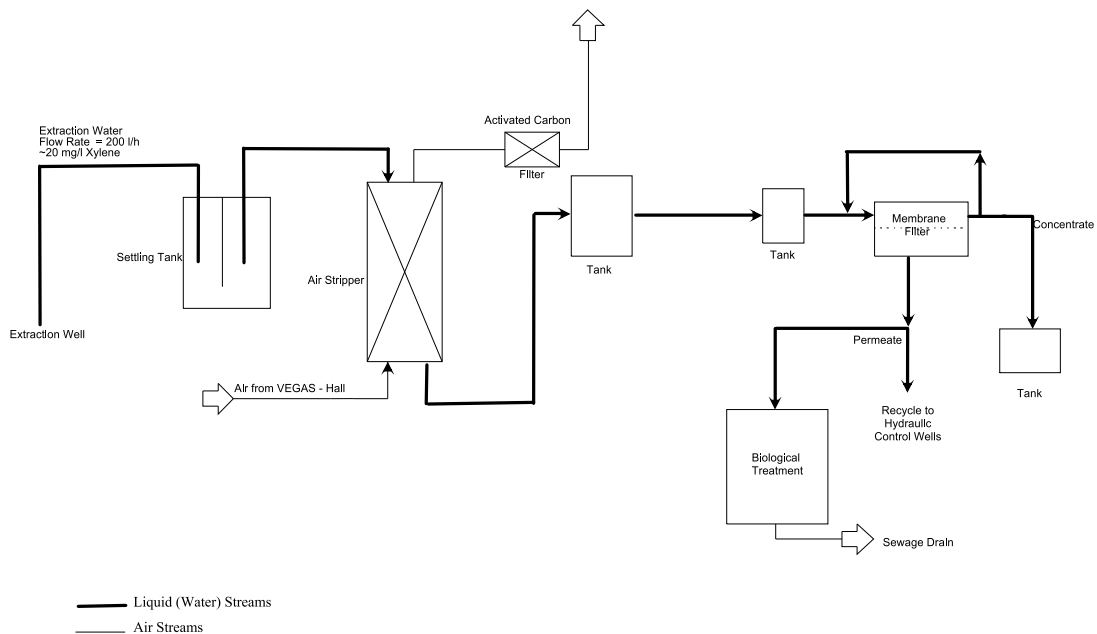


Surfactant-Enhanced Extraction Technology Evaluation

EPA - BMBF Bilateral Site Demonstration

Versuchseinrichtung zur
Grundwasser-und
Altlastensanierung (VEGAS) Facility
Stuttgart, Germany

Innovative Technology Evaluation Report



SURFACTANT-ENHANCED EXTRACTION TECHNOLOGY EVALUATION

EPA - BMBF BILATERAL SITE DEMONSTRATION

Versuchseinrichtung zur Grundwasser-und Altlastensanierung (VEGAS) Facility STUTT GART, GERMANY

INNOVATIVE TECHNOLOGY EVALUATION REPORT

By
Tetra Tech EM Inc.
1230 Columbia Street, Suite 1000
San Diego, California 92101

Contract No. 68-C5-0037
Work Assignment No. 0-05

Work Assignment Manager
Ann Vega
Land Remediation and Pollution Control Division
National Risk Management Research Laboratory
Cincinnati, Ohio 45268

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

NOTICE

The information in this document has been prepared for the U.S. Environmental Protection Agency's (EPA's) Superfund Innovative Technology Evaluation program by Tetra Tech EM Inc. under Contract No. 68-C5-0037. This document has been prepared in support of a bilateral agreement between the EPA and the Federal Republic of Germany Ministry for Research and Technology. This document has been subject to the EPA's 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 or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Hugh W. McKinnon, Director
National Risk Management Research Laboratory

CONTENTS

NOTICE.....	ii
FOREWORD.....	iii
ACRONYMS AND ABBREVIATIONS.....	vii
CONVERSION TABLE.....	viii
ACKNOWLEDGMENTS.....	ix
EXECUTIVE SUMMARY.....	ES-1
1.0 INTRODUCTION.....	1
1.1 SUPERFUND INNOVATIVE TECHNOLOGY EVALUATION PROGRAM.....	3
1.2 BILATERAL AGREEMENT BETWEEN THE UNITED STATES AND GERMANY ON REMEDIATION OF HAZARDOUS WASTE SITES.....	5
1.3 SURFACTANT-ENHANCED EXTRACTION TECHNOLOGY DESCRIPTION.....	6
1.4 KEY CONTACTS.....	8
2.0 SURFACTANT-ENHANCED EXTRACTION TECHNOLOGY EFFECTIVENESS.....	10
2.1 DEMONSTRATION BACKGROUND.....	10
2.1.1 VEGAS Research Facility.....	10
2.1.2 Preparation of the Artificial Aquifer.....	12
2.1.3 Process Description and Planned Operation.....	12
2.1.4 Demonstration Objectives and Approach.....	17
2.2 DEMONSTRATION PROCEDURES.....	20
2.2.1 Sampling and Analysis Program.....	20
2.2.1.1 Sampling and Measurement Locations.....	20
2.2.2 Sampling and Analytical Methods.....	22
2.2.3 Quality Assurance and Quality Control Program.....	23
2.2.4 Chronology of Process Operations and Changes to the Sampling Program.....	23
2.3 DEMONSTRATION RESULTS AND CONCLUSIONS.....	26
2.3.1 Results and Discussion.....	26
2.3.1.1 Primary Objective P-1.....	26
2.3.1.2 Primary Objective P-2.....	27
2.3.1.3 Secondary Objective S-1.....	31
2.3.1.4 Secondary Objective S-2.....	34
2.3.1.5 Secondary Objective S-3.....	39
2.3.1.6 Secondary Objective S-4.....	39

CONTENTS (Continued)

2.3.2	Data Quality.....	41
2.3.3	Conclusions.....	45
3.0	ECONOMIC ANALYSIS	46
4.0	TECHNOLOGY APPLICATIONS ANALYSIS	47
4.1	FEASIBILITY STUDY EVALUATION CRITERIA.....	47
4.1.1	Overall Protection of Human Health and the Environment.....	47
4.1.2	Compliance with ARARs	47
4.1.3	Long-Term Effectiveness and Permanence	48
4.1.4	Reduction of Toxicity, Mobility, or Volume Through Treatment.....	48
4.1.5	Short-Term Effectiveness	48
4.1.6	Implementability	48
4.1.7	Cost	49
4.1.8	State Acceptance.....	49
4.1.9	Community Acceptance.....	49
4.2	APPLICABLE WASTES	49
4.3	LIMITATIONS OF THE TECHNOLOGY.....	49
5.0	SURFACTANT-ENHANCED EXTRACTION TECHNOLOGY STATUS	50
6.0	REFERENCES	51

FIGURES

1 LOCATION OF VEGAS RESEARCH FACILITY 2
2 PROJECT ORGANIZATION 7
3 CROSS-SECTION OF ARTIFICIAL AQUIFER 11
4 MONITORING WELL CONFIGURATION 13
5 SURFACTANT INJECTION/EXTRACTION SYSTEM 14
6 SURFACTANT RECOVERY SYSTEM 16
7 CONCEPTUAL PLOT OF ANTICIPATED XYLENE MASS REMOVAL RATES 18
8 SAMPLING AND MONITORING LOCATIONS 21
9 XYLENE MASS REMOVAL RATES DURING THE DEMONSTRATION 30

TABLES

1 CRITICAL MEASUREMENT PARAMETERS 17
2 NONCRITICAL MEASUREMENT PARAMETERS 19
3 ANALYTICAL METHODS: SURFACTANT-ENHANCED EXTRACTION SYSTEM 23
4 XYLENE EXTRACTION RATES IN THE EXTRACTED GROUNDWATER
(SAMPLING LOCATION S4, MONITORING LOCATION M1) 27
5 XYLENE CONCENTRATIONS IN THE EFFLUENT GROUNDWATER
(SAMPLING LOCATION S2) 32
6 ACUTE TOXICITY OF GROUNDWATER EFFLUENT TO DAPHNIA 34
7 SUMMARY OF THE PROCESS FLOW RESULTS 35
8 SELECTED PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE
INFLUENT GROUNDWATER 36
9 SURFACTANT CONCENTRATIONS OF GROUNDWATER EFFLUENT
(SAMPLING LOCATION S2) 40
10 RESULTS FOR MATRIX SPIKE QC SAMPLES 42

ACRONYMS AND ABBREVIATIONS

ARARs	Applicable or relevant and appropriate requirements
ArGe	Arbeitsgemeinschaft (focon Probiotec)
ASTM	American Society for Testing and Materials
ATTIC	Alternative Treatment Technology Information Center
BASF	BASF AG
BMBF	Federal Republic of German Ministry for Research and Technology
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERI	Center for Environmental Research Information
CLU-IN	Clean-up Information (on-line database)
cm	Centimeters
°C	Degrees Celsius
€	Euro
EPA	U.S. Environmental Protection Agency
GC/MS	Gas chromatography/Mass Spectrograph
HPLC	High performance liquid chromatography
ITER	Innovative Technology Evaluation Report
kg	Kilogram
LC50	Lethal concentration - 50 percent
L/h	Liters per hour
m ³	Cubic meters
MCAWW	Methods for Chemical Analysis of Water and Wastes
MS/MSD	Matrix spike/matrix spike duplicate
m/p-xylene	meta-xylene and para-xylene
NPL	National Priorities List
NRMRL	National Risk Management Research Laboratory
NTIS	National Technical Information Service
o-xylene	ortho-xylene
ORD	U.S. EPA Office of Research and Development
OSWER	U.S. Office of Solid Waste and Emergency Response
QA/QC	Quality assurance and quality control
QAPP	Quality assurance project plan
QC	Quality control
RCRA	Resource Conservation and Recovery Act
RPD	Relative percent difference
SARA	Superfund Amendments and Reauthorization Act (of 1986)
SITE	Superfund Innovative Technology Evaluation (program)
Superfund	Hazardous Substance Response Trust Fund
SVOC	Semivolatile organic compound
SW-846	Test Methods for Evaluating Solid Waste
Tauw	Tauw Umwelt GmbH Moers
Tetra Tech	Tetra Tech EM Inc.
µg/L	Micrograms per liter
VISITT	Vendor Information System for Innovative Treatment Technologies
VEGAS	Versuchseinrichtung zur Grundwasser-und Altlastensanierung
VOC	Volatile organic compound

**CONVERSION TABLE
(Metric to English Units)**

<u>To Convert</u>	<u>Into</u>	<u>Multiply By</u>
Centimeters	Feet	0.0328
Centimeters	Inches	0.393
Cubic meters	Cubic feet	35.0
Cubic meters	Gallons	264
Cubic meters	Cubic yards	1.31
Degrees Celsius	Degrees Fahrenheit	multiply by 1.80; add 32
Hectopascals	Atmosphere	0.000986
Kilograms per square meter	Pounds per square inch, absolute	0.00142
Kilograms	Pounds	2.21
Kilograms per liter	Pounds per cubic foot	12.8
Kilometers	Miles (statute)	0.621
Liters	Gallons	0.265
Liters per hour	Gallons per minute	0.0044
Liters per second	Cubic feet (standard) per minute	2.12
Meters	Feet	3.278
Millimeters	Inches	0.039
Square meters	Square feet	10.764

ACKNOWLEDGMENTS

This report was prepared under the direction of Dr. Ronald Lewis of the EPA National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio. This report was prepared by Mr. Roger Argus, Ms. Elizabeth Barr, and Mr. Steven Geyer of Tetra Tech EM Inc. Ms. Ann Vega of NRMRL, Mr. Burkhard Heuel-Fabianek of Probiotec, and Dr. Reiner Kurz of Institut Fresenius were contributors to, and reviewers of, this report.

EXECUTIVE SUMMARY

This innovative technology evaluation report (ITER) summarizes the results of an evaluation of a surfactant-enhanced extraction technology. 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). To provide performance data for the evaluation, the surfactant-enhanced extraction system was demonstrated within an artificial aquifer from February 28 through March 5, 1998 at the Versuchseinrichtung zur Grundwasser-und Altlastensanierung (VEGAS) research facility in Stuttgart, Germany. Prior to the demonstration, the artificial aquifer was injected with xylene to create a contaminant plume for the technology evaluation. During the demonstration, surfactant was injected into the artificial aquifer, groundwater containing xylene was extracted, and the system was monitored to assess the effectiveness of the technology.

The Surfactant-Enhanced Extraction Technology

The use of surfactants to enhance in-situ flushing of aquifers for remediation of non-aqueous phase liquid contaminant plumes has not yet been accepted in Germany because of the limited availability of credible test data. In order to collect more reliable data, a large-scale test of surfactant-enhanced extraction was conducted at the VEGAS research facility. The technology demonstrated uses a proprietary surfactant developed by BASF AG and a surfactant recovery system developed by Tauw Umwelt GmbH Moers. VEGAS facility personnel installed and operated the treatment system.

The VEGAS research facility was constructed to facilitate the evaluation of remediation technologies. An artificial aquifer has been constructed at the VEGAS facility to allow for controlled testing of in-situ treatment technologies. Thirty-one kilograms (kg) of xylene, an organic contaminant with low solubility in water, was injected into the artificial aquifer and "groundwater" flow was induced to stimulate a contaminant plume. Groundwater was sampled by the BMBF support contractors, ArGe focon-Probiotec and Institut Fresenius, with assistance from the EPA support contractor, Tetra Tech EM Inc. (Tetra Tech). System operating parameters were monitored by VEGAS personnel. All samples were analyzed by the Institut Fresenius laboratory in Taunusstein. The groundwater effluent from the aquifer was treated using a conventional water treatment system and recycled into the aquifer. The conventional water treatment system consisted of a sedimentation tank, a phase separator, a sand filter, and a granular activated carbon bed.

The proprietary surfactant was designed to enhance the removal of volatile organic compounds (VOCs), including xylene, from the saturated zone by increasing the partitioning of those compounds into the

groundwater phase, which is then extracted. The above-ground surfactant recovery system was designed to separate the surfactant from the extracted groundwater for recycling. This system included an air stripper to remove xylene from the extracted groundwater, a membrane filter to recover surfactant, and a bioremediation unit to treat permeate from the membrane filter. Therefore, the only wastewater stream from the system is the treated permeate stream. Five original sample and measurement points were identified to evaluate the process. Due to a change in the process configuration, sample location S6 and measurement location M6 were added. Specifically, the Tauw surfactant recovery system was not operational during the demonstration, as is described in more detail in Section 2.2.2. Therefore, it was not possible to obtain recycled water from the Tauw surfactant recovery system for reinjection. During Phase 1 of the process operations (water injection only), this equipment unavailability was overcome by passing the extracted groundwater through a carbon filter, and then recycling the carbon-treated groundwater back to the injection well or hydraulic control wells (see Figure 8, Diagram 1).

