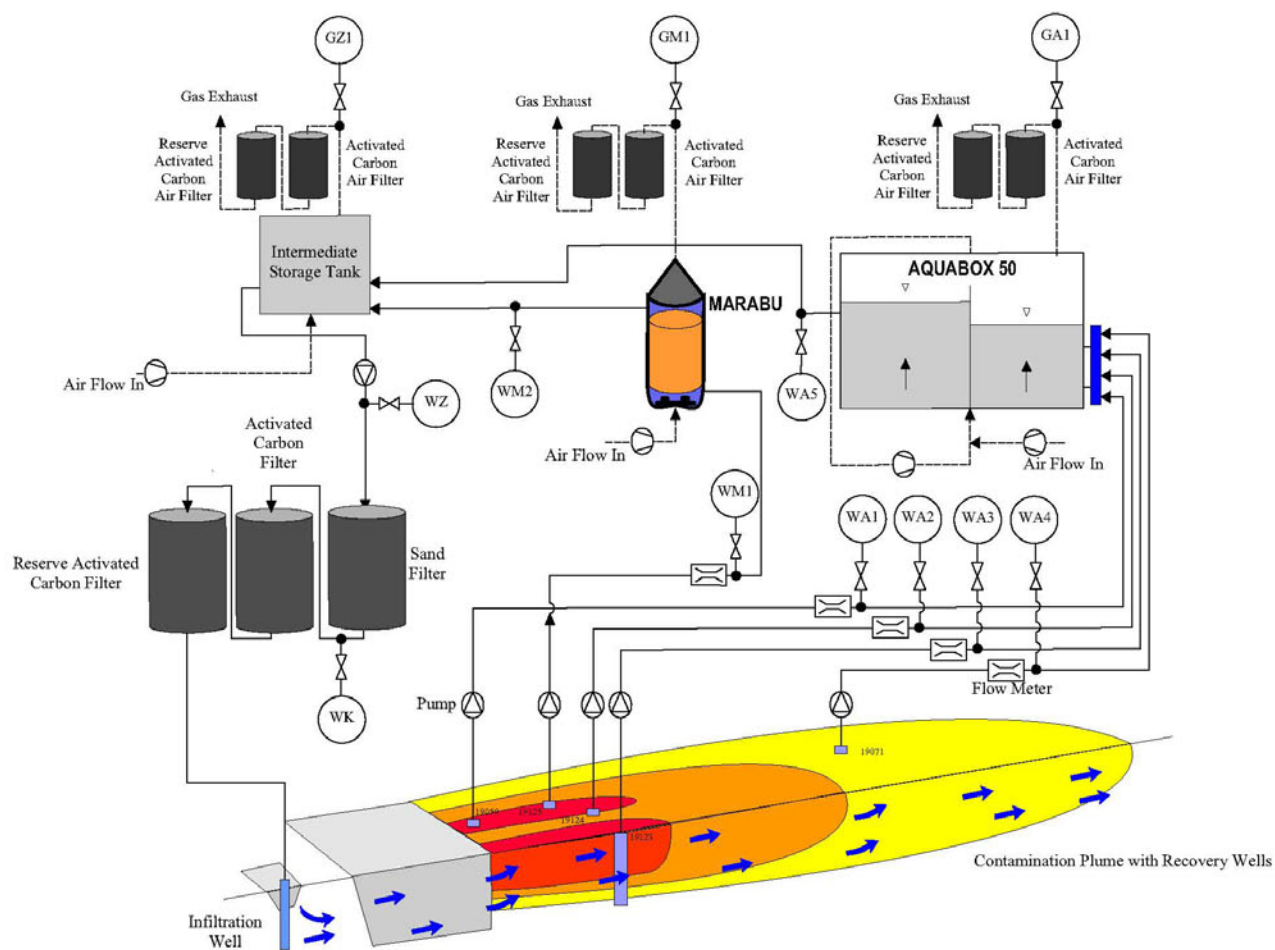# AQUABOX 50 and MARABU Packed Biological Reactor System Technology Evaluation

Innovative Technology Evaluation Report

Treatment System Schematic

SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

AQUABOX 50 AND MARABU PACKED BIOLOGICAL REACTOR SYSTEM TECHNOLOGY EVALUATION
INNOVATIVE TECHNOLOGY EVALUATION REPORT

EPA - BMBF BILATERAL SITE DEMONSTRATION
STADTWERKE DUESSELDORF AG SITE, DUESSELDORF, GERMANY

by
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NOTICE

The information in this document has been prepared for the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation program by Tetra Tech EM Inc. under Contract No. 68-C5-0037. This document has been prepared in accordance with a bilateral agreement between the EPA and the Federal Republic of Germany Ministry for Research and Technology. This document has been subject to EPA peer and administrative reviews, and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement by the EPA or recommendation for use.

FOREWORD

The Superfund Innovative Technology Evaluation (SITE) program was authorized by the Superfund Amendments and Reauthorization Act of 1986. The U.S. Environmental Protection Agency (EPA) Office of Research and Development established the program to accelerate the development and use of innovative remediation technologies applicable to Superfund and other hazardous waste sites. The SITE program accomplishes these goals through pilot- or full-scale demonstrations designed to collect performance and economic data of known quality on selected technologies.

This demonstration evaluated the effectiveness of two different biological reactors in treating groundwater contaminated with benzene, toluene, ethylbenzene, and xylenes (BTEX), naphthalene, acenaphthene, and fluorene. The AQUABOX 50 and MARABU packed biological reactors were evaluated at a former manufactured gas (coal gasification) plant that operated from 1890 to 1967 in a section of Duesseldorf, Germany known as Duesseldorf-Flingern. The primary industrial process at the former manufactured gas plant, the Stadtwerke Duesseldorf AG (SWD) site in Duesseldorf, Germany, was the conversion of coal to natural gas; associated by-products of this process include BTEX and polycyclic aromatic hydrocarbons (PAH). The facility has been operated by SWD as an operations yard from post-1967 to the present. While the manufactured gas plant was in operation, aquifer contamination occurred through storage system leaks, improper handling of by-products, and World War II bombing damage. Further contamination occurred approximately 25 years ago when the gasworks were demolished. This innovative technology evaluation report provides an interpretation of the data collected during the demonstration and discusses the potential applicability of the technology to other contaminated sites.

Hugh W. McKinnon, Director
National Risk Management Research Laboratory

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ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
BFB	4-Bromofluorobenzene
BMBF	German Federal Ministry of Education, Science, Research, and Technology
BS	Blank spike
BSD	Blank spike duplicate
BTEX	Benzene, toluene, ethylbenzene, and xylenes
EC	Degrees Celsius
Ca	Calcium
CCC	Calibration check compound
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
Cl^-	Chloride
CS_2	Carbon disulfide
DFTPP	Decafluorotriphenylphosphine
DHHS	U.S. Department of Health and Human Services
EPA	U.S. Environmental Protection Agency
F^-	Fluoride
Fe	Iron
GC/MS	Gas chromatography/mass spectroscopy
HCl	Hydrochloric acid
ICP	Inductively coupled plasma
ITER	Innovative Technology Evaluation Report
IUM	Ingenieurbuero fuer Umwelttechnik und Maschinenbau GmbH
K	Potassium
L/min	Liters per minute
m^3	Meters cubed
m^3/h	Meters cubed per hour
MCAWW	Methods for the Chemical Analysis of Water and Wastes (EPA, 1983)
MDL	Method detection limit
Mg	Magnesium
Mn	Manganese

MSD	Matrix spike duplicate
Na	Sodium
NBM	NBM Petrol Stations & Industry
NIOSH	National Institute of Occupational Safety and Health
NO_3^-	Nitrate
NO_2^-	Nitrite
NPL	National Priorities List
NRMRL	National Risk Management Research Laboratory
ORD	Office of Research and Development
PAH	Polycyclic aromatic hydrocarbons
PO_4^{3-}	Phosphate
PQL	Practical Quantitation Limit
Probiotec	ArGe focon-PROBIOTEC
PVC	Polyvinyl chloride
QA	Quality assurance
QA/QC	Quality assurance/quality control
QAPP	Quality assurance project plan
QC	Quality control
QM-TAP	Qualitätsmanagement-Testablaufplan
%R	Percent recovery
RE	Removal efficiency
RF	Response factor
RPD	Relative percent difference
%RSD	Percent relative standard deviation
SARA	Superfund Amendments and Reauthorization Act
SITE	Superfund Innovative Technology Evaluation
SO_4^{2-}	Sulfate
SPCC	System performance check compounds
SWD	Stadtwerke Duesseldorf AG

ACRONYMS AND ABBREVIATIONS (Continued)

Tetra Tech   Tetra Tech EM Inc.

UBA   Umweltbundesamt

FG/L   Micrograms per liter

VOA   Volatile organic analysis

VOC   Volatile organic compounds

CONVERSION TABLE
(Metric to English Units)

To Convert	Into	Multiply By
Centimeters	Feet	0.0328
Centimeters	Inches	0.394
Cubic meters	Cubic feet	35.3
Cubic meters	Gallons	264
Cubic meters	Cubic yards	1.31
Degrees Celsius	Degrees Fahrenheit	multiply by 1.80; add 32
Kilograms per square meter	Pounds per square inch, absolute	0.00142
Kilograms	Pounds	2.20
Kilograms per liter	Pounds per cubic foot	12.8
Kilometers	Miles (statute)	0.622
Liters	Gallons	0.260
Liters per second	Cubic feet (standard) per minute	2.12
Meters	Feet	3.28
Millimeters	Inches	0.0394
Square meters	Square feet	10.8

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

This innovative technology evaluation report (ITER) summarizes the results of an evaluation of the AQUABOX 50 and MARABU Packed Biological Reactor technologies. The evaluation was conducted under a bilateral agreement between the United States (U.S.) Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) program and the Federal Republic of Germany Ministry for Research and Technology (BMBF). The Stadtwerke Duesseldorf AG biological reactor system was demonstrated from July 15, 1999 through August 31, 1999 at the Stadtwerke Duesseldorf AG site in Duesseldorf, Germany.

The Biological Reactor Technology

Two packed biological reactors, operated concurrently in a side-by-side demonstration, were included in the evaluation: the AQUABOX 50 and the MARABU. The purpose was to evaluate the efficiencies of each reactive barrier to remove benzene, toluene, ethylbenzene, and xylenes (BTEX) and polycyclic aromatic hydrocarbons (PAHs) from the contaminated groundwater plume located at the site. The AQUABOX 50 was provided to Stadtwerke Duesseldorf AG (SWD) by NBM Petrol Stations & Industry (NBM). The MARABU was designed by SWD with design assistance from Ingenieurbuero fuer Umwelttechnik und Maschinenbau GmbH (IUM). The overall treatment system has been operated and maintained by SWD since December 1995.

The AQUABOX 50 and MARABU are designed to treat the influent groundwater through biodegradation by microbes that grow on the packed bed media. The AQUABOX 50 bioreactor consists of five connected compartments, each 2 cubic meters (m^3) in volume (for a total volume of 10 m^3), incorporating a packed bed consisting 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. Each bioreactor is supplied with an aeration system to ensure sufficient oxygen for the bacteria. These aeration systems employ air flow rates of 4 cubic meters per hour (m^3/hr) fresh air and 50 m^3/hr circulated air in the AQUABOX 50, and 5 m^3/hr fresh air in the MARABU with no circulated air.

Groundwater was extracted at varying pumping rates from five recovery wells installed within the contaminant plume. Extracted groundwater from four of the recovery wells at a combined flow rate of about 20 m^3/hr was pumped into the AQUABOX 50, and extracted groundwater from one recovery well at a flow rate of about 3 m^3/hr was pumped into the MARABU. Treated water from both the AQUABOX 50 and MARABU bioreactors flowed through separate piping into the same intermediate storage tank, with a total storage capacity of 20 m^3. This tank was aerated at a flow rate of 7 m^3/hr to reduce iron

concentrations in the treated water by promoting oxidation and precipitation which occurs within the sand filter. High iron concentrations are a natural characteristic of the facility groundwater.

The partially treated water flowed 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 provided further contaminant biodegradation in the previously treated groundwater. The groundwater was then passed through an activated carbon unit, which filtered out the residual organic contamination prior to infiltration back into the aquifer.

Exhaust gases from each system component were passed through activated carbon prior to final atmospheric discharge. Backup activated carbon units were also in place at each of the three gas exhausts and at the sand filter effluent.

Waste Applicability

Both the AQUABOX 50 and MARABU bioreactors effectively reduced dissolved-phase BTEX and PAHs from the groundwater.

Demonstration Objectives and Approach

This bilateral SITE demonstration of the AQUABOX 50 and MARABU packed biological reactor systems was designed with two primary and four secondary objectives. The objectives were chosen to provide potential users of the technology with the information necessary to assess the applicability of the biological reactor technology for treatment of groundwater at other contaminated sites. The following primary and secondary objectives were selected to evaluate the technology:

Primary Objectives

P1   *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. The overall system includes the AQUABOX 50, MARABU, and sand filter, but excludes the activated carbon system component.*

P2   *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.*

Secondary Objectives

S1   *Determine the percent of total BTEX and naphthalene that is stripped from each aerated component of the system.*

S2   *Document the physical and chemical characteristics of the treated water that could affect the performance of the evaluation system and document how these parameters change with treatment.*

S3   *Document the capital and operating costs of the SWD AQUABOX 50 and MARABU packed biological reactor system based on observations during the evaluation and data from the engineering designers and from the operator of the system.*

Demonstration Conclusions

This demonstration was limited to an evaluation of the technology's ability to remove BTEX and PAHs from groundwater. Based on the biological reactor technology demonstration, specific conclusions are summarized below.

