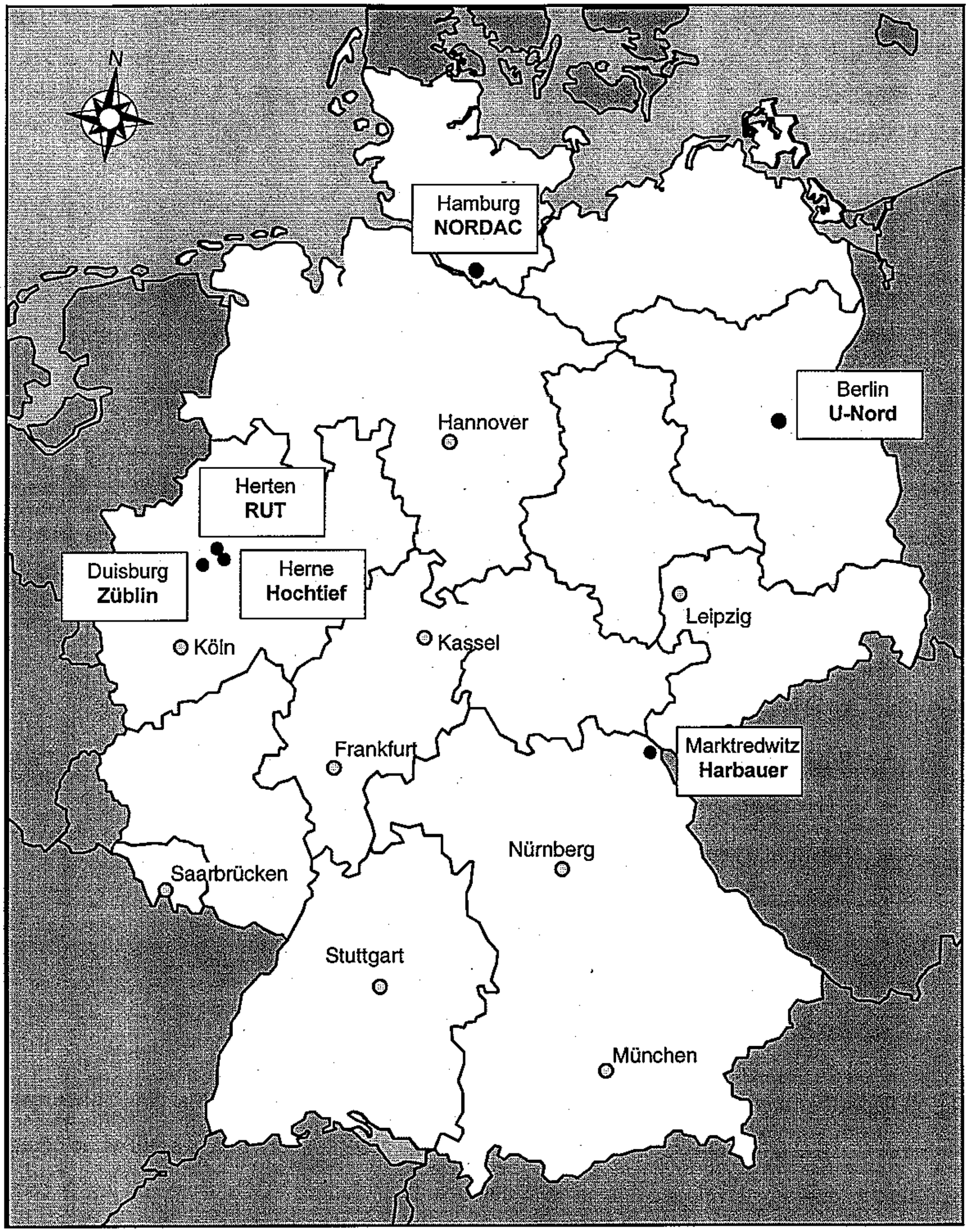


FIGURE 5

MAP OF PHASE I DEMONSTRATION SITES - GERMANY

NORDAC facility in Hamburg, Germany (PRC 1998). Soil contaminated with VOCs, specifically benzene, toluene, ethylbenzene, and xylene (BTEX), was used for the demonstration.

4.2.1.1 Process Description

The NORDAC system is a full-scale commercial treatment technology that incorporates the multi-step treatment approach illustrated in Figure 6. The NORDAC soil washing system is operated to wash contaminants from soil and to separate out fine-grained soil from coarser-grained soil (diameter greater than 25 µm). The fine-grained soil, which has a higher surface area-to-volume ratio and a correspondingly higher concentration of contaminants, is recovered and subsequently incinerated in a fluidized bed combustor, treated in a bioremediation system, or landfilled, depending on contaminant levels. Contaminant levels in the coarser-grained soils should be sufficiently reduced using the soil washing system, to allow the soil to be used in the asphalt-concrete mixture for road construction. In addition to the fine-grained soil stream, the NORDAC soil washing system generates process wastewater, air emissions, and lightweight solid residuals that are treated or disposed of by conventional methods.

The NORDAC soil washing system is fully automated and has the capacity to process 320 metric tons (mt) of soil per day, according to the developer. Before initiating the soil washing process, soils are crushed and mixed with water to form a slurry. The feed soil is initially separated by size, and materials with a diameter greater than 50 millimeters (mm) are mechanically crushed. The soil is then transported to a homogenization unit, where it is mixed with recycled process water using a plough blade mixer to create a pumpable slurry.

The slurry is transported to a water jet and baffle chamber, where it undergoes high pressure spraying with recycled process water. In the water jet and baffle chamber, the slurry passes through a series of high pressure water jets that blast the slurry into a steel wall. This impact breaks up the soil particles and exposes contaminants adhered to the soil. The water jets are configured in a circular array, producing a cone-shaped spray. The soil particles are drawn through the focal point of the water jet, which removes contaminants adhering to the soil particles. Additionally, the water jet produces a partial vacuum that draws in a large volume of air. The resulting stripping effect releases volatile compounds from the soil into the process air.

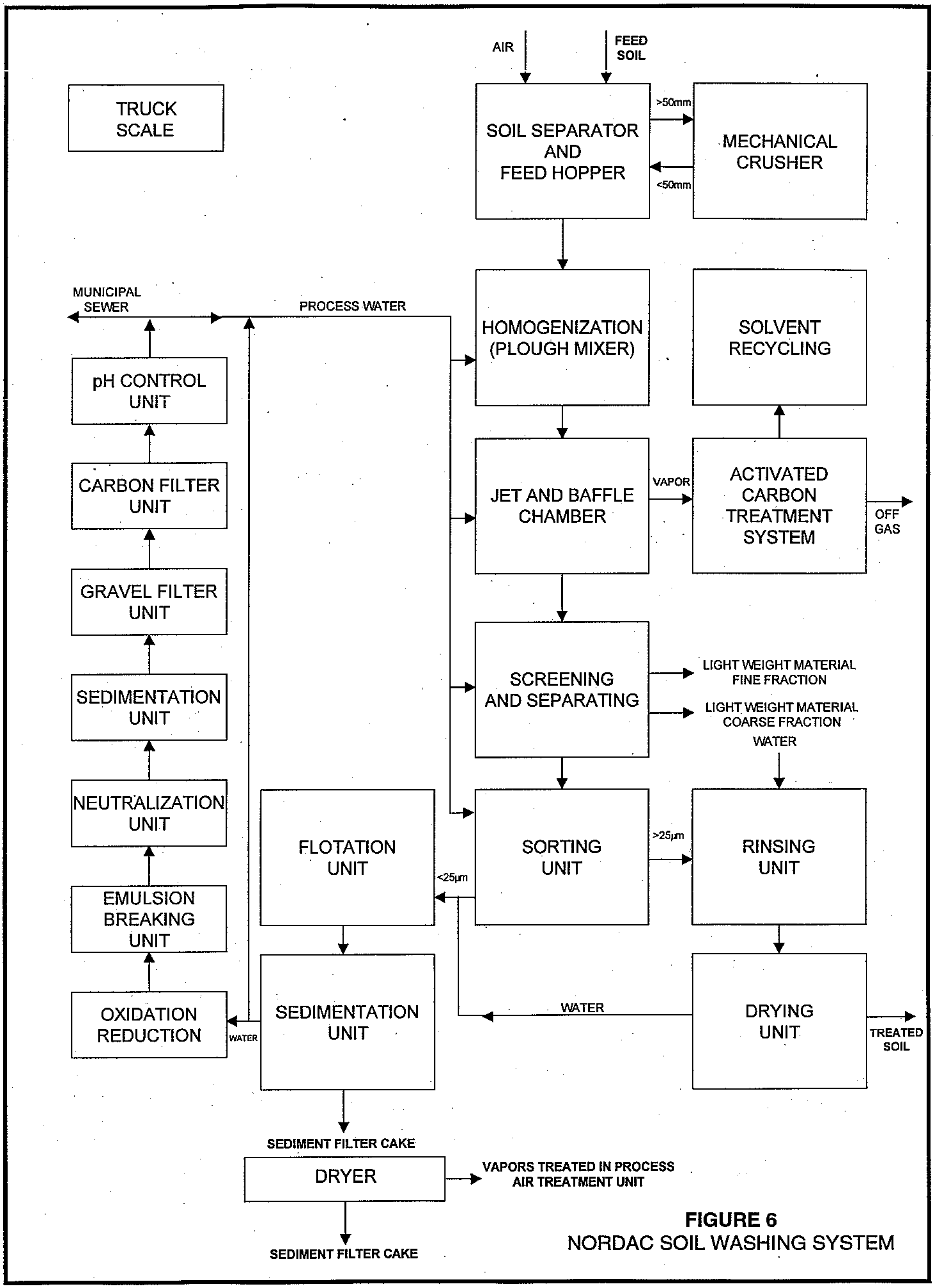


FIGURE 6
NORDAC SOIL WASHING SYSTEM

After contaminants are stripped in the jet and baffle chamber, the water/soil slurry is separated into three fractions (lightweight solids, coarse grain solids, and fine grain solids/water slurry) using a multi-step separating process. In the initial step, the lightweight fraction, including organic material such as wood and coal particles, is separated and then classified into coarse and fine material subfractions using a jig method. During the separation step, recycled process water is used to float and separate these materials. Both subfractions of lightweight material are subsequently disposed of off site as hazardous waste or treated further, if warranted. The second step removes coarse grain particles greater than 25 microns (μm) in diameter from the slurry using a spiral separator. The spiral separator also uses recycled process water to assist in separating and rinsing the coarse material. The coarse particles are then transferred to a rinsing and drying unit where clean water is used to remove any remaining fine soil particles or residual process water. The coarse grain particles are then dried using a filter press and stockpiled for reuse.

The remaining slurry consists of process water and fine grain particles less than 25 μm in diameter. In the sedimentation unit, a flotation/sedimentation system removes the remaining particulate material and a filter press dewaters the sludge. This system has the capacity to process 170 cubic meters of slurry per hour. The filter cake is disposed of by incineration or is treated by bioremediation, depending on the residual concentrations of contaminants.

Most (90 to 95 percent) of the remaining process water is recycled into the separating units described above. The concentration of contaminants in the recycled water is maintained below a proprietary limit by adding treated water as necessary. The portion of the process water that is not recycled is treated in a wastewater treatment system that incorporates a series of chemical and physical processes. These processes include an oxidation/reduction unit, an emulsion breaking unit, a neutralization unit, a sedimentation unit, a gravel filter unit, an activated carbon adsorption unit, and a pH control unit. A portion of the treated water is subsequently fed back to the system; the remainder is discharged to the municipal sewer.

Process air emissions are treated before release to meet pertinent regulatory limits. The process air treatment unit consists of a granular activated carbon adsorption system with a capacity of 8,000 cubic meters per hour. The contaminants captured by the carbon adsorption system are recovered and recycled during the carbon regeneration process. The performance of the process air treatment unit was not evaluated as part of the demonstration, so a detailed description of this unit is not provided.

The soils used for this demonstration contained high concentrations of toluene, ethylbenzene, and xylenes. Benzene concentrations were below 25 milligrams per kilogram (mg/kg); therefore, benzene was not considered a critical contaminant in the demonstration. Average toluene concentrations for each test run ranged from 28 to 55 mg/kg; average ethylbenzene concentrations ranged from 160 to 340 mg/kg; average meta- (m-) and para- (p-) xylene concentrations ranged from 730 to 1,160 mg/kg; and ortho- (o-) xylene concentrations ranged from 210 to 300 mg/kg.

During the demonstration, soil was processed at rates ranging from 10.2 to 13.7 mt per hour. For this demonstration, the processing rate was limited by the capacity of the flotation and sedimentation units to accept fine-grained material. When these units are at capacity, the contaminated soil feeding into the system must be stopped temporarily. Likewise, when the storage bin at the system exit is full, soil feeding into the system must be stopped temporarily. The NORDAC system is fully automated to allow for 24-hour operation. For this demonstration, the soil washing system operated 6 to 12 hours per day or more.

4.2.1.2 Demonstration Objectives and Approach

These were three primary objectives and three secondary objectives in evaluating the NORDAC technology.

<u>Primary Objectives:</u>

- Determine the removal efficiency for individual VOCs that are detected in the untreated soil at greater than the minimum concentration of 25 mg/kg
- Determine the concentration of individual VOCs in the treated soil at the 95 percent confidence level
- Determine the mass fraction of total feed soil discharged as process residuals requiring further treatment or disposal because this soil is a hazardous waste according to the Toxicity Characteristic Leaching Procedure (TCLP)

<u>Secondary Objectives:</u>

- Document the particle size distribution of the feed soil

- Document the average feed soil processing rate on a mass per hour basis over the duration of three 6-hour test runs
- Document commercial treatment costs of the process as provided by NORDAC

Data to assess the demonstration objectives were collected over three test runs, each of which lasted at least 6 hours. QA/QC procedures were followed as specified in the approved QAPP. All QC samples met the acceptance criteria.

4.2.1.3 Results and Conclusions

The conclusions for each NORDAC technology demonstration objective are summarized below.

- The average removal efficiencies achieved by the NORDAC treatment system were 98.3 percent for toluene, 97.3 percent for ethylbenzene, 97.5 percent for m- and p-xylene, and 95.6 percent for o-xylene. Removal efficiencies ranged from 94.4 to 99.4 percent during three test runs.

- The 95 percent upper confidence limit of critical contaminant concentrations in the treated soil is presented in the following table.

- TCLP-leachable VOCs could not be determined for this demonstration, but BTEX concentrations in the sediment filter cake are greater than the TCLP level, indicating that if 100 percent of the BTEX leached out, the sediment filter cake would be characterized as hazardous waste. Sediment filter cake represents 21 percent of the total mass of soil treated by the NORDAC system.

95 PERCENT UPPER CONFIDENCE LIMIT IN TREATED SOIL

Contaminant	Concentration (mg/kg)		
	Test Run 1	Test Run 2	Test Run 3
Toluene	0.88	3.90	0.28
Ethylbenzene	10.7	34.0	2.87
m-& p-xylene	37.6	114.0	13.7
o-xylene	17.8	30.9	9.66

- Average BTEX concentrations in the process water were 317 µg/L of toluene, 1,780 µg/L of ethylbenzene, 6,270 µg/L of m- and p-xylene, and 1,880 µg/L of o-xylene. Process water samples collected during test runs 1 and 2 were not preserved with hydrochloric acid. Therefore, the most accurate data is taken from the process water sample collected during the third test run which was preserved with hydrochloric acid and was found to contain BTEX concentrations of 139 µg/L of toluene, 800 µg/L of ethylbenzene, 3,230 µg/L of m- and p-xylene; all detections were and 930 µg/L of o-xylene, significantly less than overall average concentrations.

- The native moisture content of the contaminated soil ranged from 10.1 percent to 15.2 percent by weight. The moisture content of the treated soil exiting the soil washing process ranged from 11 percent to 15 percent by weight. The moisture content of the sediment filter cake before going through the dryer ranged from 44.7 to 51.5 percent by weight. The moisture content of the sediment filter cake after going through the dryer ranged from 34.5 to 54.3 percent by weight.

- The feed soil was characterized as sand for all 3 test runs. Additionally, treated soil was determined to be sand for test runs 1 and 2, and loam for test run 3. Sediment filter cake was determined to be sand for test run 1 and sandy loam for test runs 2 and 3.

- During the demonstration, the NORDAC system processed soil at rates ranging from 14.6 metric tons per meter (mt/hr) to 19.6 mt/hr. The quantities of treated materials were 1,407 mt of treated soil, 74 mt of lightweight fraction, and 401 mt of sediment filter cake.

- The commercial cost for the NORDAC technology used at the Hamburg site was estimated at 100 to 200 DM per metric ton ($52 to $104/mt assuming a 1.92 DM to one U.S. dollar exchange rate).

4.2.1.4 Vendor Contacts

Franz Nacken
NORDAC
Oberwerder Damm 1-5
20539 Hamburg
(040) 789178-0

4.2.2 Entsorgungsbetriebe Duisburg/ZÜBLIN Catalytic Oxidation

The Entsorgungsbetriebe Duisburg/ZÜBLIN KNV catalytic oxidation system developed by ZÜBLIN Umwelttechnik GmbH, Stuttgart, Germany, was demonstrated on June 13, August 6, and August 13, 1996, at the Entsorgungsbetriebe Duisburg soil gas and groundwater treatment facility located at Usedomstrasse 17 in Duisburg-Neumuehl, State of Nordrhein-Westfalen, Germany (PRC 1997). The treatment facility was built on the site of a former coal-gasification plant. The technology evaluation focused only on the ZÜBLIN KNV catalytic oxidation systems effectiveness in treating soil gas and stripping air (from the air stripper used to treat contaminated groundwater at the treatment facility), which is contaminated with high levels of BTEX compounds.

4.2.2.1 Process Description

The full-scale soil gas and groundwater treatment facility was designed by ZÜBLIN Umwelttechnik GmbH, of Stuttgart, Germany, and uses conventional processes to treat groundwater. The off-gases from the groundwater treatment system and the soil gas extraction system are treated using the ZÜBLIN KNV catalytic oxidation system. The facility incorporates the following processes:

- Soil gas and groundwater extraction
- Groundwater treatment (skimming, stripping, and biodegradation)
- Soil gas and stripping air treatment

The treatment facility process flow diagram is shown in Figure 7.

Soil Gas and Groundwater Extraction

Soil gas and groundwater contaminated with high levels of VOCs are extracted from soil using 10 gas extraction wells and three groundwater extraction wells. The groundwater extraction wells have an inner diameter of 15.24 centimeters (cm) and are equipped with floating filters (developed by ZÜBLIN) for the removal of light nonaqueous phase liquids (LNAPLs). LNAPLs are drawn from the wells and collected in an interim storage tank for subsequent disposal. Soil gas is extracted and fed directly to the ZÜBLIN KNV catalytic oxidation system.

