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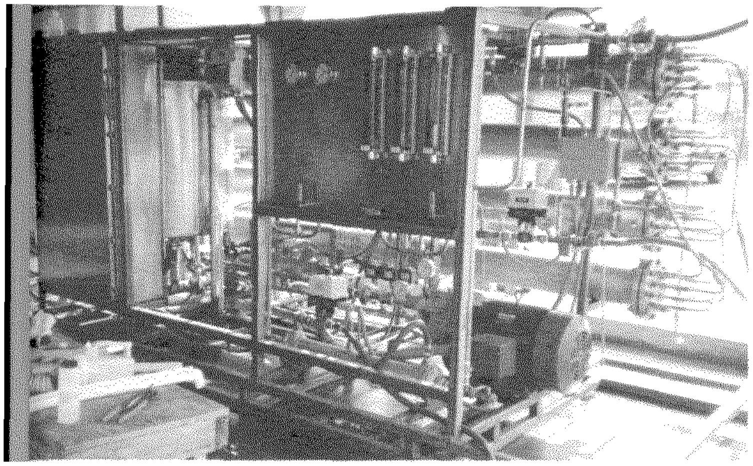
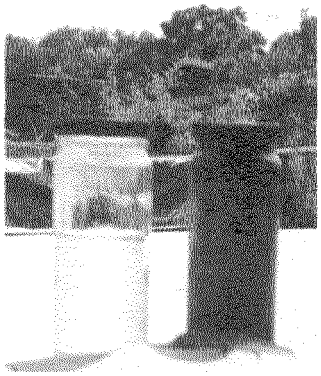
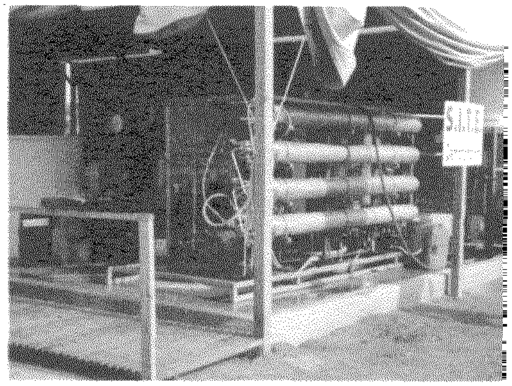
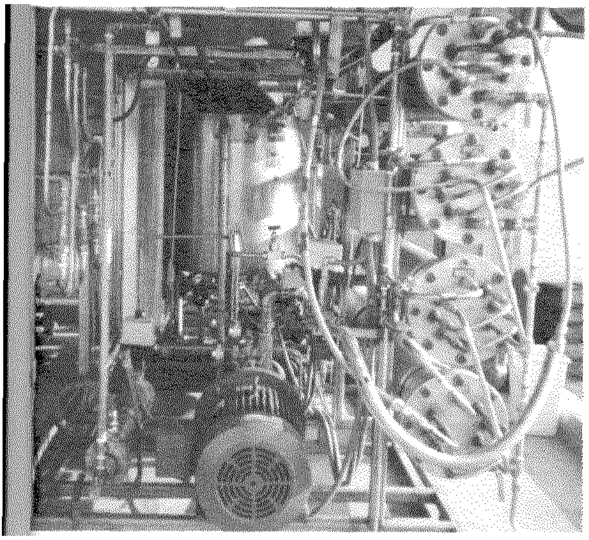
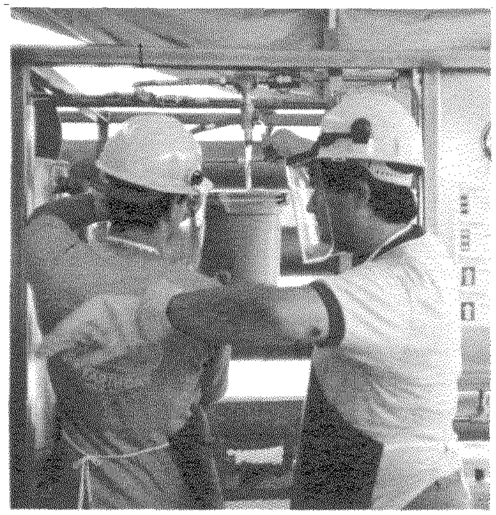
August 1993

EPA

Membrane Treatment of Wood Preserving Site Groundwater by SBP Technologies, Inc.