The groundwater effluent from the artificial aquifer is treated with a conventional water treatment system at the VEGAS facility and recycled into the artificial aquifer, forming a continuous loop of groundwater flow. The conventional water treatment system consists of a sedimentation tank, a phase separator, a sand filter, and a granular activated carbon bed.

Demonstration Conclusions

The conclusions of the surfactant-enhanced extraction technology demonstration are summarized below:

- The xylene mass removal rate increased as a result of the surfactant enhancement. Specifically, the concentration of xylene in the extracted groundwater increased by a factor of approximately 15 after the injection of the surfactant solution.
- There was no significant increase in the xylene concentration of the groundwater exiting the artificial aquifer as a result of the surfactant enhancement. Average groundwater effluent xylene concentrations were 19.8 micrograms per liter ($\mu\text{g/L}$) before surfactant injection, 7.7 $\mu\text{g/L}$ during surfactant injection, and 2.3 $\mu\text{g/L}$ following surfactant injection.
- The toxicity results indicate that the extracted groundwater was not sufficiently toxic to kill 50 percent of the *Daphnia* test organisms, even at no dilution.
- The process operational parameters were as follows: extracted groundwater flow rates ranged from 116 to 230 liters per hour (L/h); injected groundwater flow rates ranged from 101.4 to 112 L/h. Influent groundwater flow rates ranged from 207 to 252 L/h; and effluent groundwater flow rates ranged from 191 to 315 L/h. The groundwater influent temperature ranged from 18.5 to 19.1 C and the pH ranged from 7.53 to 7.9. The above ground surfactant recycling system was not operational and was not used during the evaluation; therefore, the surfactant was not separated and recycled.

- The surfactant concentrations in the effluent groundwater were all less than 0.05 milligrams per liter (mg/L) for anionic surfactants and less than 0.25 mg/L for nonanionic surfactants. The treated permeate was not analyzed since the recovery system was not operational.
- The cost of the surfactant provided by BASF was 1.78 Euros (€) per kilogram of surfactant (\$2.33 per kilogram assuming a 0.76 € to \$1 U.S. exchange rate). Because the surfactant recovery system was not operational during the demonstration and the ability to recycle surfactant was not determined, a detailed cost analysis could not be developed.

Technology Applicability

The surfactant-enhanced extraction technology demonstrated at the VEGAS facility accelerated the removal of xylene from the artificial aquifer. The developer claims that in addition to xylene, the technology can also remove other non-aqueous phase liquids from the saturated zone. The surfactant-enhanced extraction technology provides both short-term and long-term protection of human health and the environment by reducing the concentrations of non-aqueous phase liquid contaminants in the saturated zone. Because the contaminants are permanently removed, the toxicity, mobility, and volume of contaminants are also significantly reduced. Minimal adverse impacts to the community, workers, or the environment are anticipated during site preparation, system installation, and system operation.

Site preparation and access requirements for the technology can be significant. The contamination plume at the site must be in an aquifer where hydraulic control can be maintained. Operation and maintenance of the large network of surfactant injection and groundwater extraction wells requires competent technical and engineering personnel to be available at all times.

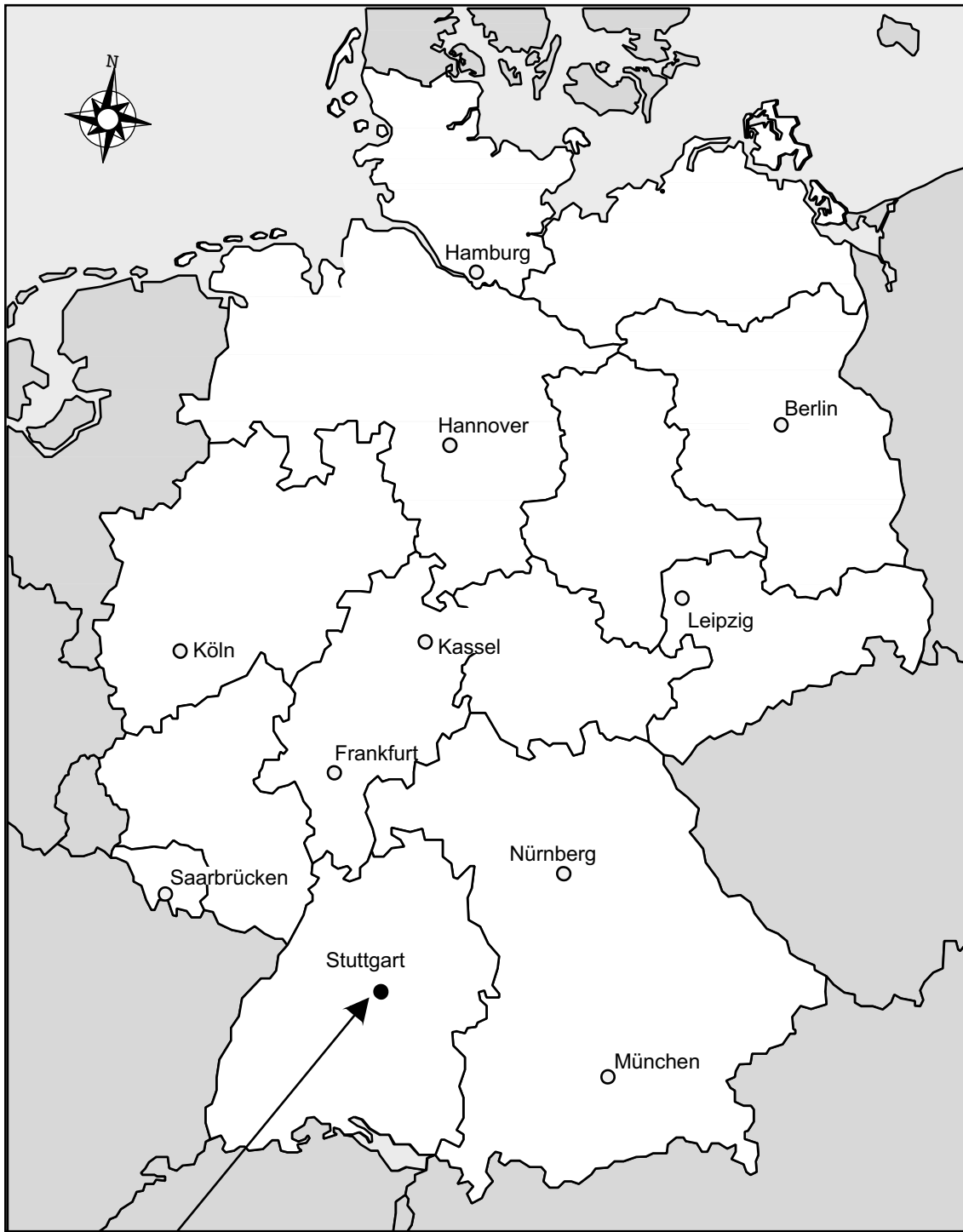
1.0 INTRODUCTION

This report documents the findings of an evaluation of a surfactant-enhanced extraction technology for removal of non-aqueous and volatile organic compounds (VOCs) liquid contaminants from the saturated zone. 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 technology was demonstrated from February 28 through March 5, 1998 at the Versuchseinrichtung zur Grundwasser-und Altlastensanierung (VEGAS) research facility in Stuttgart, Germany (see Figure 1). The VEGAS research facility was constructed to facilitate the evaluation of remediation technologies and includes an artificial aquifer to allow for controlled testing of in-situ technologies. Thirty-one kilograms (kg) of xylene, an organic contaminant with low solubility in water, was injected into the artificial aquifer at four different locations (and at four depths), and “groundwater” flow was induced to stimulate a contaminant plume.

The surfactant-enhanced extraction technology was demonstrated at the VEGAS facility to evaluate its effectiveness in enhancing the removal of a light non-aqueous liquid, specifically xylene, from the artificial aquifer. Groundwater was sampled by a field team of personnel from the BMBF support contractors, Institut Fresenius and ArGe focon-Probiotec, with assistance from the EPA technical support contractor, Tetra Tech EM Inc. (Tetra Tech). System operating parameters were monitored by VEGAS personnel. All samples were analyzed by the Institut Fresenius laboratory in Taunusstein. All demonstration activities were conducted in accordance with the February 1998 quality assurance project plan (QAPP) (Tetra Tech 1998).

The technology demonstration involved three test phases: Phase I - Groundwater flow in the artificial aquifer with injection and extraction of water only (pump and treat without surfactants); Phase II - Groundwater flow in the artificial aquifer with surfactant injection and extraction of groundwater; and Phase III - Groundwater flow in the artificial aquifer with the injection and extraction of groundwater only to remove residual surfactant. Groundwater samples were collected and flow rates were measured during each phase. VEGAS personnel conducted routine monitoring and adjusted the extraction flow rates during the initiation of each phase of the demonstration. Once VEGAS personnel had initiated each phase, Institut Fresenius personnel collected the necessary groundwater samples. The decision of when to begin injection of surfactants was made by VEGAS personnel.



Location of VEGAS Research Facility

Figure 1
Location of the VEGAS Research Facility

This report documents the results of the demonstration and provides information that is intended to be useful to remedial managers, environmental consultants, and other potential technology users in implementing surfactant-enhanced extraction technologies 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 process flow diagrams, demonstration procedures, and the results and conclusions of the evaluation. 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 assessment of the technology related 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 U.S. Superfund law and the EPA SITE program. Additional information about the SITE program, the surfactant-enhanced extraction technology, and the technology demonstration can be obtained by contacting the key individuals listed in Section 1.4.

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 the development, demonstration, evaluation, and use of innovative technologies for site cleanups.

The SITE program has four goals:

- Identify and remove impediments to development and commercial use of innovative technologies, where possible
- Conduct demonstrations of the more promising innovative technologies to establish reliable performance and cost information for site characterization and cleanup decision-making
- Develop procedures and policies that encourage selection of effective innovative treatment technologies at uncontrolled hazardous waste sites
- Structure a development program that nurtures emerging technologies

Each year EPA selects the best available innovative technologies for demonstration evaluation. The screening and selection process for these technologies is based on four factors: (1) the technology’s capability to treat Superfund wastes, (2) expectations regarding the technology’s performance and cost, (3) the technology’s readiness for full-scale demonstrations and applicability to sites or problems needing remedy, and (4) the developer’s capability for and approach to testing. SITE program demonstration evaluations are administered by EPA’s Office of Research and Development (ORD) through the National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio.

SITE demonstration 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 surfactant-enhanced extraction technology demonstration, the VEGAS site was selected cooperatively by EPA and BMBF. The EPA-BMBF bilateral agreement is discussed in Section 1.2.

SITE and bilateral SITE demonstration evaluations provide detailed data on the performance, cost effectiveness, and reliability of innovative technologies. These data will provide 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.

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 evaluations conducted during SITE technology demonstrations are intended to generate performance data of known quality. Therefore, sampling and analysis procedures are critical and approved quality assurance and quality control (QA/QC) procedures are stringently applied as part of all technology evaluations under SITE.

1.2 BILATERAL AGREEMENT BETWEEN THE UNITED STATES AND GERMANY 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 goals:

- Facilitate an understanding of each country's approach to remediation of contaminated sites
- Demonstrate innovative remedial technologies as if the demonstrations had taken place in each country
- Facilitate international technology exchange

Technologies in the U.S. and in 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 demonstrations; those occurring in Germany correspond to full-scale site remedial activities and are referred to as bilateral SITE demonstrations. In the case of the U.S. evaluations, technology evaluation plans are prepared following routine SITE procedures. Additional monitoring and evaluation measurements required for evaluation of the technology under German regulations will be specified by the German partners. For the demonstrations occurring in Germany, the German partners provide all required information to allow the U.S. to develop an EPA NRML QAPP. An EPA-approved QAPP entitled "Quality Assurance Project Plan for the Surfactant-Enhanced Extraction Technology Evaluation" and dated February 1998 was prepared for this technology evaluation (Tetra Tech 1998).

ArGe focon-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 ArGe focon-Probiotec technical consulting partnership is not directly involved in the German remedial actions, and

the partnership does not influence actual site remediation activities. Tetra Tech has been contracted by the U.S. EPA to provide comprehensive technical support to U.S. evaluations and to coordinate U.S. activities for bilateral SITE evaluations. The bilateral project organization is presented in Figure 2.

1.3 SURFACTANT-ENHANCED EXTRACTION TECHNOLOGY DESCRIPTION

Surfactants and other chemicals have recently been applied as enhancements to conventional soil flushing technology to accelerate the in situ extraction of contaminants from the saturated zone. In conventional soil flushing, water is circulated through a contaminated zone to wash out chemical contaminants. The use of surfactants in the circulated water can increase the mobility or solubility of many organic contaminants, including particularly non-aqueous phase liquids (NAPLs), further facilitating extraction. Specifically, surfactants can disperse and solubilize NAPLs through the formation of micelles.

The use of surfactants to enhance in situ soil flushing has not yet been accepted in Germany because limited credible test data are available for this technology. In order to collect more reliable data, a pilot-scale demonstration of in situ surfactant-enhanced extraction was conducted at the VEGAS research facility.

The specific surfactant-enhanced extraction technology evaluated during this bilateral SITE demonstration employs a proprietary mixture of anionic and nonionic surfactants developed by BASF AG (BASF) and a surfactant recovery system developed by Tauw Umwelt GmbH Moers (Tauw). The surfactant recovery system incorporates an air stripper to remove xylene from the extracted water stream, a membrane filter to recover surfactant, and a bioremediation unit to treat permeate from the membrane filter. These two components of the surfactant-enhanced extraction technology provide for the accelerated extraction of NAPL contaminants and for the separation of the surfactant mixture so that it can be recycled.