Groundwater Treatment

This conventional process, shown in Figure 7, involves removing organic contaminants from the groundwater in four major process steps. The water treatment process is located in a 15- by 25-meter steel container and consists of four primary units:

- Phase separator
- Stripping tower
- Bioreactor

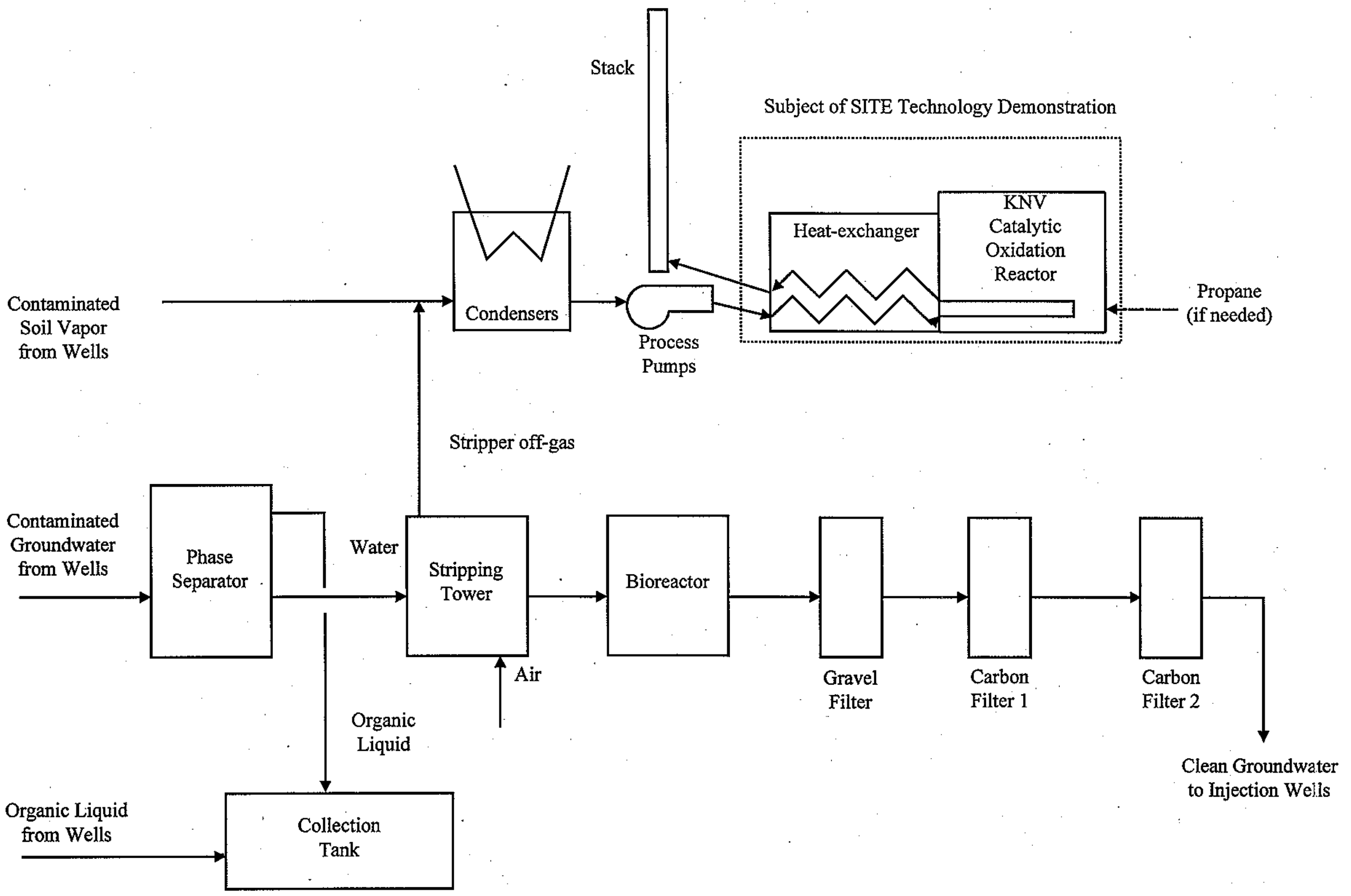


FIGURE 7

ZÜBLIN TREATMENT FACILITY PROCESS FLOW DIAGRAM

- Filter/adsorption units

In the first step of the process, groundwater is fed to a phase separator (skimmer) unit to remove LNAPL floating on the water surface. The removed LNAPL is then transferred to a collection tank. Next, the underflow water from the skimmer unit is sprayed into a conventional stripping tower to remove VOCs. The stripping tower is made of high density polyethylene (HDPE), has an inner diameter of 1.4 m, and is 12 m high. The throughput capacity is 30 m^3 of water per hour. Once it exits the stripping tower, water is fed to a bioreactor where semivolatile contaminants, such as petroleum hydrocarbons and PAHs, are biodegraded. The bioreactor is a floating bed reactor with a polymeric carrier aerated by ambient air.

The off-gases from the stripping tower and the bioreactor are fed to the ZÜBLIN KNV catalytic oxidation system. Bioreactor effluent water is passed through a gravel filter to remove fine particulates prior to activated carbon polishing. The treated water is then reinjected into the aquifer.

Soil Gas and Stripping Air Treatment

The innovative part of the Entsorgungsbetriebe Duisburg soil gas and groundwater treatment facility is the ZÜBLIN KNV catalytic oxidation system, which is used as an afterburner to thermally oxidize gaseous organic contaminants at a temperature greater than 400 °C (752 °F). Oxidation products are carbon dioxide and water/steam. The maximum throughput capacity of the ZÜBLIN KNV catalytic oxidation system is 5,000 normal cubic meters (Nm^3 - cubic meter at standard conditions: 273 K, 1.013 bar, dry) of gas per hour, and is the biggest catalytic oxidation system in hazardous waste site remediation in Germany. ZÜBLIN claims that the system can be operated autothermally (with no additional fuel) when the benzene concentration in the gas is 3 grams per cubic meter (g/m^3) or higher. ZÜBLIN also claims that the system can be operated economically when the benzene concentration is higher than 1 g/m^3.

Excess moisture in extracted soil gas and stripping air is removed by condensation. The condensers are equipped with sampling devices to monitor the benzene concentration. When the benzene concentration exceeds 25 percent of the lower explosive limit, the respective gas extraction line is automatically shut down.

Condensed water is then fed to the water treatment train. A blower withdraws gas from the condensers and routes it through the cold side of a heat exchanger, through the catalytic bed in the reactor, and subsequently through the warm side of the heat exchanger. Through this process, hot treated gas is used to preheat the cold untreated feed gas. Treated off-gases, which must meet the emissions standards, are released to the atmosphere via a 30-meter-high stack.

4.2.2.2 Demonstration Objectives and Approach

There two primary and two secondary objectives in evaluating the ZÜBLIN KNV catalytic oxidation technology.

Primary Objectives:

- Determine the removal efficiencies of the ZÜBLIN KNV catalytic oxidation system for gas contaminated with benzene, toluene, ethylbenzene, and o-, m-, p-xylenes
- Document the critical contaminant concentrations in the treated gas at a confidence level of 95 percent.

Secondary Objectives:

- Document key, nonproprietary system operating parameters
- Document remediation costs per year of operation

To obtain the data required to meet the specified project objectives, samples were collected and process measurements taken during each of the three evaluation days (June 13, August 6, and August 13, 1996). QA/QC procedures were followed as specified in the approved QAPP. All QC samples met the acceptance criteria.

4.2.2.3 Results and Conclusions

The ZÜBLIN KNV catalytic oxidation technology concluded that the treatment system can significantly reduce BTEX concentrations in contaminated soil gas and stripping air. During the demonstration, BTEX concentrations were consistently reduced from the 700 to 1000 mg/Nm^3 range (total BTEX) to less than the detection level of 0.5 mg/Nm^3 (for each compound). Prior to the technology demonstration, ZÜBLIN indicate that total BTEX concentrations had been reduced from the 3,000 to 4,000 mg/Nm^3 range to below 1 mg/Nm^3, which corresponds to greater than 99 percent removal efficiency.

Specific conclusions for each primary and secondary objective are summarized below:

- The overall average removal efficiency rates were 99.9 percent for benzene, greater than 99.8 percent for toluene, 94.7 percent for ethylbenzene, greater than 99.8 percent for m- and p-xylenes, and greater greater 98.6 percent for o-xylene.
- Exact values for the 95 percent upper confidence level of BTEX concentrations in treated gas were not calculated because all six post-treatment BTEX concentrations were below the 0.5 mg/Nm^3 detection level.
- Stack gas flow rates ranged from 2,500 m^3/hr to 3,300 m^3/hr (at actual temperature and pressure). Reactor temperatures ranged from 520 °C to 580 °C (968 °F to 1076 °F).
- The annualized remediation cost is 754,000 Deutsche Mark (DM) (US$393,000 assuming a 1.92 DM to $1.00 exchange rate) based on information provided by ZÜBLIN.

4.2.2.4 Vendor Contact

Dr. Hans-Georg Edel and Mr. Wofgang Maier-Osswald
Züblin Umwelttechnik GmbH
Albstadweg 1
D-70567 Stuttgart, Germany
(0711) 7883-249 and (0711) 7883-636

4.2.3 RUT TERRA • POR Low Temperature Thermal Desorption

The Ruhrkohle Umwelttechnik (RUT) TERRA • POR thermal desorption soil treatment pilot plant located in Herten, Nordrhein-Westfalen, Germany was used to treat soil from the Ölifad site in 1995 (PRC 1995). This soil was contaminated with tar products (teeröle).

4.2.3.1 Process Description

The RUT TERRA • POR soil treatment technology, which was developed by RUT GmbH, Bottrop, Germany, is a continuous thermal desorption system for treating contaminated soil. The RUT TERRA • POR pilot plant is capable of treating 150 kilograms of contaminated soil per hour (kg/hr).

The pilot plant combines the following treatment processes: (1) Thermal Desorption Soil Treatment (2) Vapor Phase Treatment, and (3) Liquid Phase Treatment .

The treatment principle of the RUT TERRA • POR technology is thermal desorption of contaminants from soil, followed by condensation of contaminant vapors and collection of the condensate for recycling. Soil contaminated with volatile and semivolatile organic and inorganic compounds is heated to temperatures at which the contaminants evaporate from the soil and partition into the vapor phase. Intense agitation inside the evaporator unit breaks up clumps of loamy and clayey soil, thereby enhancing the removal of contaminants from the soil. Injection of steam further improves the desorption of contaminants with high boiling points, between 250 °C and 300 °C. Steam enhances energy transfer and dilutes the PAH concentration in the vapor phase, thereby re-establishing equilibrium through increased partitioning of PAH from the soil to the vapor phase.

Contaminants in the vapor phase are captured and condensed in a multi-step condensation process. The condensate (a mixture of water and contaminants) is separated by gravity separation in an oil-water separator. Nonaqueous phase liquid contaminants are removed from the oil-water separator and stored in drums. Contaminated water is then removed from the oil-water separator, and is treated by air stripping and subsequent carbon polishing.

The RUT TERRA • POR soil treatment system will be marketed as a treatment alternative for loamy and clayey soil contaminated with solvents, high boiling point tar/oil compounds, and mercury. Marketing of the system will target remediation projects involving the treatment of smaller quantities of soil. Because of the mobility of the RUT TERRA • POR soil treatment system, it may be more cost-effective to treat contaminated soil on site rather than transport the soil to a fixed facility for treatment.

The RUT TERRA • POR thermal desorption treatment process involves heating contaminated soil to a temperature that is high enough to volatilize the organic contaminants and volatile metals. The thermal treatment system is installed in two 6-meter trailer containers. One trailer container houses the evaporator unit, steam generator, and thermo-oil heater. The other trailer container houses the condenser, treatment systems for water and vapors, and control panel for the pilot plant. A process flow diagram of the system is presented in Figure 8.

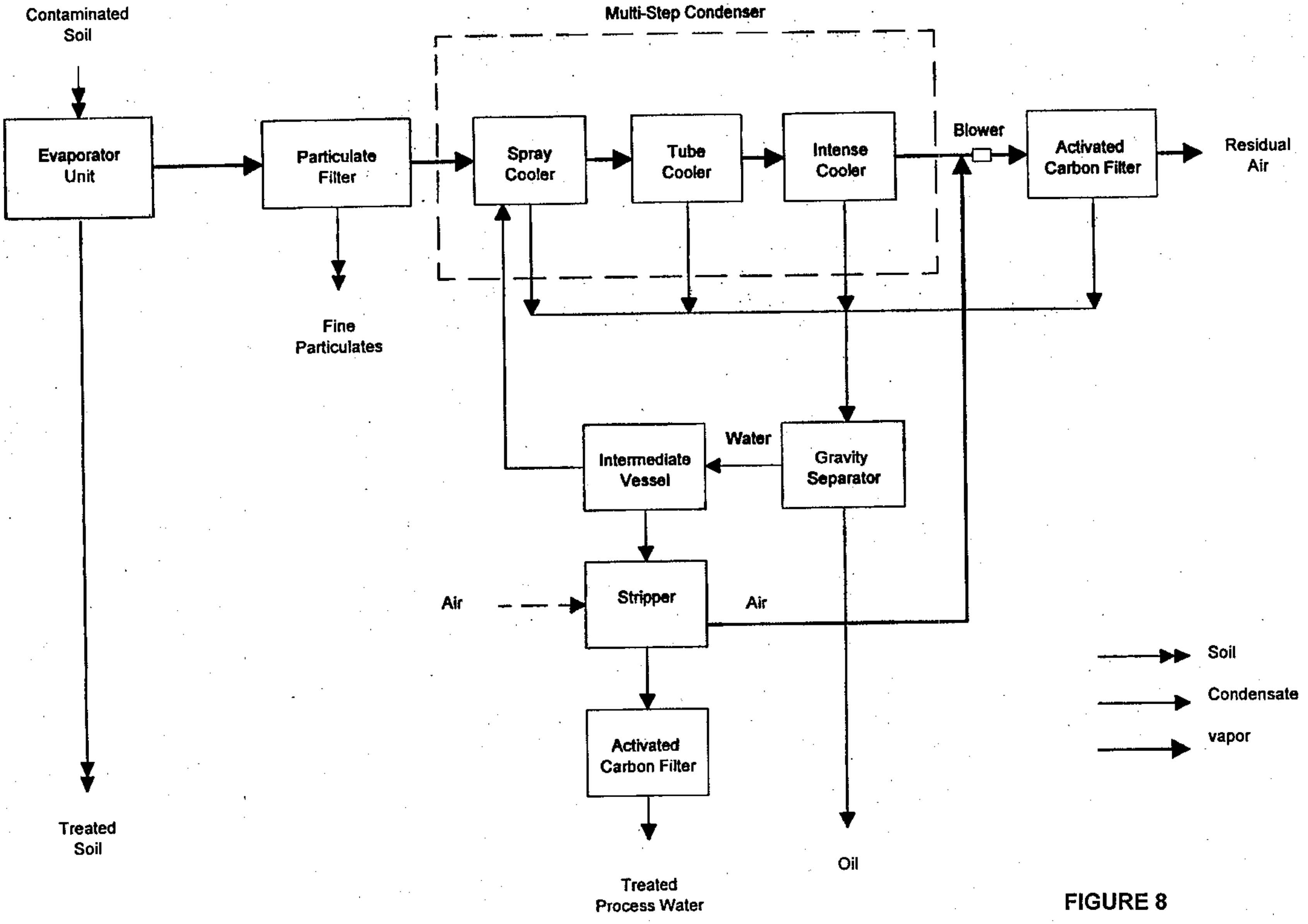


FIGURE 8

RUT TERRA•POR PROCESS FLOW DIAGRAM

Contaminated soil was crushed and sieved at the Dortmund Dorstfeld interim storage facility to reduce the grain size to less than 5 mm, which is the maximum grain size for this pilot plant. Approximately 3,600 kg of this soil was transported to the RUT TERRA • POR pilot plant test site in Herten for the demonstration.

Contaminants removed from the contaminated feed soil in the evaporator unit enter the vapor phase treatment process. Following initial filtering through the particulate filter, contaminant-laden vapors are fed through a multi-step condenser system. This process has a maximum capacity of about 50 m^3/hr. The amount of vapor generated during routine system operation is typically between 20 and 40 m^3/hr. The multi-step condenser system consists of three stages in which contaminant-laden vapors are cooled in a step-wise fashion to a final temperature of about 0 °C to 5 °C. The first step in the condensation process is a water spray that reduces the temperature of the vapors from about 270 °C to 95 °C. The second step is a parallel flow water tube cooler that reduces the temperature of the vapor to about 25 °C. The third step is an intense cooler using chilled water that further reduces the temperature of the vapor to about 0 °C to 5 °C. At these low temperatures, most of the contaminants condense into a liquid phase that is separated from the air stream. The air stream is treated with activated carbon before it is discharged to the atmosphere.

During the treatment of contaminant-laden vapor in the multi-step condenser system, liquid condensate is generated that consists of contaminants in the free phase and contaminants dissolved in water. Free phase and dissolved phase contaminants are gravity separated in an oil-water separator. The free phase liquid contaminants are removed from the oil-water separator, collected in drums, and recycled. Contaminated water is fed into an air stripping unit, and then into an activated carbon filter to remove dissolved contaminants before discharge to the municipal sewer system. The typical amount of water discharged to the sewer system is about 35 to 50 liters per hour.

Spent activated carbon from the vapor phase treatment process is regenerated on site by countercurrent steam injection using excess steam from the steam generator. Contaminated water generated from the carbon regeneration process is fed back to the water treatment system (oil-water separator) for recycling and treatment.

At the test site, contaminated soil is manually weighed and fed into the evaporator unit through a gas-tight rotary feed lock valve system. The evaporator unit is indirectly heated to 300 °C by heated thermo-oil that circulates through the outer shell of the unit and through the agitation devices described below. The thermo-oil is heated in a 48 kW conventional electrical heater. The pilot plant has an overall power consumption of 60 kW per hour.

The evaporator unit is a trough-shaped steel structure that is equipped with two horizontal shafts carrying mixing blades. Inside the evaporator unit, the mixing blades provide intense agitation that breaks up clumps of loamy and clayey soil. The double shafts and the mixing blades are hollow steel structures that are heated by circulating heated thermo-oil. The internal dimensions of the evaporator are 1.50 meters long by 0.40 m wide by 0.30 m high. The rotational speed of the two shafts is about 30 to 40 revolutions per minute.

4.2.3.2 Demonstration Objectives and Approach

There were five primary objectives and three secondary objectives in evaluating the RUT TERRA • POR soil treatment system.

Primary Objectives:

- Determine contaminant removal efficiencies of the RUT TERRA • POR soil treatment system for PAHs
- Document the critical compound concentrations in the treated soil at a confidence level of 95 percent
- Document critical compound concentrations in the stack gas from exhaust stack of the activated carbon unit
- Document critical compound concentrations in the process water effluent
- Document critical compound concentrations in the fines generated by the particulate filter blowdown

Secondary Objectives:

- Document the particle size distribution of the contaminated feed soil and the treated soil
- Document key nonproprietary system operating parameters
- Document remediation costs per metric ton of soil

To achieve these objectives, samples and measurements were collected and analyzed during three 6-hour test runs. QA/QC procedures were followed as specified in the approved QAPP.

4.2.3.3 Results and Conclusions

Results of the demonstration indicate that contaminant removal efficiencies varied widely over the three test runs. This was due primarily to low contaminant concentrations in the feed soil. As a result of low contaminant concentrations, the demonstration objectives could not be evaluated and a detailed Innovative Technology Evaluation Report was not prepared for this demonstration.

4.2.3.4 Vendor Contacts

Mr. Peter Jans
RUT GmbH
Gleiwitzer Platz 3
D-46236 Bottrop, Germany
(02041) 166 614

4.2.4 Hochtief Thermal Desorption

The Hochtief Umwelt technology demonstration was conducted on February 22 through February 25, 1995, in Herne, Germany (Tetra Tech 1998d). The demonstration evaluated the technology's effectiveness in remediating soil contaminated with TRPH, PAHs, and BTEX. The soil was from the Gaswerk Hannoversch Munden (GHM) site, a former coal-gasification plant in Hannoversch Munden, Germany.

4.2.4.1 Process Description

Hochtief Umwelt operates a full-scale, commercial soil remediation facility in Herne, Germany. The facility houses a continuous thermal desorption system capable of remediating soil contaminated with organic chemicals and some inorganic chemicals. The system consists of three main processes: (1) mechanical preparation (sieving and crushing), (2) thermal desorption, and (3) flue gas treatment. Each of these processes are described below.

Mechanical Preparation Process

Soil contaminated with high levels of VOCs is stored in a container storage area at the Hochtief Umwelt facility. Front-end loaders are used to introduce soil into a three-step size reduction process that reduces the material from a maximum grain size of 40 centimeters (cm) in diameter to a grain size of smaller than 2.0 cm in diameter. Slowly rotating blade-shredders crush concrete and debris and break clumps of clayey and loamy soil. Scrap metal is removed by a magnetic device. Once the soil is reduced in size, it is transported by an enclosed conveyor belt to an interim storage pile. From the interim storage pile, the soil is transported by front-end loaders to the feed hopper of the thermal desorption unit.

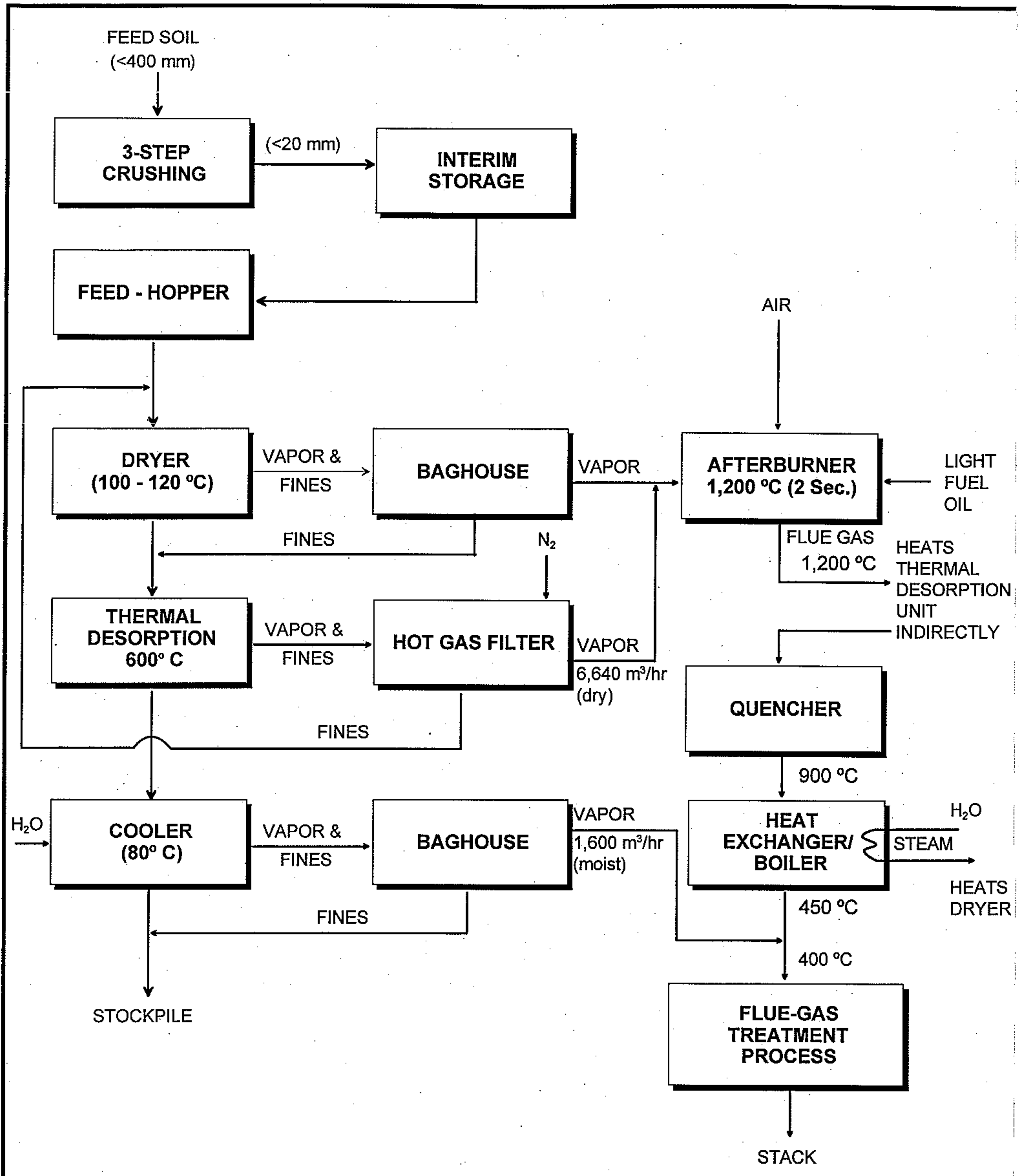
Thermal Desorption Process

A process flow diagram for the thermal desorption process is shown in Figure 9. The thermal desorption process heats feed soil to a temperature high enough to volatilize organic contaminants and volatile metals. The thermal desorption process occupies a 40-square-meter (m^2) area and consists of three primary units: (1) a dryer unit, (2) a thermal desorption unit, and (3) a cooler unit.