Applications Analysis Report


SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

EPA/540/AR-92/014
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Membrane Treatment of Wood Preserving Site Groundwater by SBP Technologies, Inc.

Applications Analysis Report

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

Printed on Recycled Paper

Notice

The information in this document has been funded by the U.S. Environmental Protection Agency under the auspices of the Superfund Innovative Technology Evaluation (SITE) Program under Contract No. 68-CO-0048 to Science Applications International Corporation. It has been subjected to the Agency's peer and administrative review, and it 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 Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments. The Program is a joint effort between EPA's Office of Research and Development and Office of Solid Waste and Emergency Response. The purpose of the program is to assist the development of hazardous waste treatment technologies necessary to implement new cleanup standards which require greater reliance on permanent remedies. This is accomplished through technology demonstrations designed to provide engineering and cost data on selected technologies.

This project was designed to evaluate the effectiveness of SBP's formed-in-place membrane process on wood preserving waste contaminated groundwater and establish the potential applicability at other Superfund or hazardous waste sites. This process separates contaminated water into a large volume of relatively uncontaminated permeate potentially suitable for discharge and a smaller volume of a contaminant-rich concentrate suitable for biodegradation or other means of final destruction. The study was carried out at the American Creosote Works facility in Pensacola. Florida, a site where wood preserving operations had been carried from 1902 to 1981 using creosote and. more recently, pentachlorophenol. The study is summarized in this Applications Analysis Report and described in more detail in the companion Technology Evaluation Report.

Additional copies of this report may be obtained at no charge from EPA's Center for Environmental Research Information, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268. using the EPA document number found on the report's front cover. Once this supply is exhausted, copies can be purchased from the National Technical Information Service, Ravensworth Bldg., Springfield, VA, 22161, 703-487-4600. Reference copies will be available at EPA libraries in their Hazardous Waste Collection.

E. Timothy Oppelt. Director
Risk Reduction Engineering Laboratory
U.S. Environmental Protection Agency

Abstract

This document provides an evaluation of the SBP Technologies, Inc. (SBP) formed-in-place membrane hyperfiltration process. The purpose of the technology is to reduce the volume of waste requiring further treatment through such techniques as immobilization or destruction. This volume reduction technology, when coupled with other technologies, may reduce total treatment costs and minimize off-site transportation of hazardous materials. Using cross-flow filtration to minimize fouling, the membrane filtration system separates contaminated groundwater and other waste waters into a small, concentrated stream that can be treated biologically or otherwise, and a relatively clean permeate that can be discharged, reinjected. or reused with little or no additional treatment. In hyperfiltration, pollutants are separated on the basis of molecular weight, molecular size, polarity, or charge.

This report summarizes the utility and application of SBP's membrane system to the treatment of organic contaminated wastewater. This analysis utilizes information from the Superfund Innovative Technology Evaluation (SITE) Program's demonstration at the American Creosote Works wood preserving site in Pensacola, Florida as well as data from other SBP investigations. Conclusions were reached concerning the technological effectiveness and economics of the process and its suitability for use at other sites and with other waste waters.

During the SITE demonstration, operations were carefully monitored to establish a database against which the vendor's claims for the technology could be evaluated. These claims were that the filtration system would (1) provide an 80% volume reduction for the contaminants in the feed stream; and (2) achieve 90% removal of semivolatile contaminants. based on a comparison of the concentrations in the feed stream and those in the permeate from the filtration system.

Based on the demonstration study using the system as configured and as used, an 83% reduction in the volume of the contaminated feed water was achieved. However, the system achieved a 74% overall removal of the designated semivolatile components, which included low molecular weight phenols and polynuclear aromatic hydrocarbons (PAHs). The filtration system was much more effective at removing the PAHs than phenols. The average removal efficiencies were 92% for PAHs and 18% for phenols.

Capital and operating costs for the system are estimated to be between $220 and $1,740 per thousand gallons (on an annual basis), dependent on the type and magnitude of contamination encountered in the waste stream.