C   The removal efficiencies for the three target PAHs, acenaphthene, fluorene and napthalene, and BTEX for the total system were all greater than 99 percent. These removal efficiencies exceeded the target removal efficiencies of 60 percent for the PAHs and 95 percent for the total BTEX.

C   The removal efficiencies for the three target PAHs and the total BTEX were calculated for three components of the system, the AQUABOX 50, the MARABU and the sand filter. The removal efficiencies of the AQUABOX 50 for acenaphthene, fluorene and napthalene ranged from 70.4 percent to 99.8 percent, 75.2 percent to 99.2 percent, and 91.0 percent to 99.8 percent, respectively. The removal efficiency for total BTEX of the AQUABOX 50 ranged from 92.3 percent to 97.0 percent. The removal efficiencies of the MARABU for acenapthene, fluorene and napthalene ranged from 47.0 percent to 66.1 percent, 53.6 percent to 71.5 percent, and 75.3 percent to 90.2 percent, respectively. The removal efficiency for total BTEX of the MARABU ranged from 67.6 percent to 74.6 percent. The removal efficiencies of the sand filter unit for acenaphthene, fluorene and napthalene ranged from 99.0 percent to 99.4 percent, 95.7 percent to 97.2 percent, and 97.5percent to 98.9 percent, respectively. The removal efficiency for total BTEX of the sand filter unit ranged from 28.6 percent to 94.6 percent.

C   The stripping efficiencies (percent of influent mass stripped into the exhaust gas) for the three target PAHs and the total BTEX were calculated for the three components of the system. Stripping efficiencies of the AQUABOX 50 for acenaphthene, fluorene, and naphthalene, ranged from <0.01 percent to <0.06 percent, <0.04 percent to <0.1 percent, and <0.02 percent to <0.08 percent, respectively. Stripping efficiency for total BTEX of the AQUABOX 50 ranged from 0.2 percent to 1.0 percent. Stripping efficiencies of the MARABU for acenaphthene, fluorene, and napthalene, ranged from 0.1percent to 0.2 percent, <0.06 percent to <0.08 percent, and 0.2 percent to 0.4 percent, respectively. Stripping efficiency for total BTEX of the MARABU ranged from 6.9 percent to 8.8 percent. Stripping efficiencies of the sand filter for acenaphthene,

fluorene, and napthalene, ranged from <0.02 percent to <0.06 percent, <0.1 percent to <0.2 percent, and 0.2 percent to 0.5 percent, respectively. Stripping efficiency for total BTEX of the sand filter ranged from 3.2 percent to 28.4 percent.

C   The following physical and chemical characteristics of the treated water were measured at the four influent wells to the AQUABOX 50, the one influent well to the MARABU, and the effluent well from the sand filter: pH, sodium, potassium, calcium, iron, magnesium, manganese, chloride, floride, nitrite, nitrate, phosphate, sulfate, bicarbonate (alkalinity), lead, copper, cadmium, zinc, nickel, chromium, arsenic, and mercury. The following trends were noted:

- Groundwater samples taken from influent sampling well to the AQUABOX 50 located at WA3 had the highest sodium, potassium, calcium, iron, manganese, chloride, floride, sulfate, and zinc concentrations.

- Groundwater samples taken from the influent sampling well to the MARABU located at WM1 had the lowest sodium, calcium, magnesium, nitrate, phosphate, and sulfate concentrations.

- Groundwater samples taken from the effluent located at WK had the lowest iron, manganese, nitrite, phosphate, and zinc concentrations. All of these analytes had been significantly reduced, most likely due to the precipitation reactions occurring within the biological reactive boxes. The highest concentration of nitrate was recorded in samples taken from the effluent sampling location.

- Lead, cadmium, chromium, and mercury concentrations were less than the detection limit in all monitoring wells. Copper and nickel concentrations were detected in two of the influent wells at low concentrations. Arsenic was detected in all monitoring wells at low concentrations.

- The initial capital cost of the biological reactor system at the Stadtwerke Duesseldorf AG Site, including site preparation, permitting and regulatory costs, construction materials and labor, and startup was about 218,700 DM ($113,900 U.S. dollars assuming a 1.92 DM to $1 U.S. dollar exchange rate). Monitoring and other periodic costs amounted to about 37,000 DM ($19,300 U.S.) per year.

1.0   INTRODUCTION

This report documents the findings of an evaluation of two biological reactors. The AQUABOX 50 was provided to Stadtwerke Duesseldorf AG (SWD) by NBM Petrol Stations & Industry (NBM). The MARABU was designed by SWD with design assistance from Ingenieurbuero fuer Umwelttechnik und Maschinenbau GmbH (IUM). The overall treatment system, which incorporates of these two biological reactors set up side-by-side and operated concurrently, was operated and maintained by SWD at the Stadtwederke Duesseldorf AG site in Duesseldorf, Germany (see Figure 1 for location). The demonstration period was from July 15 through August 31, 1999. This evaluation was conducted under a bilateral agreement between the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) program and the Federal Republic of Germany Ministry for Research and Technology (BMBF).

The demonstration evaluated each technology's effectiveness in enhancing the removal of benzene, toluene, ethylbenzene, and xylenes (BTEX) and the polycyclic aromatic hydrocarbons (PAHs) naphalene, fluorene, and acenaphthene, from contaminated groundwater. The evaluation was carried out by Tetra Tech EM Inc. (Tetra Tech), ArGe focon-PROBIOTEC (Probiotec), SWD facility personnel, and Institut Fresenius, in accordance with the July 1999 quality assurance project plan (QAPP) (Tetra Tech 1999). Groundwater was sampled by Institut Fresenius with assistance from Probiotec and Tetra Tech. Probiotec was responsible for ensuring that all sampling, analytical, and QA/QC requirements were effectively communicated to Institut Fresenius. Probiotec reviewed the sampling and analytical data obtained during the system evaluation for validity and assessed measurement systems for precision and accuracy. SWD demonstrated the technology.

The subject site is currently owned by a public utility company (Stadtwerke Duesseldorf AG). SWD was responsible for facilitating access to the site and for supporting the evaluation. SWD also operated, maintained, and monitored the treatment system at the site. SWD was responsible for coordinating evaluation activities with Probiotec and Institut Fresenius to ensure that all requirements are met, and for reporting operational and monitoring data. All samples were analyzed by the Institut Fresenius laboratory in Taunusstein. All demonstration activities were conducted in accordance with the referenced QAPP.
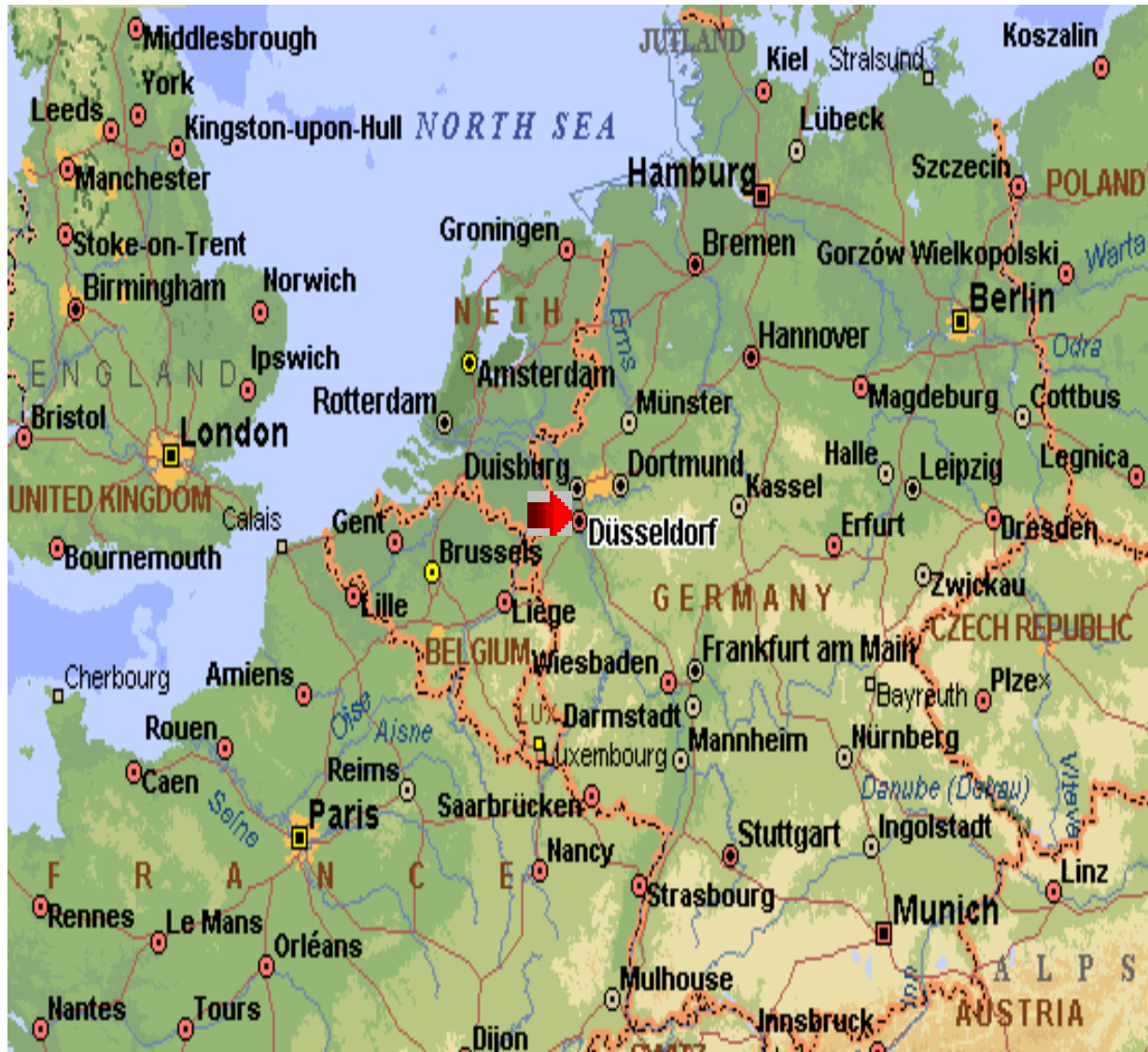
FIGURE 1
SITE LOCATION

Probiotec focon-Probiotec, Stadtwerke Duesseldorf AG facility personnel, and Institut Fresenius contributed to the development of this document.

This report provides information from the bilateral SITE demonstration of the AQUABOX and MARABU biological reactor technologies that is useful for remedial managers, environmental consultants, and other potential technology users in implementing this technology at contaminated sites. Section 1.0 presents an overview of the SITE program and bilateral agreement, describes the technology, and lists key contacts. Section 2.0 presents information relevant to the technology's effectiveness, including contaminated aquifer characteristics and site background, demonstration procedures, and the results and conclusions of the demonstration. Section 3.0 presents information on the costs associated with applying the technology. Section 4.0 presents information relevant to the technology's application, including an assessment of the technology in relation to nine feasibility study evaluation criteria used for decision making in the Superfund process. Section 4.0 also discusses applicable wastes/contaminants and limitations of the technology. Section 5.0 summarizes the technology status, and Section 6.0 lists references used in preparing this report.

1.1   SUPERFUND INNOVATIVE TECHNOLOGY EVALUATION PROGRAM

This section provides background information about the EPA SITE program. Additional information about the SITE program, the AQUABOX 50 and MARABU biological reactor technology, and the technology demonstration can be obtained by contacting the key individuals listed in Section 1.4.

EPA established the SITE program to accelerate the development, demonstration, and use of innovative technologies to remediate hazardous waste sites. The demonstration portion of the SITE program focuses on technologies in the pilot-scale or full-scale stage of development. The demonstrations are intended to collect performance data of known quality. Therefore, sampling and analysis procedures are critical. Approved quality assurance and quality control (QA/QC) procedures are stringently applied throughout the demonstration.

Past hazardous waste disposal practices and their human health and environmental impacts prompted the U.S. Congress to enact the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (PL96-510). CERCLA established a Hazardous Substance Response Trust Fund (Superfund) to pay for handling emergencies at and cleaning up uncontrolled hazardous waste sites.

Under CERCLA, EPA has investigated these hazardous waste sites and established national priorities for site remediation. The ultimate objective of the investigations is to develop plans for permanent, long-term site cleanups, although EPA initiates short-term removal actions when necessary. EPA's list of the nation's top-priority hazardous waste sites that are eligible to receive federal cleanup assistance under the Superfund program is known as the National Priorities List (NPL).