From the feed hopper, untreated soil moves by conveyor belt to a rotating drum soil dryer. A constant feed rate of 6.5 metric tons per hour (mt/h) (maximum) is maintained and controlled by a belt scale. The dryer is steam-heated to 100 to 120 °C, but is also equipped with standby burners that may be used during system start-up or during nonroutine operation. The soil residence time in the dryer is between 30 and 40 minutes. The dryer evaporates water and some volatile contaminants from the soil. Soil exiting the dryer has a residual moisture content of about 8 percent by weight.

A bucket-chain conveyor feeds dried soil to the thermal desorption unit. The desorption unit operates at an average temperature of 600 °C, which causes contaminants to volatilize from the solids. The desorption unit is a rotating cylinder heated indirectly by flue gas from the afterburner unit. The rotational speed of the desorption unit controls the residence time of the soil in the unit. Trial runs on GHM soil in a pilot-scale unit demonstrated that the best removal efficiencies occurred at temperatures of 600 °C with residence times of approximately 30 minutes in the desorption unit. The unit is operated under a vacuum of 0.2 to 0.4 millibar (mbar) to minimize fugitive emissions.

The outer shell of the desorption unit is divided into eight heating zones. The temperature of each zone is controlled by automatic flaps; the flaps allow different volumes of flue gas to enter the zones at



Note: Temperatures and flow rates shown in this figure are typical operating conditions only.

FIGURE 9

HOCHTIEF UMWELT THERMAL DESORPTION SYSTEM

1,200 °C to maintain a surface temperature of 600 °C in the unit. Temperature is continuously monitored using probes in the inner walls of the desorption unit.

After exiting the desorption unit, soil is transported to the cooler by an enclosed vibratory duct. The cooler is a rotating drum equipped with water sprayers to spray water onto the soil. The cooled soil (at approximately 80 °C) is transported out of the plant and stockpiled. The final water content of the treated soil is maintained at 10 to 15 percent by weight to control fugitive dust emissions and to improve handling of the treated soil.

Flue Gas Treatment Process.

Flue gas from the drying and desorption units flows to the afterburner through heated pipes. First, however, organic and metallic vapors and dust particles, or fines, are removed by a hot gas filter and a baghouse. The ceramic elements of the hot gas filter are periodically shock flushed with nitrogen to loosen the fines retained in the filter. These fines are returned to the untreated soil entering the dryer. Fines from the baghouse are fed to the thermal desorption process.

The afterburner consists of a 9-m long horizontal cylindrical incineration chamber with an outside diameter of 5 m. The afterburner is designed to operate at a flue gas residence time of 2 seconds, a temperature of 1,200 °C, and an excess oxygen content of 1.5 percent. Fuel oil is used to operate the afterburner; during nonroutine operations, the unit may also be run with propane.

Flue gas leaves the afterburner at 1,200 °C and is returned to the desorption unit where it is circulated through the outer shell for heat recovery purposes. After heating the desorption unit, flue gas flows to a quencher unit, which cools the flue gas to approximately 900 °C prior to feeding to the boiler.

The saturated steam boiler operates at a steam pressure of 16 bar and a temperature of 200 °C. Steam is generated at a rate of 4 cubic meters per hour (m^3/h) and is used to heat the soil dryer. Flue gas exits the boiler at a temperature of 450 °C and is combined with the gas from the soil cooler baghouse.

Flue gas exiting the boiler is cooled to 450 °C. This 450 °C exit temperature for the flue gas leaving the boiler is the minimum required to avoid generation of dioxins if chlorinated organic compounds and carbon are present in the gas phase. Between about 200 and 450 °C, dioxins can be formed by chemical reactions known as De-Novo-Synthesis. Therefore, to avoid the De-Novo-Synthesis reaction, flue gas must be quenched from 400 °C to less than 200 °C very rapidly.

In the Hochtief Umwelt flue gas treatment process, flue gas exiting the boiler or heat exchanger is first quenched in a spray dryer to 180 °C. The spray dryer uses alkaline scrubber water from the flue gas scrubber units as quenching water. The quenching water evaporates in the spray dryer, leaving fine particles of alkaline salts and dust entrained in the flue gas. These particles are removed from the flue gas by a baghouse, and baghouse solids are disposed of as hazardous waste. The solid residue amounts to about 50 kg/h during routine operation, which is 0.3 to 0.4 percent of the hourly throughput of soil.

After exiting the baghouse, flue gas, which flows at about 8,650 m^3/h at this point in the process, enters a series of gas scrubbers. First, in the venturi scrubber, the acidic components (for example, hydrochloric acid) are removed from the flue gas using a sodium hydroxide (NaOH) solution. The spent scrubber solution exiting the venturi scrubber flows to the spray dryer. In the next scrubbing step, slightly acidic components such as sulfur dioxide (SO_2) are removed from the flue gas in a countercurrent scrubber. The resulting solution is neutralized with NaOH; after adding trimercaptotriazine (at a rate of 1 kg/h) to precipitate metals as sulfides, the wash solution flows to the spray dryer.

Flue gas from the scrubbers is additionally treated by carbon polishing. When treating soil contaminated with organic compounds, the activated carbon bed may be bypassed and the scrubbed flue gas (about 9,000 m^3/h dry) can be directed to the 40-m high stack. The carbon unit was not used during the demonstration. Therefore, a detailed description of this unit is not provided in this report.

The Hochtief Umwelt facility holds a permit to treat soil contaminated with dioxins and furans, PCBs, and other halogenated hydrocarbons. For special emission control when treating soil that contains or may generate dioxins, a flue gas treatment system with an air stream adsorber may be added to the process. This system is on standby during normal operation and can be operated as needed. When the air stream adsorber is used, the flue gas exiting the spray dryer is fed to the adsorber prior to the baghouse. In the air stream adsorber, a mixture of powdered lime and activated carbon is sprayed into the flue gas stream at a maximum rate of 50 kg/h. Organic components and heavy metals are adsorbed by this mixture and are removed with the solids in the baghouse. During this technology demonstration, the optional air stream adsorber unit was not used because of the low likelihood of dioxin generation in the thermal desorption system flue gas.

4.2.4.2 Demonstration Objectives and Approach

There were three primary objectives and four secondary objectives in evaluating the Hochtief Umwelt thermal desorption technology.

<u>Primary Objectives</u>

- Determine the removal efficiency of the Hochtief Umwelt thermal desorption system for the following critical compounds:

    -TRPH
    -Naphthalene
    -Acenaphthene
    -Acenaphthylene
    -Fluorene
    -Phenanthrene
    -Anthracene
    -Fluoranthene
    -Pyrene
    -Benz (a)anthracene
    -Chrysene
    -Benzo(b)fluoranthene
    -Benzo(k)fluoranthene
    -Benzo(a)pyrene
    -Indeno(1,2,3,c,d)pyrene
    -Dibenzo(a,h)anthracene
    -Benzo(g,h,i)perylene
    -Benzene
    -Toluene
    -Ethylbenzene
    -Xylene

- Document the critical contaminant concentrations in the treated soil at a confidence level of 95 percent
- Document critical compound concentrations in the stack emissions

<u>Secondary Objectives</u>

- Document the moisture content and the particle size distribution of the feed and treated soil in the thermal desorption process
- Document key nonproprietary system operating parameters
- Document remediation costs per metric ton of soil
- Document stack emission characteristics for informational purposes only

These objectives were achieved by collecting representative samples of contaminated feed soil, treated soil, and stack gas by monitoring and measuring other appropriate process parameters during three test runs. QA/QC procedures were followed as specified in the approved QAPP.

4.2.4.3 Results and Conclusions

This demonstration was limited to an evaluation of the technology's ability to remove TRPH, PAH, and BTEX from soil. Based on the Hochtief Umwelt bilateral SITE demonstration, specific conclusions for each primary and secondary objective are summarized below:

- The average removal efficiencies were 99.0 percent for TRPH, 99.7 percent for PAHs, and 99.0 percent for BTEX.

- The 95 percent UCL of concentrations in treated soil for Test Run 1 was 16.1 mg/kg for TRPH, 34.0 mg/kg for PAHs, and 2.17 mg/kg for BTEX. The 95 percent upper confidence limit of concentrations in treated soil for Test Run 2 was 17.5 mg/kg for TRPH, 35.7 mg/kg for PAHs, and 1.01 mg/kg for BTEX. The 95 percent upper confidence limit of concentrations in treated soil for Test Run 3 was 16.8 mg/kg for TRPH, 33.3 mg/kg for PAHs, and 1.16 mg/kg BTEX.

  Soil PAH results were compromised by some noncompliant recoveries in the MS/MSD analyses, indicating that a potential high or low bias may exist for some individual PAH analytes. As a result, the soil PAH results described above should be considered estimates.

- PAH concentrations in stack emissions ranged from 92.6 to 224 µg per dry standard cubic meter (dscm) and BTEX concentrations ranged from 181 to 350 µg/dscm.

- The moisture content of the contaminated feed soil ranged from 17.4 to 18.8 percent by weight and the moisture content of the treated soil ranged from 8.0 to 8.28 percent by weight. Soils treated during the demonstration were identified as silty sand.

- The average feed soil flow rate for each test run was 6.5 mt/h. The stack gas flow rate ranged from 19,700 to 19,900 Nm^3/h and averaged 19,800 Nm^3/h during the demonstration. The temperature of soil exiting the dryer unit ranged from 125 to 131 °C and averaged 128 °C during the demonstration. The temperature of the thermal desorption unit ranged from 737 to 742 °C and averaged 740 °C during the demonstration. The temperature of the soil exiting the thermal desorption unit ranged from 488 to 535 °C and averaged 511 °C during the demonstration. The temperature of the gas stream exiting the thermal desorption unit ranged from 593 to 605 °C and averaged 598 °C. The temperature of soil exiting the cooling unit ranged from 66 to 781 °C and averaged 70.3 °C.

- The concentration of total carbon in stack emissions ranged from 2.5 to 13.5 mg/m^3 and averaged 7.70 mg/m^3; hydrochloric acid was not detected in any of the samples; carbon monoxide concentrations ranged from 1 to 24 mg/m^3 and averaged 13.6 mg/m^3; sulfur dioxide concentrations ranged from less than 1.00 to 5 mg/m^3 and averaged 1.1 mg/m^3; particulate matter concentrations ranged from less than 1.00 to 2 mg/m^3 and averaged 1.03 mg/m^3.

- The commercial cost, provided by Hochtief Umwelt, for application of the Hochtief technology at the Herne site was 430 DM per metric ton ($220 per metric ton assuming a 1.92 DM to $1 U.S. exchange rate).

4.2.4.4 Vendor Contacts

Mr. Harald Kimmel
Hochtief Umwelt
Huyssenallee 86-88
D-45128 Essen
(0201) 1753-670 and (0201) 1753-5

Mr. Jorg Odparlik
Hochtief Umwelt GmbH
Huyssenallee 86-88
D-4528 Essen
(0201) 1753-670 and (0201) 1753-5

4.2.5 Harbauer Vacuum Distillation

The Harbauer technology demonstration was conducted on November 23 and 24, 1994 (the stack gas sampling portion of the demonstration was performed on August 24, 1995) at the Harbauer facility, located in W`lsau near Marktredwitz, Landkreis (County of) Wunsiedel, State of Bavaria, Germany (PRC 1996). Elemental mercury-contaminated soil from the Chemische Fabrik Marktredwitz (CFM) site was used for this demonstration.

4.2.5.1 Process Description

The Harbauer treatment system consists of two main processes: soil washing and vacuum distillation. The soil washing process separates the contaminated feed soil into a coarse-grained fraction and a fine-grained fraction. The coarse soil fraction (2 to 60 mm) is analyzed and, if the mercury concentration is less than 50 mg/kg, it is disposed of in the adjacent CFM landfill. If the mercury concentration in the coarse soil is greater than or equal to 50 mg/kg, it is crushed and treated in the vacuum-distillation unit. The fine soil fraction (< 2 mm), which contains mercury at concentrations up to 5,000 mg/kg, is treated in the vacuum-distillation unit.

The vacuum-distillation process heats contaminated soil under a vacuum to volatilize and remove mercury from the soil. Contaminated soil is heated to approximately 380 °C under a reduced pressure (vacuum) of approximately 100 to 200 hectopascals (hPa). The boiling point of elemental mercury is approximately 350 °C at 1014 hPa (1 atmosphere); therefore, the reduced pressure causes mercury to be volatilized more rapidly and removed from the soil at the system temperature. Mercury volatilizes from the soil and the mercury vapors are removed from the vacuum-distillation unit. The mercury vapors enter a water-cooled multistep condenser unit that liquefies the vapors into elemental mercury. The treated fine soil fraction, which contains residual mercury at concentrations ranging from 11 to 31 mg/kg, is mixed with the coarse soil fraction (containing mercury at less than 50 mg/kg) and disposed of in the CFM landfill.

The Harbauer soil washing/vacuum-distillation unit is a full-scale, commercial, transportable plant configured as shown in Figure 10. In addition to soil washing and vacuum-distillation processes, the unit incorporates process water and air treatment processes.

Soil Washing Process

The Harbauer soil washing process is a continuous, water-based (no detergents or surfactants are used), volumetric reduction process that is based on two mechanisms:

1. Removal of mercury from coarse-grained soils (soils with a particle diameter greater than 2 mm).
2. Separation of the coarse-grained soils from fine-grained soils (soils with a particle diameter less than 2 mm).

The soil washing process results in a coarse-grained fraction that contains residual mercury at concentrations less then 50 mg/kg, and a fine-grained fraction that contains mercury at concentrations greater than 50 mg/kg.

Contaminants tend to chemically and physically adhere to the fine-grained soil fraction (silts and clays) due to its greater surface area and higher natural organic matter content. The silts and clays, in turn, tend to adhere to coarser sand and gravel particles. The soil washing process removes the more highly contaminated silt and clay from the coarser soil fractions and scrubs the coarser fractions, resulting in clean or only slightly contaminated sand and gravel.

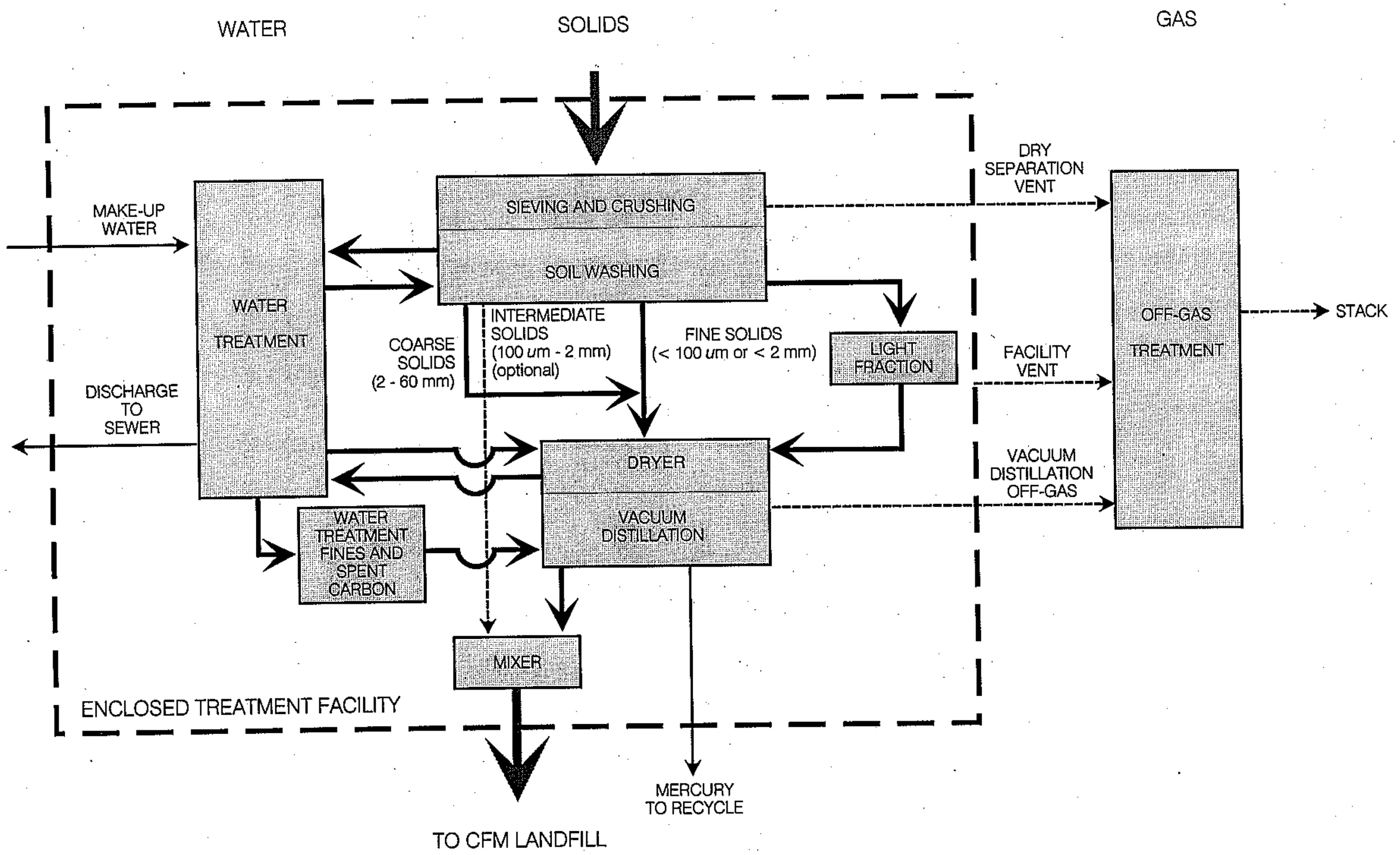


FIGURE 10
HARBAUER SYSTEM FLOW DIAGRAM

The soil washing process involves (1) sieving and crushing soil to a particle diameter less than 60 mm (2) mixing the soil with recycled process water in a double-shaft blade washer; and (3) separating the soil into a relatively clean coarse fraction (particle diameter between 2 and 60 mm), a highly contaminated fine fraction (particle diameter smaller than 2 mm), and a light-weight coarse fraction.

The soil washing process involves the following steps:

1. Initial Screening
2. Crushing (if necessary)
3. Blade washing
4. Screening
5. Attrition scrubbing
6. Hydraulic classification via settling or hydraulic sorting
7. Final screening

Initially, the soil is mechanically sieved in a vibratory screen to less than 60 mm in diameter. Materials greater than 60 mm in diameter are crushed by a mechanical crusher and re-fed to the screening device. After the initial screening and crushing, the soil is transported via an encapsuled conveyor belt to the highest point of the treatment facility and is transferred downward by gravity through the various washing and separation steps. First, the soil is fed continuously to a double-axis blade washer unit where the soil is mixed with water at a rate of one cubic meter of water per metric ton of soil. Recycled process water used as feed water for to the bladewasher. A constant feed rate of contaminated soil is maintained by a belt-scale, feed-back control system.

The soil-water slurry exiting the blade washer unit is transferred to a screening unit consisting of a double screen and a hydrocyclone. The soil particles with a diameter less than 100 µm pass through the screens and cyclone and are separated as part of a process water slurry. This slurry is pumped to the vacuum-distillation unit. Soil particles with a diameter of 100 µm to 2 µm are transferred to an attrition scrubber, where additional recycled process water is added and the slurry is intensely mixed. During mixing, surface contamination is scrubbed from the coarser grained soil by abrasion of particles against each other.