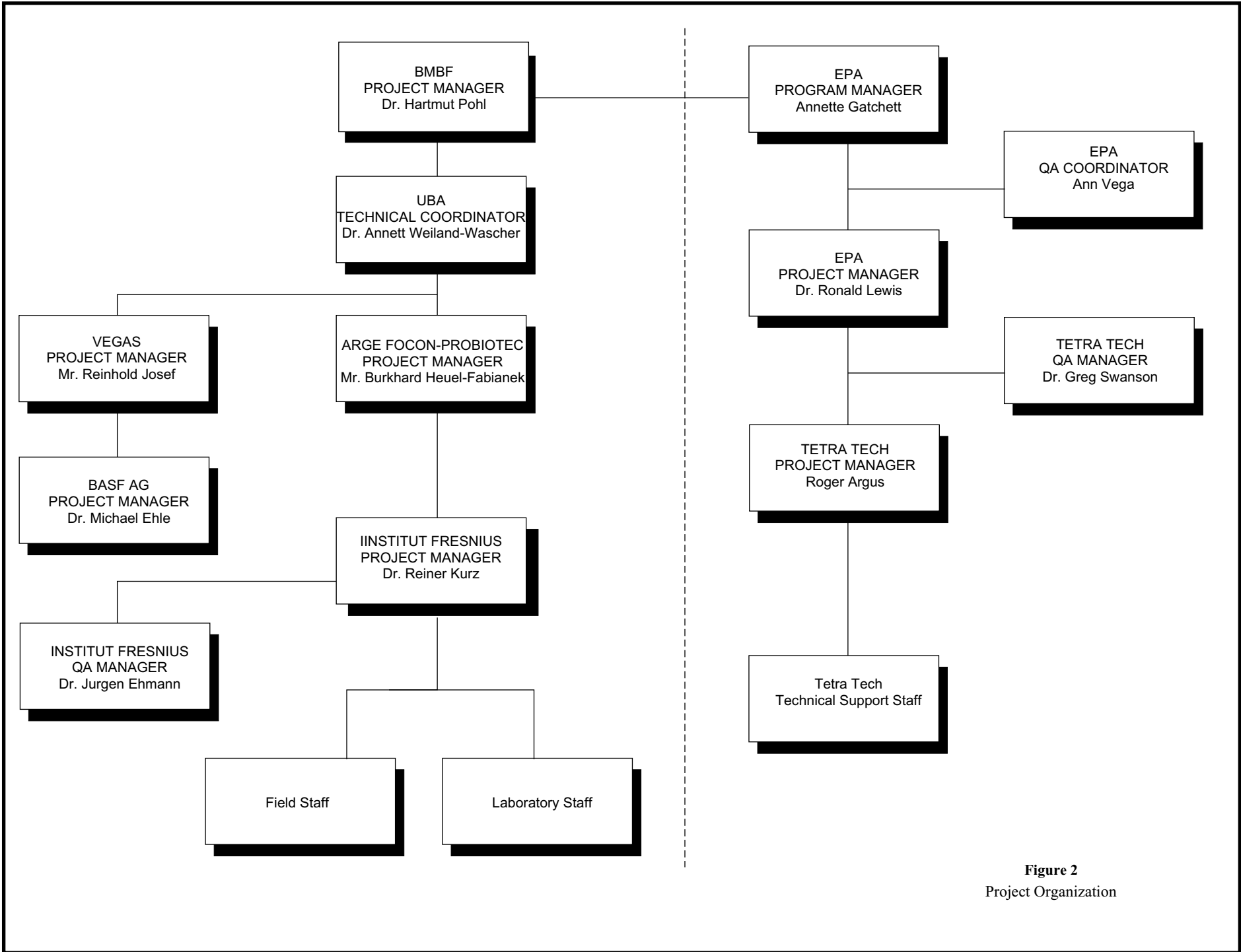


Figure 2
Project Organization

1.4 KEY CONTACTS

Additional information on the surfactant-enhanced extraction technology and the EPA-BMBF bilateral technology evaluation program can be obtained from the following sources:

Surfactant-Enhanced Extraction Technology

Reinhold Josef
VEGAS Project Manager
Institut für Wasserbau
Universität Stuttgart
Pfaffenwaldring 61
70550 Stuttgart
07 11 / 685 7023

EPA-BMBF Bilateral Technology Evaluation Program

Annette Gatchett Bilateral Program Manager
U.S. Environmental Protection Agency
Office of Research and Development
26 West Martin Luther King Drive
Cincinnati, Ohio 45268
513-569-7697

Information on the SITE program is available through the following on-line information clearinghouses:

- The Alternative Treatment Technology Information Center (ATTIC) System (operator: 703-908-2137) is a comprehensive, automated information retrieval system that integrates data on hazardous waste treatment technologies into a centralized, searchable source. This data base provides summarized information on innovative treatment technologies.
- The Vendor Information System for Innovative Treatment Technologies (VISITT) (Hotline: 800-245-4505) data base contains current information on nearly 350 technologies submitted by nearly 210 developers, manufacturers, and suppliers of innovative treatment technology equipment and services.
- The Office of Solid Waste and Emergency Response (OSWER) Clean-up Information (CLU-IN) electronic bulletin board contains information on the status of SITE technology evaluations. Its web site is www.clu-in.org.

Technical reports may be obtained by contacting the Center for Environmental Research Information (CERI), 26 West Martin Luther King Drive in Cincinnati, Ohio 45268 at (513) 569-7562. Additional information is available on the EPA home page at: www.epa.gov/oerrpage/superfund/sites.

2.0 SURFACTANT-ENHANCED EXTRACTION TECHNOLOGY EFFECTIVENESS

This section provides background information and documents the field and analytical procedures as well as the operation of the process during the demonstration. This section further describes the results and conclusions of the surfactant-enhanced extraction technology demonstration.

2.1 DEMONSTRATION BACKGROUND

The bilateral SITE evaluation of the surfactant-enhanced extraction technology was conducted at the VEGAS research facility in Stuttgart, Germany. Xylene, an organic contaminant with low solubility in water, was injected into an artificial aquifer and groundwater flow was induced to stimulate a contaminant plume. The surfactant-enhanced extraction technology was then applied to remove the xylene contaminant from the artificial aquifer.

2.1.1 VEGAS Research Facility

The VEGAS research facility was constructed to facilitate the evaluation of remediation technologies. At the VEGAS facility, an artificial aquifer has been constructed to allow for controlled testing of in situ technologies. The artificial aquifer is located in a container that has a length of approximately 9 meters, a width of approximately 6 meters, and a depth of approximately 4.5 meters. The artificial aquifer within the container was constructed with inclined layers of sand (fine, medium, and coarse sand) resulting in hydrologic strata with differing hydraulic permeabilities. The permeability (kf value) of the three kinds of sand strata have been determined by VEGAS personnel using tracer studies. The value of kf was determined to be 3.2×10^{-4} meters per second for fine sand, 12.0×10^{-4} meters per second for medium sand, and 35×10^{-4} meters per second for coarse sand. A cross-section of the artificial aquifer is shown in the Figure 3.

The container is fitted with 378 sampling and monitoring probes that are available to technology developers to monitor and control system operation. These probes can be used to measure the height of the water table, to monitor the hydraulic conditions during the experiment, and to sample the groundwater.

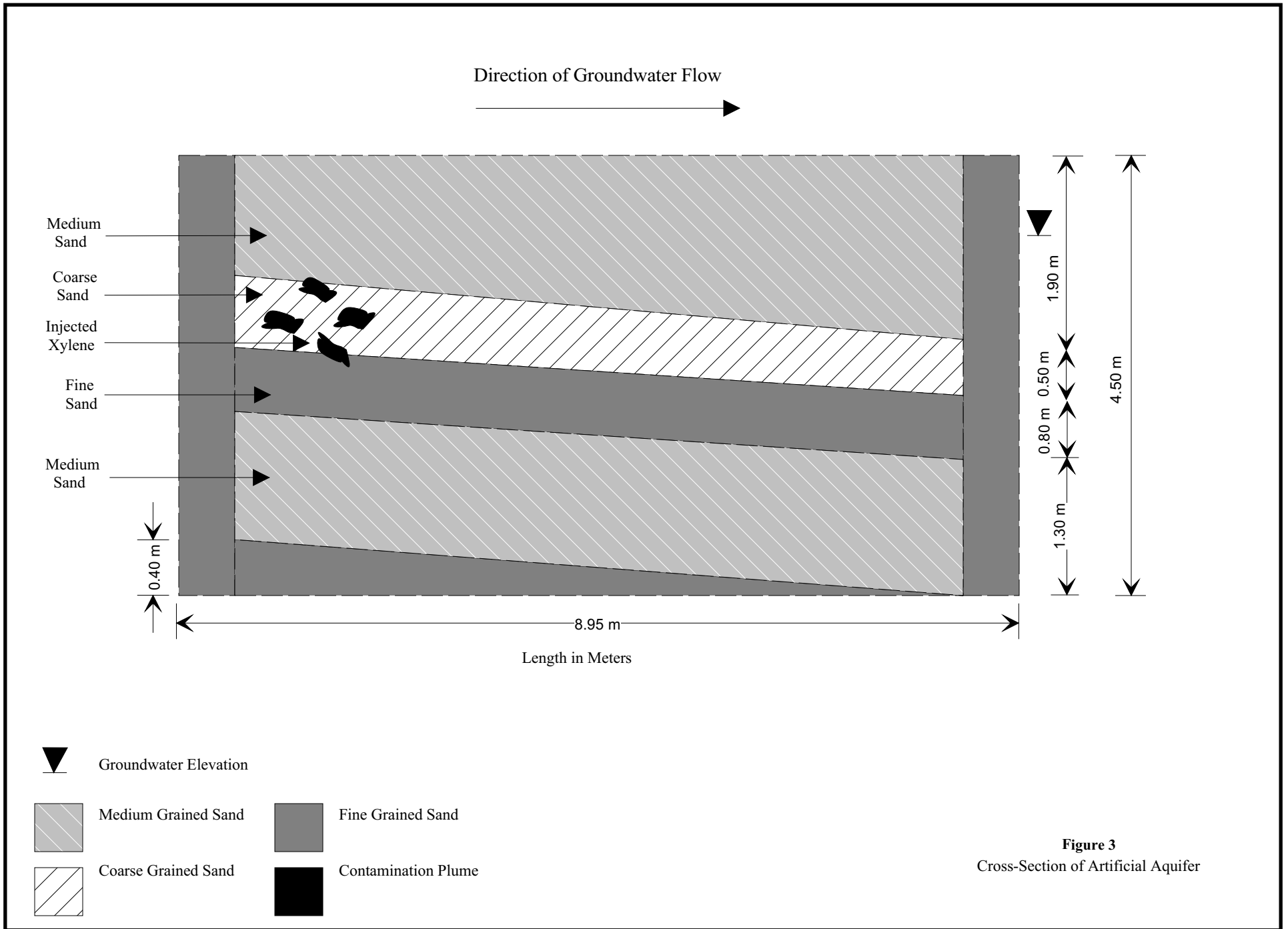


Figure 3
Cross-Section of Artificial Aquifer

“Groundwater” is fed to the container through a permeable wall to maintain a flow of approximately 180 liters per hour. The groundwater table in the container is approximately 3.70 meters from the bottom of the container. A hydraulic gradient of 0.6 percent is maintained for groundwater flow.

2.1.2 Preparation of the Artificial Aquifer

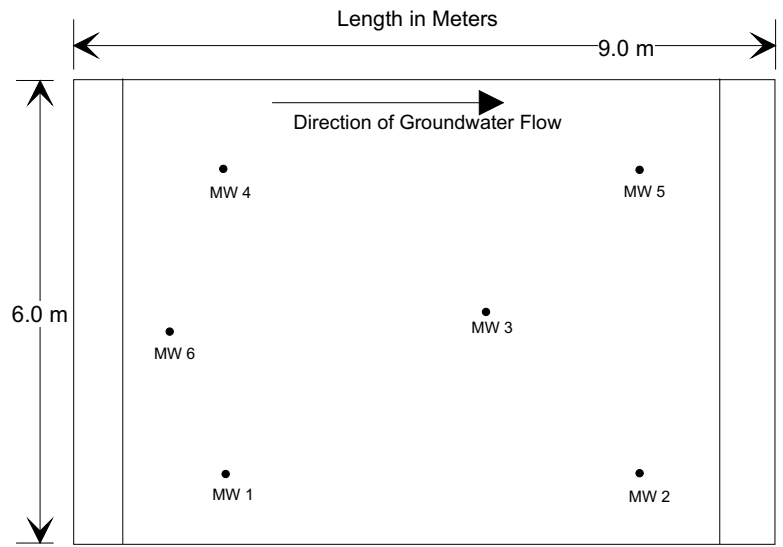
For the demonstration of the surfactant-enhanced extraction technology, six wells were installed in the container and labeled MW 1 through MW 6, as shown in Figure 4. The wells labeled MW 1, MW 2, MW 4, and MW 5 were screened across the top two strata. MW 3 was screened across two intervals: the top strata and the bottom strata. MW 6 was screened from 90 centimeters (cm) to 185 cm below the top to the well casing.

Approximately 3 months prior to the demonstration, on November 25, 1997, 31 kilograms (kg) of xylene solution were injected into the aquifer at four different locations between MW 1 and MW 4 and at four depths (a total of 16 injection points). After termination of the four injections at the first depth, the groundwater table was raised to just above the first injection depth. The injection at the next depth was then made and the groundwater table was raised again. This process was repeated for each of the specified depths and, after the final xylene injection, the groundwater was raised to result in a saturated thickness of 3.70 meters above the bottom of the artificial aquifer. Analysis of samples collected from the groundwater effluent before application of the surfactant-enhanced extraction technology indicated a relatively constant xylene concentration of about 20 milligrams per liter.

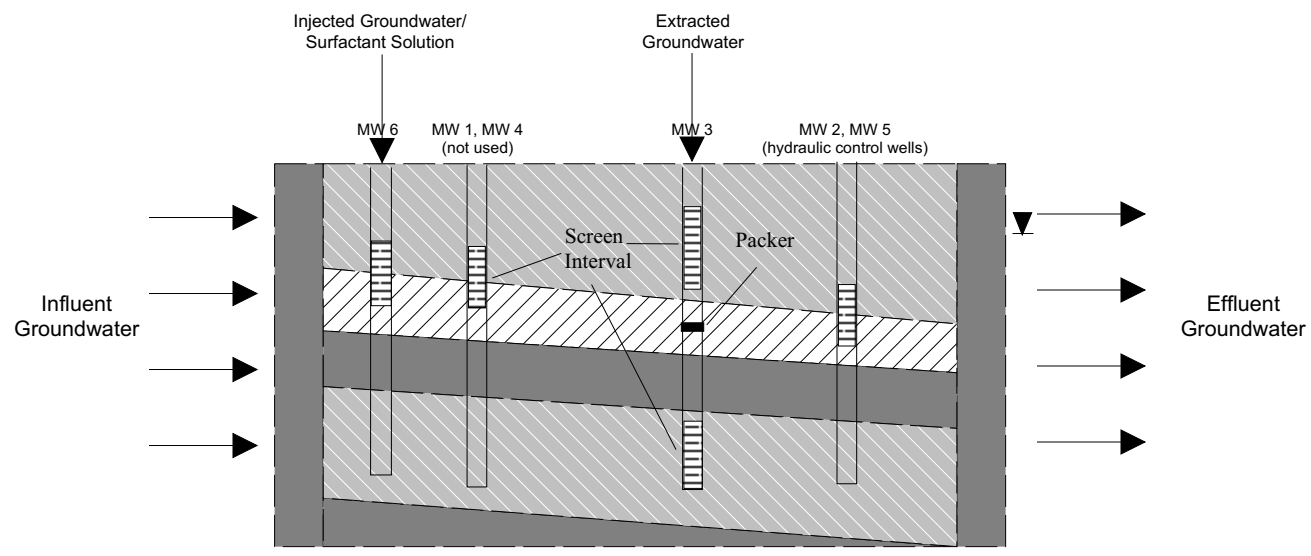
2.1.3 Process Description and Planned Operation

This section describes the system that was installed and the planned mode of operation. It should be noted that the actual operation changed from these plans as described in Section 2.2.4.