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Abbreviations and Symbols

BOD	biochemical oxygen demand (mg oxygen/liter)
BTEX	benzene, toluene, ethyl benzene, and xylenes
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
COD	chemical oxygen demand (mg oxygen/liter)
GC/MS	gas chromatograph/mass spectrometer
gpd	gallons per day
gpm	gallons per minute
HSWA	Hazardous and Solid Waste Amendments to RCRA - 1984
kwh	kilowatt-hour
Mgd	million gallons per day
mg/L	milligrams per liter
ng/kg	nanograms per kilogram
ng/L	nanograms per titer
NPL	National Priorities List
O&G	oil and grease
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration or Act
OSWER	Office of Solid Waste and Emergency Response
PAHs	polynuclear aromatic hydrocarbons

PCBs	polychlorinated biphenyls
PCP	pentachiorophenol
PEL	Permissible Exposure Limit
POTW	publicly owned treatment works
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act of 1976
RI/FS	Remedial Investigation/Feasibility Study
RREL	Risk Reduction Engineering Laboratory
SAIC	Science Applications International Corporation
SARA	Super-fund Amendments and Reauthorization Act of 1986
SITE	Superfund Innovative Technology Evaluation
SBP	SBP Technologies, Inc., formerly Southern Bio Products, Inc.
TDS	total dissolved solids (mg solids/liter)
TOC	total organic carbon (mg carbon/liter)
TPH	total petroleum hydrocarbons
TSS	total suspended solids (mg solids/liter)
VOCs	volatile organic compounds

Conversion Factors

	English (US)	x	Factor	=	Metric
Area:	1 ft2	x	9.2903 x 10-2	=	m^2
	1 in2	x	6.4516	=	cm^2
Flow Rate:	1 gal/min	x	6.3090×10^{-5}	=	m^3/s
	1 gal/min	x	6.3090×10^{-2}	=	L/s
	1 Mgal/d	x	43.8126	=	L/s
	1 Mgal/d	x	3.7854×10^{3}	=	m^3/d
	1 Mgal/d	x	4.3813×10^{-2}	=	m^3/s
Length:	1 ft	x	0.3048	=	m
	1 in	x	2.54	=	cm
	1 yd	x	0.9144	=	m
Mass:	1 lb	x	4.5359×10^{2}	=	g
	1 lb	x	0.4536	=	kg
Volume:	1 ft^3	x	28.3168	=	L
	1 ft^3	x	2.8317×10^{-2}	=	m^3
	1 gal	x	3.7854	=	L
	1 gal	x	3.7854×10^{-3}	=	m^3

ft = foot, ft^2 = square foot, ft^3 = cubic foot
in = inch, in^2 = square inch
yd = yard
lb = pound
gal = gallon
gal/min (or gpm) = gallons per minute
Mgal/d (or MGD) = million gallons per day
m = meter, m2 = square meter, m3 = cubic meter
cm = centimeter, cm2 = square centimeter
L = liter
g = gram
kg = kilogram
m3/s = cubic meters per second
Us = liters/sec
m3/d = cubic meters per day

Acknowledgements

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Finally, the project could not have been carried out without the efforts of the many SAIC and S-Cubed personnel who were responsible for the actual sample collection and analyses.

SECTION 1

EXECUTIVE SUMMARY

1.1 Introduction

The SBP Technologies, Inc. membrane filtration system, using a formed-in-place hyperfiltration membrane, has been used to treat a creosote and pentachlorophenol (PCP) contaminated groundwater stream at a Pensacola, Florida site on the Superfund National Priorities List. Operational and cost data were collected for that investigation and are the basis for the evaluation of this process.

SBP's membrane technology can be used as an integral part of a remediation system to significantly reduce the volume and toxicity of contaminated wastewater. The technology is particularly suited for the treatment of contaminated groundwater as part of a pump and treat system. The technology reduces risks to human health and the environment by transferring the contaminants to a smaller volume facilitating destruction or detoxification by other technologies. The technology is particularly applicable to the treatment- of dilute waste streams, where the concentration of the contaminants into a reduced volume would result in significant cost savings as well as minimize off-site treatment. The reduced-volume concentrated residual could be further treated on-site. or transported off-site for treatment and disposal.