After passing the attrition scrubber, the soil-water mixture enters a hydraulic sorter, where the lightweight particles are removed. After being screened from the water stream and washed with a process water spray, the lightweight fraction is collected in bins. The remaining soil-water mixture that passed the hydraulic sorter is fed to a cyclone, where the grains with a size less than 100 µm (newly generated from breakdown of larger grains or clumps during processing in the attrition scrubber) are separated and pumped to the vacuum-distillation process.

Soil particles larger than 100 µm are screened from the process water, washed with a process water spray, and removed as treated soil via a vertical discharge pipe directly into a mixer. The mixer blends the washed fraction with the treated fines from the vacuum-distillation process.

The coarse-grained solids from the initial screening step are conveyed to a settling unit in which the lightweight fraction is removed. This coarse lightweight fraction is added to the 100 µm to 2 µm lightweight fraction for final screening and collection in bins.

The heavier coarse solids are drawn from the settling unit into a final screening/spray washing step before they are blended with the washed 100 µm to 2 µm soil and the treated fines. The separated process water is treated and recycled except for a slipstream, which is discharged to the municipal sewer after a final polishing treatment step.

Soil processing time of the entire soil washing process is approximately 25 minutes. The maximum throughput of the soil washing unit is approximately 20 mt/h.

Vacuum-Distillation Process

The fine grained (< 2 mm diameter), highly contaminated fraction of soil that is separated by the soil washing process is transferred as a slurry to the vacuum-distillation unit. The vacuum-distillation process involves heating the soil to a temperature high enough to volatilize mercury. At 1 atmosphere (1014 hPa), the boiling point of elemental mercury is approximately 350 °C (662 °F). The Harbauer vacuum-distillation process heats the soil to approximately 380 °C (716 °F) under reduced pressure (vacuum) conditions. The reduced pressure (100 to 200 hPa) lowers the boiling point of mercury, resulting in more efficient removal of mercury from the soil and lower energy consumption.

The vacuum-distillation process consists of four primary units:

- Mechanical dewatering
- Drying
- Vacuum distillation
- Cooling

Prior to mechanical dewatering, Ferrogranul (an iron chloride sulfate) and a polymeric flocculating agent are added to the soil slurry, causing heavy metals to precipitate. The slurry is then allowed to settle in six clarifiers operated in parallel. The flocculating agent causes the fine particles to aggregate, settle, and separate from the process water. The concentrated solids are then mechanically dewatered in a filter press to minimize the energy consumption of the subsequent drying process. The fine particle filter cake from the filter press is transported via a conveyor to the top-most point of the vacuum-distillation process and passes downward, by gravity, through the various process units. The process water from the concentrating and dewatering steps is sent to the water treatment system for purification prior to reuse.

The filter press solids are fed to a rotating-drum dryer that is steam heated to approximately 100 °C. The steam is produced in a noncontact heat exchanger using excess thermal energy from the off-gas of the vacuum-distillation unit. The dryer is also equipped with additional stand-by burners that may be used during process start-up or nonroutine operation. The residence time of the soil in the dryer is approximately 30 minutes. Soil exiting the dryer has a residual moisture content of less than 1 percent by weight. The off-gas from this drying step is treated in the off-gas treatment process. Solids exiting the dryer are fed through a double chamber vacuum lock via a screw-conveyor to the vacuum-distillation unit (a cylindrical rotating processor heated indirectly by propane burners). Under reduced pressure conditions of 100 to 200 hPa and an average temperature of 380 °C, the mercury and other compounds are volatilized from the soil.

After passing through he vacuum-distillation unit, the soil is transported via a screw conveyor to a cooler. The cooler is a water-cooled rotating drum. The cooled soil (temperature less than 50 °C) passes a dual-chamber vacuum lock and enters the mixer via a conveyor belt and a vertical discharge pipe. The treated soil (containing between 5 and 30 mg/kg of mercury) is mixed with washed, coarse-grained soil and is disposed of in the CFM landfill adjacent to the treatment facility.

Air Treatment Process

The entire Harbauer system is encapsulated and maintained under a slight vacuum. The off-gas from the facility is captured, treated, and released to the atmosphere. The air treatment process treats approximately 40,000 m^3/h of off-gas. The dry (mechanical) separation vent, which contains emissions from the crusher, is passed through a dust filter before joining the plant vent gases. Stack gas treatment consists of two activated carbon beds (iodinized and non-iodinized) arranged in series. Water vapor and mercury vapor are removed from the vacuum-distillation unit by vacuum and enter the off-gas treatment process. Mercury volatilizes primarily in the vacuum-distillation unit and enters a water-cooled, multistep condenser unit. Harbauer estimates that approximately 90 percent of the mercury is condensed and recovered as liquid elemental mercury. The relatively small amounts of off-gas exiting the condenser unit (approximately 500 m^3/h) are treated in a conventional wet gas scrubber and are then blended with the larger amount of off-gas from the facility ventilation system. The individual performance of these air treatment process units was not evaluated during this demonstration. Therefore, a detailed description of these units is not provided here.

4.2.5.2 Demonstration Objectives and Approach

There were five primary objectives and three secondary objectives in evaluating the Harbauer technology.

Primary Objectives:

- Document the mercury concentration in the treated soil at a confidence level of 95 percent
- Determine the mercury removal efficiency achieved by the Harbauer treatment system
- Document the levels of TCLP leachable mercury in the untreated and the treated soil
- Document stack gas and process water treatment effluent mercury concentrations
- Determine the mercury removal efficiency of the vacuum-distillation process

Secondary Objectives:

- Document the moisture content and the particle size distribution of the contaminated feed soil and the treated soil from the soil washing process and the vacuum-distillation process
- Document key nonproprietary system operating parameters
- Document remediation costs per metric ton of soil

The primary objectives were achieved by collecting representative samples of contaminated feed soil, treated soil, treated process water, and stack gas and other appropriate measurements during three test runs. QA/QC procedures were followed as specified in the approved QAPP.

4.2.5.3 Results and Conclusions

This section presents the conclusions of the Harbauer Bilateral SITE demonstration at Marktredwitz, Germany. The overall conclusion of the demonstration is that the Harbauer treatment system consistently reduced mercury concentrations in contaminated soil (sandy loam and loam) and construction debris (concrete and brick) from the CFM site from more than 1,000 mg/kg to less than 27 mg/kg. The soil processing rate ranged from 2.4 to 3.7 mt/h. Specific conclusions of the Harbauer treatment system demonstration are summarized below:

- The 95 percent upper confidence limit of mercury concentrations in treated soil for the three test runs were 24.0 mg/kg, 26.6 mg/kg, and 23.6 mg/kg.
- The mercury removal efficiencies achieved by the Harbauer treatment system for the three test runs were 97.6 percent, 97.7 percent, and 98.0 percent.
- TCLP-leachable mercury was reduced from an average of 82 µg/L to 6 µg/L. The TCLP regulatory level for mercury is 200 µg/L and the U.S. federal maximum contaminant level (MCL) for mercury is 2 µg/L
- The average mercury concentrations in the stack gas discharged to the atmosphere during the demonstration was 2.92 mg/Ncm at an average discharge rate of 30,300 Ncm/hr.
- Mercury concentrations in the treated process water discharged to the sewer during the three test runs were 4.39 µg/L, 5.80 µg/L, and 4.68 µg/L. These concentrations are close to the U.S. federal MCL for mercury of 2 µg/L.
- The mercury removal efficiencies achieved by the vacuum-distillation process for the three test runs were 98.7 percent, 98.4 percent, and 96.6 percent.

- The native moisture content of the contaminated soil from the CFM site ranged from 17.1 percent to 19.5 percent by weight. The moisture content of the dewatered soil from the soil washing process ranged from 19 percent to 37.4 percent by weight. The moisture content of the treated soil exiting the vacuum-distillation unit ranged from 0.00 to 0.03 percent by weight.

- Because all of the contaminated soil and construction debris was crushed to a fairly uniform size for this demonstration, the process did not significantly change the particle size distribution (break up coarser particles and create more fines) of the soils.

- The internal temperature of the soil dryer was 130 °C during the demonstration.

- The internal temperature of the vacuum-distillation unit ranged from 430 °C to 500 °C during the demonstration.

- During the demonstration, the Harbauer system processed soil at rates ranging from 2.4 to 3.7 mt/hr. The quantities of soil treated and operational time during the three test runs were 29.6 mt (8 hours), 20 mt (8 hours), and 14.4 mt (6 hours).

- Treated process water was discharged to the sewer at rates ranging from 2.9 to 10.3 m^3/hr. Quantities of treated process water discharged during the three test runs were 43.2 m^3, 82.4 cubic meters (m^3), 17.4 m^3, respectively.

- The cost for treating mercury contaminated soil from the CFM site is 870 DM/mt ($453/mt assuming a 1.92 DM to $1 exchange rate) based on an agreement between Harbauer and the client, Landkreis Wunsiedel. This cost covers half the cost of the facility (45,000,000 DM [$23,000,000]). Harbauer estimates that the cost for treating soil from other sites will be 480 DM/mt ($250/mt).

4.2.5.4 Vendor Contact

Dr. Winfried Groschel and Mr. Andreas Schmidt
Harbauer GmbH & Co KG
Flughafenstrasse 21
D-12053 Berlin, Germany
(030) 613730 0

4.2.6 Umweltchutz-Nord TERRANOX

The Umweltschutz-Nord (U-Nord) soil treatment system was used to treat soil from the Haynauerstrasse site in Berlin, Germany in 1994 (PRC 1993a). The soils are contaminated with high levels of petroleum hydrocarbons, aromatic hydrocarbons, and chlorinated hydrocarbons.

4.2.6.1 Process Description

The U-Nord soil treatment system is a two-step process whose main components are a TERRANOX bioreactor and a biopile (See Figure 11). The bioremediation process is a batch treatment with an individual batch capacity of approximately 60 cubic meters (about 100 mt).

TERRANOX Bioreactor

The TERRANOX bioreactor is a horizontal encapsulated system for soil treatment. It has a modular design and consists of a variable number of interconnected tank segments with covers. For the Haynauerstrasse demonstration, the bioreactor had a total length of approximately 40 m with only 30 m filled with soil. The system was 2.17 m high, with only 1.70 to 0.75 m filled, and 1.60 m wide.

Three longitudinal mixing shafts run through the bioreactor. These shafts include mixing blades that agitate the soil in each segment of the bioreactor continuously and intensively. The mixing blades can be moved longitudinally along the length of the bioreactor to mix each of the system segments. The rate of longitudinal motion of the mixing scraper through the tank segments can be varied using an adjustable frequency converter.

The TERRANOX system is fully automated with an electronic control and safety system that includes speed control, temperature probes, alternation switches, and an integrated automatic timer to allow for 24-hour operation. To control the balance of nutrient, pH, and microorganism levels in the soil for optimum biodegradation, the scraper is equipped with a dosing container and spray nozzles. The nozzles evenly distribute nutrients and calcium chloride (pH adjuster) within the soil material.

Emissions from the bioreator are controlled with (1) a biofilter containing approproximately 10 m^3 of a proprietary compost and (2) an activated carbon bed. This emission control system has a treatment capacity of off-gas of approximately 1,200 m^3/h.

Partially decontaminated soil that has been discharged from the TERRANOX bioreactor is placed into biopiles, which are usually 5 to 6 m long, 5 to 6 m wide, and 1.5 to 2 m deep. The total volume of a typical biopile is approximately 1,200 m^3. The biopiles are located in a large enclosed area equipped

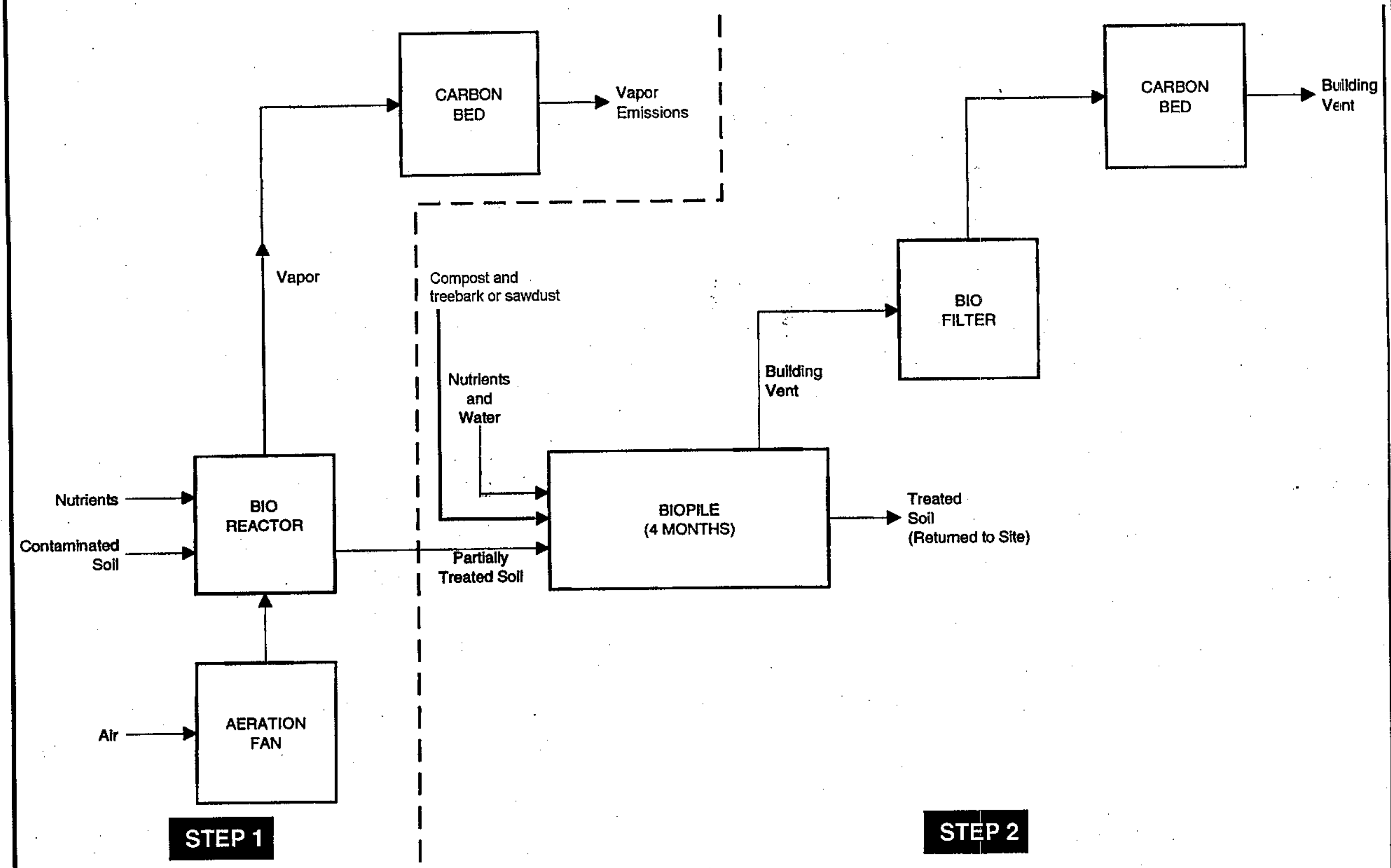


FIGURE 11

U-NORD SOIL TREATMENT SYSTEM PROCESS FLOW DIAGRAM with an off-gas treatment system for health and safety reasons. Approximately once per month the biopiles are turned over using a special device called a "mole." The turning process typically takes two days for one large biopile; however, the turning process for the demonstration biopile took less than 1 day. During this procedure, nutrients and water can be added to the soil, if required.

4.2.6.2 Demonstration Objectives and Approach

There was one primary objective and five secondary objectives in evaluating the U-Nord technology.

Primary Objectives:

- Measure the reduction efficiency at a confidence level of 95 percent for the following critical compounds:

  Benzene toluene
  Total xylenes
  Trichloromethane
  Dichloromethane
  1, 1, 1-TCA
  PCE
  TRPH

Secondary Objectives:

- Determine contaminant reductions at various stages of the treatment process
- Document key, nonproprietary system operating parameters and untreated soil characteristics
- Assess the presence of volatile and semivolatile organic biodegradation byproducts in the treated soil
- Document remediation costs per metric ton of soil
- Determine whether the treated soil meets the following Lower Saxony cleanup criteria:

Total Aromatic Hydrocarbons:	<0.2 mg/kg
Total Chlorinated Hydrocarbons:	<0.2 mg/kg
Total Petroleum Hydrocarbons:	< 500 mg/kg

4.2.6.3 Results and Conclusion

A preliminary review of the demonstration data indicated that the system, as operated during the evaluation period, did not achieve the demonstration objectives. Therefore, a detailed assessment of technology performance was not conducted.

4.2.6.4 Vendor Contacts

Carolin Beier
Umweltshutz Nord
Industriepark 6
2875 Ganderkesee, Germany
(0000) 4222-47-0

5.0 PHASE II DEMONSTRATION ACITIVITIES

Under Phase II of the Bilateral Agreement, 10 technologies were demonstrated and evaluated, including 5 technologies in the U.S. and 5 technologies in Germany. Technology evaluations occurring in the U.S. correspond to EPA SITE demonstrations; those occurring in Germany corresponded to full-scale site remediation activities. SITE Program quality management protocols were reviewed and used to develop a German equivalent, the DETAD. Both quality management protocols were applied to the Phase II technology evaluations. These evaluations are currently under review; results and conclusions were not yet available. The final report will include these results.

5.1 RESULTS OF PHASE II U.S. DEMONSTRATION ACTIVITIES

Five technologies were demonstrated and evaluated in the United States as part of Phase II of the Bilateral Agreement. This report describes the technology process; summarizes the demonstration objectives, results, and conclusions; and provides vendor contact information for each technology. The following U.S. technologies were evaluated as part of Phase II of the Bilateral Agreement:

- Earth Tech Enhanced In Situ Bioremediation
- ETI Reactive Media
- GII Electroheat-Enhanced Product Removal
- RMRS and Star Organics Soil Amendment Technologies
- KSE Photocatalytic Reactor

5.1.1 Earth Tech Inc., In Situ Bioremediation

The enhanced In-Situ Bioremediation Process of Earth Tech, Inc. (Earth Tech) was demonstrated at the ITT Night Vision facility in Roanoke, Virginia (Science Applications International Corporation 1998). The technology, licensed to Earth Tech by the Department Of Energy Savannah River, demonstrated the ability to degrade chlorinated volatile compounds in the groundwater downgradient of the source. In addition to chlorinated volatile compounds, the destruction of acetone and isopropyl alcohol were investigated as part of this demonstration.

5.1.1.1 Process Description

The primary components of the enhanced in situ bioremediation system consist of an injection well, monitoring wells, soil vapor monitoring points, and air injection equipment. The injection well is designed to deliver air, nutrients, and methane to groundwater in the shallow bedrock 30 to 50 feet below ground surface. Monitoring wells are located upgradient, downgradient, and laterally from the injection location in order to monitor groundwater quality surrounding the in situ system. These wells are constructed to allow for conversion from monitoring wells to injection wells as needed. Soil vapor monitoring points are installed in the injection area and adjacent areas to monitor the vapors present in the overburden. If elevated amounts of vapor phase VOCs, methane, or nutrients accumulate in the overburden due to injection operations, these soil vapor monitoring points are converted to soil vapor extraction points. A compressor, monitored with pressure and flowrate controls, supplies air for injection. Gaseous phase nutrients and methane are added to the air stream during a series of testing cycles. Earth Tech implemented their own internal analytical program to document initial conditions, monitor the system during testing, and provide data to determine optimal system performance as the testing phases conclude.

A process schematic for the injection system is shown in Figure 12. The injection system includes a compressor, pressure and flow controls, and manifolds for nutrient and methane addition. The compressor is capable of delivering 15 to 30 pounds per square inch (psi) and approximately 20 standard cubic feet per minute (scfm) to the injection well. The compressor includes a condensate tank and drain, air line and coalescing filters, pressure relief valve, and appropriate pressure regulators and controls.

During air- or nutrient-only injection phases, the system is controlled manually with system pressure and flow control valves. Pressure relief valves are set to prevent pressure conditions.

During methane injection phases, the system is controlled using a programmable logic controller (PLC), with automatic shut off and system alarms for elevated methane conditions. Pressure gauges and valved flow meters is installed to monitor and control injection parameters. All switches and valves are normally closed to prevent power failure induced above the lower explosive limit (LEL). In addition, the valving on the methane injection line is constructed in a manner that it cannot be physically opened past the LEL.