As the Superfund program matured, Congress expressed concern over the use of land-based disposal and containment technologies to mitigate problems caused by releases of hazardous substances at hazardous waste sites. As a result of this concern, the 1986 reauthorization of CERCLA, called the Superfund Amendments and Reauthorization Act (SARA), mandates that EPA "select a remedial action that is protective of human health and the environment, that is cost effective, and that utilizes permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable." In response to this requirement, EPA established the SITE program to accelerate development, demonstration, and use of innovative technologies for site cleanups. The SITE program has four goals:

C   Identify and remove impediments to development and commercial use of innovative
        technologies, where possible

C   Conduct evaluations of the more promising innovative technologies to establish reliable
        performance and cost information for site characterization and cleanup decision-making

C   Develop procedures and policies that encourage selection of effective innovative
        treatment technologies at uncontrolled hazardous waste sites

The Demonstration Program is the flagship of the SITE Program. Its objective is to conduct field demonstrations and high quality performance verifications of viable remediation technologies at sites that pose high risks to human health and/or the environment are common throughout the region or the nation, or where existing remediation methods are inadequate, unsafe, or too costly. The SITE Program solicits applications annually from those responsible for clean-up operations at hazardous waste sites. A panel of SITE Program scientists, engineers, and associated environmental experts reviews the applications to identify those technologies that best represent solutions for the most pressing environmental problems. The resulting data and reports are intended for use by decision-makers in selecting remediation options and for increasing credibility in innovative applications.

SITE evaluations are usually conducted at uncontrolled hazardous waste sites, such as EPA removal and remedial action sites, sites under the regulatory jurisdiction of other federal agencies, state sites, EPA testing and evaluation facilities, sites undergoing private cleanup, the technology developer's site, or privately owned facilities. In the case of the biological reactor technology demonstration, the Stadtwerke Duesseldorf AG site was selected cooperatively by EPA and BMBF.

SITE and bilateral SITE evaluations provide detailed data on the performance, cost effectiveness, and reliability of innovative technologies. These data were provided potential users of a technology with sufficient information to make sound judgments about the applicability of the technology to a specific site or waste and to allow comparisons of the technology to other treatment alternatives.

**1.2   UNITED STATES AND GERMAN BILATERAL AGREEMENT ON
          REMEDIATION OF HAZARDOUS WASTE SITES**

In April 1990, EPA and BMBF entered into a bilateral agreement to gain a better understanding of each country's efforts in developing and demonstrating remedial technologies. The bilateral agreement has the following three goals:

- C   Facilitate an understanding of each country's approach to remediation of contaminated sites

- C   Demonstrate innovative remedial technologies as if the demonstrations had taken place in each country

- C   Facilitate international technology exchange

Technologies under development in the U.S. and Germany are evaluated under the bilateral agreement. Individual, or in some cases, multiple remedial technologies are demonstrated at each site. Technology evaluations occurring in the U.S. correspond to SITE evaluations; those occurring in Germany correspond to full-scale site remedial activities and are referred to as bilateral SITE evaluations. In the case of the U.S. evaluations, demonstration plans are prepared following routine SITE procedures. Additional monitoring and evaluation measurements required for evaluation of the technology under German regulations were specified by the German partners. For the demonstrations occurring in Germany, the German partners were provided all required information to allow the U.S. to develop an EPA NRMRL Applied Research QAPP. An EPA NRMRL Applied Research QAPP, "Quality Assurance Project Plan for the SWD AQUABOX 50 and MARABU Packed Biological

Reactor System Technology at the Stadtwerke Duesseldorf AG Site in Duesseldorf, Germany," dated July 1999, was prepared for this demonstration (Tetra Tech 1999).

Probiotec (a partnership of two German environmental consulting firms) was commissioned by BMBF to compile summary reports for the German technologies and sites, to evaluate the U.S. demonstration plans, and to facilitate the bilateral agreement on behalf of BMBF. The Probiotec technical consulting partnership is not directly involved in the German remedial actions, and the partnership does not influence actual site remediation activities. The bilateral project organization is presented in Figure 2.

1.3 BIOLOGICAL REACTOR TECHNOLOGY DESCRIPTION

This section describes the process equipment and system operations of the AQUABOX 50 and MARABU packed biological reactors. This section also describes the conventional components of the overall treatment system technology.

1.3.1 Process Equipment

The AQUABOX 50 bioreactor consists of five connected compartments, each 2 cubic meters (m^3) in volume (for a total volume of 10 m^3), incorporating a packed bed consisting of a polyvinyl chloride (PVC) mat with rough, linear extrusions. The MARABU bioreactor consists of one 1.5m^3 compartment, incorporating a packed bed consisting of polyethylene rings. A schematic of the treatment system is shown in Figure 3.

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Jennifer Guigliano

TETRA TECH
Field Support Staff
Sarah Woodland

Field Staff
To be assigned

Laboratory Staff
to be assigned

FIGURE 2
BILATERAL PROJECT ORGANIZATION
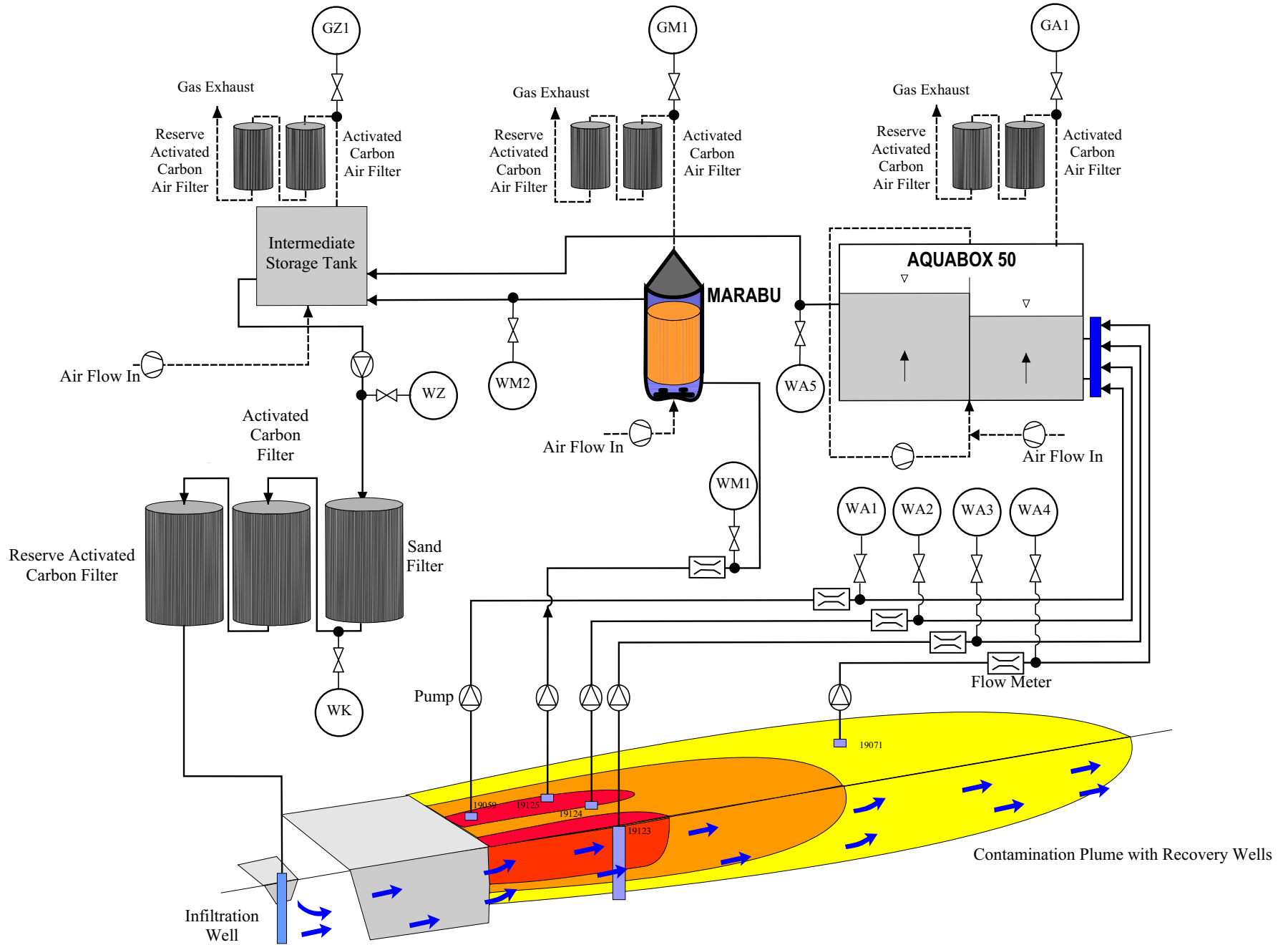
FIGURE 3
TREATMENT SYSTEM
SCHEMATIC

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1.3.2 **System Operations**

Groundwater is extracted at varying pump rates from five recovery wells installed within the contaminated groundwater 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 with no circulated air in the MARABU. Treated water from both the AQUABOX 50 and MARABU bioreactors flows through separate piping into the same intermediate storage tank with a total storage capacity of 20 m^3. This tank is aerated at a flow rate of 7 m^3/h which promotes the precipitation of the oxidated iron to occur within the sand filter. (The presence of high concentrations of iron in the facility groundwater is a natural characteristic of the area.)

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 also in place at each of the three gas exhausts and at the sand filter effluent.

1.4 **KEY CONTACTS**

Additional information on the biological reactor technology and the EPA-BMBF bilateral technology evaluation program can be obtained from the following sources:

Dr. Karlheinz Huebenthal
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26 West Martin Luther King Drive
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Information on the SITE Program is also available through the following on-line information clearinghouse: The Vendor Information System for Innovative Treatment Technologies (Hotline: (800) 245-4505) database contains information on 154 technologies offered by 97 developers. Technical reports may be obtained by contacting U.S. EPA/NCEPI, P.O. Box 42419, Cincinnati, Ohio 45242-2419, or by calling (800) 490-9198.

2.0   BIOLOGICAL REACTOR TECHNOLOGY EFFECTIVENESS

This section documents the background, field and analytical procedures, results, and conclusions of the Stadtwerke Duesseldorf AG bilateral SITE technology evaluation.

2.1   BACKGROUND

The bilateral SITE demonstration of the SWD AQUABOX 50 and MARABU Packed Biological
Reactors was conducted at the Stadtwerke Duesseldorf AG site in Duesseldorf, Germany (Figure 1).
The site background and an overview of the demonstration objectives and approach are described in
the following subsections.

2.1.1   Site Background

The bilateral SITE demonstration of these technologies was conducted at a facility owned and
operated by a public utility company, SWD. The facility was operated as a manufactured gas (coal
gasification) plant from 1890 to 1967. The primary industrial process at manufactured gas plants is
the conversion of coal to natural gas; associated by-products of this process include BTEX and
polycyclic aromatic hydrocarbons (PAH). The facility has been operated by SWD as an operations
yard from post-1967 to the present. While the manufactured gas plant was in operation, aquifer
contamination occurred through storage system leaks, improper handling of by-products, and World
War II bombing damage. Further contamination occurred approximately 25 years ago when the
gasworks were demolished.

Environmental assessments conducted between 1991 and 1993 identified several dissolved-phase
hydrocarbon plumes in the facility groundwater. The results of these assessments were used to
prioritize release areas at the facility in terms of clean-up priority. The top-priority plume (based on
measured benzene) is located at an area of the facility historically used for benzene production. This
plume has been chosen as the study area for this technology evaluation. Components of this plume
include BTEX and PAHs. The contaminant plume is approximately 600 meters long by 100 meters
wide by 10 to 15 meters in height, the top of which is approximately 6.5 to 7.5 meters below the
ground surface (bgs) (and 1.5 meters below the water table). Groundwater samples were collected
and analyzed from within this plume on March 23, 1999 to document current conditions.

2.1.2   Demonstration Objectives and Approach

Demonstration objectives were selected to provide potential users of the system with the necessary technical information to assess the applicability of the treatment system at other contaminated sites. For this bilateral SITE evaluation, two primary objectives and three secondary objectives were developed and are summarized below:

<u>Primary Objectives</u>

P1   *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. The overall system includes the AQUABOX 50, MARABU, and sand filter, but excludes the activated carbon system component.*

To accomplish this objective samples were collected from the influent water wells, labeled WA1 through WA4 for the AQUABOX 50 reactor, and one water location labeled WM1 for the MARABU reactor. Samples were also taken from the effluent water location labeled WK. Samples were collected once per week for a total of 4 weeks and analyzed for BTEX and the three most prevalent PAHs, acenaphthene, fluorene, and napthalene. Summary results were expressed as a mean and a range of removal efficiencies obtained over the 4-week evaluation period, and the mean result was compared to the objective.

To achieve objective P1, a removal efficiency (RE) was calculated on a mass basis for the entire system (excluding the pre-infiltration activated carbon filter) for each sampling event using the following equation:

$$RE = \frac{(QC_i - QC_e)}{QC_i} \, X100$$

Where:

RE   =   Removal efficiency (%)

C_i =   Calculated contaminant concentration in the influent to the system (a single flow-weighted average concentration was calculated based on the measured contaminant concentrations in the flow lines from the five influent wells - WA1 through WA4 and WM1)

C_e =   Measured concentration in the effluent from the gravel filter (WK)

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Q   =   Flow rate of groundwater through the system (sum of flows for each of the five influent flow lines - WA1 through WA4 and WM1)

The above equation was applied to data from each sampling event. Four separate REs were calculated for the system for each sampling event: total BTEX, acenaphthene, fluorene, and naphthalene.