A simplified flow diagram of the surfactant-enhanced extraction system that was installed at the VEGAS facility is shown in Figure 5. Originally, only five wells were installed in the container (MW 1 through MW 5); it was planned that the surfactant solution would be injected into MW 1 at approximately 50 liters per hour (L/h) and extracted from MW 2 at 200 L/h. Further, MW 4 and MW 5 were to serve as hydraulic control wells through the injection of 75 L/h of groundwater into each well. However, it was later decided to install a sixth well (MW 6) and to alter the planned hydraulic flow scheme as follows:



Top View of Artificial Aquifer



Side View of Artificial Aquifer

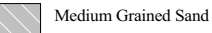


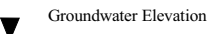
-  Medium Grained Sand
-  Fine Grained Sand
-  Coarse Grained Sand
-  Groundwater Elevation

Figure 4
Monitoring Well Configuration

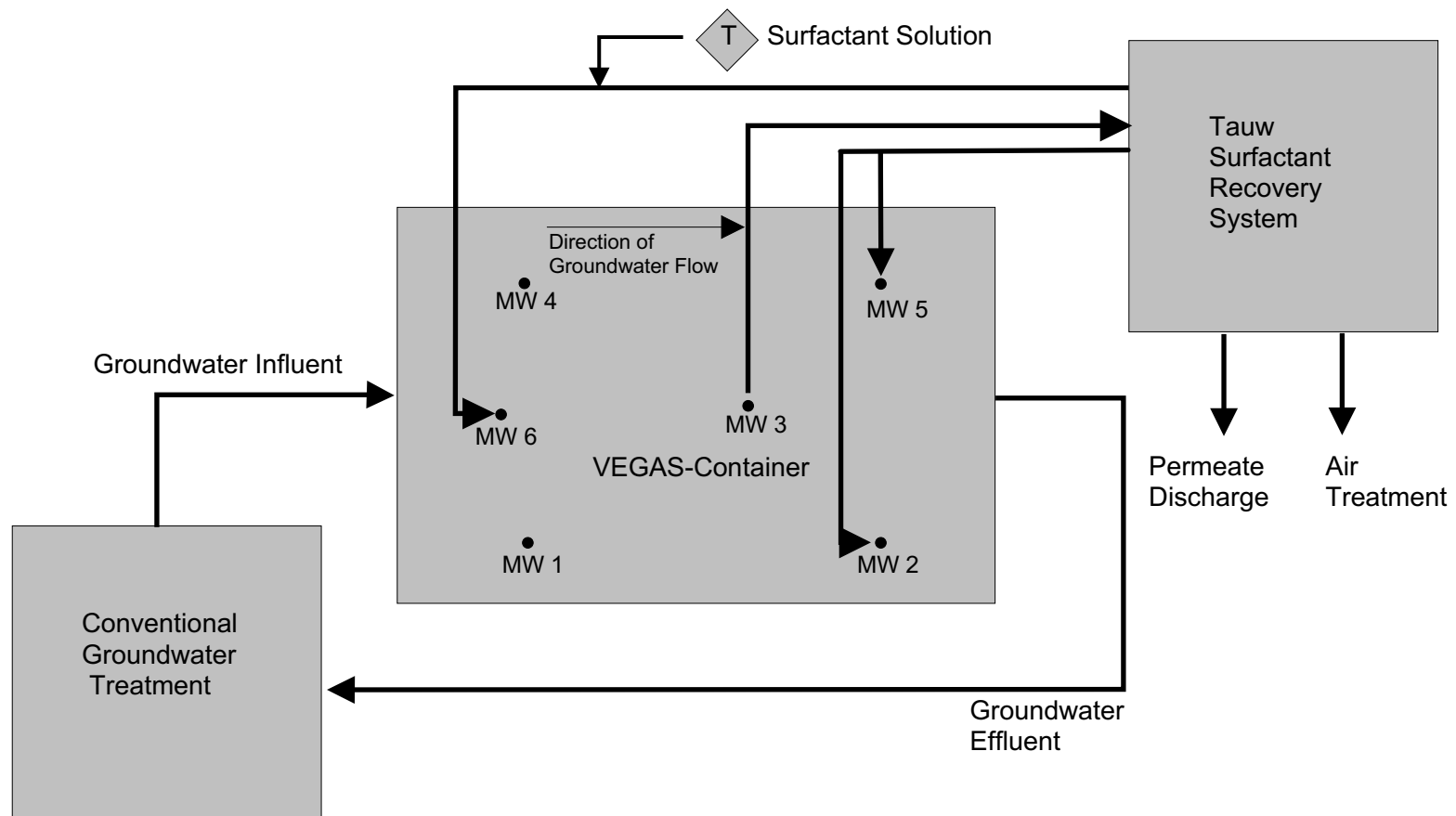


Figure 5
Surfactant Injection/Extraction System

- MW 1 and MW 4 - Not used
- MW 2 and MW 5 - Hydraulic control wells
- MW 3 - Extraction well
- MW 6 - Surfactant/groundwater solution injection well

Thus, in the revised hydraulic flow scheme, surfactant solution is injected through MW 6 and extracted through MW 3. After processing in the surfactant recovery system to remove the extracted xylene and to separate the surfactant, the extracted groundwater is recycled to supply the hydraulic control wells (MW 2 and MW 5) as well as the injection well (MW 6). This is the flow scheme that was ultimately implemented at the VEGAS facility.

The above-ground surfactant recovery system includes an air stripper to remove xylene from the extracted water stream, a membrane filter to recover surfactant, and a bioremediation unit to treat permeate from the membrane filter. A schematic flow diagram is shown as Figure 6. The only wastewater stream from this system is the treated permeate stream. The system was designed to meet German discharge limits for the treated permeate, which are 0.5 milligrams per liter (mg/L) for xylene (a VEGAS facility permit requirement) and 200 mg/L for surfactants (a self-imposed limit not required by the VEGAS facility permit).

The groundwater effluent from the artificial aquifer is treated with a conventional water treatment system at the VEGAS facility and recycled into the artificial aquifer, forming a continuous loop of groundwater flow. The conventional water treatment system consists of a sedimentation tank, a phase separator, a sand filter, and a granular activated carbon bed.

The surfactant enhanced extraction technology is implemented in three phases:

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

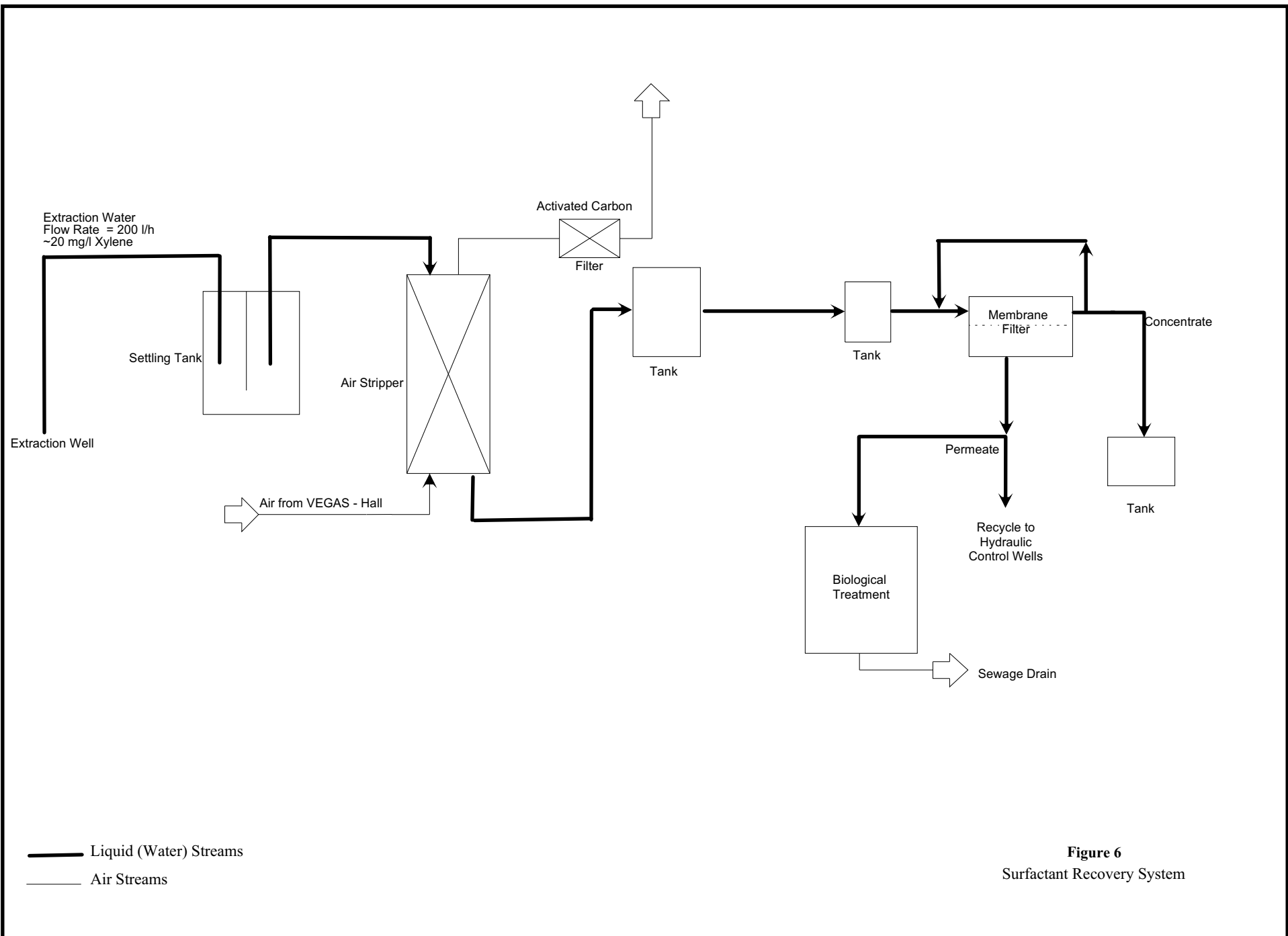


Figure 6
Surfactant Recovery System

Figure 7 is a conceptual plot of the anticipated contaminant mass removal rates during these three operational phases. As shown in this figure, contaminant mass removal rates increase dramatically immediately following the initiation of surfactant injection. After two days of surfactant injection, much of the extractable contaminant mass is removed from the aquifer and removal rates begin to decline. At this point, surfactant injection is stopped, and the surfactant as well as residual contaminant is washed out of the aquifer through continued injection of water alone.

2.1.4 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 to other contaminated sites. Primary objectives and secondary objectives bilateral were developed and agreed upon for this SITE demonstration.

The primary objectives and associated critical measurements to evaluate these objectives are listed in Table 1. The secondary project objectives and associated non-critical measurements required to evaluate those objectives are listed in Table 2.

TABLE 1. CRITICAL MEASUREMENT PARAMETERS

Primary Objective	Measurement Parameters
P1. Determine whether xylene mass removal rate increases due to surfactant enhancement.	Flow rate and concentration of xylene in the extracted groundwater during three test phases.
P2. Verify that there is no statistically significant increase in xylene concentrations in groundwater exiting the artificial aquifer due to surfactant enhancement.	Concentration of xylene in groundwater effluent from the artificial aquifer to determine whether xylene mobilized by the surfactant is captured in the extracted groundwater.