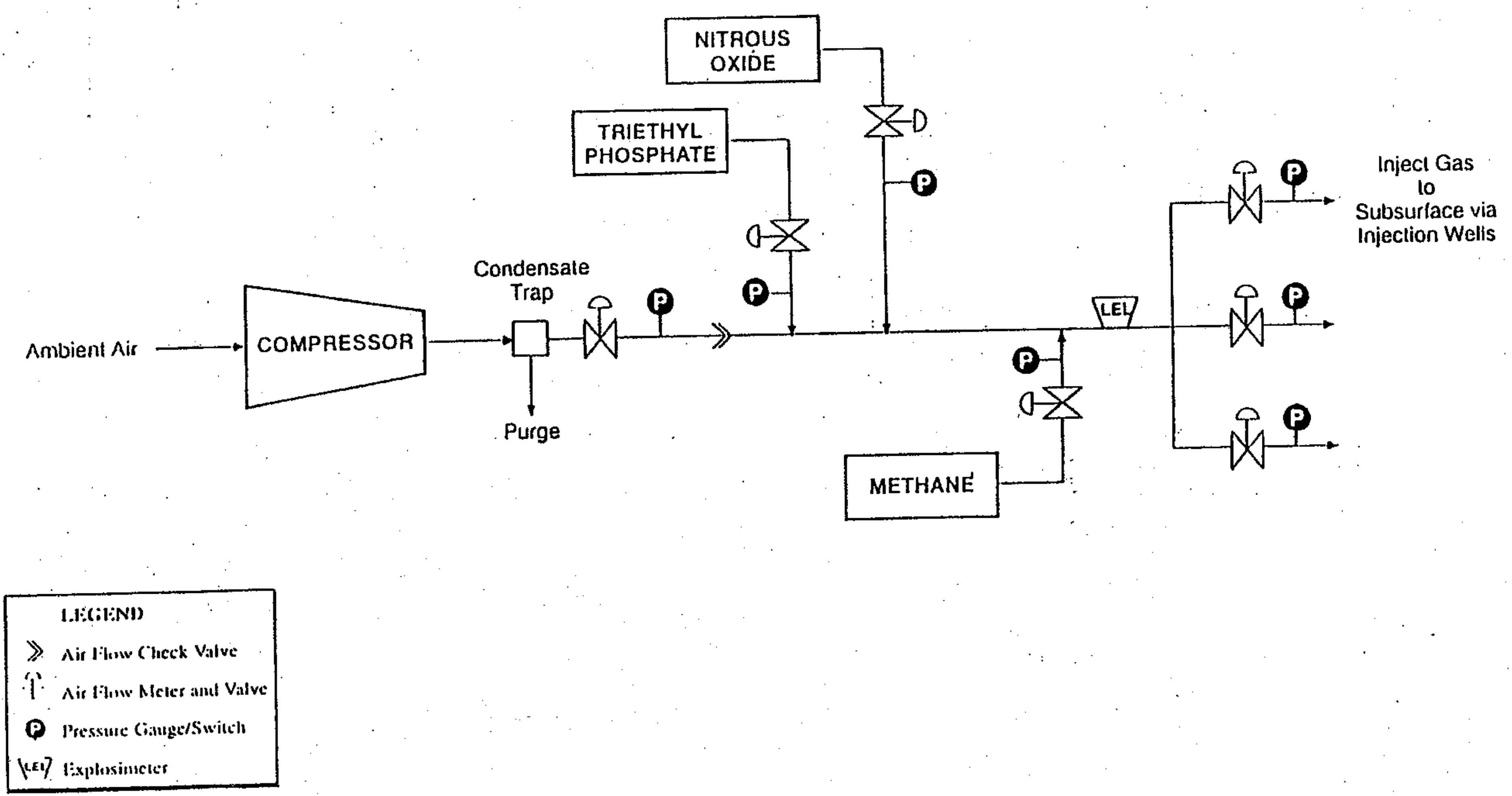


FIGURE 12

EARTH TECH, INC. INJECTION SYSTEM PROCESS SCHEMATIC

5.1.1.2 Demonstration Objectives and Approach

There was one primary objective and six secondary objectives in evaluating the Earth Tech in situ enhanced bioremediation technology.

Primary Objectives:

- Evaluate the following vendor claim: On average, there will be a 75 percent reduction (with a 90 percent confidence interval) in the groundwater concentrations of each of the individual target chlorinated VOCs after 6 months of treatment. Target analytes include: DCA, chloroethane (CA), cis-1,2-dichloroethene (DCE), and vinyl chloride (VC).

Secondary Project Objectives:

- Evaluate changes (baseline to final) in detectable chlorinated VOCs, acetone, and isopropyl alcohol, as a result of the methanotrophic process, in seven individual wells within the study area.
- Evaluate changes in detectable chlorinated VOCs, acetone, and isopropyl alcohol at two intermediate events during the 6-month treatment.
- Determine the presence and extent (if any) of chlorinated VOCs, acetone, and isopropyl alcohol in vadose zone soil gas that may be attributable to the injection of gas-phase amendments into the saturated zone.
- Evaluate changes in detectable chlorinated VOCs, acetone, and isopropyl alcohol in the shallow zone of the aquifer in order to determine if these compounds are being sparged into the upper portions of the aquifer due to the injection of gas-phase amendments.
- Track changes in the microbial community (throughout the six-month demonstration) in groundwater samples, as an indicator of microbial activity within the solid-phase of the aquifer.
- Characterize changes in groundwater characteristics that may affect, control, or be modified by process performance over the course of the demonstration, including nutrients, total organic carbon (TOC), total inorganic carbon, dissolved gases (methane, ethane, and ethene), iron, oxygen concentration, oxidative-reduction potential, and pH.
- Collect and compile information pertaining to the cost of implementating of the bioremediation technology to clean up of VOC-contaminated sites similar to the ITT-Night Vision site.

Process performance was evaluated by comparing average concentrations for each of the analytes of concern from a baseline sampling event immediately before system start-up to a final sampling event after 6 months of treatment. In addition, intermediate sampling events were used to determine changes in groundwater contaminants and characteristics from various technology processes over time. QA/QC procedures were followed as specified in the approved QAPP.

5.1.1.3 Results and Conclusions

Demonstration data are currently under evaluation; and results and conclusions are not yet available for inclusion in this report.

5.1.1.4 Vendor Contacts

Barbara Buckley Lemos
Earth Tech, Inc.
Project Manager
Boston, Massechussettes
(978) 371-4119

5.1.2 ETI Reactive Media

The Reactive Media technology was developed and patented by EnviroMetal Technologies Inc. (ETI) of Waterloo, Canada, to treat metals and VOCs in water. The Reactive Media demonstrated its effectiveness in reducing the concentrations of uranium and VOCs in Mound Site Plume groundwater at the Rocky Flats Environmental Technology Site (RFETS) in Golden, Colorado (Tetra Tech 1998c).

5.1.2.1 Process Description

The Reactive Media technology is an innovative treatment system that uses the oxidation capacity of zero-valent iron to induce reductive dechlorination of chlorinated VOCs and to immobilize some metals, such as uranium, in groundwater. The technology is based on an electrochemical process.

The technology may be used for in situ or ex situ treatment of groundwater. In situ systems may be contained in subsurface vessels to facilitate maintenance access to the reactive iron medium. In situ systems may also be deployed as permeable reactive iron walls constructed directly across the path of groundwater flow, combining the benefits of both containment and treatment systems.

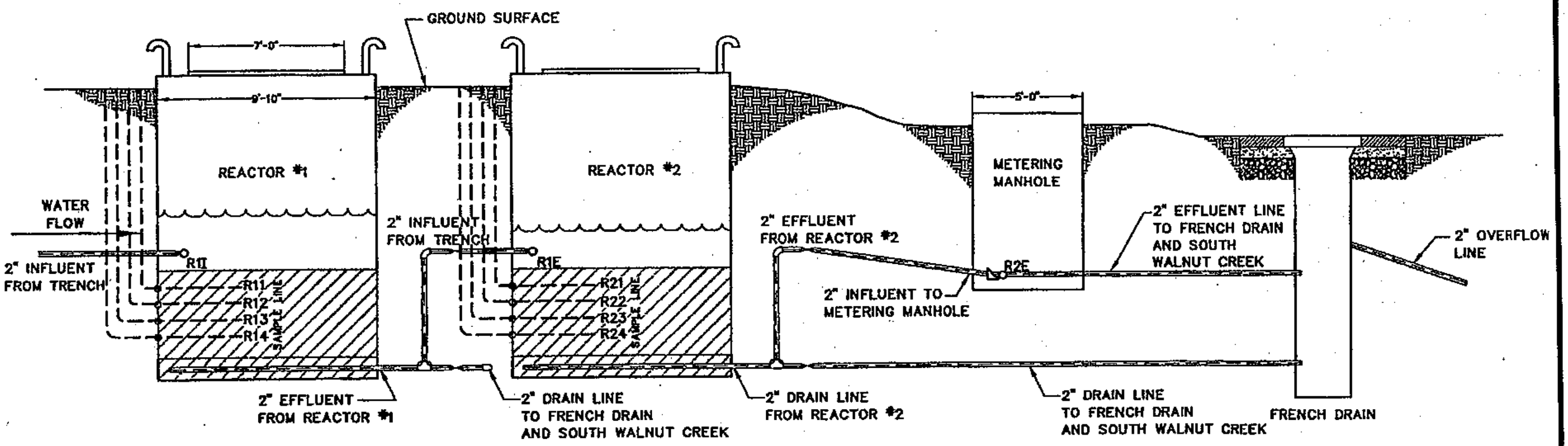
Figure 13 is a schematic diagram of the Reactive Media treatment system at RFETS. A subsurface hydraulic barrier (French drain) and piping system was coupled with a passive zero-valent iron treatment system to treat groundwater from the Mound Site Plume. The French drain was installed in the path of the migrating contaminant plume in the shallow, unconfined aquifer to depths ranging from 8 to 15 feet below ground surface. The drain diverts groundwater flow to piping that transfers it by gravity to the Reactive Media treatment system. Flows to the system were anticipated to range between 0.1 and 2 gallons per minute (gpm) and to average 0.5 gpm. The treatment system consists of two reactors installed in series, below grade. Each reactor contains 377 cubic feet of granular, reactive (zero valent) iron. As groundwater flows by gravity through the reactive iron, chlorinated VOCs are sequentially dechlorinated, ultimately to nonchlorinated hydrocarbons, and uranium in the oxidized state (U^{6+}) is converted to uranium in the reduced state (U^{4+}) and precipitated within the rector. The treatment system has been sized to provide a residence time for groundwater in each reactor of 20 hours at a flow rate of 1 gpm. ETI conservatively estimated that 20 hours of residence time within the reactor would be required to reduce VOC concentrations in the Mound Site Plume groundwater to the required limits. Groundwater flows from Reactor 1 to Reactor 2 at all times, the groundwater flow was only sampled when the flow through the system exceeded 1 gpm. Treated groundwater exits the system directly into a French drain located adjacent to South Walnut Creek.

5.1.2.2 Demonstration Objectives and Approach

There were two primary objectives and four secondary objectives in evaluating the ETI Reactive Media technology.

Primary objectives:

- Demonstrate a contaminant removal efficiency (CRE) for the Reactive Media system for the following critical parameters: carbon tetrachloride; trichloromethane; dichloromethane; tetrachloroethene; TCE; cis-1,2-dichloroethene; 1,1- dichloroethene; TCA; and VC of 95



LEGEND

▨ REACTIVE IRON
○ SAMPLE LOCATION
﹏ WATER LINE
– – – SAMPLE LINE

NOT TO SCALE

FIGURE 13
ETI REACTIVE MEDIA PROCESS FLOW DIAGRAM

percent or higher at a confidence level of 90 percent; and demonstrate a CRE for the critical parameter total uranium of 90 percent or higher at a confidence level of 90 percent.

- Demonstrate that the Reactive Media system reduces the concentrations of carbon tetrachloride, trichloromethane, dichloromethane, tetrachloroethene, TCE, cis- 1,2-dichloroethene, 1, 1-dichloroethene, TCA, and VC to Colorado Water Quality Standards for Segment 5 of Big Dry Creek as required by the Rocky Flats Cleanup Agreement (RFCA) at a 90 percent confidence level, and demonstrate that the system reduces the concentration of total uranium to surface water standards required by the RFCA at a 90 percent confidence level.

Secondary objectives:

- Document geochemical characteristics in water of pH, Eh, dissolved oxygen (DO), temperature, electrical conductivity, anions, and cations
- Document the volume of water treated by the system during each sampling interval
- Document production of dissolved gases which may be breakdown products of the dehalogenation process
- Estimate the capital and operating costs of constructing and maintaining an in situ Reactive Media treatment system

These objectives were achieved by monitoring the in situ Reactive Media treatment for a period of 1 year. QA/QC procedures were followed as specified in the approved QAPP.

5.1.2.3 Results and Conclusions

Demonstration data are currently under evaluation; results and conclusions are not yet available for inclusion in this report.

5.1.2.4 Vendor Contacts

John Vong
Environmenttal Technologies Inc.
Guelph, Ontario, Canada
(509) 824-0432

5.1.3 GII Electroheat-Enhanced Product Removal

Electroheat-enhanced product removal is an innovative technology developed by Geokinetics International, Inc. (GII). The technology was evaluated to remove viscous fuel oil product from subsurface soils at the Millican field area near Quarry Loch at Pearl Harbor Naval Base (NAVBASE) on the island of Oahu, Hawaii. The GII technology was demonstrated from October 1998 through April 1999 (Tetra Tech 1998a).

5.1.3.1 Process Description

Thermal enhancement is one method to improve performance of conventional belt skimming and vacuum-enhanced belt skimming technologies in removing LNAPLs, particularly heavy fuel oils, from the subsurface. By increasing the subsurface soil and groundwater temperature, GII claims it will be able to reduce the viscosity, increase the effective hydraulic permeability, and increase the mobility of the LNAPL.

To accomplish this thermal enhancement, GII used AC resistance heating (electroheat-enhancement) to warm the subsurface soil around the recovery well and extract the mobilized LNAPL. During the technology demonstration, GII used proprietary metal electrodes with metallic conductors placed directly into the ground. Three-phase AC was used, and each electrode was connected to a single phase of a delta supply in a series of interlocking triangles. The ground-groundwater matrix then formed the connection between the phases, and the resistance of the matrix forms the heating element. GII claims it uses direct AC resistance heating for the following reasons:

- It is the most energy efficient. Conversion of electrical energy to heat energy occurs directly within the soil matrix, and heat conversion efficiencies are 96 to 98 percent
- Excessive temperature gradients are avoided
- Equipment and deployment are relatively simple and are based on proven industrial components, which improves project safety
- The presence of preferential hydraulic flow paths in the soil is not as important when soils are heated electrically. As soil and groundwater are exposed to electrical current, the soil is heated relatively homogeneously
- By using electrode housings that allow the injection of water, warm water extracted as part of the process can be reinjected into soil after being run through an oil-water separator, minimizing heat loss

5.1.3.2 Demonstration Objectives and Approach

There were two primary objectives and five secondary objectives in evaluating the Geokinetics Electroheat-Enhanced Product Removal technology.

Primary Objectives:

- Estimate removal efficiency for GII's electroheat-enhanced technology for treatment of TPH within the electroheat-enhanced treatment zone.

- Evaluate if the electroheat-enhanced product removal technology caused product in the subsurface to migrate vertically.

Secondary Objectives

- Evaluate the temperature influence of the electrode array for the electroheat-enhanced product removal system.
- Evaluate the influence of the electroheat-enhanced product removal on water levels in nearby wells HC-2 and HC-3.
- Document the volume of product recovered during each technology demonstration and estimate the average recovery rate.
- Document operating parameters of the technology.
- Estimate capital and operating costs for the technology.

These objectives were achieved by sampling and monitoring the demonstration test site over a 28-week test period. QA/QC procedures were followed as specified in the approved QAPP.

5.1.3.3 Results and Conclusions

Demonstration data are currently under evaluation; results and conclusions are not yet available for inclusion in this report.

5.1.3.4 Vendor Contacts

Stephen Clarke
Geokinetics International, Inc.
829 Heinz Street
Berkeley, California 94710
(510) 704-2940

5.1.4 RMRS and Star Organics Soil Amendment Technologies

Two soil amendment technologies were evaluated under this demonstration. Rocky Mountain Remediation Services, L.L.C. (RMRS) of Golden, Colorado, has developed the Envirobond™ process, a soil amendment technology, to treat soil contaminated with metals. RMRS claims that Envirobond™ converts each metal contaminant from its leachable form to an insoluble, stable, nonhazardous, metallic complex (Tetra Tech 2000b). Star Organics, L.L.C. (STAR), of Forney, Texas, has also commercialized a soil amendment technology (Soil Rescue) to treat soil contaminated with metals. STAR similarly claims that Soil Rescue converts each metal contaminant from its leachable form to an insoluble, stable, nonhazardous, metallic complex (Tetra Tech 2000c) The technologies were demonstrated at two separate sites in Roseville, Ohio, in September 1998. For the demonstration, the Soil Rescue and Envirobond™ processes were applied to 10 experimental units at the American Legion Trailer Park (VFW) site and one experimental unit at the Friendship Pottery I (FS1) site.

5.1.4.1 Process Description

Envirobond™

Envirobond™ is a combination of a proprietary powder and solution that binds with metals in contaminated soils and other wastes. RMRS claims that the treatment process effectively prevents metals from leaching and can be used with mechanical compaction to reduce the overall volume of contaminated media by 30 to 50 percent. The process generates no secondary wastes and involves minimal handling, transportation, and disposal costs. In addition, unlike some pozzolanic-based reagents, the Envirobond™ liquid and powder are safe to handle and do not generate any emissions.

Envirobond™ consists of a mixture of additives containing oxygen, sulfur, nitrogen, and phosphorous; each additive has an affinity for a specific class of metals. RMRS claims that Envirobond™ converts each metal contaminant from its leachable form to an insoluble, stable, nonhazardous metallic complex. Envirobond™ is essentially a mixture of ligands that act as chelating agents. In the chelation reaction, coordinate bonds attach the metal ion to at least two ligand nonmetal ions to form a heterocyclic ring. The resulting ring structure is inherently more stable than simpler structures formed in many binding processes. RMRS claims that, by effectively binding the metals, the process reduces soil TCLP metal concentrations to less than regulated levels, subsequently reducing the risks posed to human health and the environment.

Envirobond™ can be deployed as an in situ or ex situ treatment process. RMRS reports that the Envirobond™ process is capable of achieving processing rates of 20 to 40 tons per hour for ex situ treatment and can be used with contaminated media containing as much as 10 percent debris.

Soil Rescue

The Soil Rescue process is a soil amendment technology in which a remediation fluid is added to soils or wastes contaminated with toxic metals. Mixing of the remediation fluid into the soil or waste allows it to bond and immobilize selected toxic metals.

The Soil Rescue remediation fluid is an alkaline solvent made by a proprietary method involving the extraction of organic acids and alcohols, and the formation of phosphoryl esters, in a batch process. Raw materials for the proprietary extractant include a medley of compost sources, which are extracted in a ratio that STAR has tested and found to provide the widest spectrum, and highest concentration, of desirable complexing components. STAR claims that Soil Rescue converts the metal contaminant from its leachable form to an insoluble, stable, nonhazardous, organo-metallic complex. The Soil Rescue remediation fluid is essentially a mixture of ligands that act as chelating agents. In the chelation reaction, coordinate bonds attach the metal ion to at least two ligand nonmetal ions to form a heterocyclic ring. STAR claims that by effectively binding the metals, the process reduces soil TCLP metal concentrations to less than the regulated levels, thereby reducing the risks posed to human health and the environment. The process generates no secondary wastes and requires minimal handling, transportation, and disposal costs.

5.1.4.2 Demonstration Objectives and Approach

There were two primary objectives and four secondary objectives in evaluating the Envirobond™ technology.

Primary Objectives (Envirobond™):

- Demonstrate that the Envirobond™ process can decrease the bioavailability of lead in soil by 25 percent or higher at a confidence level of 90 percent, as defined by an in vitro physiologically based extraction test (PBET).
- Evaluate whether the Envirobond™ process can remediate soil at a site to meet the Resource Conservation and Recovery Act (RCRA)/Hazardous and Solid Waste Act (HSWA) lead nonwastewater Universal Treatment Standard (UTS) for D008 Characteristic Waste of 0.75 mg/L TCLP lead at a confidence level of 90 percent. The Envirobond™ process will also be evaluated to determine if the TCLP lead concentrations were reduced by at least 90 percent, or below 10 times the UTS to meet the alternative Land Disposal Restriction treatment standards for contaminated soil as specified in 40 Code of Federal Regulations (CFR) 268.49.

Secondary Objectives (Envirobond™):

- Demonstrate the long-term stability of the treated soil
- Demonstrate that the application of the Envirobond™ process does not increase the risk of public health and worker exposure to lead
- Document geophysical conditions in the soil before applying the Envirobond™ process
- Document operating and design parameters of the soil amendment technology

For this demonstration, soil samples were taken before and after application of the Envirobond™ binding agent in order to evaluate whether the technology could achieve the treatment goals of this demonstration project. QA/QC procedures were followed as specified in the approved QAPP.

There were two primary objectives and four secondary objectives in evaluating the Soil Rescue technology.

Primary Objectives (Soil Rescue):

- Demonstrate that the Soil Rescue technology can decrease the bioavailability of lead in soil by 25 percent or higher at a confidence level of 90 percent, as defined by an in vitro PBET.

- Evaluate whether the STAR Soil Rescue technology can remediate soil at an industrial site to meet the RCRA/HSWA lead nonwastewater UTS for D008 Characteristic Waste of 0.75 mg/L TCLP Lead at a confidence level of 90 percent. The technology also will be evaluated to determine if the TCLP lead concentrations were reduced by at least 90 percent, or below 10 times the UTS to meet the alternative Land Disposal Restriction treatment standards for contaminated soil as specified in 40 CFR 268.49.