To achieve objective P2, individual REs were calculated for the AQUABOX 50, MARABU, and sand filter using the above equation, with the following variable description substitutions:

RE   =   Removal efficiency (%) of each of the bioreactors and the sand filter
C_i =   Contaminant concentration in the influent to each of the bioreactors and the sand filter (a single weighted average concentration was calculated for the AQUABOX 50 based on the detected contaminant concentrations of the four influent wells - WA1 through 4; the concentration at WM1 was used for the MARABU; the concentration at WZ was used for the sand filter)

C_e =   Contaminant concentration in the effluent from each of the bioreactors (WA5 and M2) and the sand filter (WK)

P2   *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.*

To accomplish this objective, influent samples were collected from the influent wells as described above, with the addition of the sand filter influent sample location (WZ). Effluent samples were collected from each of the bioreactor effluents, including the AQUABOX 50 (WA5) and the MARABU (WM2) as well as the the sand filter effluent (WK). Samples were collected once per week for a total of 4 weeks and analyzed for BTEX and the three most prevalent PAHs, acenaphthene, fluorene, and napthalene. Summary results were expressed as a mean and a range of removal efficiencies obtained over the 4-week evaluation period, and the mean result was compared to the objective.

To achieve objective P2, individual REs were calculated for the AQUABOX 50, MARABU, and sand filter using the above equation under objective P1, with the following variable description substitutions:

RE   =   Removal efficiency (%) of each of the bioreactors and the sand filter

C_i =   Contaminant concentration in the influent to each of the bioreactors and the sand filter (a single weighted average concentration was calculated for the AQUABOX 50 based on the detected contaminant concentrations of the four influent wells - WA1 through 4; the concentration at WM1 was used for the MARABU; the concentration at WZ was used for the sand filter)

C_e = Contaminant concentration in the effluent from each of the bioreactors (WA5 and WM2) and the sand filter (WK)

Secondary Objectives

S1 *Determine the percent of total BTEX and naphthalene that is stripped from each aerated component of the system.*

To accomplish this objective, individual exhaust gas samples were collected from each of the system components at locations before the activated carbon units (GA1, GM1, and GZ1). These exhaust gas samples were collected on the same schedule as the influent/effluent water sampling activities (once per week for a 4-week period) and analyzed for BTEX and napthalene. Summary results were expressed as a mean and a range of the percentage removed by air stripping over the 4-week evaluation period.

To achieve objective S1, the percentage of total BTEX and naphthalene removed by the aeration component of the treatment system was calculated using the following equation:

$$SE = \frac{Q_{a,e}C_{a,e}}{Q_{w,i}C_{w,i}}$$

Where:

SE = Stripping efficiency (%)

$Q_{a,e}$ = Air flow rate at emission sampling point

$C_{a,e}$ = Concentration of contaminant in the air stream at the sampling point

$Q_{w,i}$ = Groundwater flow rate in the influent to each of the bioreactors and the sand filter

$C_{w,i}$ = Contaminant concentration in the influent groundwater

S2 *Document the physical and chemical characteristics of the treated water that could affect the performance of the evaluation system and document how these parameters change with treatment.*

To accomplish this objective, samples were collected once per week from five influent water wells and the effluent water well for the total system during the 4-week sampling period. These samples were analyzed for pH; major cations, including sodium (Na), potassium (K), calcium (Ca), iron (Fe), magnesium (Mg) and manganese (Mn); and anions, including chloride (Cl^-), fluoride (F^-), nitrate (NO_3-), nitrite (NO_2-), phosphate (PO_4^{3-}), and sulfate (SO_4^{2-}).

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S3 *Document the capital and operating costs of the SWD AQUABOX 50 and MARABU packed biological reactor system based on observations during the evaluation and data from the engineering designers and from the operator of the system.*

SWD had estimated the capital and operating costs of this system based on operating requirements observed during the evaluation and on capital and operating cost information available from the designers and operator of the system. To accomplish this objective, the preliminary construction cost estimate was updated, and operational costs were also compiled based on data provided by SWD.

2.2   DEMONSTRATION PROCEDURES

This section describes the methods and procedures used to collect and analyze samples for the bilateral SITE demonstration of the biological reactor system technology. The activities associated with the biological reactor technology demonstration included (1) evaluation design, (2) groundwater collection and analysis, and (3) field and laboratory QA/QC. Section 2.2.1 presents the evaluation design. The methods used to collect and analyze samples are outlined in Section 2.2.2. Field and laboratory QA/QC procedures are described in Section 2.2.3.

2.2.1   Evaluation Design

The purpose of the evaluation was to collect and analyze data of known and acceptable quality to achieve the objectives as described in Section 2.1.2.

2.2.2 Sampling and Analysis Program

The main objective of the sampling and analysis program is to provide sufficient data to allow EPA to evaluate the performance of the SWD AQUABOX 50 and MARABU packed biological reactor treatment system through meeting the primary and secondary evaluation objectives discussed in Section 2.1.2. Because of logistical constraints and the schedule requirements of the German bilateral partners, the evaluation of this system was limited to a time period of 4 weeks during July, 1999. Thus, samples that are representative of long-term operation cannot be practically obtained. Therefore, the goal of the planned sampling procedures was to obtain a sufficient number of samples to be representative of this short evaluation period and to maximize the representativeness of these samples so that the results accurately reflect the performance of the treatment system during the evaluation period.

2.2.2.1 Sampling and Measurement Locations

Sampling locations selected based on the configuration of the treatment system and project objectives are shown in Figure 3.

- **WA1**: Influent water from recovery well 19059 into AQUABOX 50 (flow rate of ~5 m^3/h)
- **WA2**: Influent water from recovery well 19124 into AQUABOX 50 (flow rate of ~3 m^3/h)
- **WA3**: Influent water from recovery well 19123 into AQUABOX 50 (flow rate of ~3 m^3/h)
- **WA4**: Influent water from recovery well 19071 into AQUABOX 50 (flow rate of ~9 m^3/h)
- **WM1**: Influent water from recovery well 19125 into MARABU (flow rate of ~ 3 m^3/h)
- **WA5**: Effluent water from AQUABOX 50
- **WM2**: Effluent water from MARABU
- **WZ**: Effluent water from intermediate storage tank/influent to sand filter
- **WK**: Effluent water from sand filter; total system (except carbon) effluent sampling location
- **GA1**: Exhaust gas stream from AQUABOX 50
- **GM1**: Exhaust gas stream from MARABU
- **GZ1**: Exhaust gas stream from intermediate storage tank

2.2.2.2   Sampling and Analytical Methods

This section described procedures for collecting representative samples at each sampling location and analyzing collected samples. Grab sampling techniques were employed throughout the demonstration. Samples were collected at nine locations.

System operating parameters were monitored continuously by facility personnel. Sampling began after facility personnel judged that the system was operating at a steady state.

Groundwater Samples

Influent and effluent water samples were collected from the treatment system once per week for a total of 4 weeks. The effluent water samples were collected after the influent, to account for the retention time in the system in order to obtain a representative sample. Water samples were collected during each event at each of the water sampling locations described in Section 2.2.1.2.

Water samples were collected as grab samples from a valved tap directly into sample containers from each location. Each sample collected for BTEX analysis was collected in 20-milliliter volatile organic analysis (VOA) vials containing hydrochloric acid (HCl) to acidify the sample to a pH of less than 2. Water was introduced into the sample containers gently to reduce agitation that may drive off volatile organic compounds (VOCs). Each vial was filled, and then tap checked for bubbles. If any air bubbles were present, the sample was recollected. The second sample vial served as a backup to the original sample in the event that one vial was broken or its integrity was otherwise compromised.

Water samples collected to analyze for PAHs were contained in two 1-liter glass jars. Again, the second sample bottle served as a backup to the original sample in the event that one bottle was broken or its integrity otherwise compromised.

Water samples collected for physical and chemical parameters necessary to fulfill objective S2 were collected in one 500-milliliter plastic jar and one 1-liter plastic jar.
Prior to collecting water samples from a given location, the valve on the tap was opened and water was purged to flush any stagnant water out of the tap.

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Gas Samples

Gas samples were collected during each sampling event at each of the gas sampling locations described above in Section 2.2.1.1 (GA1, GM1, and GZ1). Gas sampling times were based on a maximum sampling time of 50 minutes per location and take into account the water residence time through each of the associated aerated components.

Samples were collected according to the series of National Institute of Occupational Safety and Health (NIOSH) gas sampling methods that incorporate charcoal tube adsorption for specific groups of VOCs and pre-filtered XAD resin adsorption for napthalene. Sampling was conducted in accordance with modified NIOSH Methods 1501 for BTEX and 5515 for napthalene.

Two charcoal tube adsorbent samples for BTEX and two pre-filtered sorbent resin samples for naphthalene were taken at different sample volumes (20 and 50 liters) from each gas sampling location. These volumes were calculated by Institut Fresenius to achieve desired detection limits. Therefore, two samples of differing volumes were collected for BTEX at each gas sampling location and two samples of differing volumes were collected for naphthalene at each gas sampling location, for a total of four exhaust gas adsorbent samples collected at each gas sample location per sampling event.

Leak checks were performed before and after collection of each gas sample. After the post-sampling leak check, the traps were sealed with end caps and returned to their glass containers for storage and transport.

Analytical Methods

Table 1 lists the analytical methods used for samples collected during the evaluation.

Table 1   Analytical Methods

Matrix	Parameter	Reference Method	Method Name
Water	BTEX	SW-846 5030B/8260B	Purge-and-trap; Capillary Column; GC/MS
	PAH	SW-846 3520C/8270C	Continuous Liquid-Liquid Extraction; Capillary Column; GC/MS
	pH	MCAWW 150.1	pH
	Major Cations	SW-846 3010A/6010B	Metals by ICP/Atomic Emission Spectroscopy (Na, K, Ca, Fe, Mg, Mn)
	Major Anions	SM 4110B	Ion Chromatography (Cl$^-$, F$^-$, NO$_2^-$, NO$_3^-$, PO$_4^{-3}$, SO$_4^{-2}$)
Gas	BTEX	NIOSH 1501 SW-846 8260B	Extraction of Charcoal Adsorbent with CS$_2$; BTEX by GC/MS
	Naphthalene	NIOSH 5515 SW-846 8270C	Extraction of XAD Resin with Toluene;Naphthalene by GC/MS

Notes:
GC/MS   Gas chromatography/mass spectrometry
ICP   Inductively coupled plasma
MCAWW   Methods for the Chemical Analysis of Water and Wastes
NIOSH   National Institute of Occupational Safety and Health
SM   Standard Methods for the Examination of Water and Wastewater
BTEX   Benzene, toluene, ethylbenzene, and total xylenes
PAH   Polyaromatic hydrocarbons

2.2.3   Quality Assurance and Quality Control Program

Quality control checks were an integral part of the bilateral SITE evaluation. These checks and procedures focused on the collection of representative samples absent of external contamination and on the generation of comparable data. The QC checks and procedures conducted during the evaluation were of two kinds: (1) checks controlling field activities, such as sample collection and shipping; and (2) checks controlling laboratory activities, such as extraction techniques and analysis. The results of the field and laboratory QC checks are summarized in Section 2.3.3. Figure 4 presents the data reduction, validation, and reporting scheme for this demonstration.