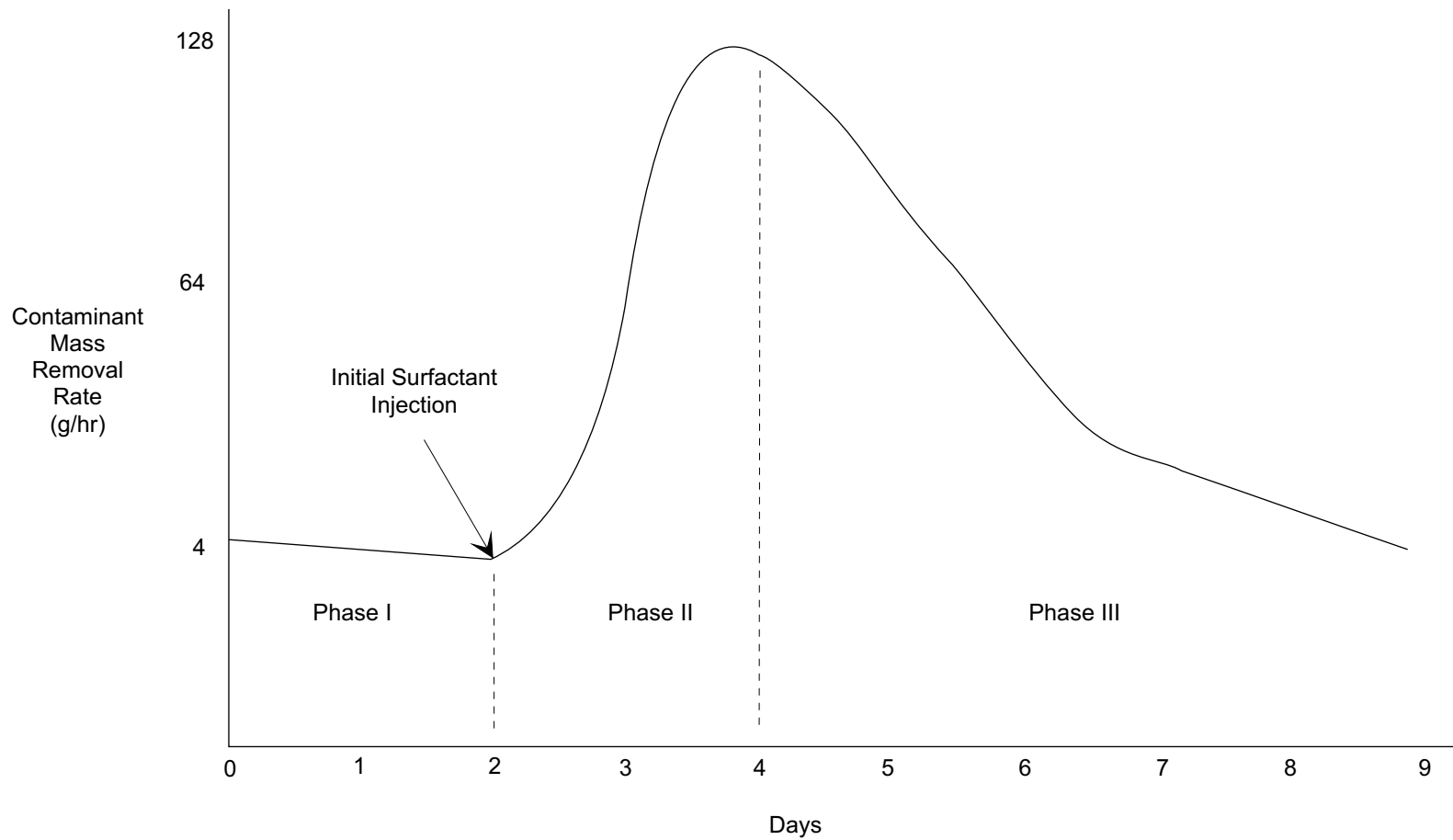


Figure 7
Conceptual Plot of
Anticipated Xylene Mass Removal Rates

TABLE 2. NONCRITICAL MEASUREMENT PARAMETERS

Secondary Objective	Measurement Parameter
S1. Evaluate the acute toxicity of the treated permeate from the surfactant recovery system and of groundwater effluent from the artificial aquifer before and after surfactant injection.	LC50 acute tests on samples of surfactant recycling system permeate and groundwater effluent. Toxicity tests on samples of influent groundwater to provide a baseline.
S2. Document process operating parameters.	Process operating parameters: influent and effluent groundwater, injected surfactant/groundwater solution, and extracted groundwater flow rates; surfactant use rates; and flow rate of treated permeate. Documentation of soil and stratigraphic information, and any operational problems and difficulties as well as resolutions. Measurement of physical/chemical groundwater parameters (temperature; pH; conductivity, and metals content) in three samples collected from the influent groundwater to the artificial aquifer.
S3. Document the xylene and surfactant concentration in the treated surfactant recovery permeate and surfactant concentration in the effluent groundwater.	Analysis of samples of treated surfactant recovery permeate for total xylene according to EPA method SW-846 8260B (EPA 1996) and surfactants according to Standard Method 5540C and D (APHA et al. 1994). Analysis of samples of groundwater effluent from the artificial aquifer for surfactants according to Standard Method 5540C.
S4. Estimate capital and operating costs.	Based on (1) process operating parameters mentioned above, (2) operating requirements observed during the evaluation, and (3) capital costs and operating information provided by VEGAS and Tauw.

Notes:

- EPA U.S. Environmental Protection Agency
- LC₅₀ Lethal concentration - 50 percent
- SW-846 Test Methods for Evaluating Solid Waste
- VEGAS Versuchseinrichtung zur Grundwasser-und Altlastensanierung

To perform the measurements needed to meet each of the objectives, samples were collected and analyzed and field data were recorded using the methods and procedures summarized in the following section.

2.2 DEMONSTRATION PROCEDURES

This section describes the methods and procedures used to collect and analyze samples for the bilateral SITE evaluation of the surfactant-enhanced extraction technology and discusses the operation of the process during the demonstration.

2.2.1 Sampling and Analysis Program

This section describes the sampling and analysis program, including sample collection frequencies and locations.

2.2.1.1 Sampling and Measurement Locations

Sampling and measurement locations were selected based on the configuration of the treatment system and project objectives. These locations are shown in Figure 8 and include the following sampling ports:

- *Location S1:* The groundwater influent sampling port
- *Location S2:* The groundwater effluent sampling port
- *Location S3:* The surfactant/water injection stream port
- *Location S4:* The groundwater extraction stream sampling port.
- *Location S5:* Not used
- *Location S6:* The conventional groundwater treatment system effluent sampling port

These locations also include the following flow measurement points:

- *Location M1:* The extracted groundwater
- *Location M2:* The injected surfactant/water solution rotameter
- *Location M3:* The influent groundwater
- *Location M4:* The effluent groundwater
- *Location M5:* Not used
- *Location M6:* The injected water for hydraulic control (MW 5 and MW 2)

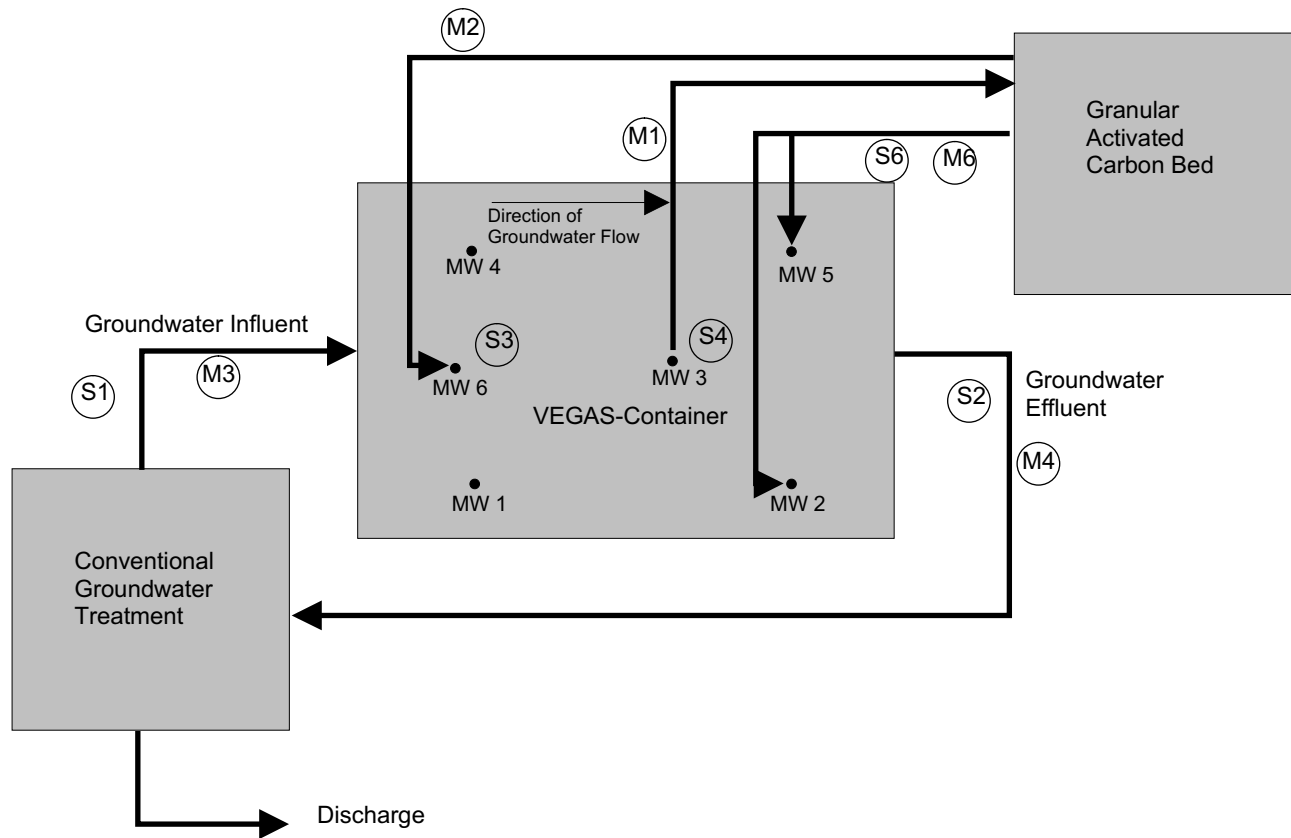


Diagram 1: Simplified Process Flow Diagram for Phase 1

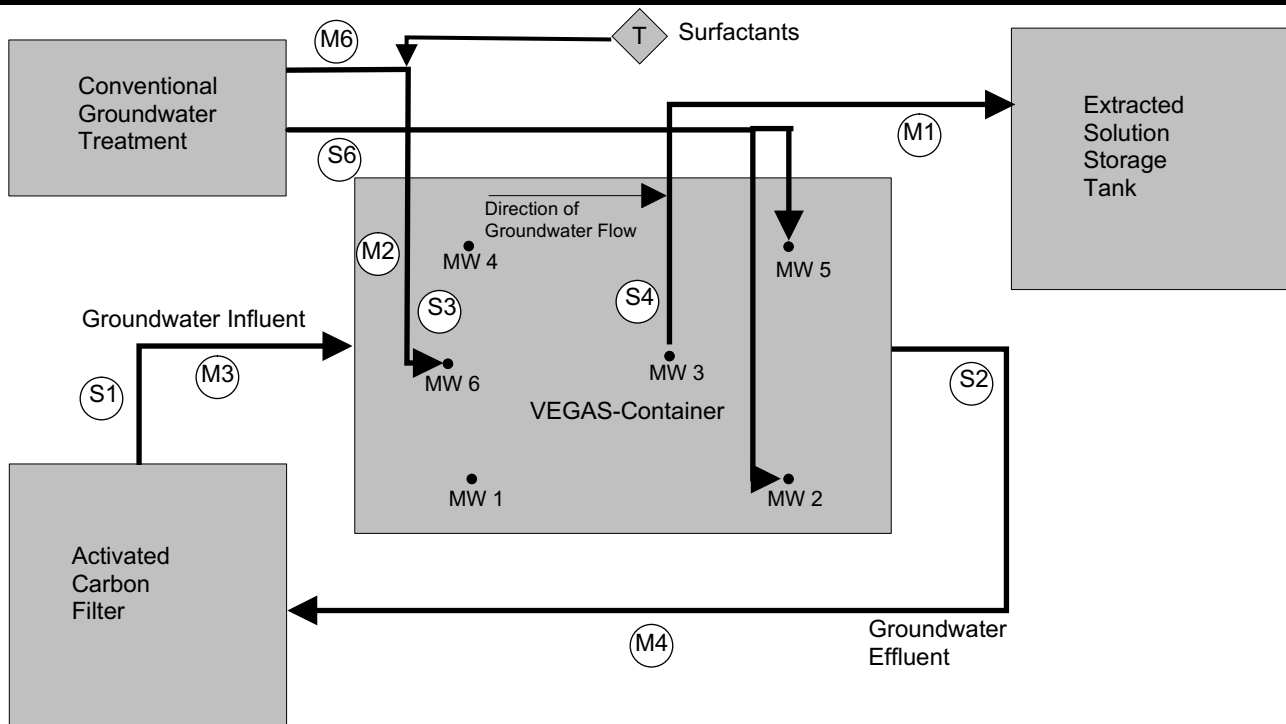


Diagram 2: Simplified Process Flow Diagram for Phases 2 and 3

Legend

- (S1) Sampling location
- (M1) Monitoring location

Source: ArGe focon PROBIOTEC, 1997

Figure 8
Sampling and Monitoring Locations

It should be noted that sample location S6 and measurement location M6 were added to the list of five original sample points, and sample location S5 and measurement location M5 were deleted due to a change in the process configuration. Specifically, the Tauw surfactant recovery system was not operational during the demonstration, as is described in more detail in Section 2.2.2. Therefore, it was not possible to sample or monitor the permeate or to obtain recycled water from the Tauw surfactant recovery system for reinjection. During Phase I of the process operations (water injection only), this equipment unavailability was overcome by passing the extracted groundwater through a carbon filter, and then recycling the carbon-treated groundwater back to the injection well or hydraulic control wells (see Figure 8, Diagram 1).

The groundwater effluent from the artificial aquifer is treated with a conventional water treatment system at the VEGAS facility and recycled into the artificial aquifer, forming a continuous loop of groundwater flow. The conventional water treatment system consists of a sedimentation tank, a phase separator, a sand filter, and a granular activated carbon bed.

2.2.2 Sampling and Analytical Methods

This section briefly summarizes the sampling frequencies and procedures as well as analytical methods used during the evaluation. Details of these sampling procedures and analytical methods are described in the QAPP (Tetra Tech 1998).

Groundwater samples were collected at the six locations described in the Section 2.2.1. Grab sampling techniques were employed for all samples taken from the designated sampling ports throughout the demonstration. Samples of major process streams (the injected and extracted groundwater as well as the influent and effluent groundwater) were collected approximately every 4 hours. Samples of other process streams were taken either once per day or once per phase, as specified in the QAPP.

Table 3 lists the analytical procedures used to measure the parameters of interest for the samples collected during the demonstration. These measurements were made on the samples collected from all locations. Flow rates were measured by in-line flow meters maintained by VEGAS personnel.

**TABLE 3. ANALYTICAL METHODS
SURFACTANT-ENHANCED EXTRACTION SYSTEM**

Method Source	Parameter	Name of Method
SW-846 8260B	VOCs	VOCs by GC/MS: Capillary Column Technique (preparation method is included in 8260B)
EPA/600/4-90/027	Acute toxicity	48-hour Static Acute Toxicity Test (Definitive) Using <i>Ceriodaphnia dubia</i> (<i>C. dubia</i>)
SW-846 3010A/6010A	Metals	Acid digestion of Aqueous Samples/Inductively coupled Plasma-Atomic Emission Spectroscopy
MCAWW 170.1	Temperature	Temperature
SW-846 9040B	pH	pH Electrometric Measurement
SW-846 9050	Conductivity	Specific Conductance
SM 5540C and D	Surfactants	Surfactants

Notes:

VOCs	Volatile Organic Compounds
	GC/MS Gas Chromatograph/Mass Spectrograph
MCAWW	Methods for Chemical Analysis of Water and Wastes (EPA, 1983)
SW-846	Test Methods for Evaluating Solid Waste (EPA, 1996)

2.2.3 Quality Assurance and Quality Control Program

Quality control checks were an integral part of the bilateral SITE demonstration to ensure that the QA objectives were met. These checks and procedures focused on the collection of representative samples absent of external contamination and on the generation of data of acceptable precision and accuracy. The QC checks and procedures conducted during the demonstration were of two kinds: (1) checks controlling field activities, such as sample collection and shipping, and (2) checks controlling laboratory activities, such as extraction and analysis. The results of the field and laboratory QC checks are summarized in Section 2.3.3.

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

2.2.4 Chronology of Process Operations and Changes to the Sampling Program

This section summarizes the operation of the surfactant-enhanced extraction system during the bilateral SITE demonstration. The system was operated from February 28, 1998 at 5:00 p.m. (beginning of Phase

I sampling) to March 5, 1998 at 11:00 a.m. (end of Phase III), for a total of 114 hours. The Tauw surfactant recovery system was not fully operational, and therefore, sampling of the permeate was not performed during the demonstration.