Secondary Objectives (Soil Rescue):

- Demonstrate the long-term stability of the treated soil
- Demonstrate that the application of the remediation fluid does not increase the risk of public health and worker exposure to lead
- Document geophysical conditions in the soil before adding the remediation fluid
- Document operating and design parameters of the remediation fluid

These objectives were evaluated by collecting and analyzing soil samples before and after the Soil Rescue treatment was applied. Primary objective 1 was evaluated at the VFW site. Primary objective 2 was evaluated at FS1 site (samples were also collected from the VFW site, but not analyzed as a primary objective). QA/QC procedures were followed as specified in the approved QAPP.

5.1.4.3 Results and Conclusions

The following items summarize the significant results of the Envirobond™ process demonstration:

- Based on the analysis of the data, the Envirobond™ process did not reduce the relative percent bioavailable lead by at least 25 percent. The Envirobond™ process did reduce the relative percent bioavailable lead by approximately 12.1 percent. Additionally, the Envirobond™ process reduced the concentration of the soluble lead in the PBET extract by 39.1 percent. However, the EPA, at this time, does not endorse an in vitro test for determining lead bioavailability.
- The data analysis also shows that the Envirobond™ process did not reduce the TCLP lead concentration to below the UTS of 0.75 mg/L. The technology did reduce the mean TCLP lead concentration from 382 mg/L to 1.6 mg/L. Therefore, the TCLP lead concentrations were reduced by at least 90 percent, or below 10 times the UTS to meet the alternative Land Disposal Restriction treatment standards for contaminated soil as specified in 40 CFR 268.49.
- Long-term stability of the soil treated by the Envirobond™ process is suggested by the results from the multiple extraction procedure (MEP, lead speciation using scanning electron microscopy, lead speciation using sequential extraction, and cation exchange capacity analytical procedures. The acid neutralization capacity results only indicate long-term stability of the treated soil at the VFW site. Long-term stability of the treated soil was not

suggested by the results from the synthetic precipitation leaching procedure, pH, and Eh analytical procedures.

- As demonstrated by the air monitoring analytical results, lead exposure was not increased due to the dust generated by demonstration activities. Therefore, the public health and worker exposure is not expected to increase as a result of dust emissions while remediating the residential and industrial sites using the Envirobond™ process.

- Using information obtained from the SITE Demonstration, RMRS, and other sources, an economic analysis examined 12 cost categories for a scenario in which the Envirobond™ process was applied at full scale to treat lead contaminated soil at a one-acre site (807 cubic yards) within the Crooksville/Roseville Pottery Area of Concern (CRPAC). The cost estimate assumed that the lead concentrations in the soil were the same as those encountered during the Roseville Demonstration. Based on these assumptions, the cost was estimated to be $36.93 per cubic yard of treated soil. However, cost for using this technology is site specific.

The following items summarize the significant results of the Soil Rescue demonstration:

- Based on the analysis of the data, the Soil Rescue technology did not reduce the relative percent bioavailable lead by at least 25 percent. The Soil Rescue technology did reduce the relative percent bioavailable lead by approximately 2.9 percent. Additionally, the Soil Rescue technology did not reduce the concentration of the soluble lead in the PBET extract. However, the EPA at this time, does not endorse an in vitro test for determining lead bioavailability.

- The data analysis also shows that the Soil Rescue technology did not reduce the TCLP lead concentration to below the UTS of 0.75 mg/L. The technology did reduce the average TCLP lead concentration from 403 mg/L to 3.28 mg/L. Therefore, the TCLP lead concentrations were reduced by at least 90 percent, or below 10 times the UTS to meet the alternative Land Disposal Restriction treatment standards for contaminated soil as specified in 40 CFR 268.49.

- Long-term stability of the soil treated with the Soil Rescue technology is suggested by the analytical results from the MEP lead, lead speciation using electron microprobe, lead speciation using sequential extractions, and cation exchange capacity analytical procedures.

- As demonstrated by the air monitoring analytical results, lead exposure was not increased by the dust generated during demonstration activities. Therefore, the public and workers' health risk is not expected to increase as a result of dust emissions while remediating the residential and industrial sites using the Soil Rescue technology.

- Using information obtained from the SITE demonstration, STAR, and other sources, an economic analysis examined 12 cost categories for a scenario in which the full-scale Soil Rescue technology was applied to treat lead contaminated soil at a 1-acre site (807 cubic yards) within the CRPAC. The cost estimate assumed that the lead concentrations in the soil were the same as those encountered during the Roseville Demonstration. Based on these assumptions, the cost was estimated to be $40.27 per cubic yard of soil treated. However, total cost for using this technology is site specific.

5.1.4.4 Vendor Contacts

James Barthel
Rocky Mountain Remediation Services, LL.C.
1819 Denver West Drive
Building 26, Suite 200
Golden, CO 80401
(303) 215-1103

Kevin Walsh
Star Organics
5 Mustang Circle
Forney, TX 75126
(972) 552-1423

5.1.5 KSE Photocatalytic Reactor

The KSE Inc. (KSE) photocatalytic reactor demonstration at the Stamina Mills Superfund site in North Smithfield, Rhode Island, was conducted to evaluate the technology's effectiveness in removing TCE from soil and groundwater stripper off-gases without producing hazardous by-products (Tetra Tech 1999c).

5.1.5.1 Process Description

The KSE AIR-II process combines two unit operations, adsorption and chemical reaction, to treat air streams containing dilute concentrations of VOCs. The chemical and physical processes involved in the AIR-II treatment technology are described below.

Process Chemistry

In the KSE technology, a contaminated air stream containing VOCs flows into a photocatalytic reactor that destroys chlorinated and nonchlorinated VOCs. VOCs are trapped on the surface of a proprietary catalytic adsorbent that is continuously illuminated with ultraviolet light. The ultraviolet light destroys the adsorbed, concentrated VOCs through enhanced photocatalytic oxidation. The system design simultaneously destroys VOCs and continuously regenerates the catalytic adsorbent. The only necessary reactant is oxygen, which is present in the air stream.

Treated effluent contains carbon dioxide and water, both of which exit the system in the air stream from the reactor. For chlorinated VOCs such as TCE, chlorine atoms are converted primarily to hydrogen chloride gas with some chlorine gas also being formed. The formation of these reaction products is based on the estimated laboratory and field data. Using TCE as an example, approximately 2.55 molecules of hydrogen chloride gas (HCl) would be formed for every TCE molecule entering the AIR-II unit. These reaction products can be removed from the air stream with conventional scrubbers and adsorbents.

KSE claims that the AIR-II process offers advantages over other photocatalytic technologies because of the high activity, stability, and selectivity of the photocatalyst. The particulate-based photocatalyst contains various types of semiconductors that rapidly and economically treat VOCs in air. Previous results indicate that the photocatalyst is highly resistant to deactivation, even after thousands of hours of operation in the field.

Physical Process Description

A dual-phase extraction system that extracts both contaminated vapors and groundwater was constructed at the site in order to treat the TCE contamination found in both the overburden soil and weathered portions of the bedrock. The SVE system, which consists of 26 wells installed in the overburden, is designed primarily to remove contaminated vapors. The multi phase extraction (MPE) system, which consists of 31 wells installed into the saprolite/fractured bedrock, treats both contaminated vapors and groundwater. The original KSE AIR-II photocatalytic reactor installed and tested during 1998, was replaced with an entirely new unit. A simplified schematic of the system layout, depicting the major unit operations and sampling locations, is shown in Figure 14.

While the system is operating, contaminated air is drawn from either the soil gas extraction wells, from the groundwater stripper, or simultaneously from both. Physical site conditions, such as the elevation of the groundwater and contaminant concentrations in both the overburden and fractured bedrock influence the makeup of the air source to the AIR-II unit. The nominal flow rate to the AIR-II unit is 700 scfm. The contaminated air passes through a cooler and is fed to the AIR-II unit. Treated vapor is introduced to a waterscrubber to remove hydrogen chloride gas and then polished in an activated carbon adsorption unit. The scrubber and activated carbon system are off-the-shelf items and not a part of the AIR-II technology being evaluated as a part of the SITE demonstration. Due to HCl formation, the SITE economic analysis of the technology at this site includes the cost of the scrubber; the regulated analytes were measured after the scrubber to determine whether their concentrations meet State of Rhode Island standards.

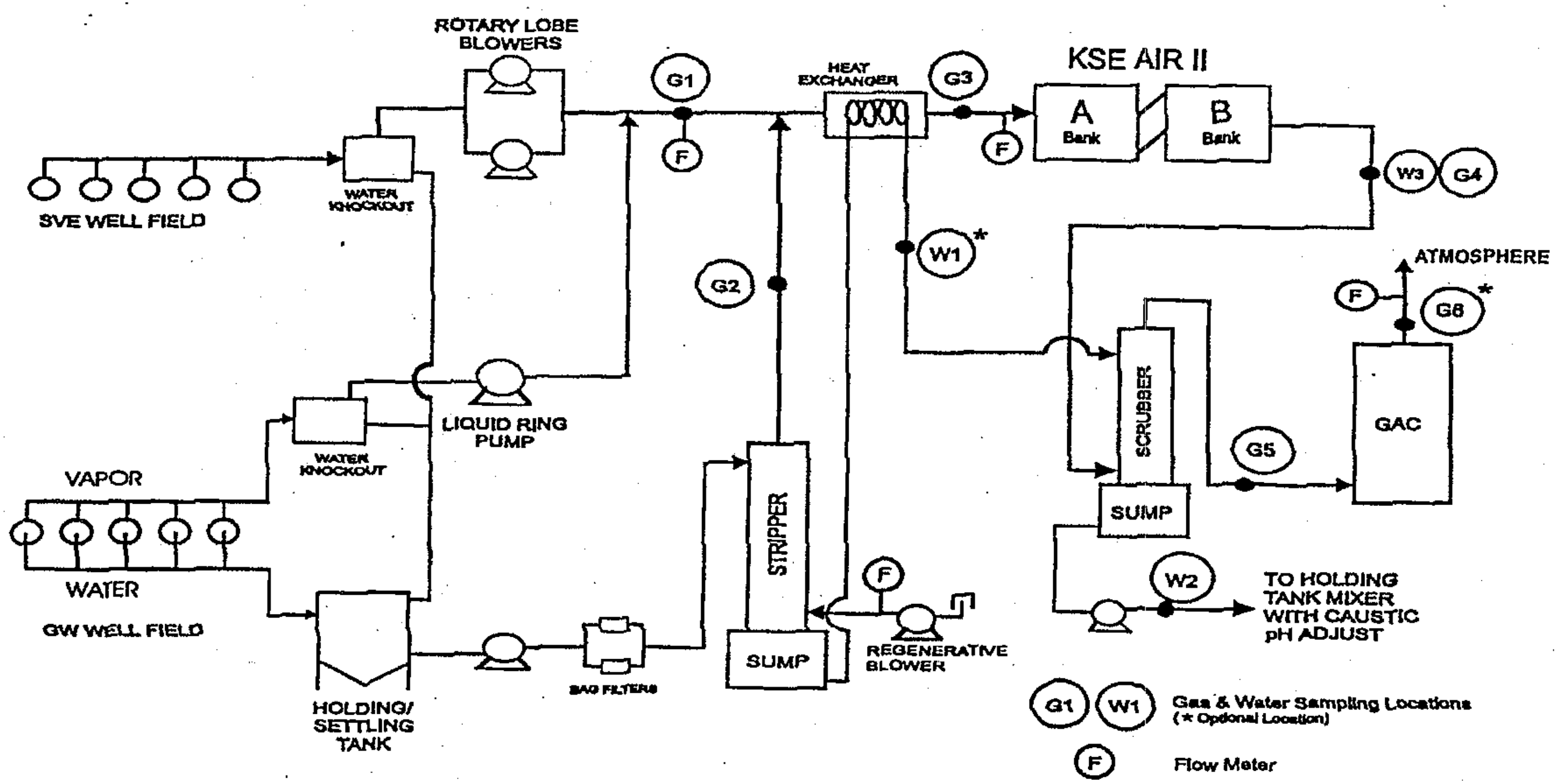


FIGURE 14

SCHEMATIC OF KSE TREATMENT SYSTEM AT THE STAMINA MILLS SITE

5.1.5.2 Demonstration Objectives and Approach

There were three primary objectives and five secondary objectives in evaluating the KSE technology.

Primary Objectives

- Demonstrate the KSE AIR-II reactor design objective of a TCE CRE of 95 percent or higher at a confidence level of 90 percent. The average and range of CREs that the KSE reactor achieves for TCE will be reported
- Demonstrate that the TCE and chloroform emissions from the scrubber that follows the AIR-II reactor meet the Rhode Island emission standards at a 90 percent confidence level
- Demonstrate whether the KSE AIR-II unit effectively degrades TCE and that the activity of the photocatalyst remains constant over an extended time period

Secondary Objectives

- Document the operating conditions of the AIR-II system, including gas-stream flow rates, pressure, electrical consumption, sodium hydroxide consumption, and influent and effluent reactor temperatures, based on data obtained during the demonstration or by data and calculations of input TCE concentrations
- Document the capital and operating costs of the AIR-II system, including electric consumption, sodium hydroxide consumption, and other costs, based on observations during the demonstration and data supplied by the on-site operator and technology developer
- Evaluate photocatalyst selectivity by identifying and estimating the concentration of any non-target VOCs in the untreated and treated gases that may be byproducts of the treatment process or otherwise present
- Determine TCE concentration in the various process gas and water streams
- Demonstrate that the AIR-II unit achieves an overall VOC removal efficiency of 95 percent or greater

Changes in the project objectives and the sampling and analysis plans were instituted to address the problems and limitations encountered in the initial phase of tests. To achieve these objectives, samples were collected and the system was monitored during a 3 month period. QA/QC procedures were followed as specified in the approved QAPP.

5.1.5.3 Results and Conclusions

Demonstration data are currently under evaluation; results and conclusions are not yet available for inclusion in this report.

5.1.5.4 Vendor Contacts

Jim Kittrell
KSE, Inc.
655 Amherst Road
Sunderland, Massachusetts 01375
(413)549-5506

5.2 RESULTS OF PHASE II GERMAN DEMONSTRATION ACTIVITIES

Five technologies were demonstrated and evaluated in Germany during Phase II of the Bilateral Agreement (see Figure 15). This report describes the technology process; summarizes the demonstration objectives, results, and conclusions; and provides vendor contact information for each technology. The Following German technologies were evaluated as part of Phase II:

- VEGAS Surfactant-Enhanced Extraction
- Pranter Catalytic Oxidation
- Plambeck ContraCon Bioremediation System
- Mull & Partner Reactive Barrier
- SWD Biological Groundwater Treatment

5.2.1 VEGAS Surfactant-Enhanced Extraction

Surfactants and other chemicals have recently been applied as enhancements to conventional soil flushing technology to accelerate the in situ extraction of contaminants from the saturated zone. In conventional soil flushing, water is circulated through a contaminated zone to wash out chemical contaminants. The use of surfactants in the circulated water can increase the mobility or solubility of

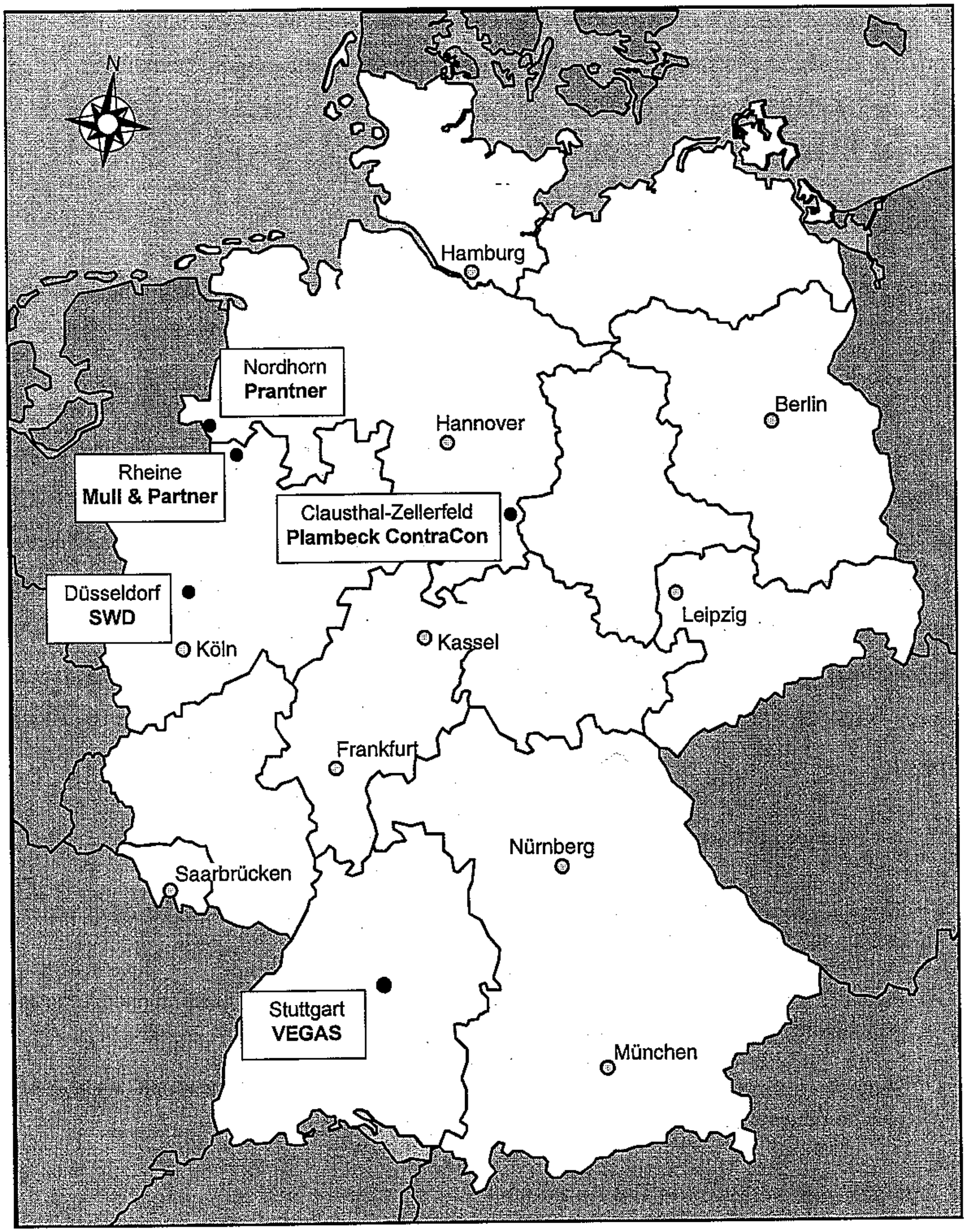


FIGURE 15

MAP OF PHASE II DEMONSTRATION SITES - GERMANY

many organic contaminants, including particularly non-aqueous phase liquids (NAPLs), further facilitating extraction. Specifically, surfactants can disperse and solubilize NAPLs through the formation of micelles. The bilateral SITE demonstration of the surfactant-enhanced extraction technology was conducted at the VEGAS research facility in Stuttgart, Germany from February 28 through March 5, 1998 (Tetra Tech 2000a).

5.2.1.1 Process Description

The specific surfactant-enhanced extraction technology tested during this bilateral SITE demonstration employs a proprietary mixture of anionic and nonionic surfactants developed by BASF AG (BASF).

At the VEGAS research facility, xylene, an organic contaminant with low solubility in water, was injected into an artificial aquifer and groundwater flow was induced to stimulate a contaminant plume. The surfactant-enhanced extraction technology was then applied to remove the xylene contaminant from the artificial aquifer. A simplified flow diagram of the surfactant-enhanced extraction system that was installed at the VEGAS facility is shown in Figure 16. In the hydraulic flow scheme shown in Figure 16, surfactant solution is injected through MW 6 and extracted through MW 3. After processing in the surfactant recovery system to remove the extracted xylene and to separate the surfactant, the extracted groundwater is recycled to supply the hydraulic control wells (MW2 and MW 5) as well as the injection well (MW6).

The surfactant enhanced extraction technology is implemented in three phases:

- Phase 1 - groundwater flow in the artificial aquifer with injection and extraction of water only (pump and treat without surfactants)
- Phase 2 - groundwater flow in the artificial aquifer with surfactant injection and extraction of groundwater
- Phase 3 - groundwater flow in the artificial aquifer with the injection and extraction of water only to remove residual surfactant

5.2.1.2 Demonstration Objectives and Approach

There were two primary objectives and four secondary objectives in evaluating the VEGAS surfactant enhanced extraction technology.