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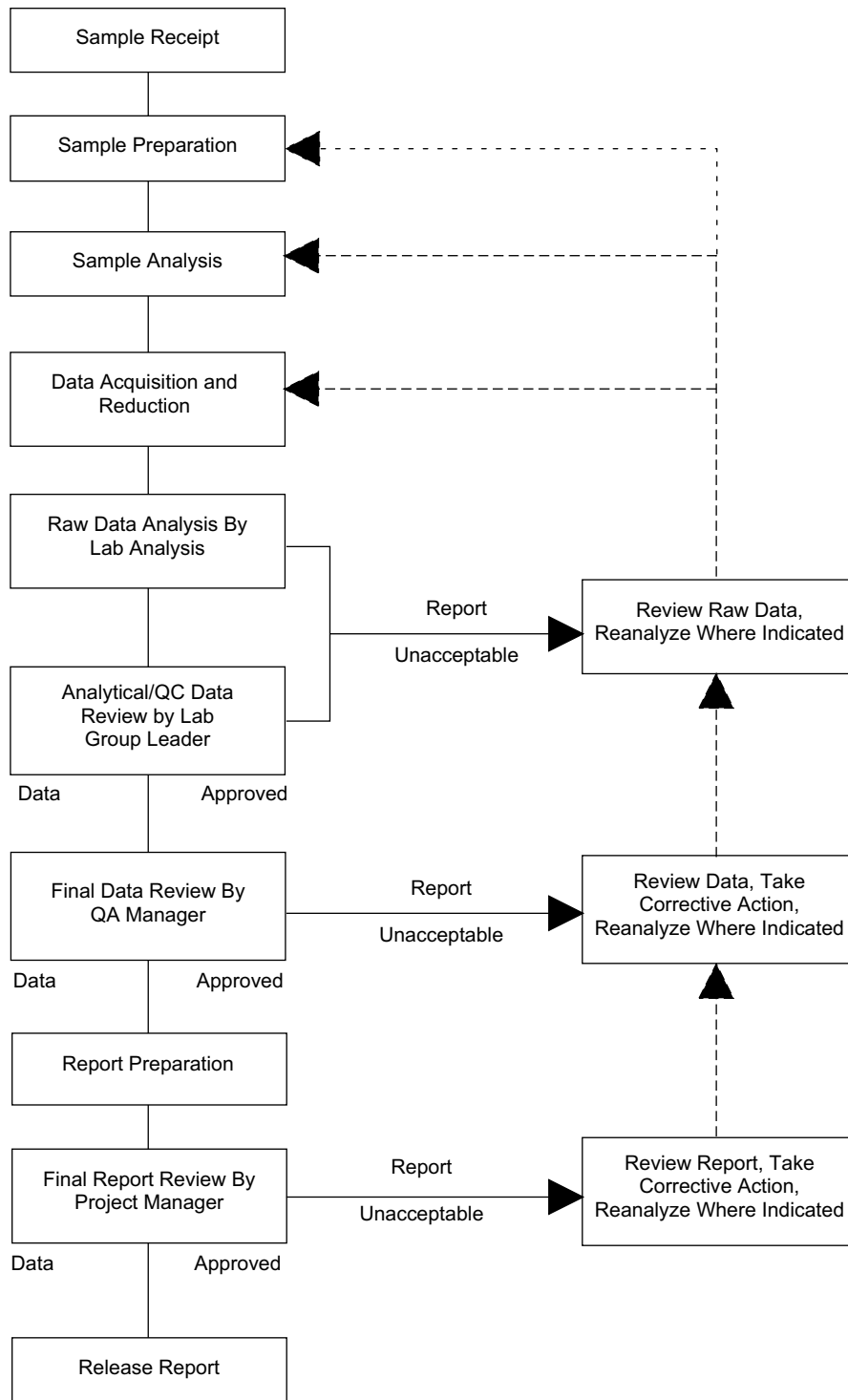
FIGURE 4
DATA REDUCTION, VALIDATION, AND
REPORTING SCHEME

2.2.3.1 Field Quality Control Checks

As a check on the quality of field activities, including sample collection, shipment, and handling, three types of field QC samples (field blanks and trip blanks) were collected. In general, these QC checks assess the potential for contamination of samples in the field and ensure that the degree to which the analytical data represent site conditions is known and documented.

2.2.3.2 Laboratory Quality Control Checks

Laboratory QC checks are designed to assess the precision and accuracy of the analysis, to demonstrate the absence of interferences and contamination from glassware and reagents, and to ensure the comparability of data. Laboratory-based QC checks consisted of method blanks, matrix spikes/matrix spike duplicates, surrogate spikes, blank spikes/blank spike duplicates, and other checks specified in the analytical methods. The laboratory also conducted initial calibrations and continued calibration checks according to the specified analytical methods.

2.2.3.3 Field and Laboratory Audits

No project specific audits were conducted during this technology demonstration. However, general systems audits of Institut Fresenius laboratories have been conducted under other bilateral technology demonstrations.

2.3 EVALUATION RESULTS AND CONCLUSIONS

This section describes the operating conditions, results, data quality, and conclusions of the bilateral SITE evaluation of the biological reactor system technology.

2.3.1 Operating Conditions

The AQUABOX 50 and MARABU biological reactors are active technologies that require operation and maintenance of the system components. During this bilateral SITE evaluation, the biological reactor system was operated at conditions determined by the developer, SWD.

2.3.1.1 Treatment System Configuration

The configuration of the biological reactor system components is shown in Figure 3.

2.3.1.2 Operating Parameters

The developer and facility owner monitored the biological reactor system throughout the demonstration. System operating parameters included individual well extraction rates and overall groundwater flow rates. Various operating parameters obtained from the on-site operators of the system were monitored to collect the operational data needed to fulfill the objectives of this evaluation. These parameters included:

> *(1) Extracted groundwater flow rates (for each of five recovery wells)*: Groundwater flow rates were read at the inlet port to each reactor when the influent groundwater sampling was performed (i.e. one measurement per day per event at each location).

> *(2) Ventilation gas flow rates (for AQUABOX 50, MARABU, and intermediate storage tank)*: Gas flow rates were read at the outlet port from each reactor and the intermediate storage tank, when the influent groundwater sampling was performed (i.e. one measurement per day per event at each location).

> *(3) Electric power consumption for the evaluation system*: Electrical power measurements were read and recorded by the field team at the beginning and end of each sampling event to determine power consumption. Cost information was compiled by Probiotec from the power consumption data recorded and reviewed by Tetra Tech.

The flow meters were calibrated by a state calibration office ("Staatliches Eichamt") before they were purchased from the vendor and were ready for immediate use. On-site operating personnel were responsible for maintaining all existing monitoring instruments.

2.3.2   Results and Discussion

This section presents the results of the bilateral SITE evaluation of the biological reactor technologies at Duesseldorf, Germany. The results are presented by and have been evaluated in relation to the project objectives. The specific primary and secondary objectives are shown at the top of each section in italics, followed by a discussion of the objective-specific results.

2.3.2.1   Primary Objectives

P1 *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. The overall system includes the AQUABOX 50, MARABU, and sand filter, but excludes the activated carbon system component.*

The SWD AQUABOX 50 and MARABU packed biological reactor system was designed to reduce total BTEX concentrations in water by greater than 95 percent and total PAH concentrations in water by greater than 60 percent. Based on the relatively low initial PAH concentrations in the groundwater, detection limit resolution was a concern for total PAH measurement. As such, removal efficiencies were only calculated for the three PAHs present at the highest initial concentrations: acenaphthene, fluorene, and naphthalene. Removal efficiencies were calculated using the average influent concentration and effluent concentration of the three critical PAHs and total BTEX.

The removal efficiencies for the target PAHs, acenaphthene, fluorene, and naphthalene ranged from >99.7 percent to >99.9 percent, >98.9 percent to >99.4 percent, and >99.6 percent to >99.9 percent, respectively. The removal efficiency of total BTEX ranged from >99.5 percent to >99.7 percent. (Note: removal efficiencies that are calculated from effluent concentrations less than the detection limit are designated as ">". Using the removal efficiency formula in Section 2.1.2, an influent concentration minus a less than the detection limit ("<") effluent concentration is presented as a ">" difference.) Table 2 presents the ranges and means of the removal efficiencies for these critical compounds, and Table 3 presents the influent concentrations, effluent concentrations, and calculated removal efficiency for each sampling event. Table 4 presents the flow rates [*Q,* see the removal efficiency equation in Section 2.1.2, where *Q* equals the flow rate of groundwater through the system (sum of flows for each of the five influent flow lines - WA1 through WA4 and WM1)] at the five influent wells for each sampling event that were used to calculate an average influent concentration. (Note: The effectiveness of the activated carbon filter in removing these contaminants from the water stream was not evaluated because activated carbon filters are conventional technology). Ranges and

averages of removal efficiencies for analytes that had concentrations less than the detection limits were calculated using half of the detection limit for each nondetect result.

Table 2   Range and Mean Mass Removal Efficiencies for the Total System

Compound	Range (Percent)	Mean (Percent)
Acenaphthene	>99.7 - >99.9	>99.7
Fluorene	>98.9 - >99.4	>99.1
Naphthalene	>99.6 - >99.9	>99.8
Total BTEX	>99.5 - >99.7	>99.6

P2 *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.*

The average removal efficiencies for the 4-week demonstration period were calculated on an individual mass basis for the target PAHs and total BTEX across each of the biological treatment units and the sand filter units (Table 5). The removal efficiencies for the PAHs were significantly lower than the removal efficiencies of the total BTEX, most likely due to volatization of the BTEX to air or increased

Table 3   Summary of Removal Efficiency Calculations for the Total System

Compound	Sampling Event No. 1			Sampling Event No. 2			Sampling Event No. 3			Sampling Event No. 4		
	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Removal Efficiency (%)
Acenaphthene	193	<1.0	>99.7	171.4	<1.0	>99.7	184	<0.5	>99.9	157	<0.5	>99.8
Fluorene	57	<1.0	>99.1	45.3	<1.0	>98.9	52.1	<0.5	>99.5	42.1	<0.5	>99.4
Naphthalene	208.5	<1.0	>99.8	129	<1.0	>99.6	248	<0.5	>99.9	184	<0.5	>99.9
Benzene	76.6	<1.0	>99.3	48.1	<1.0	>99.0	88.6	<1.0	>99.4	47.8	<1.0	>99.0
Toluene	494.5	1.8	99.6	420	<1.0	>99.9	403	<1.0	>99.9	462	<1.0	>99.9
Ethylbenzene	26.6	<1.0	>98.1	22.1	<1.0	>97.7	27.9	<1.0	>98.2	28.2	<1.0	>98.2
Total xylenes	222.8	1.0	99.6	182	1.0	99.5	206	1.0	99.5	245	1.0	99.6
Total BTEX	820	3.8	>99.5	672	2.5	>99.6	726	2.5	>99.7	783	2.5	>99.7

Notes:
Conc.   Concentration
Fg/L   Microgram per liter
%   Percent
BTEX   Benzene, toluene, ethylbenze and total xylenes

Table 4 Summary of the Influent Flow Rates to the System

Total Influent Flow Rates	Sampling Event No. 1 Influent Flow Rate (m³/hr)	Sampling Event No. 2 Influent Flow Rate (m³/hr)	Sampling Event No. 3 Influent Flow Rate (m³/hr)	Sampling Event No. 4 Influent Flow Rate (m³/hr)
Total (sum of the 4 influent flow rates) to the AQUABOX 50 unit	20.7	19.9	17.7	19.3
One influent flow rate to the MARABU unit	2.99	2.95	2.96	3.00
Total (sum of the 5 influent flow rates) to the system	23.7	22.9	20.7	22.3

Notes:
m³/hr   Cubic meters per hour

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biodegradation. The removal efficiencies of the AQUABOX 50 unit for acenaphthene, fluorene and naphthalene ranged from 76.0 percent to >99.8 percent, 80.7 percent to >99.3 percent, and 91.0 percent to >99.8 percent, respectively. The removal efficiency for total BTEX of the AQUABOX 50 unit ranged from 92.1 percent to >97.1 percent. The removal efficiencies of the MARABU unit for acenaphthene, fluorene, and napthalene ranged from 47.0 percent to 66.1 percent, 53.6 percent to 71.5 percent, and 75.3 percent to 90.2 percent, respectively. The removal efficiency for total BTEX of the MARABU unit ranged from 67.6 percent to 74.6 percent. The removal efficiencies of the sand filter unit for acenaphthene, fluorene, and naphthalene ranged from >99.0 percent to >99.4 percent, >95.7 percent to >97.1 percent, and >97.5 percent to >98.9 percent, respectively. The removal efficiency for total BTEX of the sand filter unit ranged from >40.5 percent to >94.6 percent. (Note: the flow rates, Q, used in the removal efficiency calculating, are presented in Table 4. See the equation in Section 2.1.2).

Because the three target PAHs and BTEX were detected at low concentrations in the influent well to the sand filter unit, the associated calculated removal efficiencies are not significant. The concentrations of these target analytes both in the influent wells and effluent from the sand filter unit were either low or less than the detection limit, resulting in removal efficiencies that are not meaningful. Table 6 presents influent and effluent analyte concentrations and removal efficiencies per event.

2.3.2.2 Secondary Objectives

The secondary project objectives and the associated noncritical measurement parameters required to achieve those objectives were presented in Section 2.1.2. The results of each secondary objective are discussed in the following subsections.

S1 *Determine the percent of total BTEX and naphthalene that is stripped from each aerated component of the system*

Aeration systems provide air flow through the AQUABOX 50, MARABU, and intermediate storage tank. Airflow strips BTEX and to a lesser extent PAHs (acenaphthene, fluorene, and naphthalene) from the groundwater. Resulting exhaust gases are discharged to the atmosphere through activated carbon filters. To assess the quantity of the total BTEX and volatile PAHs (acenaphthene, fluorene, and naphthalene) that are removed by air stripping, individual exhaust gas samples were collected from each of the system components at locations before the activated carbon units (GA1, GM1, and GZ1). These exhaust gas samples were collected on the same schedule as the influent/effluent water sampling activities (once per

week for a 4-week period). Results of the stripping efficiency calculations are presented in Table 7.
Summary results were expressed as a mean and a range of the percentage stripped over the 4-week
evaluation period are presented in Table 8.

Percentages of the PAHs and BTEX that were removed from the groundwater by the biological reactor
and percentages removed to the air due to the aeration in the biological reactors were determined. Table 8
presents the percentages of the contaminants that were volatilized, or stripped, to the air. The PAHs,
which are semivolatile, were stripped at lower percentages than the volatile BTEX. The PAHs detected in
the gas were all either lower than the detection limit or detected at low concentrations.