As planned, the process was operated and samples were collected in three test phases. The purpose of Phase I (injection and extraction of water only) was simply to establish steady state operation prior to the injection of any surfactants. Phase II incorporated the surfactant injection into MW 6 and the enhanced removal of xylene in the groundwater extracted from MW 3. Phase III returned to water-only injection to MW 6 to remove the residual surfactant for recovery. The injection and extraction rates during each phase were set by VEGAS personnel during startup of that phase based on the planned flow rates and observed operational conditions. Injection into hydraulic control wells MW 2 and MW 5 was maintained during Phases II and III.

Several changes to the planned operation of the system were implemented during the demonstration by VEGAS operational personnel. As a result, the on-site personnel from the bilateral SITE sampling team had to adapt some sampling procedures to meet the demands of the revised process operations. A chronology of the process operations and descriptions of the changes to planned procedures is included below. For convenience, all references to the timing of events during the demonstration are hereinafter referred to by hour and minute using the initiation of Phase I as Time 00:00.

Phase I

Time 00:00. The initial injection rate into MW 6 and the extraction rate from MW 3 were set at approximately 120 L/h. The water extracted from MW 3 was passed through an activated carbon bed prior to recycling to MW 6, since the Tauw surfactant recovery system was not yet operational. No injection into MW 2 or MW 5 was conducted since these wells were for hydraulic control during surfactant injection.

Time 26:00 to 28:00. To prepare for the surfactant injection, the pumping rate at the extraction well (MW 3) was increased to approximately 200 L/h. To compensate for this increase and maintain the water balance in the aquifer container, water from the VEGAS water treatment system was pumped into the aquifer at MW 2 and MW 5 at a rate of approximately 80 L/h.

Time 49:00. The last Phase I samples were taken.

Phase II

Time 50:00. The pumping configuration was changed by increasing the pumping rate at MW 3 to 200 L/h. As a result of the change in the pumping configuration for the extraction of water, concern arose as to whether the hydraulic conditions of the aquifer might have been altered. The U.S.-German Bilateral team decided that additional samples of the extracted groundwater would be collected for xylene analysis at half-hour intervals from Time 54:30 to Time 60:00 and at 1-hour intervals from Time 60:00 to Time 87:00. The purpose of these samples was to determine whether changes in the hydraulic conditions affected the xylene concentration at the extraction well and to track the arrival of the surfactant at the extraction well. This sampling period was designated as Phase IIa, and the samples were labeled accordingly. Subsequent to this decision, some additional adjustments to the sampling times were necessary throughout the remainder of Phase II because of various technical modifications (for example, air in the lines precluding effective sampling, thereby requiring a new sampling point to be installed).

Time 50:20. The injection of surfactant began at MW 6. The surfactant was a 2.2 percent solution of the BASF proprietary mixture. The volume of surfactant solution was 2.7 cubic meters (m³) and was contained in a 12 m³ vat in the basement of the VEGAS research facility. The vat employed a stirring mechanism to keep the solution mixed. A pump was used to inject the surfactant solution and groundwater into MW 6 at a rate of 100 to 120 L/h.

Time 61:00. Foaming was noted in the water extracted from MW 3. This indicated that the surfactant had migrated to the extraction well and that the corresponding travel time from the injection well (MW 6) to the extraction well (MW 3) was approximately 11 hours or less.

Time 70:00. The vat containing the surfactant ran dry. The surfactant had been injected into MW 6 for approximately 20 hours. The input to the injection well was switched from the surfactant vat to water from the VEGAS on-site water treatment system. This water was sampled twice (once on March 3 and once on March 4, 1998) for toxicity tests. No additional samples were collected at MW 6 following the completion of surfactant addition.

On the third day of operation, Tauw was unable to get their surfactant recovery system to operate as intended; therefore, no treated permeate samples were collected. All water and surfactant extracted at MW 3 was collected for processing through the Tauw system and stored in a 12 m³ storage tank in the basement of the VEGAS research facility. Phase II sampling continued through the fourth day of operation. During the fifth day of operation, the xylene concentration in a grab sample from MW 3 was determined by on-site high performance liquid chromatography (HPLC) to be 270 milligrams per liter (mg/L). Also, water could not be injected into MW 2 so all 80 L/hr of flow for hydraulic control was being injected into MW 5.

Phase III

Time 110:00. Phase III began on the morning of March 5, 1998. A grab sample collected in mid-morning from MW 3 was analyzed by on-site HPLC and contained a xylene concentration of 85 mg/L. This analysis confirmed the beginning of Phase III because this was the first sign of a decreased xylene concentration in the extracted groundwater. A grab sample also was collected from the extracted groundwater storage tank; the xylene concentration in this sample was 500 mg/L.

Time 114:00. The 12 m³ storage tank was noted to be full and therefore the demonstration was ended shortly after. Because Tauw continued to be unable to get their surfactant recovery system to operate as intended, no treated permeate samples were collected during the demonstration.

2.3 DEMONSTRATION RESULTS AND CONCLUSIONS

This section presents the results of the field measurements and groundwater sampling and analysis conducted over the 5-day period of the demonstration. This section then describes the conclusions of the bilateral SITE demonstration of the surfactant-enhanced extraction technology.

2.3.1 Results and Discussion

The results of the bilateral SITE demonstration of the surfactant-enhanced extraction technology are presented below in relation to the project objectives. In each subsection below, the specific primary or secondary objective is shown in italics, followed by a discussion of the objective-specific results. Data quality and conclusions based on these results are presented in Sections 2.3.3 and 2.3.4, respectively.

2.3.1.1 Primary Objective P-1

Determine whether the xylene mass removal rate increases due to surfactant enhancement.

To determine the mass removal rate, samples of groundwater entering and exiting the system were collected during the three test phases. The mass removal rate was calculated based on the measured flow rates and xylene concentrations in the extracted groundwater from the artificial aquifer.

The xylene mass removal rates were calculated using the xylene concentration data from samples collected at S4 and the flow rate of the extracted groundwater measured at M1.

Specifically, the mass removal rates were calculated by multiplying each xylene concentration by the flow rate at the time each sample was collected, as listed in Table 4. A graph of the removal rate over all three phases of the demonstration is shown in Figure 9. The figure shows a mass removal rate pattern that is consistent with what was expected (Figure 7). However, at Time 76:00, an anomalous decrease in the xylene concentration from 500 to 126 mg/L was noted. This anomalous data point appears to be related to an increase in the injection rate of groundwater (from 93 to 189 L/h) at MW 5 at that time due to plugging in the second hydraulic control well (MW 2).

2.3.1.2 Primary Objective P-2

Verify that there is no statistically significant increase in xylene concentrations in groundwater exiting the artificial aquifer due to surfactant enhancement.

TABLE 4. XYLENE EXTRACTION RATES IN THE EXTRACTED GROUNDWATER (SAMPLING LOCATION S4, MONITORING LOCATION M1)

Sample Description	Sampling Date and Time	Total Xylene Concentration (µg/L)	Flow Rate (L/h)	Xylene Mass Removal Rate (µg/h)
Phase I 1-1-1-1	2/28/98 00:00	33.0	144	4,750
Phase I 1-1-1-2	2/28/98 04:00	32.5	143	4,650
Phase I 1-1-1-3	3/1/98 07:30	32.6	131	4,270
Phase I 1-1-1-4	3/1/98 15:00	35.6	130	4,630
Phase I 1-1-1-5	3/1/98 20:00	36.7	121	4,440
Phase I 1-1-1-6	3/1/98 25:00	35.9	116	4,160
Phase I 1-1-1-7	3/1/98 30:00	27.6	206	5,690
Phase I 1-1-1-8	3/2/98 39:00	26.1	192	5,010
Phase I 1-1-1-9	3/2/98 44:00	26.8	192	5,150
Phase I 1-1-1-10	3/2/98 49:00	26.9	184	4,950
Phase IIa 2a-1-1-1	3/2/98 54:30	28.7	202	5,800
Phase IIa 2a-1-1-2	3/3/98 55:00	26.3	202	5,310
Phase IIa 2a-1-1-3	3/3/98 55:30	26.7	202	5,390

TABLE 4. XYLENE EXTRACTION RATES IN THE EXTRACTED GROUNDWATER (SAMPLING LOCATION S4, MONITORING LOCATION M1)

Phase IIa 2a-1-1-4	3/3/98 56:00	27.5	200	5,500
Phase IIa 2a-1-1-5	3/3/98 56:30	14.4	200	2,880
Phase IIa 2a-1-1-6	3/3/98 57:00	27.3	200	5,460
Phase IIa 2a-1-1-7	3/3/98 57:30	28.1	203	5,700
Phase IIa 2a-1-1-7	3/3/98 58:00	28.4	202	5,740
Phase IIa 2a-1-1-8	3/3/98 58:30	25.0	202	5,050
Phase IIa 2a-1-1-9	3/3/98 59:00	28.1	203	5,700
Phase IIa 2a-1-1-10	3/3/98 59:30	27.0	202	5,450
Phase IIa 2a-1-1-11	3/3/98 60:00	27.1	203	5500
Phase IIa 2a-1-1-12	3/3/98 61:00	28.3	204	5,770
Phase IIa 2a-1-1-13	3/3/98 62:00	28.0	230	6,440
Phase IIa 2a-1-1-14	3/3/98 63:00	31.0	181	5,610
Phase II 2-1-1-1	3/3/98 64:00	64.5	209	13,500
Phase II 2-1-1-2	3/3/98 66:00	184	211	38,800
Phase II 2-1-1-3	3/3/98 68:00	387	209	80,900
Phase II 2-1-1-4	3/3/98 70:00	506	214	108,000
Phase II 2-1-1-5	3/3/98 72:00	486	226	110,000
Phase II 2-1-1-6	3/3/98 74:00	128	227	29,000
Phase II 2-1-1-7	3/3/98 76:00	567	223	12,700
Phase II 2-1-1-8	3/3/98 78:00	534	224	120,000
Phase II 2-1-1-9	3/4/98 80:00	506	217	110,000
Phase II 2-1-1-10	3/4/98 82:00	516	219	113,000
Phase II 2-1-1-11	3/4/98 84:00	453	219	99,200
Phase II 2-1-1-12	3/4/98 86:00	397	217	86,100
Phase II 2-1-1-13	3/4/98 88:00	274	214	58,600
Phase II 2-1-1-14	3/4/98 90:00	294	219	64,400
Phase II 2-1-1-15	3/4/98 92:00	239	216	51,600

TABLE 4. XYLENE EXTRACTION RATES IN THE EXTRACTED GROUNDWATER (SAMPLING LOCATION S4, MONITORING LOCATION M1)

Phase II 2-1-1-16	3/4/98 94:00	207	215	44,500
Phase II 2-1-1-17	3/4/98 96:00	143	220	31,500
Phase II 2-1-1-18	3/4/98 98:00	121	218	26,400
Phase II 2-1-1-19	3/4/98 100:00	113	216	24,400
Phase II 2-1-1-20	3/4/98 102:00	98.0	207	20,300
Phase II 2-1-1-21	3/5/98 104:00	95.0	218	21,400
Phase II 2-1-1-22	3/3/98 106:00	91.1	230	21,000
Phase II 2-1-1-23	3/3/98 108:00	85.6	181	15,500
Phase III 3-1-1-1	3/5/98 111:00	81.0	221	17,900
Phase III 3-1-1-2	3/5/98 112:00	70.4	221	15,600
Phase III 3-1-1-3	3/5/98 114:00	69.5	218	15,200
Phase III 3-1-1-4	3/5/98 116:00	64.5	218	14,100
Phase III 3-1-1-5	3/5/98 118:10	63.3	213	13,500
Phase III 3-1-1-6	3/5/98 120:00	59.9	213	12,800
Phase III 3-1-1-7	3/5/98 122:00	53.3	213	11,400
Phase III 3-1-1-8	3/5/98 126:00	49.8	212	10,600
Phase III 3-1-1-9	3/6/98 130:00	45.5	200	9,100
Phase III 3-1-1-10	3/6/98 134:00	44.7	200	8,940
Phase III 3-1-1-11	3/6/98 138:00	39.6	200	7,920
Phase III 3-1-1-12	3/6/98 142:00	39.5	194	7,660

Notes:

µg/L micrograms per liter

L/h liters per hour

µg/h micrograms per hour

Xylene Mass Removal Rates During the Demonstration

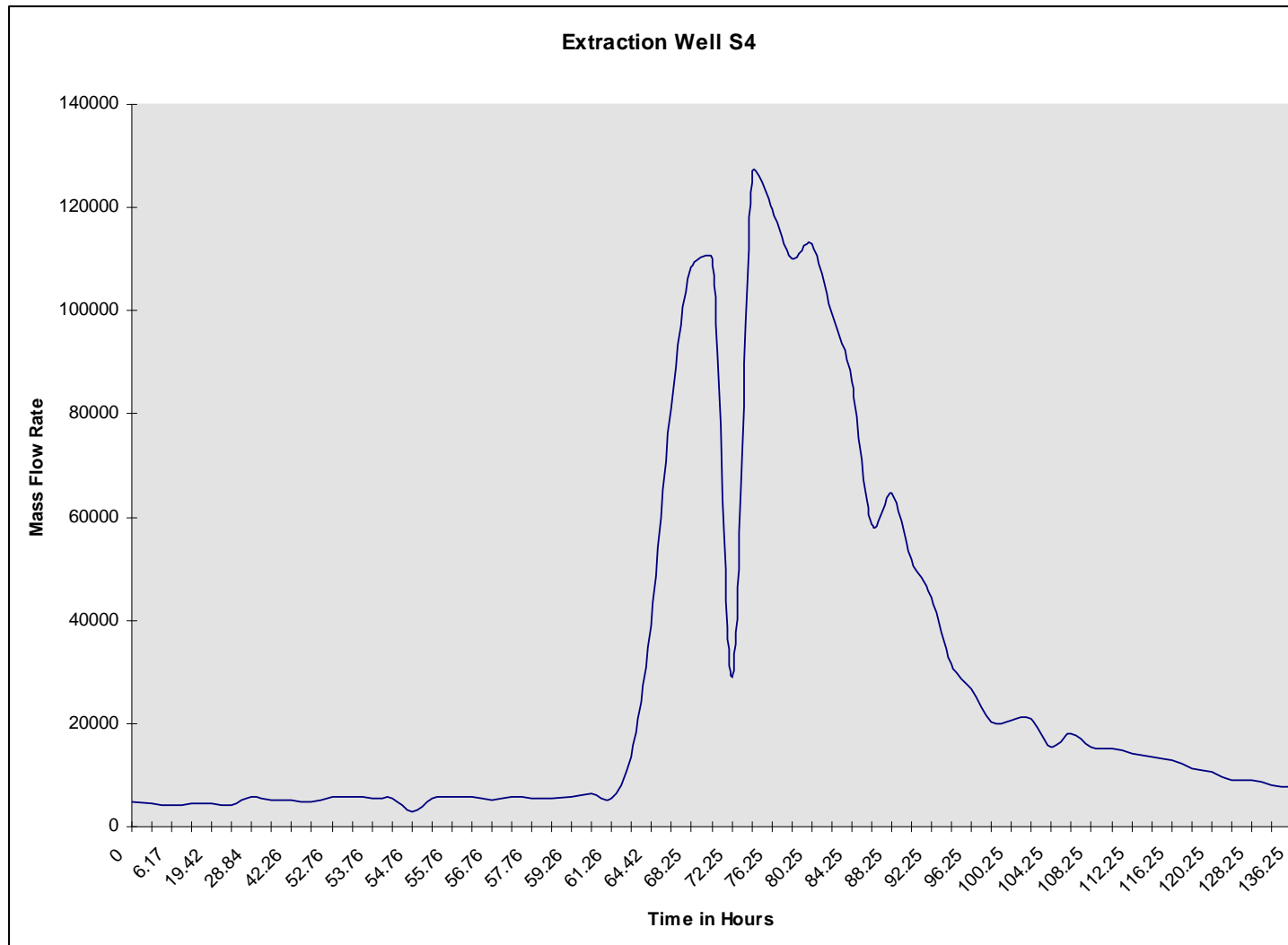


Figure 9

This objective was to be achieved by calculating a test statistic to determine the probability of observing that particular result or one more extreme. However, the xylene concentrations detected during Phase I of the demonstration, which were expected to serve as a constant baseline for which to compare the data obtained during Phase II and Phase III, were decreasing throughout Phase I and were not constant to serve for a basis of comparison.