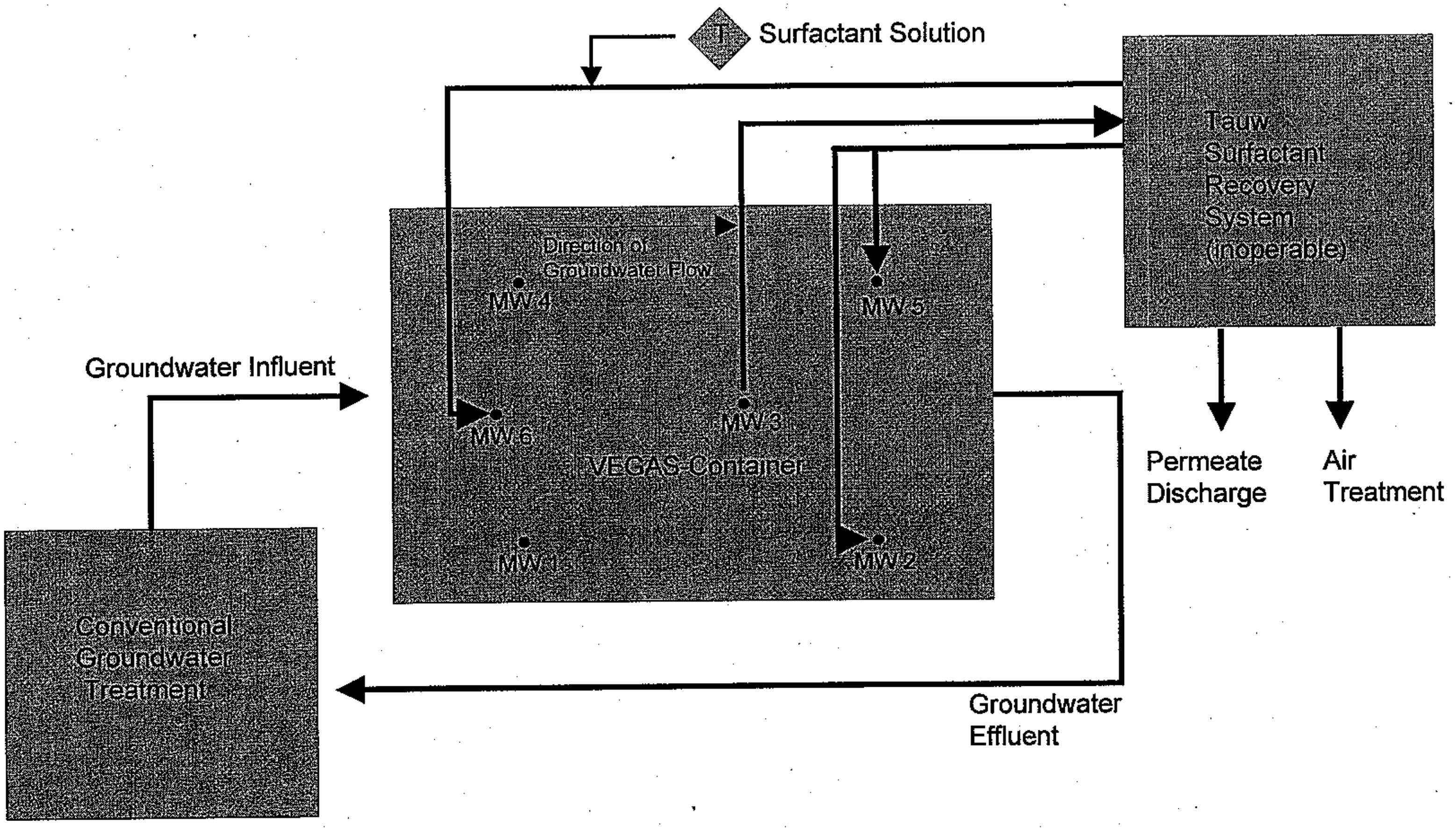


FIGURE 16
SURFACTANT INJECTION/EXTRACTION SYSTEM

Source: ArGe focon PROBIOTEC, 1997

Primary Objectives:

- Determine whether xylene mass removal rate increases due to surfactant enhancement
- Verify that there is no statistically significant increase in xylene concentrations in groundwater exiting the artificial aquifer due to surfactant enhancement

Secondary Objectives:

- Evaluate the acute toxicity of the treated permeate from the surfactant recovery system and of groundwater effluent from the artificial aquifer before and after surfactant injection
- Document process operating parameters
- Document the xylene and surfactant concentration in the treated surfactant recovery permeate and surfactant concentration in the effluent groundwater
- Estimate capital and operating costs

5.2.1.3 Results and Conclusions

The surfactant-enhanced extraction technology demonstrated at the VEGAS facility accelerated the removal of xylene from the artificial aquifer. The conclusions of the demonstration are listed below in relation to the two primary and four secondary objectives:

- The xylene mass removal rate increased due to surfactant enhancement. The concentration of xylene in the extracted groundwater increased by a factor of approximately 15 after the injection of the surfactant solution
- There was no significant increase in the xylene concentration of the groundwater exiting the artificial aquifer as a result of the surfactant enhancement. Average groundwater effluent xylene concentrations were 19.8 µg/L before surfactant injection, 7.7 µg/L during surfactant injection, and 2.3 µg/L following surfactant injection.
- The acute toxicity (LD50) of the groundwater effluent from the artificial aquifer before and after surfactant injection were all 0 mortality for the fish and Daphnia; and <2 for the luminescent bacteria. An evaluation of the treated permeate was not performed since the surfactant recovery system was not operational during the evaluation.
- The process operational parameters were as follows: extracted groundwater flow rates ranged from 116 to 230 L/h; injected groundwater flow rates ranged from 101.4 to 112 L/H. Influent groundwater flow rates ranged from 207 to 252 L/H; and effluent groundwater flow rates ranged from 191 to 315 L/H. The groundwater influent temperature ranged from 18.5 to 19.1 °C and the pH ranged from 7.53 to 7.9. The above ground surfactant recycling system was not operational and was not used during the evaluation; therefore, the surfactant was not

separated and recycled.

- The surfactant concentrations in the effluent groundwater were all <0.05 mg/L for anionic surfactants and <0.25 mg/L for nonanionic surfactants. The treated permeate was not analyzed since the recovery system was not operational.
- The cost of the surfactant provided by BASF was 3.50 DM per kilogram of surfactant ($1.82 per kilogram assuming a 1.92 DM to $1 U.S. exchange rate). Because the surfactant recovery system was not operational during the demonstration and the ability to recycle surfactant was not determined, a detailed cost analysis could not be developed.

5.2.1.4 Vendor Contact

Reinhold Josef
VEGAS Project Manager
Insitut fur Wasserbau
Universitat stuttgart
Pfaffenwaldring 61
70550 Stuttgart, Germany
(0711) 685-7023

5.2.2 Prantner Catalytic Oxidation

The Prantner & Partner GmbH (Prantner) catalytic oxidation (CatOx) system was demonstrated at the Landkreis Graftschaft Bentheim site in Nordhorn, Germany, to evaluate the technology's effectiveness in treating a soil vapor extract and associated groundwater stripping air that wascontaminated with high levels of VOCs. The Prantner CatOx system was demonstrated in June and July 1998 (Tetra Tech 1998e).

5.2.2.1 Process Description

Although this technology demonstration focused on the innovative part of the treatment facility, the Prantner catalytic oxidation reactor, this section also describes the soil gas and groundwater treatment facility in operation at the site. The entire site remediation system was not demonstrated (1) because most of the soil vapor extraction and water treatment equipment is conventional and (2) because of budgetary, logistical, and schedule limitations.

The complete SVE/CatOx treatment system is shown schematically in Figure 17 and is currently in continuous operation at the Landkreis Graftschaft Bentheim site. The facility extracts soil vapor and groundwater from the subsurface. The groundwater is ultimately air stripped to form an additional gas stream containing VOCs for processing through the Prantner CatOx system. The soil vapor extract flow rate average about 240 m^3/h, and the gas stream resulting from stripping of groundwater averages about 300 m^3/h during system operations.

Extracted groundwater is pumped through an iron/manganese removal unit, which aerates the water. The groundwater is filtered to remove reduced iron and manganese, so that subsequent scaling and precipitation problems are minimized. The groundwater is then stripped of VOCs in a packed column with an air stream; the stripped vapors are compressed and sent to the CatOx system for treatment with the soil vapor extract. Stripped groundwater is sent to the wastewater storage tank for interim storage while awaiting ultimate disposal.

The soil vapor extract from the series of wells in the reactor room is withdrawn and passed through demisters to remove excess moisture. Following compression, the vapor is sampled semicontinuously and analyzed by gas chromatography (GC) for operational monitoring purposes. This soil vapor extract is then (1) combined with the gas stream from air stripping extracted groundwater, (2) recompressed, and (3) passed through a heat exchanger to elevate the temperature before it is fed to the CatOx reactor. A supplemental electric heater is operated, if necessary, to ensure that the feed gas to the reactor is at or above 350 °C.

The CatOx reactor consists of an isolated tubular casing containing cylindrical catalyst pellets of 1 to 2 cm length and 3 to 4 mm diameter. The catalyst is composed of mixed metal oxides impregnated on a ceramic support.

The combusted gas stream leaves the CatOx reactor at about 500 °C and passes back through the heat exchanger to warm the incoming gas. The gas stream is then passed through a packed bed scrubber to cool the gas and remove acid gases. Prior to discharge to the atmosphere at a temperature of about 150 °C.

Scrubber blowdown water is returned to the wastewater storage tank and combined with any stripped groundwater in the tank. Ultimately, the combined wastewater from the storage tank is passed through an activated carbon filter, which removes any final traces of organic contaminants. The wastewater is

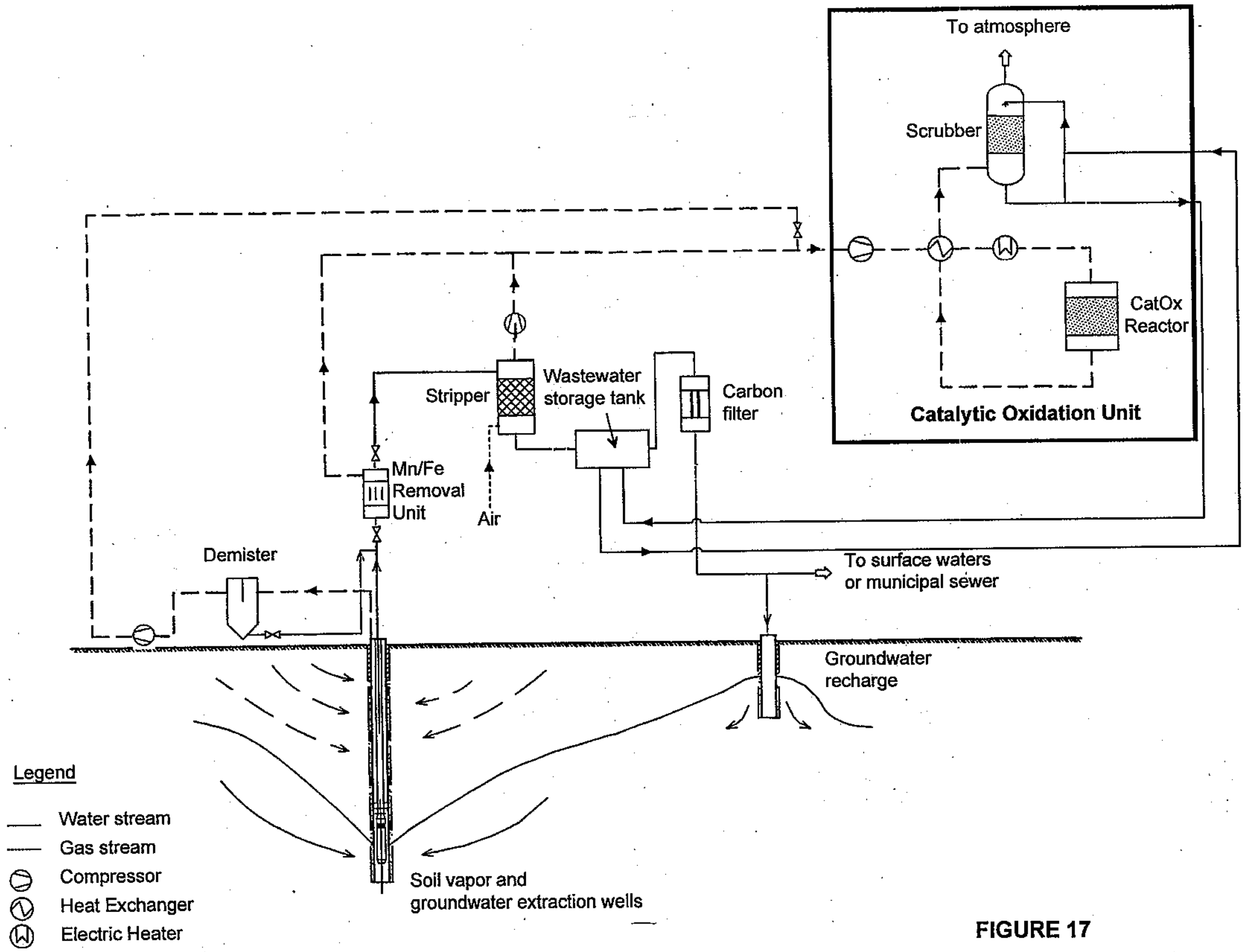


FIGURE 17

PRANTNER SVE/CATOX PROCESS FLOW DIAGRAM

then discharged batch-wise to the municipal sewer system or to a storm water channel if not contaminated above regulatory criteria. The option also exists to recharge this wastewater effluent to the subsurface through a well outside of the reactor room.

5.2.2.2 Demonstration Objectives and Approach

There were two primary objectives and three secondary objectives in evaluating the Prantner technology.

Primary Objectives:

- Calculate the average and range of removal efficiencies that the Prantner CatOx reactor achieves for two categories of VOC contaminants, including BTEX and chlorinated hydrocarbons, during each of three test runs
- Document the concentrations of each target VOC detected in the Prantner CatOx system feed gas and stack gas for each of three test runs

Secondary Objectives:

- Measure the concentrations of target VOC contaminants in the extracted groundwater, stripped groundwater, and final wastewater discharge during three test runs
- Document the operating conditions of the Prantner CatOx system, including gas stream flow rates and CatOx reactor temperatures.
- Document the capital and operating costs of the Prantner CatOx system, including the electric power cost for supplemental heating of the CatOx feed gas.

These objectives were achieved by collecting representative samples of feed gas and stack gas emissions and other appropriate measurements during three test runs. QA/QC procedures were followed as specified in the approved QAPP.

5.2.2.3 Results and Conclusions

Demonstration data are currently under evaluation; and results and conclusions are not yet available for inclusion in this report.

5.2.2.4 Vendor Contacts

Dr. Jörg Siebert
Probiotec GmbH
Shillingsstrasse 333
52355 Düren-Gürzenich, Germany
02421/6909-0

5.2.3 Plambeck ContraCon Bioremediation System

The Plambeck ContraCon Bau und Umwelttechnik GmbH (Plambeck ContraCon) bioremediation system was demonstrated at the Werk Tanne site located in Clausthal-Zellerfeld, to evaluate its effectiveness in treating soil contaminated with high levels of 2,4,6-trinitrotoluene (TNT) (Tetra Tech 1998b).

5.2.3.1 Process Description

The Plambeck ContraCon bioremediation process involves sequential anaerobic and aerobic processing to convert TNT in soils to a reduced form, which is then immobilized in the soil matrix. A description of the chemistry and physical operations of this unique process follows.

Process Chemistry

The Plambeck ContraCon bioremediation system is based on sequential anaerobic and aerobic processing of contaminated soil with native bacteria to (1) achieve a high degree of reduction of TNT and related nitroaromatics and (2) achieve subsequent immobilization of the reduced compounds in the soil matrix. The benefits of this treatment can be measured as a substantial decrease in the levels of TNT and related nitroaromatics in the soil matrix and as lower of soil toxicity.

Due to the strong electron-withdrawing character of the nitro groups, TNT is a highly electron-deficient compound. Thus, TNT seems to be unsusceptible to oxidative degradation by aerobic microbial cultures. In contrast, anaerobic bacteria readily reduce TNT to yield 2,4,6-triaminotoluene (TAT) under strict anaerobic conditions (oxidation and reduction potential [Eh] $\leq$ 200 millivolts [mV]). The process only requires an electron donor, such as glucose, which is typically provided within a cosubstrate. Figure 18 illustrates the main steps in this microbially facilitated anaerobic reduction process.

TAT formed by the complete reduction of TNT binds to the clay minerals and organic matter of soil under anaerobic conditions. During subsequent aerobic treatment, oxidative polymerization occurs, and the long-chain products that are generated become part of the soil organic matter (a process sometimes called humification). Thus, a sequential anaerobic and aerobic microbial treatment has been found to (1) reduce TNT in soils to TAT, and (2) facilitate subsequent binding and polymerization reactions. Other nitroaromatic compounds associated with TNT contamination, such as dinitrotoluenes, undergo similar reactions and are lessened in the soil matrix.

Physical Process Description

The Plambeck ContraCon bioremediation facility consists of a temporary enclosure (15 by 24 by 5 m high), that contains three concrete treatment boxes (about 4 by 10 by 1 m high), of which one is kept empty to allow transfer of the soil piles during the mixing process. To mix the contents of a box, the contents are picked up, moved, and dumped into the empty box in about 1 cubic meter increments using a wheeled front-end loader.

Before undergoing treatment, TNT-contaminated soil at the Werk Tanne site was excavated from preselected locations and stockpiled into a large pile. The soil was then screened to remove large rocks and debris (greater than about 6 cm in diameter), and mixed well using a front-end loader to ensure that the concentrations of contaminants were similar for the treatment technology evaluation.

Each of two treatment boxes were filled with alternating front-end loader shovel loads of contaminated soil and cosubstrate. The cosubstrate was an agricultural by-product, such as chopped sugar beets or potato starch. Plambeck ContraCon added the cosubstrate in a ratio of about 1 to 5 (cosubstrate to soil mass). The soil and cosubstrate were then mixed using the front-end loader. Water was added as necessary to ensure that the soil and substrate mixture has an optimal water content of about 20 percent. In addition, one biopile was mechanically compacted in order to assess the potential advantage of compaction in facilitating anaerobic reduction of TNT and improving overall system performance.

5.2.3.2 Demonstration Objectives and Approach

There were two primary objectives and seven secondary objectives in evaluating the Plambeck ContraCon technology.

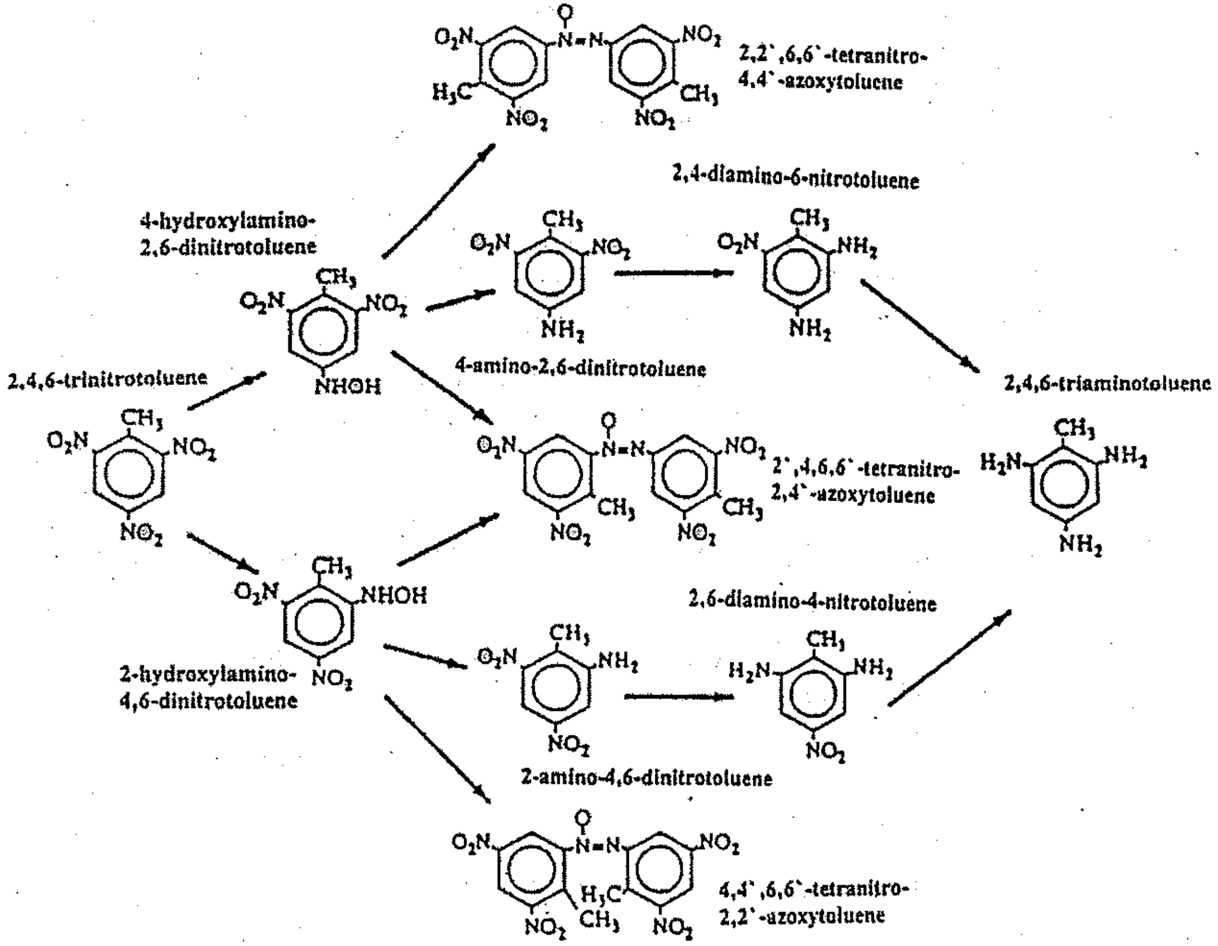


FIGURE 18

CHEMISTRY OF TNT TRANSFORMATIONS IN SOIL

Source: Stolpmann and others, 1995

Primary Objectives:

- Determine the TNT removal efficiency over the period of demonstration (16 weeks) for each of two soil treatment piles
- Document the concentrations of TNT and related nitroaromatic compounds in the soil throughout the demonstration for each of two soil treatment piles

Secondary Objectives:

- Evaluate the toxicity of each of the soil piles both before and after treatment using five toxicity tests
- Identify and estimate the concentration of any non-target SVOCs in both the untreated and treated soil throughout the demonstration
- Determine the concentrations of TNT and related nitroaromatic compounds in an aqueous leachate of both the untreated and treated soil for each of the two soil treatment piles
- Characterize the general properties of the soil (including particle size distribution [PSD], moisture content, TOC content, and pH) before and after treatment
- Measure toxic metals concentrations in each of the soil piles h before and after treatment
- Document the operating conditions of the process based on information supplied by Plambeck ContraCon
- Record cost information, as available from Plambeck ContraCon, for the implementation of the technology at the Werke Tanne site

These objectives were achieved by analyzing representative samples from each soil pile at the beginning and end of the treatment period as well as at two intermediate sampling points. QA/QC procedures were followed as specified in the approved QAPP.