The system is simple to operate, reliable and requires a minimum of operator attention or maintenance once the membrane has been formed. The stability of the system makes it particularly suitable for long-term use as is necessary for extended pump and treat remedial programs

The demonstration at the American Creosote Works was designed to evaluate the two most critical process parameters for membrane systems; volume reduction and contaminant reduction. A summary of the demonstration results for these critical processes parameters are presented below.

1.2 Conclusions

Based on the results of the SITE demonstration project at the American Creosote Works site in Pensacola, Florida and information concerning other studies provided by the vendor, SBP Technologies, Inc., for different wastes at other sites, several conclusions can be drawn. The conclusions are organized based on the evaluation factors of volume reduction and contaminant reduction. In addition, unit operability and waste applicability are also presented. These factors are critical in applying the technology to other sites and wastes.

1. Contaminant Reduction - The SBP filtration unit (as configured) effectively removed high molecular weight compounds from the feed stream. but smaller molecular weight compounds were not removed.

- The formed-in-place membrane system is quite effective (92%) at removing polynuclear aromatic hydrocarbons (PAHs) found in creosote from the feed water and producing a permeate with little of these materials.

- However. the membrane - as used in the demonstration - is not very efficient at removing phenolics. Rejections were in the range of 18% for phenolics. (see Appendix B for vendor discussion.)

- Overall, based on a comparison of total concentrations of a predesignated list of creosote-derived PAH and phenolic semivolatile contaminants in the permeate versus the feed water, the system did not meet the claimed rejection efficiency of 90%. On the combined basis, rejection was 74% over the six days of tests.

- On the basis of the PAH rejections of over 90%, the permeate would be expected to be acceptable for discharge to POTWs with little or no polishing.

- Other pollutants found in contaminated waters at wood treatment facilities (e.g., polychlorinated dioxins and furans) also are concentrated in the reject stream based on results of this and other SBP studies. The permeate retains little of these species.

- Other constituents commonly encountered at such sites including colloidal oils and suspended solids are also extensively removed by the membrane process. Removal efficiencies for oil and grease were 93%. Suspended solids were removed to non-detectable levels. These materials did not appear to have an adverse effect on the filtration process.

2. Volume Reduction - The system effectively concentrates organic contaminants into a concentrate of much smaller volume.

- The volume of wood preserving waste contaminated waste water was reduced by over 80%. This means that only 20% of the volume of the feed water would require further treatment to immobilize or destroy the organic contaminants.

- During an extended run of the system, the volume of contaminated waste water was reduced by 96.3%. This represents the maximum volume reduction capability of the unit for the waste stream tested.

3. Operability -The filtration unit operated consistently and reliably over the six day testing period. The unit was easy to operate and maintain.

- The filtration unit operated in a batch mode for six hours each day, for six days, and processed approximately 1,000 gallons of feed per day. Over the six day test period, permeate flux was a relatively constant 0.0085 gallons/min/ft^2 (coefficient of variation < 10%). Based on a total membrane area of 300 ft^2 for the system, the permeate flow rate for the four module filtration unit averaged 2.6 gpm.

- Excessive fouling of the membrane, necessitating frequent cleaning or regeneration, was not encountered. However, the membrane system did exhibit a gradual and controllable fouling which required periodic cleaning.

- The operating cost for the membrane process as used at American Creosote Works is in the range of $220 to $1,740/1,000 gallons, depending on system size. Major conaibutors are labor and residuals disposal. Labor costs decrease significantly as the scale of the process increases.

- Auxiliary equipment that could be needed to support this process is comparable to that which would be needed for other above-ground treatment systems such as oil/water separators and clarifiers for pretreatment, and filters, carbon adsorbers, etc. for effluent polishing as required.

4. Waste Applicability

- With membranes similar to those manufactured for the American Creosote Works site, the system could be well suited for the concentration of polynuclear aromatic hydrocarbons from wastewaters (groundwater. process wastes, lagoon leakage, etc.) found at coke plants, wood preserving sites, and some chemical plants.

- Based on the expected mechanisms of membrane filtration and results from this study, the technology also may be useful for waste waters containing other large molecules such as polychlorinated biphenyls (PCBs) and polychlorinated dioxins and furans, particularly where these are associated with oil or particulate matter. It probably is also highly effective for oils, colloidal solids, and greases.

- According, to the developer, the formed-in-place membrane can be easily modified to conform to waste characteristics and degree of contaminant removal desired. Therefore, the membrane can be tailored to the unique characteristics of the waste stream.