Therefore, this objective, to show a statistical significance in the change of xylene concentrations in groundwater exiting the artificial aquifer, could not be conducted. The data obtained to achieve this objective are presented in Table 5. The range and average xylene concentration during each phase of the demonstration was as follows:

- Phase I (steady state without surfactant addition): range of from <1 to 43.5 µg/L, with an average concentration of 19.8 µg/L (assuming a value equal to the detection limit for results below the detection limit)
- Phase II (surfactant addition): range of from 3.8 to 12.9 µg/L, with an average concentration of 7.7 µg/L
- Phase III (post-surfactant addition): range of from <1 to 4.6 µg/L, with an average concentration of 2.3 µg/L (assuming a value equal to the detection limit for results below the detection limit)

These results show that the xylene concentration was actually decreasing in the effluent groundwater during the surfactant addition and post-surfactant addition phases. These results appear to reflect the degree of success achieved in removing the xylene mass from the artificial aquifer. With less xylene mass present during the surfactant addition and post-surfactant addition phases, there was apparently less mobilization into the groundwater flow exiting the artificial aquifer. This explanation is supported by the fact that the effluent xylene concentrations declined with time over both Phase II and Phase III of the demonstration.

Even though a statistical test could not be calculated on the data, the data obtained during Phase II and Phase III does not show an upward trend. No notable increase was observed between Phase II and Phase III. Therefore, the hydraulic control wells appeared to have functioned as planned.

2.3.1.3 Secondary Objective S-1

Evaluate the acute toxicity of the treated permeate from the surfactant recovery system and of groundwater effluent from the artificial aquifer before and after surfactant injection.

**TABLE 5. XYLENE CONCENTRATIONS IN THE EFFLUENT GROUND WATER
(SAMPLING LOCATION S2)**

Phase Sample Time	Sampling Date	Total Xylene Concentration (µg/L)
Phase I 0:00	2/28/98	<1
Phase I 4:00	2/28/98	<1
Phase I 7:30	3/1/98	<1
Phase I 15:00	3/1/98	<1
Phase I 20:00	3/1/98	39.6
Phase I 25:00	3/1/98	43.5
Phase I 30:00	3/1/98	39.8
Phase I 39:00	3/2/98	29.9
Phase I 44:00	3/2/98	24.3
Phase I 49:00	3/2/98	17.7
Phase II 64:00	3/3/98	12.9
Phase II 68:00	3/3/98	12.9
Phase II 72:00	3/3/98	11.4
Phase II 76:00	3/3/98	9.7
Phase II 80:00	3/4/98	9.1
Phase II 84:00	3/4/98	6.3
Phase II 88:00	3/4/98	5.4
Phase II 92:00	3/4/98	6.7
Phase II 96:00	3/4/98	5.0
Phase II 100:00	3/4/98	4.6
Phase II 104:00	3/5/98	3.8
Phase II 108:00	3/5/98	4.6
Phase III 111:00	3/5/98	4.6
Phase III 112:00	3/5/98	NA

Phase III 114:00	3/5/98	3.5
Phase III 118:00	3/5/98	3.2
Phase III 122:00	3/5/98	2.6
Phase III 126:00	3/5/98	2.5
Phase III 130:00	3/6/98	1.2
Phase III 134:00	3/6/98	1.1
Phase III 138:00	3/6/98	<1
Phase III 142:00	3/6/98	1.1

Notes:

µg/L Microgram per liter

The results of the evaluation of acute toxicity of groundwater effluent before and after surfactant injection are presented in Table 6. The toxicity results indicate that the extracted groundwater was not sufficiently toxic to kill 50 percent of the Daphnia test organisms, even at no dilution. An evaluation of the treated permeate was not performed since the surfactant recovery system was not operational.

TABLE 6. ACUTE TOXICITY OF GROUNDWATER EFFLUENT TO DAPHNIA

Sample Phase and Time	Sampling Date	Effluent Concentration for 50% Mortality (%)
Phase I 00:00	2/28/98	>100
Phase II 64:00	3/3/98	>100
Phase II 76:00	3/3/98	>100
Phase II 80:00	3/4/98	>100
Phase II 104:00	3/5/98	>100
Phase III 111:00	3/5/98	>100
Phase III 130:00	3/6/98	>100

Notes:

% Percent

2.3.1.4 Secondary Objective S-2

Document process operating parameters.

Various process operating parameters were measured to document system conditions throughout the demonstration. Process flow rates are presented in Table 7. A summary of other process flow rates is given below:

- The injected groundwater flow rate ranged from 101.4 to 112 L/h; the extracted groundwater flow rate ranged from 116 to 230 L/hr
- The influent groundwater flow rate ranged from 207 to 252 L/h; the effluent groundwater flow rate ranged from 191 to 315 L/h.

Additionally, selected groundwater physical and chemical characteristics (temperature, pH, conductivity and metals) were monitored for the influent groundwater to the artificial aquifer. The results of these measurements are presented in Table 8.

**TABLE 7
SURFACTANT CONCENTRATIONS
OF GOUNDWATER INFLUENT**

Sample Description	Sampling Date	Anionic Surfactants (mg/L)	Nonanionic Surfactants (mg/L)
1-4-X-1	2/28/98	<0.05	<0.25
2-4-X-1	3/3/98	<0.05	<0.25
2-4-X-3	3/3/98	<0.05	<0.25
2-4-X-4	3/3/98	<0.05	<0.25
2-4-X-6	3/4/98	<0.05	<0.25
2-4-X-7	3/4/98	<0.05	<0.25
2-4-X-9	3/4/98	<0.05	<0.25
2-4-X-11	3/5/98	<0.05	<0.25
3-4-X-3	3/5/98	<0.05	<0.25
3-4-X-5	3/5/98	<0.05	<0.25
3-4-X-8	3/6/98	<0.05	<0.25
3-4-X-10	3/6/98	<0.05	<0.25

- **Note: Acute toxicity values expressed in the mortality of species for each tested; Fish, Daphnia, and Leuchtakterien repectively.**

TABLE 8. SELECTED PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE INFLUENT GROUNDWATER

Sample Description: Sample Date:	Phase I Groundwater Effluent (S2) 03/01/98	Phase I Injected Groundwater (S3) 03/01/98	Phase II Injected Groundwater (S3) 03/04/98	Phase II Injected into Hydraulic Control Wells (S6) 03/04/98	Phase III Injected Groundwater (S3) 03/05/98	Phase III Groundwater Injected into Hydraulic Control Wells (S6) 03/05/98
Temperature (C)	18.5	18.5	19.1	19.1	18.6	18.6
pH	7.53	7.53	7.9	7.9	7.83	7.83
Surfactants, anionic (mg/L)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Surfactants, nonionic (mg/L)	<0.25	<0.25	<0.25	<0.25	0.27	<0.25
Metals						
Al (µg/L)	45	<40	<40	65	<40	<40
Sb (µg/L)	<30	<30	<30	<30	<30	<30
As (µg/L)	<50	<50	<50	<50	<50	<50
Ba (µg/L)	172	83	159	64	143	66
Be (µg/L)	<1	<1	<1	<1	<1	<1
Cd (µg/L)	<4	<4	<4	<4	<4	<4
Cr (µg/L)	<10	<10	<10	<10	<10	<10
Co (µg/L)	<10	<10	<10	<10	<10	<10
Cu (µg/L)	11	<10	<10	<10	<10	<10
Fe (µg/L)	484	<10	851	<10	864	<10
Pb (µg/L)	<40	<40	<40	<40	<40	<40
Li (µg/L)	<5	<5	7	<5	7	5

TABLE 8. SELECTED PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE INFLUENT GROUNDWATER (Continued)

Sample Description: Sample Date:	Phase I Groundwater Effluent (S2) 03/01/98	Phase I Injected Groundwater (S3) 03/01/98	Phase II Injected Groundwater (S3) 03/04/98	Phase II Injected into Hydraulic Control Wells (S6) 03/04/98	Phase III Injected Groundwater (S3) 03/05/98	Phase III Groundwater Injected into Hydraulic Control Wells (S6) 03/05/98
Mn (µg/L)	849	7	676	<5	552	<2
Mo (µg/L)	<10	<10	<10	<10	17	<10
Ni (µg/L)	15	<15	<15	<15	<15	<15
Se (µg/L)	<80	<80	<80	<80	<80	<80
Ag (µg/L)	<10	<10	<10	<10	<10	<10
Sr (µg/L)	541	465	514	419	504	423
TI (µg/L)	<40	<40	<40	<40	<40	<40
V (µg/L)	<10	<10	<10	<10	<10	<10
Zn (µg/L)	15	370	5	2	<2	7
Na (mg/L)	153	154	151	115	155	112
K (mg/L)	12.5	12.4	12.7	9.1	12.2	9.7
Mg (mg/L)	8.9	8.5	8.4	7.2	8.5	7.6
Ca (mg/L)	97.1	84.2	95.5	73.0	92.0	75.0
Ammonia (mg/L)	<0.02	0.10	0.26	<0.02	0.15	<0.02
F (mg/L)	0.18	0.17	0.18	0.15	0.18	0.16
Cl (mg/L)	264	262	263	186	257	187
NO2 (mg/L)	<0.02	1.2	<0.02	<0.02	<0.02	<0.02
NO3 (mg/L)	0.3	1.2	<0.3	0.5	<0.3	0.7
HCO3 (mg/L)	210	177	197	177	195	176

Sample Description:	Phase I Groundwater Effluent (S2) 03/01/98	Phase I Injected Groundwater (S3) 03/01/98	Phase II Injected Groundwater (S3) 03/04/98	Phase II Injected into Hydraulic Control Wells (S6) 03/04/98	Phase III Injected Groundwater (S3) 03/05/98	Phase III Groundwater Injected into Hydraulic Control Wells (S6) 03/05/98
SO4 (mg/L)	94	85	93	66	89	68

Notes:

C Degrees Celsius
mg/L Milligrams per liter
µg/L Micrograms per liter

As shown in Table 8, the influent groundwater was relatively consistent in its physical and chemical characteristics. Specifically, the groundwater influent temperature ranged from 18.5 C to 19.1 C and the pH ranged from 7.53 to 7.9. Major cations and anions also showed little variability.

2.3.1.5 Secondary Objective S-3

Document the xylene and surfactant concentrations in the treated surfactant recovery permeate and surfactant concentration in effluent groundwater.

The results of the surfactant concentration measurements for samples of the groundwater effluent are presented in Table 9. As shown in this table, neither anionic nor nonionic surfactants were detected in any of the groundwater effluent samples. Thus, the injection of groundwater into the hydraulic control wells appears to have been successful in excluding surfactant from the groundwater effluent.

Results were not available for the treated permeate since the surfactant recovery system was not operational during the demonstration.

2.3.1.6 Secondary Objective S-4

Estimate capital and operating costs.

Because the surfactant recovery system was not operational during the demonstration and the ability to recycle surfactant was not determined, a detailed cost analysis of the surfactant-enhanced extraction technology could not be developed. The cost of the surfactant provided by BASF was 3.50 DM per kilogram of surfactant (\$1.82 per kilogram assuming a 1.92 DM to \$1 U.S. exchange rate). A further discussion of cost information is provided in Section 3.0.

**TABLE 9. SURFACTANT CONCENTRATIONS IN GROUNDWATER EFFLUENT
(SAMPLE LOCATION S2)**

Sample Phase and Time	Sampling Date	Anionic Surfactants (mg/L)	Nonanionic Surfactants (mg/L)
Phase I 00:00	2/28/98	<0.05	<0.25
Phase II 64:00	3/3/98	<0.05	<0.25
Phase II 72:00	3/3/98	<0.05	<0.25
Phase II 76:00	3/3/98	<0.05	<0.25
Phase II 84:00	3/4/98	<0.05	<0.25
Phase II 88:00	3/4/98	<0.05	<0.25
Phase II 96:00	3/4/98	<0.05	<0.25
Phase II 104:00	3/5/98	<0.05	<0.25
Phase III 114:00	3/5/98	<0.05	<0.25
Phase III 122:00	3/5/98	<0.05	<0.25
Phase III 134:00	3/6/98	<0.05	<0.25
Phase III 142:00	3/6/98	<0.05	<0.25

Notes:

mg/L Milligram per liter

< Less than

2.3.2 Data Quality

This section summarizes the results for quality control samples collected and analyzed during the demonstration and addresses associated data quality issues. The results of this assessment were used to produce the known, defensible information employed to define the investigation findings and to draw conclusions.

The primary QC samples processed in relation to the sole critical analysis (xylene in groundwater samples) included trip blanks and field blanks, matrix spike/matrix spike duplicates (MS/MSDs). Xylene concentrations reported in previous sections for evaluation of process performance are total xylenes concentrations, measured as the sum of ortho-xylene (o-xylene) and combined meta-xylene and para-xylene (m/p-xylene). For the quality control samples, o-xylene and m/p-xylene are reported separately.