Table 5 Range and Mean Removal Efficiencies for the System Components

Compound	Percent Removal Efficiencies	
	Range (Percent)	Mean (Percent)
AQUABOX 50 Unit		
Acenaphthene	76.0 - >99.8	>84.6
Fluorene	80.7 - >99.3	>87.7
Naphthalene	91.0 - >99.8	>94.8
Total BTEX	92.1 - >97.1	>94.8
MARABU Unit		
Acenaphthene	47.0 - 66.1	52.8
Fluorene	53.6 - 71.5	64.4
Naphthalene	75.3 - 90.2	82.6
Total BTEX	67.6 - 74.6	71.7
Sand Filter Unit		
Acenaphthene	>99.0 - >99.4	>99.2
Fluorene	>95.7 - >97.2	>96.5
Naphthalene	>97.5 - >98.9	>98.2
Total BTEX	>40.5 - >94.6	>80.0

Notes:
BTEX   Benzene, toluene, ethylbenzene, and total xylenes

Table 6 - Summary of Mass Removal Efficiency Calculations for System Components

Compound	Sampling Event No. 1			Sampling Event No. 2			Sampling Event No. 3			Sampling Event No. 4		
	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Mass Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Mass Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Mass Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Mass Removal Efficiency (%)
AQUABOX 50 Unit												
Acenaphthene	171	40.9	76.1	163	39.1	76	142.0*	19.3*	86.4*	139	<0.5	>99.8
Fluorene	50.5	9.3	86.1	47.1	9.1	80.7	41.0	4.5	89.0	38.0	<0.5	>99.3
Naphthalene	134	8.3	93.8	114	10.3	91.0	114.3*	6.1*	94.7*	126.7	<0.5	>99.8
Benzene	42.2	2.7	93.6	35.9	2.1	94.1	24.4	<1.0	>97.9	21.3	<1.0	>97.7
Toluene	555	39.6	92.9	527	32.1	93.9	491.1	13.0	97.4	499	13.3	97.3
Ethylbenzene	24.9	3.1	87.5	24.0	2.7	88.8	24.8	1.4	94.4	27.1	1.4	94.8
Total xylenes	234	22.1	90.5	216	20.3	90.6	224.9	8.1	96.4	254.9	8.4	96.7
Total BTEX	856	67.5	92.1	803	57.2	92.9	765.2	23.0	97.0	802	23.6	97.1
MARABU Unit												
Acenaphthene	347.3	173.6	50.0	394.9	204.5	48.2	354.2*	120.1*	66.1*	356.4	189.0	47.0
Fluorene	101.2	33.8	66.6	111.9	38.3	65.8	96.8	27.6	71.5	88.2	40.9	53.6
Naphthalene	720.7	95.3	86.8	848.6	186.0	78.1	787.4*	77.1*	90.2*	836.2	206.8	75.3
Benzene	312.0	72.5	76.8	346.1	94.3	72.8	347.0	109.9	68.3	487	115	76.4
Toluene	79.4	16.9	78.7	68.0	14.6	78.5	48.3	15.0	68.9	129.2	22.9	82.3
Ethylbenzene	38.5	13.2	65.7	40.0	15.1	62.3	40.3	13.8	65.8	48.2	17.2	64.3
Total xylenes	149.3	48.2	67.7	149.1	54.2	63.6	131.8	45.3	65.6	167.2	55.7	66.7

Table 6 - Summary of Mass Removal Efficiency Calculations for System Components (Continued)

Compound	Sampling Event No. 1			Sampling Event No. 2			Sampling Event No. 3			Sampling Event No. 4		
	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Mass Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Mass Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Mass Removal Efficiency (%)	Influent Conc. (Fg/L)	Effluent Conc. (Fg/L)	Mass Removal Efficiency (%)
Total BTEX	579.2	150.8	74.0	603.2	178.2	70.5	567.4	184.0	67.6	831.9	211.0	74.6
Sand Filter Unit												
Acenaphthene	49.4	<1.0	>99.0	50.1	<1.0	>99.0	37.7*	<0.5*	>99.3*	39.6	<0.5	>99.4
Fluorene	11.8	<1.0	>95.8	11.5	<1.0	>95.7	9.0	<0.5	>97.2	8.6	<0.5	>97.1
Naphthalene	20.4	<1.0	>97.5	20.6	<1.0	>97.6	23.0*	<0.5*	>98.9*	23.4	<0.5	>98.9
Benzene	7.4	<1.0	>93.2	6.6	<1.0	>92.4	9.9	<1.0	>94.9	<1.0	<1.0	>0
Toluene	25.8	1.8	93.0	19.1	<1.0	>97.4	8.8	<1.0	>94.3	2.2	<1.0	>77.3
Ethylbenzene	3.0	<1.0	>83.3	3.1	<1.0	>83.9	2.3	<1.0	>78.3	<1.0	<1.0	>0
Total xylenes	18.7	1.0	94.7	17.2	1.0	94.2	9.9	1.0	89.9	1.0	1.0	0
Total BTEX	54.9	3.8	>93.1	46.0	2.5	>94.6	30.9	2.5	>91.9	4.2	2.5	>40.5

Notes:
*   MS/MSDs for these compounds did not meet the QA objectives during this event.
Fg/L   Micrograms per liter
%   Percent

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The results indicate removal efficiencies for the PAHs in groundwater ranging between 76.0 percent and 99.8 percent for the AQUABOX 50, and 48.2 and 90.2 percent for the MARABU. The gas concentration for PAHs were either less than the detection limit or very low indicating a minimal removal due to stripping. The BTEX gas concentrations stripped from the AQUABOX 50 range from 0.2 percent to 1.0 percent; BTEX gas concentrations stripped from the MARABU ranged from 6.9 percent to 8.8 percent.

S2   *Document the physical and chemical characteristics of the treated water that could affect the performance of the evaluation system and document how these parameters change with treatment.*

Parameters measured include pH, major cations (Na, K, Ca, Fe, Mg, Mn), and anions (Cl$^-$, F$^-$, NO$_2^-$, NO$_3^-$, PO$_4^{3-}$, SO$_4^{2-}$). To accomplish this objective, samples were collected once per week for the influent to (WA1 through WA4, WM1) and effluent from (WK) the treatment system during the 4-week sampling program. These samples were analyzed for each of the parameters identified above; results are presented as a mean and a range of the four measured values (see Table 9).

S3   *Document the capital and operating costs of the SWD AQUABOX 50 and MARABU packed biological reactor system based on observations during the evaluation and data from the engineering designers and from the operator of the system.*

Capital and operating costs of this system, as applied at the SWD site, were estimated based on operating requirements observed during the evaluation and on capital and operating cost information available from the designers and operator of the system. The initial capital cost of the biological reactor system at the Stadtwerke Duesseldorf AG Site, including site preparation, permitting and regulatory costs, construction materials and labor, and startup was about 218,700 DM ($113,900 U.S. assuming a 1.92 DM to $1 U.S. exchange rate).   Monitoring and other periodic costs amounted to about 37,000 DM/year ($19,300 U.S./year).

Table 7 Stripping Efficiencies for Each Component of the Treatment System

Compound	Sampling Event No. 1			Sampling Event No. 2			Sampling Event No. 3			Sampling Event No. 4		
	Inf. H_2O mg/hr	Gas mg/hr	SE %	Inf. H_2O mg/hr	Gas mg/h	SE %	Inf. H_2O mg/hr	Gas mg/hr	SE %	Inf. H_2O mg/hr	Gas mg/hr	SE %
AQUABOX 50 Unit												
Acenaphthene	3510	<0.5	<0.01	1810	<1.0	<0.06	1690	<0.5	<0.02	4720	<0.5	<0.01
Fluorene	1040	<0.5	<0.04	525	<0.4	<0.08	488	<0.5	<0.1	1290	<0.5	<0.04
Naphthalene	2740	<0.5	<0.02	1270	<1.1	<0.08	1360	<0.5	<0.04	4300	<0.5	<0.02
Benzene	866	2.7	0.3	400	3.4	0.9	290	<1.2	<0.4	724	1.3	0.2
Toluene	11400	43.9	0.4	5870	54.4	0.9	5840	25.0	0.4	16900	25.0	0.1
Ethylbenzene	511	3.8	0.7	268	5.0	0.4	295	2.88	1.0	919	2.9	0.3
Total xylenes	4790	22.0	0.5	2410	26.6	1.1	2680	13.0	0.5	8650	14.8	0.2
Total BTEX	17600	72.4	0.4	8950	89.5	1.0	9110	42.0	0.5	27200	44.0	0.2
MARABU Unit												
Acenaphthene	1040	1.4	0.1	1160	1.6	0.1	1050	2.4	0.2	1070	2.4	0.2
Fluorene	304	<0.2	<0.06	330	<0.2	<0.06	287	<0.2	<0.06	265	<0.2	<0.08
Naphthalene	2160	7.1	0.3	2500	6.2	0.2	2330	9.2	0.4	2510	9.4	0.4
Benzene	936	50.3	5.4	1020	54.1	5.3	1030	63.9	6.2	1460	92.8	6.4
Toluene	238	13.4	5.6	201	12.1	6.0	143	11.8	8.3	388	21.5	5.5
Ethylbenzene	116	11.1	9.6	118	12.6	10.7	119	10.6	8.9	145	17.6	12.1
Total xylenes	448	30.3	6.8	440	30.1	6.8	390	26.8	6.9	502	44.0	8.8
Total BTEX	1740	139	8.0	1780	152	8.5	1680	138.6	8.3	2500	173.0	6.9
Sand Filter Unit												
Acenaphthene	1160	<0.3	<0.02	706	<0.3	<0.04	560	<0.3	<0.06	1460	<0.3	<0.02
Fluorene	278	<0.3	<0.1	162	<0.3	<0.2	134	<0.3	<0.2	318	<0.3	<0.1
Naphthalene	480	1.5	0.3	290	1.5	0.5	342	1.6	0.5	864	1.6	0.2
Benzene	174	7.3	4.2	93	10.2	11.0	147	15.7	10.7	<18	15.7	<87
Toluene	607	18.8	3.1	269	23.5	8.7	131	12.7	9.7	<81	12.7	<15.7
Ethylbenzene	71	3.0	4.2	44	4.1	9.3	34	3.6	10.6	<18	3.6	<20.0
Total xylenes	440	12.4	2.8	243	14.4	5.9	147	11.9	8.1	37	11.9	32.2
Total BTEX	1290	41.5	3.2	649	52.2	8.0	459	44.0	9.6	155	44.0	28.4

Notes: H_2O = Water; mg/hr = Milligrams per hour; SE = Stripping Efficiency by Aeration; % = Percent

Table 8 Ranges and Mean Stripping Efficiencies for Each Component

Compound	Percent Stripping Efficiencies	
	Range (Percent)	**Mean (Percent)**
AQUABOX 50 Unit		
Acenaphthene	>0.005 - > 0.03	>0.01
Fluorene	>0.02 - >0.05	>0.03
Naphthalene	>0.009 - >0.04	>0.02
Total BTEX	0.2 - 1.0	0.5
MARABU Unit		
Acenaphthene	0.1 - 0.2	0.2
Fluorene	>0.03 - >0.04	>0.03
Naphthalene	0.2 - 0.4	0.3
Total BTEX	6.9 - 8.8	8.0
Sand Filter Unit		
Acenaphthene	>0.01 - >0.03	>0.02
Fluorene	>0.05 - >0.1	>0.7
Naphthalene	0.2 - 0.5	0.4
Total BTEX	3.2 - 28.4	12.3

Notes:

BTEX   Benzene, toluene, ethylbenzene, and total xylenes

Table 9 - Physical and Chemical Characteristics of the Treated Water

Parameter	Units	Sampling Location											
		Influent - WA1		Influent -WA2		Influent - WA3		Influent - WA 4		Influent - WM1		Effluent - WK	
		Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
pH		7.01-7.18	7.11	6.88-6.95	6.92	6.95-7.03	6.99	6.94-7.98	7.24	6.95-6.99	6.97	7.18-7.26	7.23
Temp.	EC	13.7-14.2	13.9	13.7-14.6	14.0	13.9-14.1	14.0	14.6-14.9	14.7	13.4-13.8	13.6	14.6-15.0	14.9
Conductivity	high 4th F S/cm	649-864	718	647-859	712	754-1010	835	697-927	766	626-831	689	672-896	734
Redox-potential	mV	-210 - -102	-149	-159 - -90	-113	-139 - -87	-115	-153 - -100	-122	-215 - -118	-163	110-250	174
Dissolved O$_2$	mg/L	0.1-0.5	0.3	0.14-0.5	0.3	0.2-0.99	0.6	0.1-0.4	0.2	0.1-0.7	0.3	3.35-5.8	4.2
Na	mg/L	59.7-61.1	60.3	60.3-62.6	61.4	63.8-64.8	64.3	62.6-64.6	63.9	58.0-60.7	59.5	61.5-64.2	62.9
K	mg/L	13.0-17.3	14.6	12.9-13.5-	13.1	21.9-22.4	22.0	9.0-9.8	9.3	13.0-13.9	13.5	13.1-13.3	13.2
Ca	mg/L	143-149	146	141-144	142	172-179	175	147-152	149	134-138	137	143-148	146
Fe	mg/L	3.8-4.1	4.0	6.2-6.6	6.4	10.3-11.2	10.6	7.8-8.9	8.4	6.0-6.2	6.1	0.024-0.049	0.041
Mg	mg/L	16.4-17.1	16.7	16.3-16.6	16.5	18.3-19.2	18.7	18.8-19.8	19.4	15.5-15.9	15.8	17.2-17.6	17.5
Mn	mg/L	0.77-0.79	0.78	1.5-1.5	1.5	2.1-2.1	2.1	1.5-1.5	1.5	1.1-1.1	1.1	0.024-0.054	0.041
Cl	mg/L	86-93	88	73-78	75	68-73	71	85-89	87	75-79	77	82-85	84
F	mg/L	0.36-0.37	0.37	0.63-0.68	0.65	0.73-0.75	0.74	0.3-0.3	0.3	.66-.70	0.68	0.45-0.47	0.46
Nitrite	mg/L	<0.02-<0.02	<0.02	<0.02-0.06	0.02	0.04-0.12	0.08	<0.02-.11	0.05	0.1-0.1	0.1	<0.02-<0.02	<0.02
Nitrate	mg/L	<0.3-<0.3	<0.3	1.3-1.4	1.3	1.5-1.9	1.7	0.9-1.6	1.3	<0.3-<0.3	<0.3	7.7-8.2	7.9
Phosphate	mg/L	0.3-0.5	0.4	0.1-0.6	0.4	0.4-0.7	0.6	0.5-0.7	0.6	0.9-1.1	1.0	<0.02-0.1	0.03