7.3 Discussion of Conclusions

A small scale Filtration Unit with a nominal 5-10 gpm capacity was tested at the American Creosote Works site under the Superfund Innovative Technology Evaluation (SITE) program. Extensive data were collected over six days (six hours each day) of operation to assess (a) the removal of wood preserving wastes from contaminated groundwater at the site; (b) the operational requirements of the system: and (c) the cost of operation. The data from this study serve as the primary basis for the foregoing conclusions.

Additional supporting evidence was provided by SBP in the form of results from other field studies.

A Quality Assurance (QA) program was conducted by SAIC in conjunction with EPA's QA program. including audits and data review along with corrective action procedures and special studies to resolve specific data quality problems. This program is the basis for the high quality of the data derived from the SITE project. Discussion of the QA program and the results of audits, data reviews, and special studies can be found in the Technology Evaluation Report for this project.

Extensive data were collected on primary pollutants (PCP, other phenols, and PAHs) and on secondary pollutants (oil, suspended and dissolved solids, COD, dioxins. and VOC's).

The results of this SITE project demonstrated the ability of the formed-in-place membrane, operating in a cross-flow mode, to minimize fouling, and to remove polynuclear aromatic hydrocarbons from the contaminated feed water. As operated rejection of the PAHs appears to increase with the number of aromatic rings, from 78% for naphthalene to 94+% for the 4-ring PAHs. However, similar correlations appear to exist with molecular weight as well as with the partition coefftcient reflecting hydrophobicity. The permeate, accounting for approximately 80% of the feedwater, contained only about 12% of the predominant PAHs, naphthalene and phenanthrene.

The removal of phenol and methyl phenols was not comparably high under the conditions of the demonstration, with an average rejection of 18%. The concentrations of phenolics in the permeate could present a regulatory problem, depending on the concentrations in the feedwater and the final disposition of the permeate, However, the vendor states that different membranes and tube configurations could resolve this issue.

Secondary constituents, such as oil, suspended solids, and dissolved solids, did not appear to interfere with operation of the process at the concentrations present in the waste water studied during the demonstration. Decreases in chemical oxygen demand (COD), total organic carbon (TOC) and oil and grease (O&G) indicated that the system removes other organic species as well as PAHs, but not necessarily with the same efficiency.

The SBP membrane process would be most applicable to wastewaters containing large molecular weight organic compounds (PAHs, dioxins/furans, polychlorinated oiphenyls. and certain pesticides/herbicides). The system can remove smaller weight molecular compounds (phenols, benzene, toluene, ethylbenzene, xylenes) if larger molecular weight compounds are not abundantly present. Removal of smaller weight molecular compounds can be accomplished by modifying the structure of the formed-in-place membrane. For these applications, the pores of the membrane are reduced, resulting in higher retentions of smaller components as well as a reduction in the flux (throughput) of the system. To compensate for the reduced flux, either additional membrane modules can be added or more time will be required to accomplish the remediation. In either case, the overall cost may be higher.

The SBP system may be most suitable to treating relatively dilute, but toxic, wastestreams in which the percent reduction of contaminants will allow discharge of the permeate without further treatment. This feature makes the unit highly suitable for polishing effluents as part of a multi-technology treatment train. In this system, the primary treatment technology can be utilized to remove the bulk of the contamination, with the filtration unit being used as a final polishing step.

A major attribute of the SBP system is its ability to minimize fouling. SBP effectively controlled excessive fouling, in spite of the problematical nature of the wood preserving waste feed, through a combination of cross-flow operation and membrane cleaning. The membrane cleaning process effectively regenerated the membrane to its original clean permeate flux conditions. This enabled the membrane to be reused, without the necessity to reformulate.

The ability to repeatedly regenerate the flux after the cleaning procedure is a good indication that the formed-in-place membrane is stable and can be used over an extended length of time. In the unlikely event of an irreversible fouling, the membrane can be cost-effectively and easily reformed on-site with a minimum of downtime.