5.2.3.3 Results and Conclusions

Demonstration data are currently under review, and results and conclusions were not yet available for inclusion in this report.

5.2.3.4 Vendor Contact

Dr. Ralf Winterberg
Plambeck ContraCon
Peter-Henlein-Strass 2 – 4
27472 Cuxhaven, Germany
04721/718-371

5.2.4 Mull & Partner Reactive Barrier

The Mull und Partner Ingenieurgesellschaft GmbH (Mull and Partner) reactive barrier system was demonstrated to evaluate the effectiveness of the Mull and Partner reactive barrier system in treating groundwater, contaminated with chlorinated hydrocarbons at a site in the City of Rheine, which is located in the State of Nordrhein-Westfalen, Germany (Tetra tech 1999a).

5.2.4.1 Process Description

Reactive barriers are a class of remediation technology in which a permeable reaction wall is installed across the flow path of a groundwater contaminant plume. The reactive barrier technology of Mull and Partner employs reactive elemental iron in an electrochemical process. In this system, groundwater contaminated with chlorinated hydrocarbons passes through a wall of specially prepared reactive iron, which oxidizes and thereby induces reductive dehalogenation (dechlorination) of the chlorinated hydrocarbon contaminants. During this electrochemical process, chlorinated hydrocarbons are degraded to nonhazardous substances (hydrocarbons), which escape the reactive barrier as gases.

The chemistry of this process is not completely understood, but the results of previous research suggest the following mechanisms. In the reactive barrier, elemental iron (Fe^0) oxidizes, releasing electrons and creating a highly reducing environment in the surrounding groundwater. As a result, the hydrocarbon-chlorine (R-Cl) bonds in the chlorinated hydrocarbon contaminants become unstable and break down sequentially, forming less chlorinated compounds and releasing chloride ions into the groundwater. The hydrocarbon (R-H) formed by complete dehalogenation is nontoxic and is either released as a gas or is naturally biodegraded. The rate of the dehalogenation reaction primarily depends on the surface area of the iron and its abundance in the permeable reactive media.

Although it is not known conclusively how the reaction occurs, the following reaction mechanism has been proposed by researchers:

Half Reactions:

$$2Fe^{0} \text{ ---> } 2Fe^{++} + 4e^{-}$$

$$2H^{+} + 2e^{-} \text{ ----> } H_2$$

$$R\text{-}Cl + H^{+} + 2e^{-} \text{ ----> } R\text{-}H + Cl^{-}$$

Full Reaction:

$$2Fe^{0} + R\text{-}Cl + 3\ H_2O \text{ ----> } 2Fe^{++} + Cl^{-} + R\text{-}H + 3\ OH^{-} + H_2$$

where:

Fe^0 = Elemental iron metal
Fe^{++} = Oxidized iron cation (ferrous iron)
e^- = Electron
H^+ = Hydrogen ion
OH^- = Hydroxyl ion
H_2 = Hydrogen gas
R-Cl = Halogenated (chlorinated) hydrocarbon
R-H = Dehalogenated (dechlorinated) hydrocarbon
Cl^- = Chloride ion

In addition to the dechlorination reaction described above, simple oxidation (rusting) of the elemental iron in the barrier occurs according to the following reaction:

$$Fe^{0} + 2H_2O \text{ ----> } Fe^{++} + 2\ OH^{-} + H_2$$

The Mull and Partner reactive barrier has a length of approximately 22.5 m, and extends into the aquitard below the aquifer. A schematic illustration of the reactive iron barrier is shown in Figure 19. The reactive iron barrier system was constructed as a series of overlapping pilings that contain the reactive iron and extend down to the bottom of the groundwater aquifer.

The reactive barrier consists of two sections (north and south), which are hydraulically separated from each other by a concrete pile. The northern section of the barrier extends 12.5 m and is filled with a special reactive iron material called sponge iron. Sponge iron is typically used as an additive in the manufacturing of steel. The grain diameter of sponge iron ranges from 4 to 20 mm, and is composed primarily of iron (90 to 92 percent) and carbon (1.5 to 2.5 percent), with silicon, calcium, aluminum, and magnesium (approximately 5 percent). The southern section of the barrier extends approximately 10 m and is filled with a mixture of iron filings and gravel. The iron filings, also called "gray cast iron granular," are produced from cuttings from the metal working industry. The grain diameter of the iron filings ranges from approximately 0.1 mm to 3 mm; however, most filings are 1 to 2 mm. Chemically, the iron filings are composed of iron (90 to 92 percent); carbon (1.5 to 2.5 percent); silicon (2 percent); and an amalgam of phosphorus, chromium, nickel, and aluminum (approximately 5 percent). The filings are decontaminated through a mechanical-thermal process, which also renders the filings hydrophilic.

A liner and slotted gas drainage pipes were installed at the top of each barrier section to capture and convey the gas (predominantly hydrogen) that is generated by the chemical reactions within the reactive iron barrier.

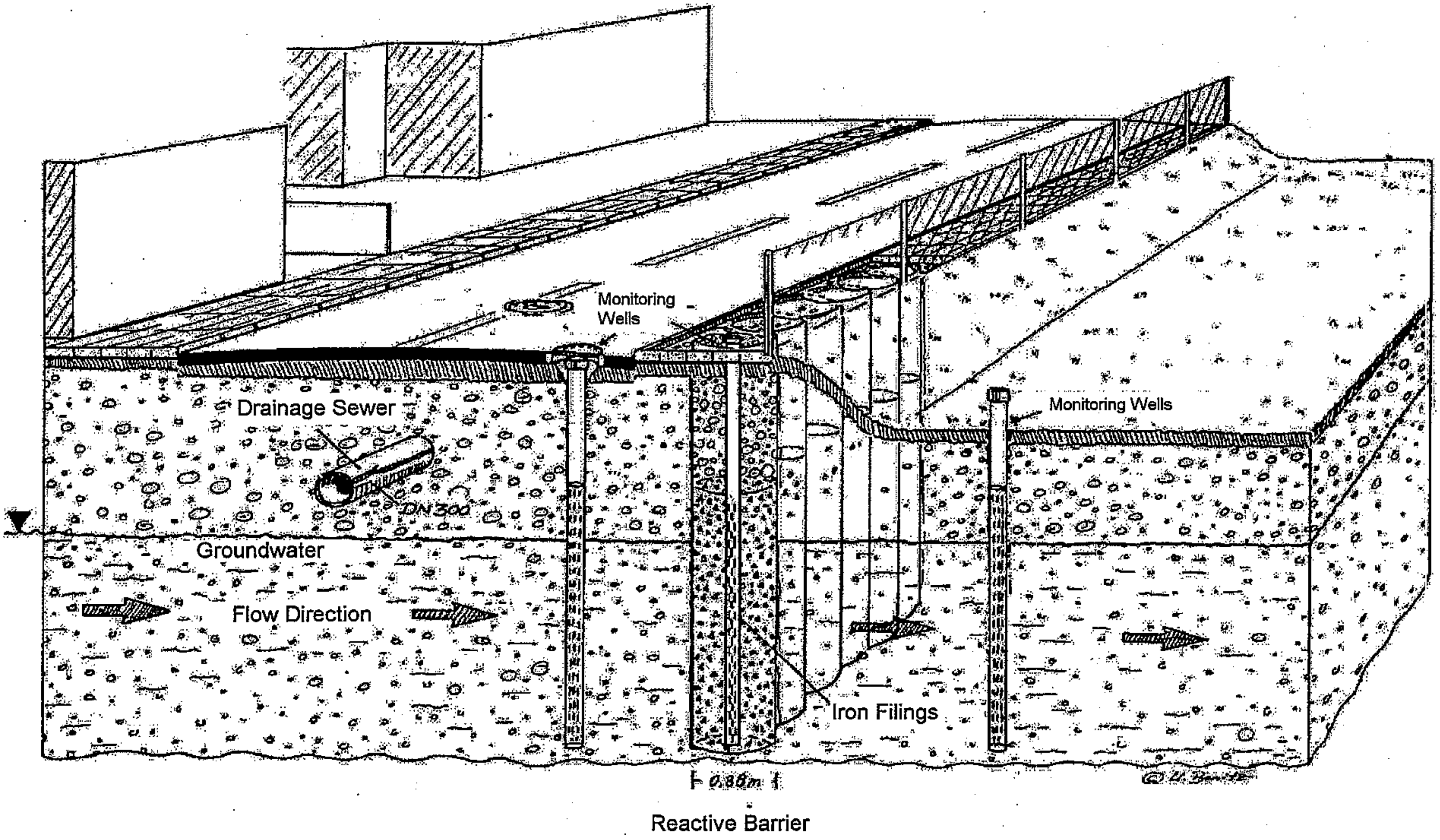
5.2.4.2 Demonstration Objectives and Approach

There were two primary objectives and three secondary objectives in evaluating the Mull and Partner reactive barrier system.

<u>Primary Objectives:</u>

- Determine the removal efficiency for tetrachloroethene in each section of the reactive iron barrier

Determine the concentration of other chlorinated hydrocarbons in groundwater upgradient and downgradient of the reactive barrier in each of the two sections



NOT TO SCALE

FIGURE 19

SCHEMATIC ILLUSTRATION OF THE REACTIVE IRON BARRIER SYSTEM

Secondary Objectives:

- Document the physical and chemical characteristics of the groundwater that could affect the performance of the reactive iron barrier and document how these parameters change as a result of the reactive iron barrier treatment
- Determine the mass flux of hydrogen, C1 through C5 hydrocarbons, and chlorinated hydrocarbons in the gas emitted from the two gas drainage systems
- Estimate the costs for the reactive iron barrier treatment based on data provided by Mull and Partner

These objectives were achieved through analysis of representative groundwater sample, both up gradiant and downgraadient of the reactive barrier once a month for four months. QA/QC procedures were followed as specified in the approved QAPP.

5.2.4.3 Results and Conclusions

This demonstration was limited to an evaluation of the technology's ability to reduce chlorinated hydrocarbon concentrations in the groundwater. The results of the primary objective, to determine the removal efficiency for tetrachloroethene in each of the two sections, were caclulated to be 99.5 percent in the sponge section and 94.3 percent in the granular section. The second primary objective, to document the critical contaminant concentrations of other chlorinated hydrocarbons in groundwater upgradient and downgradient of the reactive barrier in each of the two sections was completed. However, the results for most of these parameters were lower than the detection limits and no specific conclusions could be drawn. For the two parameters that did have reportable data, removal efficiencies were calculated to quantify the effectiveness of the barrier. The removal efficiency for cis-1,2-dichloroethene was calculated at 79.9 percent in the sponge iron section and 73.6 percent in the granular iron section; the removal efficiency for TCE was calculated at 81.1 percent in the granular section.

The secondary objective included documenting the physical and chemical characteristics (including pH, redox potential, temperature, electrical conductivity, dissolved oxygen and major cations and anions) of the groundwater that could affect the performance of the reactive iron barrier and documenting how these parameters change as a result of the reactive iron barrier treatment. The pH was highest inside the barrier due to the basic environment created by the hydroxyl (OH^-) groups formed during the generation of hydrogen gas. Inside the barrier, the dissolved oxygen content was lowest and the redox potential was the most negative. This was due to the strong reducing environment existing within the barrier and created by the elemental iron. Temperature, while highest inside the barrier, did not change notably as this is not a highly exothermic reaction. The electrical conductivity was highest upgradient of both sections of the barrier, as the barrier probably filtered out some of the dissolved solids as the water passed through thereby decreasing the electrical conductivity.

5.2.4.4 Vendor Contacts

Dr. Wilfried Möller
Mull und Partner Ingenieurgesellschaft mbH
Osteriede 5
30827 Garbsen, Germany
+49-5134-4694-0

5.2.5 SWD Biological Groundwater Treatment

The Stadtwerke Duesseldorf AG (SWD) AQUABOX 50 and MARABU Packed Biological Reactor system was demonstrated at the Stadtwerke Duesseldorf AG site in Duesseldorf, Germany (Tetra Tech 1999b) in 1998. The purpose of the demonstration was to evaluate the technology's effectiveness in treating groundwater contaminated with BTEX, naphthalene, acenaphthene, and fluorine.

5.2.5.1 Process Description

Although the evaluation is focused on the innovative part of the treatment technology, the AQUABOX 50 and MARABU biological reactors, this section also describes the conventional components of the technology. The AQUABOX 50 bioreactor consists of five connected compartments, each 2 m^3 in volume (for a total volume of 10 m^3), incorporating a packed bed of a polyvinyl chloride (PVC) mat with rough, linear extrusions. The MARABU bioreactor consists of one 1.5-m^3 compartment, incorporating a packed bed consisting of polyethylene rings. The complete treatment system is shown schematically in Figure 20. The system is currently in continuous operation at the SWD site in the depicted configuration.

Groundwater is extracted at varying pump rates from five recovery wells installed within the contaminant plume. Extracted groundwater from four of the recovery wells is pumped into the

AQUABOX 50 at a combined flow rate of about 20 cubic meters per hour (m^3/h). Extracted groundwater from one recovery well is pumped into the MARABU at a flow rate of about 3 m^3/h.

The AQUABOX 50 and MARABU treat the influent groundwater through biodegradation by microbes that grow on the packed bed media. Each bioreactor is supplied with an aeration system to ensure sufficient oxygen for the bacteria. These aeration systems employ air flow rates of 4 m^3/h fresh air and 50 m^3/h circulated air in the AQUABOX 50 and 5 m^3/h fresh air in the MARABU. Treated water from both the AQUABOX 50 and MARABU bioreactors flows through separate piping into an intermediate, 20 m^3 storage tank. This tank is aerated at an air flow rate of 7 m^3/h to reduce iron concentrations in the treated water by promoting oxidation and precipitation

The partially treated water flows from the storage tank through a 30-m^3 sand filter (10 m^3 water capacity) to remove residual iron. Trapped bacteria in the sand filter provide further contaminant biodegradation in the previously treated groundwater. The groundwater then filters through an activated carbon unit to remove residual organic contamination prior to infiltration back into the aquifer. Exhaust gases from each system component are passed through activated carbon prior to final atmospheric discharge. Backup activated carbon units are in place at each of the three gas exhausts and at the sand filter effluent.

5.2.5.2 Demonstration Objectives and Approach

The objectives of this project are focused on the SWD AQUABOX 50 and MARABU packed biological reactor systems and their ability to reduce dissolved-phase BTEX and PAHs in groundwater. The demonstration has two primary objectives and three secondary objectives.

Primary Objectives:

- Demonstrate greater than 95 percent average removal efficiency for total BTEX and greater than 60 percent average removal efficiency for the three most prevalent PAHs (acenaphthene, fluorene, and naphthalene) for the overall system

Measure the removal efficiencies for BTEX and the three most prevalent PAHs across each of the treatment units, including the AQUABOX 50, MARABU, and sand filter

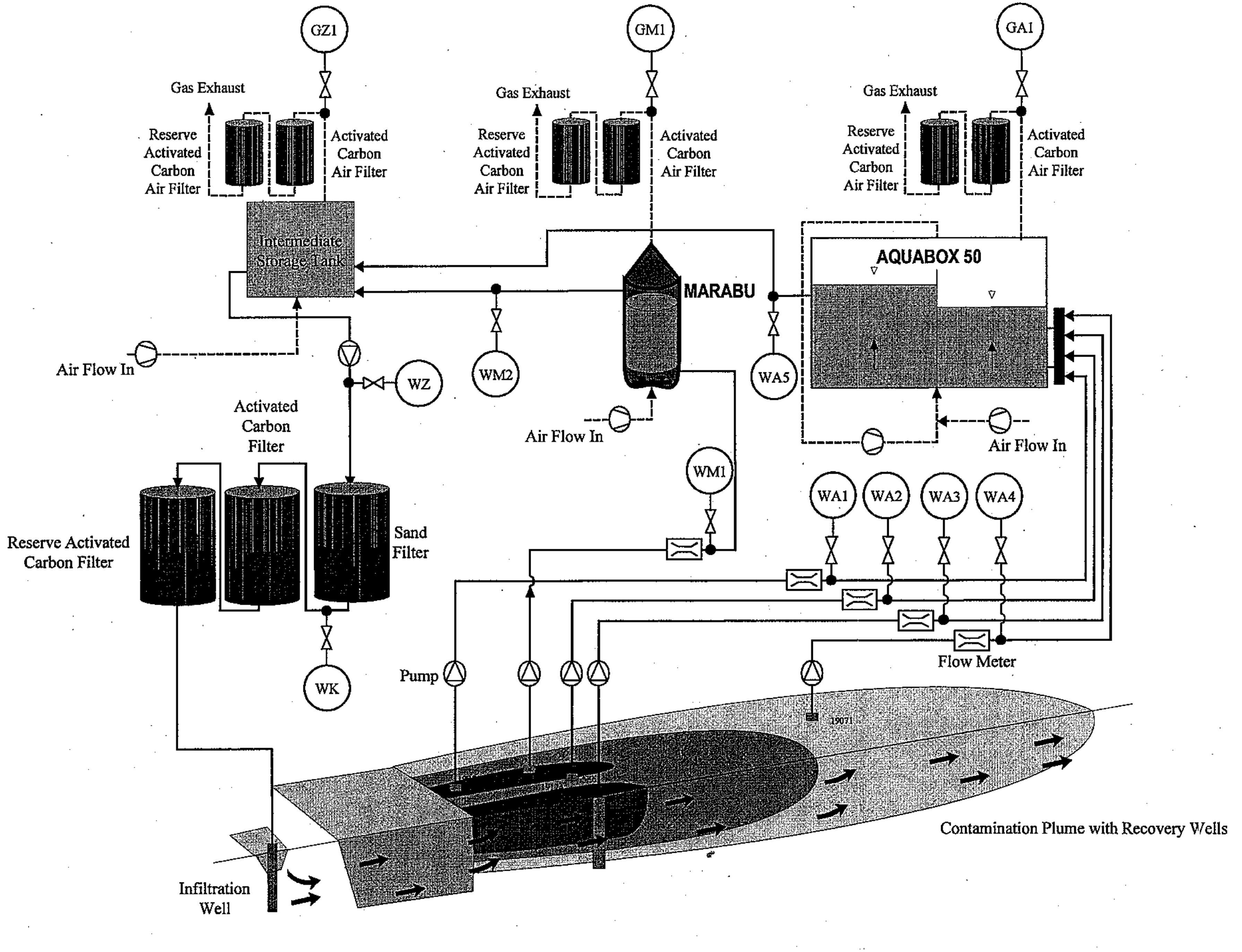


FIGURE 20

SWD AQUABOX 50 AND MARABU BIOREACTOR TREATMENT SYSTEM SCHEMATIC

Secondary Objectives:

- Determine the percent of total BTEX and naphthalene that is stripped from each aerated component of the system
- Document the physical and chemical characteristics of the treated water that could affect the performance of the system and document how these parameters change with treatment
- Document the capital and operating costs of the SWD AQUABOX 50 and MARABU packed biological reactor systems based on observations during the evaluation and data collected from the engineering designers and the system operator

These objectives were achieved through analysis of representative samples collected over a 4-week evaluation period. QA/QC procedures were followed as specified in the approved QAPP.

5.2.5.3 Results and Conclusions

Demonstration data are currently under review; results and conclusions are not available for inclusion in this report.

5.2.3.4 Vendor Contact

Dr. Hans-Peter Rohns
Stadtwerke Düsseldorf
Abt. Wasserwirtschaft und Technik
Faerberstrasse 78
40223 Duesseldorf
49-211-821-8316

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