Table 9 - Physical and Chemical Characteristics of the Treated Water (Continued)

Parameter	Units	Influent - WA1		Influent -WA2		Influent - WA3		Influent - WA 4		Influent - WM1		Effluent - WK	
		Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Sulfate	mg/L	185-192	189	193-204	199	298-313	308	187-199	193	167-173	170	201-209	205
CaCO$_3$	mmol/L	5.11-5.17	5.15	4.9-5.0	5.0	5.23-5.28	5.26	5.61-5.66	5.64	5.27-5.46	5.37	4.99-5.04	5.01
Lead	F g/L	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5
Copper	F g/L	<5 - 16	6	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5	<5-20	7	<5 - <5	<5
Cadmium	F g/L	<0.5 - <0.5	<0.5	<0.5 - <0.5	<0.5	<0.5 - <0.5	<0.5	<0.5 - <0.5	<0.5	<0.5 - <0.5	<0.5	<0.5 - <0.5	<0.5
Zinc	F g/L	80-193	117	204-639	360	343-690	446	250-310	268	129-990	420	5-52	19
Nickel	F g/L	<5 - <5	<5	<5-13	5	<5-5	3	<5-6	3	<5 - <5	<5	<5 - <5	<5
Chromium	F g/L	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5	<5 - <5	<5
Arsenic	F g/L	2-3	2	1-1	1	2-2	2	3-4	4	3-3	3	<1-2	1
Mercury	F g/L	<0.2-<0.2	<0.2	<0.2-<0.2	<0.2	<0.2-<0.2	<0.2	<0.2-<0.2	<0.2	<0.2-<0.2	<0.2	<0.2-<0.2	<0.2

Notes:
F g/L   Micrograms per liter
F S/cm   Microsiemens per centimeter
mg/L Milligrams per liter
EC   Degree Celsius
mmol   Micromole

2.3.3   Data Quality

This section summarizes the data quality for groundwater samples collected and analyzed during the biological reactor system bilateral SITE demonstration. The purpose of this data quality assessment was to identify any limitations of the data presented in this report or qualifications of the conclusions based on known information on data quality.

2.3.3.1 Groundwater Samples

For the groundwater samples, both field and laboratory QC samples were collected. Field QC samples included trip blanks and field blanks, as well as MS/MSDs.

Because BTEX in groundwater was one of the primary contamination concerns at the site, field blanks and trip blanks were collected to monitor whether field techniques or sample shipping introduced VOCs to field samples. Toluene was the only compound detected in the field blanks and trip blanks above the detection limit at 2.9 Ƒg/L and 1.8 micrograms per liter (Ƒg/L), respectively. These results suggest that small concentrations of toluene may have been introduced by field techniques or sample shipping. Trip and field blank results for the remaining analytes were all less than detection limits.

One MS/MSD sample was taken during each of the four sampling events to assess the precision and accuracy of the recoveries for the critical analytes and matrix interferences. MS/MSD sample results, presented in Tables 10 thru 14, indicate that the recoveries and relative percent differences (RPDs) for the critical analytes were within the pre-established QC limits for three of the four samples. The MS/MSD recoveries and RPDs for 7 of the 8 critical analytes in samples taken during Event 3 were outside of the acceptance criteria. The volatiles, BTEX, were reanalyzed and MSD recoveries were all within range. The PAHs were not reanalyzed; acenaphthene and naphthalene were below the lower QC limit. Therefore, the results for these two PAHs in Event 3 could be biased low.

2.3.3.2 Gas Samples

The primary QC samples processed in relation to the gas samples included field blanks, trip blanks and MS/MSD samples. All the field and trip blanks had analytical results less than detection limits for contaminants of concern. Therefore, introduction of contaminants by field or laboratory techniques was unlikely. All the MS/MSD samples met the QA objectives, as shown in Tables 15 through 18, indicating that general data quality was good and that the sample data are useable without qualification.

Table 10   Matrix Spike/Matrix Spike Results, Duplicate Event 1

Compound	Field Sample (Fg/L)	MS (Fg/L)	MSD (Fg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Acenaphthene	0.24	8.37	9.04	81.3	88.8	60-132	7.7	#30
Fluorene	0.00	8.25	8.61	82.5	86.1	71-108	4.3	#30
Naphthalene	0.00	6.87	7.28	68.7	72.8	35-120	5.8	#30
Benzene	9.0	17.9	19.4	89.9	105.3	80-120	8.2	#30
Toluene	2.0	11.6	11.2	92.9	88.4	80-120	4.0	#30
Ethylbenzene	5.8	15.3	15.6	96.8	99.8	80-120	1.9	#30
m-,p-Xylene	0.5	19.4	19.8	94.9	96.5	80-120	1.6	#30
o-Xylene	0.9	9.9	10.0	93.8	95.7	80-120	1.8	#30

Notes:

Fg/L	Microgram per liter
%	Percent
*	Outside acceptance criteria
MS	Matrix spike
MS	Matrix spike duplicate
RPD	Relative percent difference

Table 11 Matrix Spike/Matrix Spike Results, Duplicate Event 2

Compound	Field Sample (Fg/L)	MS (Fg/L)	MSD (Fg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Acenaphthene	0.00	9.36	8.30	93.6	83.0	60-132	12.0	#30
Fluorene	0.00	8.99	8.00	89.9	80.0	71-108	12.0	#30
Naphthalene	0.00	8.01	7.47	80.1	74.7	35-120	7.0	#30
Benzene	2.1	41.9	42.0	100.4	100.4	80-120	0.2	#30
Toluene	32.1	74.0	71.8	101.4	96.0	80-120	3.0	#30
Ethylbenzene	2.7	43.1	41.6	103.3	99.4	80-120	3.6	#30
m-,p-Xylene	13.4	96.5	93.5	104.3	100.6	80-120	3.1	#30
o-Xylene	6.9	48.1	44.9	107.3	99.0	80-120	6.9	#30

Notes:
Fg/L Microgram per liter
% Percent
* Outside acceptance criteria
MS Matrix spike
MS Matrix spike duplicate
RPD Relative percent difference

Table 12   Matrix Spike/Matrix Spike Duplicate Results, Event 3

Compound	Field Sample (Fg/L)	MS (Fg/L)	MSD (Fg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Acenaphthene	0.24	8.37	9.04	81.3	88.8	60-132	7.7	#30
Fluorene	0.00	8.25	8.61	82.5	86.1	71-108	4.3	#30
Naphthalene	0.00	6.87	7.28	68.7	72.8	35-120	5.8	#30
Benzene	9.1	32.3	15.1	234.3*	60.7*	80-120	72.5*	#30
Toluene	7.1	26.6	8.2	189.7*	11.4*	80-120	105.6*	#30
Ethylbenzene	2.1	25.8	13.4	242.5*	115.7*	80-120	63.3*	#30
m-,p-Xylene	5.4	54.7	18.7	247.7*	67.0*	80-120	98.1*	#30
o-Xylene	3.7	26.9	9.8	242.2*	63.9*	80-120	93.1*	#30

Notes:
Fg/L Microgram per liter MS Matrix spike
% Percent MSD Matrix spike duplicate
* Outside acceptance criteria RPD Relative percent difference

Table 13 Matrix Spike/Matrix Spike Duplicate Results, Event 3 Retest

Compound	Field Sample (Ƒg/L)	MS (Ƒg/L)	MSD (Ƒg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Acenaphthene	37.70	54.94	44.67	86.2	34.9*	60-132	20.6	#30
Fluorene	8.95	25.77	21.76	84.1	64.1	71-108	16.9	#30
Naphthalene	22.95	39.71	23.65	83.8	3.5*	35-120	50.7*	#30
Benzene	9.9	1.3	28.7	108.1	95.0	80-120	8.7	#30
Toluene	8.8	30.0	29.3	102.6	99.3	80-120	2.3	#30
Ethylbenzene	2.3	22.9	22.3	105.1	102.0	80-120	2.7	#30
m-,p-Xylene	6.0	48.1	46.5	105.7	101.7	80-120	3.4	#30
o-Xylene	3.9	24.0	23.1	104.6	99.9	80-120	3.9	#30

Notes:

Ƒg/L   Microgram per liter
%   Percent
*   Outside acceptance criteria
MS   Matrix spike
MS   Matrix spike duplicate
RPD   Relative percent difference

Table 14 Matrix Spike/Matrix Spike Duplicate Results, Event 4

Compound	Field Sample (Ƒg/L)	MS (Ƒg/L)	MSD (Ƒg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Benzene	0.3	19.0	17.5	94.3	86.7	80-120	8.3	#30
Toluene	2.2	18.9	19.9	81.2	85.9	80-120	5.0	#30
Ethylbenzene	0.2	20.2	19.1	102.3	96.5	80-120	5.8	#30
m-,p-Xylene	0.3	42.0	39.7	104.6	98.9	80-120	5.6	#30
o-Xylene	0.5	20.3	19.4	103.1	98.8	80-120	4.2	#30
Acenaphthene	0.08	8.39	8.68	83.1	86.0	60-132	3.4	#30
Fluorene	0.01	8.08	8.52	80.7	85.1	71-108	5.3	#30
Naphthalene	0.01	8.22	8.37	82.1	83.6	35-120	1.8	#30

Notes:
ug/L   Microgram per liter   MS   Matrix spike
%   Percent   MSD   Matrix spike duplicate
*   Outside acceptance criteria   RPD   Relative percent difference

Table 15 Gas Matrix Spike/Matrix Spike Duplicate Results, Event 1

Compound	Field Sample (Fg/L)	MS (Fg/L)	MSD (Fg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Acenaphthene	0.06	8.01	7.94	99.4	98.5	60-132	0.88	#30
Fluorene	0.00	7.72	7.94	96.5	99.3	71-108	2.81	#30
Naphthalene	0.09	7.99	7.82	98.8	96.6	35-120	2.15	#30
Benzene	0.00	19.04	19.04	96.1	96.1	80-120	0.00	#30
Toluene	0.03	19.64	20.06	95.0	97.0	80-120	2.12	#30
Ethylbenzene	0.00	18.91	19.46	96.5	99.3	80-120	2.87	#30
Total Xylenes	0.01	54.9	55.24	92.3	92.9	80-120	0.32	#30

Notes:
Fg/L   Microgram per liter
%   Percent
*   Outside acceptance criteria
MS   Matrix spike
MS   Matrix spike duplicate
RPD   Relative percent difference

Table 16 Gas Matrix Spike/Matrix Spike Duplicate Results, Event 2

Compound	Field Sample (Fg/L)	MS (Fg/L)	MSD (Fg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Acenaphthene	0.06	7.82	7.93	97.0	98.4	60-132	1.40	#30
Fluorene	0.00	7.75	7.40	96.9	92.5	71-108	4.62	#30
Naphthalene	0.08	7.60	7.88	94.0	97.5	35-120	3.62	#30
Benzene	0.00	19.08	18.96	96.3	95.7	80-120	0.63	#30
Toluene	0.00	20.26	19.94	98.1	96.6	80-120	1.59	#30
Ethylbenzene	0.00	19.63	19.45	100.2	99.3	80-120	0.92	#30
Total Xylenes	0.00	54.03	53.0	91.5	89.7	80-120	0.99	#30

Notes:
Fg/L   Microgram per liter
%   Percent
MS   Matrix spike
MS   Matrix spike duplicate
RPD   Relative percent difference

Table 17 Gas Matrix Spike/Matrix Spike Duplicate Results, Event 3

Compound	Field Sample (Fg/L)	MS (Fg/L)	MSD (Fg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Acenaphthene	0.00	6.33	6.40	105.5	106.7	60-132	1.10	#30
Fluorene	0.00	6.10	6.28	101.7	104.7	71-108	2.91	#30
Naphthalene	0.09	6.52	6.92	107.2	113.8	35-120	5.95	#30
Benzene	0.00	36.29	37.33	91.5	94.2	80-120	2.83	#30
Toluene	0.03	39.02	38.93	94.4	94.2	80-120	0.23	#30
Ethylbenzene	0.00	38.36	38.57	97.9	98.4	80-120	0.55	#30
Total Xylenes	0.00	113.21	113.59	95.8	96.2	80-120	0.21	#30

Notes:

Fg/L   Micrograms per liter
%   Percent
MS   Matrix spike
MS   Matrix spike duplicate
RPD   Relative percent difference

Table 18 Gas Matrix Spike/Matrix Spike Duplicate Results, Event 4

Compound	Field Sample (Fg/L)	MS (Fg/L)	MSD (Fg/L)	MS Recovery (%)	MSD Recovery (%)	Recovery Acceptance Criteria	RPD	RPD Acceptance Criteria
Acenaphthene	0.09	8.25	8.21	102.0	101.5	60-132	0.49	#30
Fluorene	0.00	7.90	7.89	98.8	98.6	71-108	0.13	#30
Naphthalene	0.07	8.37	8.47	103.8	105.0	35-120	1.19	#30
Benzene	0.00	38.39	38.58	96.8	97.3	80-120	0.49	#30
Toluene	0.02	41.07	39.87	99.4	96.5	80-120	2.97	#30
Ethylbenzene	0.01	41.55	40.82	106.0	104.2	80-120	1.77	#30
Total Xylenes	0.03	120.41	117.04	101.9	86.3	80-120	8.29	#30

Notes:

Fg/L   Microgram per liter
%   Percent
MS   Matrix spike
MS   Matrix spike duplicate
RPD   Relative percent difference

2.4   CONCLUSIONS

This section presents the conclusions of the biological reactor system. The conclusions for each objective are summarized below.