Field blanks and trip blanks were collected to monitor whether field techniques or sample shipping potentially introduced xylene into the field samples. All three trip blanks and all three field blanks had concentrations of <1 µg/L for both o-xylene and m/p-xylene. Therefore, field techniques and sample shipping did not introduce measurable concentrations of xylenes.

One extracted groundwater MS/MSD sample was analyzed in association with each of the sampling events to assess the precision and accuracy of the xylene results in the groundwater matrix. Table 10 lists the results of these MS/MSD analyses. In general, these results were within the acceptance criteria for recovery of xylene and relative percent difference (RPD) of the duplicate results. Specifically, only three recoveries out of 22 pairs of MS/MSD sample results were outside of the acceptance criteria for the associated percent recoveries. Of those three samples, two samples were also outside of the RPD acceptance criteria. Further, none of the excursions outside of the acceptance criteria were extraordinary or appeared to indicate anything other than random errors. Therefore, these MS/MSD results indicate that generally acceptable laboratory precision and accuracy were achieved for the xylene determinations in groundwater samples.

TABLE 10. RESULTS FOR MATRIX SPIKE QC SAMPLES

Sample Phase, Time	Parameter	Sample (µg/L)	MS (µg/L)	MSD (µg/L)	Spike (µg/L)	Spike Recovery	RPD (%)	QC limits (%R)	QC RPD (%)
Phase I, 08:00	m/p-xylene	<1	55.16	56.42	50.8	108.1	2.3	75-125	<20
	o-xylene	<1	27.1	26.56	24.4	110.7	2.0	75-125	<20
Phase II, 88:00	m/p-xylene	1.6	25.1	24.78	25.44	97.4	1.3	75-125	<20
	o-xylene	<1	12.02	11.78	12.2	97.7	2.0	75-125	<20
Phase III, 112:00	m/p-xylene	<1	49.84	50.42	50.88	97.9	1.2	75-125	<20
	o-xylene	<1	24.3	24.18	24.4	99.4	0.5	75-125	<20
Phase III, 122:00	m/p-xylene	<1	26.06	25.16	25.44	102.3	3.5	75-125	<20
	o-xylene	<1	12.58	11.92	12.2	103.0	5.4	75-125	<20
Phase I, 15:00	m/p-xylene	3.4	42.66	49.86	50.88	82.5	15.6	75-125	<20
	o-xylene	1.5	23.38	24.74	24.4	94.6	5.7	75-125	<20
Phase II, 80:00	m/p-xylene	29.2	58.3	55.12	50.88	103.1	5.6	75-125	<20
	o-xylene	16.4	27.9	26.94	24.4	100.9	3.5	75-125	<20
Phase III, 114:00	m/p-xylene	10.1	78.6	53.3	50.88	150.5[†]	38.4	75-125	<20
	o-xylene	7.6	38.74	25.78	24.44	152.6[†]	40.2	75-125	<20
Phase I, 15:00	m/p-xylene	5.5	54.78	55.92	50.88	104.2	1.1	75-125	<20
	o-xylene	2.6	26.76	26.82	24.4	107.5	0.2	75-125	<20
Phase II, 72:00	m/p-xylene	2.2	53.46	54.06	50.88	104.2	1.1	75-125	<20

TABLE 10. RESULTS FOR MATRIX SPIKE QC SAMPLES

	o-xylene	0.2	25.2	25.9	24.4	107.5	0.2	75-125	<20
Phase III, 118:00	m/p-xylene	0.9	49.46	53.3	50.88	96.9	7.5	75-125	<20
	o-xylene	0.4	24.3	25.78	24.4	103.1	2.8	75-125	<20
Phase I, 7:30	m/p-xylene	13.4	15.38	15.66	12.72	99.8	5.9	75-125	<20
	o-xylene	2.9	5.94	6.04	6.1	88.0	1.8	75-125	<20
Phase I, 39:00	m/p-xylene	10.8	11.86	11.8	12.72	76.3	0.5	75-125	<20
	o-xylene	2.2	5.0	5.22	6.1	74.6	4.5	75-125	<20
Phase I, 44:00	m/p-xylene	11.1	26.1	27.06	25.44	93.8	3.6	75-125	<20
	o-xylene	2.4	12.48	13.26	12.2	98.4	6.1	75-125	<20
Phase II, 60:00	m/p-xylene	238.2	69.62	68.75	25.44	86.4	1.3	75-125	<20
	o-xylene	45.1	22.02	21.96	12.2	106.6	0.3	75-125	<20
Phase II, 76:00	m/p-xylene	123.9	46.24	45.06	25.44	84.3	2.6	75-125	<20
	o-xylene	23.6	17.08	16.56	12.2	121.9	2.9	75-125	<20
Phase II, 78:00	m/p-xylene	16.0	33.68	32.98	25.44	119.9	2.1	75-125	<20
	o-xylene	3.1	15.5	15.06	12.2	121.9	2.9	75-125	<20
Phase II, 94:00	m/p-xylene	44.0	39.1	35.9	25.44	119.9	8.6	75-125	<20
	o-xylene	9.3	17.24	15.92	12.2	126.1 [†]	7.9	75-125	<20
Phase II, 102:00	m/p-xylene	9.6	25.78	24.98	25.44	93.8	3.3	75-125	<20
	o-xylene	1.7	12.36	12.44	12.2	98.4	0.8	75-125	<20
Phase II, 94:00	m/p-xylene	18.3	26.6	26.78	25.44	90.2	0.7	75-125	<20
	o-xylene	3.7	12.82	13.02	12.2	98.9	1.5	75-125	<20
Phase III, 122:00	m/p-xylene	10.2	27.78	25.62	25.44	101.1	8.1	75-125	<20

TABLE 10. RESULTS FOR MATRIX SPIKE QC SAMPLES

	o-xylene	2.0	13.5	13.28	12.2	107.3	1.7	75-125	<20
Phase III,	m/p-xylene	20.6	27.72	27.46	25.44	92.88	0.9	75-125	<20
	o-xylene	4.3	12.88	12.54	12.2	98.4	2.6	75-125	<20

Notes: † and bold font indicates QC results outside of acceptance criteria (75-125% recovery and/or <20%RPD).

2.3.3 Conclusions

The results of the surfactant-enhanced extraction bilateral SITE demonstration are discussed above in relation to the two primary and four secondary objectives. The corresponding conclusions of this evaluation are summarized below:

- The xylene mass removal rate increased as a result of surfactant injection. The concentration of xylene in the extracted groundwater increased by a factor of approximately 15 after the injection of the surfactant solution. The graph of the xylene mass removal rate (Figure 9) illustrates the increase in xylene mass removal rate after injection of the surfactant.
- There was no significant increase in xylene concentration exiting the artificial aquifer due to surfactant enhancement. Groundwater effluent xylene concentrations during: Phase I (steady state without surfactants) ranged from <1 to 43.5 µg/L with an average concentration of 19.8 µg/L; Phase II (non steady state with surfactants) ranged from 3.8 to 12.9 µg/L with an average concentration of 7.7 µg/L; and Phase III (steady state, post surfactant injection) ranged from <1 to 4.6 µg/L with an average concentration of 2.3 µg/L.
- The toxicity results indicate that the extracted groundwater was not sufficiently toxic to kill 50 percent of the Daphnia test organisms, even at no dilution.
- The process operation parameters were as follows. The extracted groundwater flow rates ranged from 116 to 230 L/h and injected groundwater (M2) flow rates ranged from 101.4 to 112 L/h. The influent groundwater (M3) flow rate ranged from 207 to 252 L/h and the effluent groundwater (Location M4) flow rate ranged from 191 to 315 L/h. The following changes were made to the planned operation: 1) A revised flow scheme was utilized and Wells MW 1, 2, and 4 were not used; a new well (MW 6) was installed and utilized as the groundwater/surfactant injection well, 2) The above ground surfactant recovery system was not operational. The groundwater influent samples temperature ranged from 18.5 to 19.1 C; and pH ranged from 7.53 to 7.9.
- The surfactant concentrations in the effluent groundwater were all less than 0.05 mg/L for anionic surfactants and less than 0.25 mg/L for nonanionic surfactants. The treated permeate was not analyzed since the recovery system was not operational.
- The cost of the surfactant provided by BASF was 1.78 Euros (€) per kilogram of surfactant (\$2.33 per kilogram assuming a 0.76 € to \$1 U.S. exchange rate). Because the surfactant recovery system was not operational during the demonstration and the ability to recycle the surfactant was not determined, a detailed cost analysis could not be developed.

3.0 ECONOMIC ANALYSIS

This section presents available cost information for the surfactant-enhanced extraction technology based on data provided by Tauw Umwelt GmbH Moers and BASF AG.

Because the surfactant recovery system was not operational during the demonstration and the ability to recycle surfactant was not determined, a detailed cost analysis of the surfactant-enhanced extraction technology could not be developed.

Cost information was solicited from Tauw Umwelt GmbH Moers and BASF AG. The only cost information provided was that provided by BASF AG for the surfactant. BASF indicated that the cost of the surfactant was 1.78 Euros (€) per kilogram of surfactant (\$2.33 per kilogram assuming a 0.76 €to \$1 U.S. exchange rate).

Although 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 surfactant-enhanced extraction technology:

- Site preparation
- Permitting and regulatory requirements
- Capital equipment
- Startup
- Labor
- Consumables and supplies
- Utilities
- Effluent treatment and disposal
- Residuals and waste shipping and handling
- Analytical services
- Maintenance and modifications
- Demobilization

4.0 TECHNOLOGY APPLICATIONS ANALYSIS

This section evaluates the general applicability of the surfactant-enhanced extraction technology to remediation of the saturated zone at contaminated 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 surfactant-enhanced extraction 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 surfactant-enhanced extraction technology provides both short-term and long-term protection of human health and the environment by removing organic contaminants from the saturated zone. Treated groundwater is recycled to the aquifer, thereby limiting exposure routes. Exposure from air emissions can be minimized by passing the system's air process stream through 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 surfactant-enhanced extraction 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 surfactant-enhanced extraction system in removing contaminants from the groundwater and the site-specific cleanup level.

4.1.3 Long-Term Effectiveness and Permanence

The surfactant-enhanced extraction system permanently removes organic contaminants from the saturated zone and recovers the surfactant for reuse. Long-term risks to treatment system workers, the community, and the environment from exposure to contaminated groundwater are mitigated by ensuring that established standards are met.

The concentrated solution of organic contaminants (the permeate) must be disposed of properly to ensure the permanence of remediation using this technology. Secondary emissions from the treatment and disposal of the permeate may present other risks not addressed in this report.

4.1.4 Reduction of Toxicity, Mobility, or Volume Through Treatment

As discussed in Section 4.1.1 and 4.1.3, the surfactant-enhanced extraction technology offers permanent removal of organic contaminants from the saturated zone. As such, the toxicity, mobility, and volume of contaminants are also significantly reduced.

4.1.5 Short-Term Effectiveness

The removal of organic contaminants is achieved relatively quickly, providing for short-term effectiveness as well as long-term effectiveness, as discussed in Section 4.1.3. Potential short-term risks presented during system operation to workers, the community, and the environment includes air emissions. Exposure to air emissions during operation, monitoring, and maintenance can be minimized through the removal of contaminants from the system's air process stream using carbon adsorption units before emitting this stream to the atmosphere.

4.1.6 Implementability

The surfactant-enhanced extraction technology has been demonstrated at a number of sites in the U.S. and in Europe. While an innovative technology, sufficient technical information is available to support application of this technology (Ground Water Remediation Technologies Analysis Center, *Technology Evaluation Report: Surfactants/Cosolvents*). The equipment and supply requirements for surfactant extraction are relatively standard, including wells, pumps, piping, and chemicals (surfactant). Surfactant separation and recovery processes are more complex, and need to be further proven prior to full-scale implementation.

4.1.7 Cost

The cost of surfactant-enhanced extraction has not been fully defined due to unresolved issues related to recycling the surfactant. However, currently available information suggest that the cost will be relatively high in comparison to other technologies. Thus, surfactant enhanced extraction should be reserved for contaminated sites where other, less expensive treatment technologies cannot accomplish the remediation goals.

4.1.8 State Acceptance

State acceptance is anticipated because the surfactant-enhanced extraction system uses widely accepted processes to remove contaminants from the saturated zone, and air emissions can be effectively treated using carbon adsorption. If remediation is conducted as part of Resource Conservation and Recovery Act (RCRA) corrective actions, state regulatory agencies will 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 in situ make this technology likely to be accepted by the public.

4.2 APPLICABLE WASTES

The surfactant-enhanced extraction technology demonstrated at Stuttgart-Vaihingen, Germany, was designed to remove xylene from the saturated zone. The developer claims and other demonstration results suggest that the technology can also remove other non-aqueous phase liquid organic contaminants. However, the technology's applicability to contaminants other than xylene was not examined as part of this demonstration.

4.3 LIMITATIONS OF THE TECHNOLOGY

The developer claims that there are no concentration limits on the contamination that can be treated by the system. However, high concentrations of contaminants may require longer operation of the technology and multiple extractions to achieve remediation goals.

5.0 SURFACTANT-ENHANCED EXTRACTION TECHNOLOGY STATUS

According to Tauw Umwelt GmbH Moers, the technology can be used for remediation of contamination in the saturated zone with both VOCs and semivolatile organic compounds (SVOCs). The surfactant-enhanced extraction technology has been or is currently being demonstrated at several sites in the U.S. There are currently no commercially operating systems in the U.S.

6.0 REFERENCES

- American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF). 1994. *Standard Methods for the Examination of Water and Wastewater*. Greenberg, Arnold E., Lenore S. Clesceri, and Andrew D. Eaton, eds. 19th edition. Washington, D.C.
- Evans, G. 1990. "Estimating Innovative Technology Costs for the SITE Program." *Journal of Air and Waste Management Assessment*. Volume 40, Number 7. July.
- Ground Water Remediation Technologies Analysis Center (GWRTAC). *Technology Evaluation Report: Surfactants/Cosolvents*.
- Tetra Tech EM Inc. (TTEMI) 1998 Quality Assurance Project Plan for the Surfactant-Enhanced Extraction Technology Evaluation in Stuttgart, Germany. February 4.
- U.S. Environmental Protection Agency (EPA). 1983. *Methods for Chemical Analysis of Water and Wastes (MCAWW)*. Environmental Monitoring and Support Laboratory. Cincinnati, Ohio. EPA-600/4-79-020. March
- EPA. 1988. "Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA." EPA/540/G-89/004. October.
- EPA. 1996. "Test Methods for Evaluating Solid Waste." Volumes 1A through 1C. SW-846. Third Edition. Update III. Office of Solid Waste and Emergency Response (OSWER). Washington, DC. December.