SBP uses a proprietary formed-in-place membrane technology. The membrane is formed on porous sintered stainless steel tubes by depositing microscopic layers of inorganic and polymeric chemicals. The properties of the formed-in-place membrane can be varied by controlling the type of membrane chemicals used, their thickness, and the number of layers. This important feature allows for customization of the membrane system to a wide variety of waste characteristics and clean-up criteria. The formed-in-place membrane can be quickly and economically reformulated in the field to accommodate changes in waste characteristics or treatment requirements.

The formed-in-place membrane is compatible with a wide variety of contaminants often encountered in hazardous wastewater streams. The SBP formed-in-place membrane is stable under most chemical environments and will not degrade even at high contaminant concentrations.

The extent of contaminant reduction required (overall and for individual pollutants) can also be an important factor in system design and operation. This will impact membrane selection, and operational requirements such as the number of cycles necessary to achieve the targeted volume reduction. Generally, as the desired level of volume-reduction increases, the overall quality of the permeate decreases, so a balance must be maintained between throughput and permeate quality. This will also affect the throughput capability (as permeate) for a particularly sized system.

Other factors that could affect the removal of PAHs or other contaminants (e.g., PCP) may include the presence of other organics, oil and grease, suspended solids, and dissolved solids in the feed water. While the levels of such contamination encountered in the demonstration project had no apparent adverse effect, it is unclear how much rejection (of PAHs) was due to molecular size or weight and how much was due to solubility in oil that was rejected and coalesced by the membrane. Additional or alternative mechanisms also may be operative.

SECTION 2

INTRODUCTION

2.7 The SITE Program

The EPA's Office of Solid Waste and Emergency Response (OSWER) and the Office of Research and Development (ORD) established the Superfund Innovative Technology Evaluation (SITE) Program in 1986 to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its sixth year. the SITE Program is helping to provide the treatment technologies necessary to meet new federal and state cleanup standards aimed at permanent, rather than temporary, remedies. The SITE Program is composed of two major elements: the Demonstration program and an Emerging Technologies Program. In addition, the Program includes research on analytical methods that can expedite cleanups at Superfund sites.

The Demonstration Program is designed to provide engineering and cost data on selected technologies. EPA and the developers participating in the program share the cost of demonstrating their innovative systems at chosen sites, usually Superfund sites. Developers are responsible for the operation of their equipment (and related costs). EPA is responsible for sampling, analyzing, and evaluating all test results and comparing these results to claims originally defined by the developer. The result is an assessment of the technology's performance. reliability, and cost. In addition to providing the deveioper with carefully documented information useful in marketing, the information. in conjunction with other data, also will be used to select the most appropriate technologies for the cleanup of other S uperfund sites.

Developers of innovative technologies apply to the Demonstration Program by responding to EPA's annual solicitation. To qualify for the program, a new technology must have a pilot or full scale unit and offer some measurable advantage over existing technologies. Mobile technologies are of particular interest to EPA.

Once EPA has accepted a proposal, EPA and the developer work with the EPA Regional offices and state agencies to identify a site containing wastes suitable for testing the capabilities of the technology. EPA's contractor designs a detailed sampling and analysis plan that will thoroughly evaluate the technology and ensure that the resulting data are reliable. The duration of a demonstration varies from a few days to several months. depending on the type of process and the quantity of waste needed to assess the technology. While meaningfui results can be obtained in a demonstration lasting one week with some technologies, such as the SBP formed-in-place membrane process, others, such as in-situ bioremediation of contaminated soil. may require months. On completion of a demonstration, EPA prepares two reports which are explained in more detail below. Ultimately, the Demonstration Program leads to an analysis of the technology's overall applicability to Superfund problems.

The second principal element of the SITE Program is the Emerging Technologies Program, which fosters the investigation and development of treatment technologies which are still at the laboratory scale. Successful validation of these technologies could lead to the development of systems ready for field demonstration. A third component of me SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative techniques and methods for better characterization of Supetfund sites.

2.2 SITE Program Reports

The results of the SlTE Demonstration Program are incorporated in two basic documents, the Technology Evaluation Report and the Applications Analysis Report. The former provides a comprehensive description of the demonstration and its results. The anticipated audience is engineers responsible for detailed evaluation of the technology for application to other sites and wastes. These technical evaluators will need to understand thoroughly the performance of the technology during the demonstration and the advantages, risks, and costs of the technology for the given application.