- The removal efficiencies for the three target PAHs, acenaphthene, fluorene and napthalene, and for total BTEX were all greater than 99 percent. These removal efficiencies exceeded the target removal efficiencies of 60 percent for the PAHs and 95 percent for the total BTEX.

- The removal efficiencies, for the three target PAHs and the total BTEX, were calculated for three components of the system, the AQUABOX 50, the MARABU and the sand filter. Removal efficiencies of the AQUABOX 50 for acenaphthene, fluorene and napthalene ranged from 70.4 percent to 99.8 percent, 75.2 percent to 99.2 percent, and 91.0 percent to 99.8 percent, respectively. Removal efficiency for total BTEX of the AQUABOX 50 ranged from 92.3 percent to 97.0 percent. Removal efficiencies of the MARABU for acenapthene, fluorene, and napthalene ranged from 47.0 percent to 66.1 percent, 53.6 percent to 71.5 percent, and 75.3 percent to 90.2 percent, respectively. Removal efficiency for total BTEX of the MARABU ranged from 67.6 percent to 74.6 percent. Removal efficiencies of the sand filter unit for acenaphthene, fluorene, and napthalene ranged from 99.0 percent to 99.4 percent, 95.7 percent to 97.2 percent, and 97.5 percent to 98.9 percent, respectively. Removal efficiency for total BTEX for the sand filter unit ranged from 28.6 percent to 94.6 percent.

- The stripping efficiencies (percent of influent mass stripped into the exhaust gas) for the three target PAHs and the total BTEX were calculated for the three components of the system.

- Stripping efficiencies of the AQUABOX 50 for acenaphthene, fluorene, and napthalene, ranged from <0.01 percent to <0.06 percent, <0.04 percent to <0.1 percent, and <0.02 percent to <0.08 percent, respectively. Stripping efficiency for total BTEX of the AQUABOX 50 ranged from 0.2 percent to 1.0 percent. Stripping efficiencies of the MARABU for acenaphthene, fluorene, and napthalene, ranged from 0.1percent to 0.2 percent, <0.06 percent to <0.08 percent, and 0.2 percent to 0.4 percent, respectively. Stripping efficiency for total BTEX of the MARABU ranged from 6.9 percent to 8.8 percent. Stripping efficiencies of the sand filter for acenaphthene, fluorene, and napthalene, ranged from <0.02 percent to <0.06 percent, <0.1 percent to <0.2 percent, and 0.2 percent to 0.5 percent, respectively. Stripping efficiency for total BTEX of the sand filter ranged from 3.2 percent to 28.4 percent.

- The following physical and chemical characteristics of the treated water were measured at the four influent wells to the AQUABOX 50, the one influent well to the MARABU, and the effluent well from the sand filter: pH, sodium, potassium, calcium, iron, magnesium, manganese, chloride, floride, nitrite, nitrate, phosphate, sulfate, bicarbonate (alkalinity), lead, copper, cadmium, zinc, nickel, chromium, arsenic, and mercury. The following trends were noted:

- Groundwater samples taken from influent sampling well to the AQUABOX 50 located at WA3 had the highest sodium, potassium, calcium, iron, manganese, chloride, floride, sulfate, and zinc concentrations.

- Groundwater samples taken from the influent sampling well to the MARABU located at WM1 had the lowest sodium, calcium, magnesium, nitrate, phosphate, and sulfate concentrations.

- Groundwater samples taken from the effluent sampling well located at WK had the lowest iron, manganese, nitrite, phosphate, and zinc concentrations. All of these analytes had been significantly reduced most likely due to the precipitation reactions occurring within the biological reactive boxes and possibly biological oxidation of nitrite by nitrifying bacteria. The highest concentration of nitrate was recorded in samples taken from the WK sampling well.

- Lead, cadmium, chromium, and mercury concentrations were less than the detection limit in all monitoring wells. Copper and nickel concentrations were detected above the detection limit in two of the influent wells at low concentrations. Arsenic was detected in all monitoring wells at low concentrations.

- The initial capital cost of the biological reactor system at the Stadtwerke Duesseldorf AG Site, including site preparation, permitting and regulatory costs, construction materials and labor, and startup was about 218,700 DM ($113,900 U.S. assuming a 1.92 DM to $1 U.S. exchange rate). Monitoring and other periodic costs amounted to about 37,000 DM ($19,300 U.S.) per year.

3.0   ECONOMIC ANALYSIS

Cost estimates presented in this section are based on data provided by SWD. Because the cost of implementing this technology at a given site depends upon various site-specific factors, costs are initially presented below as those directly incurred by SWD in the installation and operation of the biological reactor at the Stadtwerke Duesseldorf AG Site in Duesseldorf, Germany.

The initial capital cost of the biological reactor system at the Stadtwerke Duesseldorf AG Site, including site preparation, permitting and regulatory costs, construction materials and labor, and startup was about 218,700 DM ($113,900 U.S. assuming a 1.92 DM to $1 U.S. exchange rate). Monitoring and other periodic costs amounted to about 37,000 DM ($19,300 U.S.) per year.

The above overall cost estimates are approximate and were provided directly by SWD. Although groundwater treatment costs were not independently estimated, the following cost categories (Evans 1990) should be considered when evaluating the potential cost of treating groundwater using the biological reactor system technology:

C   Site preparation

C   Permitting and regulatory requirements

C   Capital equipment

C   Startup

C   Labor

C   Consumables and supplies

C   Utilities

C   Effluent treatment and disposal

C   Residuals and waste shipping and handling

C   Analytical services

C   Maintenance and modifications

C   Demobilization

Stadtwerke Duesseldorf AG provided the following cost breakdown and explanations in accordance with the above listed criteria.

Site Preparation: The cost for site preparation included the cost for the foundation and construction of the workshop hall for the treatment system.

Permitting and Regulatory Costs: The permitting and regulatory cost included the cost for obtaining the license, associated procedures necessary to comply with permitting procedures, and for the design of the construction of the treatment system. Both the expert opinion and the quality control of the groundwater treatment investigation were requested by the German authorities in order to obtain a permit for construction and operation of the biological reactor system.

Capital Equipment Costs: Capital equipment costs included the rental fees for the two packed biological reactors, the MARABU and AQUABOX 50.

Startup Costs: The two largest parts of the startup costs were for the sand filter and for the control system of the facility.

Operating Costs: Operating costs were included the salaries for the project managers and engineers.

Consumables and Supplies: The cost for consumables and supplies required for this system included the cost for replacement parts such as pumps, engines and pipes. The costs for the activated carbon are considered in the cost for "residuals and waste shipping and handling".

Utilities: This cost included the cost for electric power for the system.

Effluent Treatment and Disposal: No costs were associated with effluent treatment and disposal, since this is an in-situ passive treatment technology.

Residuals and Waste Shipping and Handling: The cost associated with residuals and waste shipping included the purchase of the activated carbon and the disposal of the sludge and working materials.

Analytical Service: The cost for monitoring the performance of the biological reactor system through the sampling and analysis of groundwater from influent and effluent monitoring wells included both the organic and inorganic analyses for the periodical monitoring of the treatment system.

Maintenance and Modification: Maintenance and modification costs included the labor costs for maintenance of the treatment system.

Demobilization: Demobilization costs included the demobilization of the foundation and the treatment system.

4.0   TECHNOLOGY APPLICATIONS ANALYSIS

This section evaluates the general applicability of the biological reactor system technology to contaminated waste sites. Information presented in this section is intended to assist decision makers in screening specific technologies for a particular cleanup situation. This section presents the advantages, disadvantages, and limitations of the technology and discusses factors that have a major impact on the performance and cost of the technology. The analysis is based both on the demonstration results and on available information from other applications of the technology.

4.1 FEASIBILITY STUDY EVALUATION CRITERIA

This section assesses the biological reactor system technology against the nine evaluation criteria used for conducting detailed analyses of remedial alternatives in feasibility studies under CERCLA (EPA 1988).

4.1.1 Overall Protection of Human Health and the Environment

The biological reactor system technology provides both short-term and long-term protection of human health and the environment by reducing the concentrations of contaminants in groundwater.

BTEX and PAHs are removed by biodegredation and air stripping the extracted groundwater. (Removal efficiency is discussed in more detail in Section 2.0.) Treated groundwater from both bioreactors is pumped into a storage tank which is aerated to reduce iron concentrations in the treated water. The partially treated water flows from the storage tank through a sand filter 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. Exposure from air emissions is minimized through the removal of contaminants from the system's air process stream using carbon adsorption units before discharge to the atmosphere.

4.1.2 Compliance with ARARs

Although general and specific applicable or relevant and appropriate requirements (ARARs) were not specifically identified for the biological reactor system technology, compliance with chemical-, location-, and action-specific ARARs should be determined on a site-specific basis. While location- and action-specific ARARs generally can be met, compliance with chemical-specific ARARs depends on the efficiency of the biological reactor system in removing contaminants from the groundwater and the site-specific cleanup level.

4.1.3 Long-Term Effectiveness and Permanence

The biological reactor system permanently reduces BTEX and PAH levels in groundwater through biodegredation and air stripping. Potential long-term risks to the treatment system workers, the community, and the environment from emissions of treated groundwater and discharge of treated groundwater are mitigated by ensuring that established standards are met.

4.1.4 Reduction of Toxicity, Mobility, or Volume through Treatment

As discussed in Section 4.1.1 and 4.1.3, the biological reactor system offers permanent removal of BTEX and PAHs. As such, the toxicity, mobility, and volume of contaminants are also significantly reduced.

4.1.5 Short-Term Effectiveness

The permanent removal of BTEX and PAHs from groundwater is achieved relatively quickly, providing for short-term effectiveness, as well as long-term effectiveness discussed in Section 4.1.3. Potential short-term risks presented during system operation to workers, the community, and the environment include air emissions. Exposure from fugitive air emissions during operation, monitoring, and maintenance are minimized through the removal of contaminants in the system's air process stream using carbon adsorption units before discharge.

4.1.6 Implementability

Implementation of the AQUABOX 50 and MARABU biological reactor system involves (1) site preparation, (2) system construction and configuration, (3) monitoring and maintenance. Minimal adverse impacts to the community and the environment are anticipated during site preparation and system installation.

4.1.7 Cost

The initial capital cost of the biological reactor system at the Stadtwerke Duesseldorf AG Site, including site preparation, permitting and regulatory costs, construction materials and labor, and startup was about 218,700 DM/year ($113,900 U.S./year assuming a 1.92 DM to $1 U.S. exchange rate). Monitoring and other periodic costs amounted to about 37,000 DM/year ($19,300 U.S./year).

4.1.8   State Acceptance

State acceptance is anticipated because the biological reactor system uses widely accepted processes to remove contaminants from groundwater and to treat air emissions. If remediation was conducted as part of Resource Conservation and Recovery Act (RCRA) corrective actions, state regulatory agencies require that permits be obtained before implementing the system, such as a permit to operate the treatment system and an air emissions permit.

4.1.9   Community Acceptance

The system's size and space requirements, as well as the principles of operation, may raise concern in nearby communities. However, proper management and operational controls coupled with minimal short-term risks to the community and the permanent removal of contaminants through these processes make this technology likely to be accepted by the public.

4.2   APPLICABLE WASTES

The biological reactor system technology demonstrated at Duesseldorf, Germany, was designed to remove BTEX and PAHs from groundwater. The technology's applicability to contaminants other than BTEX and PAHs was not examined as part of this demonstration.

4.3   LIMITATIONS OF THE TECHNOLOGY

The developer claims that high concentrations of contaminated media can be treated by the system. However, high concentrations of contaminants may require more than one pass through the system to achieve remediation goals. The full range of system applicability was not evaluated as part of this demonstration.

5.0   BIOLOGICAL REACTOR SYSTEM TECHNOLOGY STATUS

According to SWD AG, the technology can be used for remediation of contaminated groundwater, especially those contaminated with volatile and semivolatile organic compounds. There are currently no commercially operating systems in the U.S.

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