The Applications Analysis Report is directed to decision-makers responsible for selecting and implementing specific remedial actions at other sites. This report provides sufficient information to enable them to determine whether the technology merits further consideration as an option in cleaning up specific sites. If the candidate technology described in the Applications Analysis Report appears to meet the needs of the site, more thorough analysis of the technology based on the Technology Evaluation Report and site-specific information from remedial investigations for the site will be made. Thus, me Applications Analysis Report helps in determining whether the specific technology should be considered further as an option for a particular cleanup situation and the Technology Evaluation Report provides the detailed data for such further evaluation.

2.3 Purpose of the Applications Analysis Report

Each SITE demonstration evaluates the performance of a technology while treating a portion of the particular waste at the demonstration site. Additional data from other projects also will be presented where available, although such results often lack the quality control and quality assurance imposed during the SITE evaluation and, consequently, cannot be used with the same confidence.

Usually the waste at other sites being considered for remediation will differ in some way from the waste tested in a demonstration. These differences may affect waste treatability and use of the demonstrated technology at such other sites. Successful demonstration of a technology at one site does not assure that a technology will work equally well at other sites. To the extent possible during the demonstration, the operating range over which the technology performs satisfactorily is established by examining a broad range of wastes and sites. To a limited extent, this report provides an indication of the breadth of applicability of the SBP membrane filtration system by examining not only the demonsuation test data but also data available from other applications of the technology.

To encourage the widespread use of demonstrated technologies, EPA will evaluate the probable applicability of each technology to sites and wastes in addition to those tested, and will study the technology's likely costs in these applications, identifying unique characteristics that make the demonstrated technology either attractive or unattractive. The results of these analyses will be summarized and distributed to potentially interested parties through the Applications Analysis Report.

2.4 Process Description

SBP's membrane technology can be used as an integral part of a remediation system to significantly reduce the volume and toxicity of contaminated wastewater. The technology is particularly suited for the treatment of contaminated groundwater as part of a pump and treat system. The technology reduces risks to human health and the environment by transferring the contaminants to a smaller volume facilitating destruction or detoxification by other technologies.

SBP uses a proprietary formed-in-place membrane technology. The membrane is formed on porous sintered stainless steel tubes by depositing microscopic layers of inorganic and polymeric chemicals. The properties of the formed-in-place membrane can be varied by controlling the type of membrane chemicals used, their thickness, and the number of layers. This important feature allows for customization of the membrane system to a wide variety of waste characteristics and clean-up criteria. The formed-in-place membrane can be quickly and economically reformulated in the field to accommodate changes in waste characteristics or treatment requirements.

Contaminated feedwater is recirculated through the filtration unit until the desired level of volume reduction is attained. The filtration unit generates two process waste streams. A relatively clean stream, called the "permeate", passes through me membrane while a smaller portion of the feedwater. retaining those species that do not pass through the membrane, is retained in a stream called the "concentrate". The permeate stream should be clean enough for disposal as a non-hazardous waste with little or no additional treatment. The concentrate would require further treatment to immobilize or destroy the contaminants.

2.5 Key Contacts

For more information on the demonstration of the SBP Technologies Filtration System for contaminated groundwater, please contact:

1. Vendor concerning the process:

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SECTION 3

TECHNOLOGY APPLICATIONS ANALYSIS

3.1 Introduction

This section of the report addresses the potential applicability of the SBP filtration technology as a means of concentrating organic contaminants in aqueous waste streams. The prime benefit of concentrating contaminants is to minimize costly treatment of the entire wastestream. In addition, by concentrating the organic contaminants into a smaller volume, alternative treatment technologies may be feasible based on technical and/or economic criteria.

The ability of the filtration unit to concentrate organic contamination from aqueous waste streams was demonstrated on a groundwater contaminated with wood preserving wastes (phenolics, PAHs, and PCP). The results from the demonstration, in conjunction with information supplied by the vendor, were used to assess the applicability of the technology for a variety of waste types and site conditions.

The process uses a formed-in-place hyperfiltration membrane on a stainless steel support to separate and concentrate higher molecular weight contaminants. Contaminated groundwater (feed) is pumped through the modules under pressure. A portion of the feed passes through the formed-in-place membrane forming a permeate. The membrane retains certain contaminants resulting in a permeate that is clean relative to the feed. The bulk of the contamination remains in the "concentrate" fraction. The concentrate is recycled through the unit until the desired concentration or level of volume reduction is attained, or the level of contaminants in the recycling concentrate inhibits the filtration process (fouling). The system relies on a technique called "cross-flow filtration" to minimize fouling of the membrane and thus maximize throughput.

The properties of the two process streams (permeate and concentrate) are of particular importance since these characteristics define waste disposal options. The permeate stream should exhibit significant reductions in contamination so as to allow economical discharge to local wastewater ueatment facilities without extensive pretreatment requirements. The concentrate stream should be volumetrically small, relative to the original feed, in order to minimize the volume of waste requiring further treatment prior to disposal. Furthermore, the filtration process should enable the use of additional disposal options for the concentrate (as compared to the raw feed).

The following subsections summarize observations and conclusions drawn from the current study and supporting information. Included in the discussion are factors such as the application of membrane processes for waste water reduction. benefits of the SBP system, other applicable waste waters, site characteristics and constraints, applicability and impact of state and federal environmental regulations, unique handling requirements, and personnel factors. Additional information on the technology, including a process description, vendor claims. a summary of the demonstration test results and case studies of other investigations is provided in the Appendices.

3.2 Mechanisms of Membrane Separations

Membranes are semi-permeable barriers that are used to isolate and separate constituents from a fluid stream. The separation process can be accomplished through a number of physical and chemical properties of the membrane as well as the material being separated. Separation can occur through processes such as size. ionic charge, solubility, and combinations of several processes. Membranes can remove materials ranging from large visible particles to molecular and ionic chemical species. Membrane materials are diverse and can consist of synthetic polymers, natural fabrics, porous metals, porous ceramics. or liquids. The surface of the membrane can be chemically or biologically altered to perform separations on specific chemical compounds. The interaction of the components of the fluid stream with the membrane is the mechanism controlling the outcome of the separation process.

There are two basic modes of membrane separation. In dead-end filtration specific species are trapped within the matrix of the membrane material. The membrane "filters-out" these species producing a relatively clean effluent. In dead-end filtration the components that are trapped are usually not recovered and remain within the membrane matrix. In addition, the membrane eventually becomes plugged necessitating the replacement of the membrane. Dead-end filtration is principally utilized to purify a fluid in applications where the removed species is relatively dilute.

In cross-flow filtration the fluid stream is directed parallel to the surface of the membrane. This action inhibits the accumulation of components within the matrix of the membrane. The cross-flow action of the fluid keeps the surface of the membrane clean allowing for the passage of species smaller than the pores of the membrane. Cross-flow filtration produces two effluent streams. The permeate is the stream that passes through the membrane and is relatively depleted in species larger than the pore size of the membrane. The concentrate is the cross-flow stream that contains the larger species that are unable to pass through the membrane and accumulate. The concentrate can he recycled allowing for progressive concentration of species over time. Due to the ability of the cross-flow system to concentrate components from the feed stream, it is commonly used as a method to separate and recover these components. Furthermore, the cross-flow action minimizes plugging of the membrane (fouling) by constantly sweeping the membrane's surface. This cleaning action extends the life of the membrane and minimizes degradation of flow through the membrane.

Membrane systems have many applications for the pre-treatment and treatment of hazardous wastes. Membrane separation is a volume reduction technology. This technology can separate and concentrate specific contaminants from a waste stream. resulting in a significant reduction in the volume of waste requiring treatment. The concentrated contaminants can then be destroyed or rendered non-toxic. The utility of a membrane based technology is based on its ability to reduce the volume of waste by removing contaminants from the feed stream and producing an effluent stream that would require little or no further treatment. The greater the volume reduction, the more effective the technology is in reducing ultimate disposal costs. However, there is a balance between the magnitude of the volume reduction, the quality of the effluent stream. and the size and operation of the unit. A higher volume reduction would require additional recycling, reducing the overall flow through the system. In addition, higher levels of contaminant removal will usually result in lower fluxes through the membrane requiring either more membrane area or longer processing time. The balance between throughput and effluent quality is dictated by clean-up standards and treatment costs. This balance will impact such factors as the size and type of the equipment, mode of operation. time required for remediation, treatment requirements for the permeate, and ultimate disposal mechanism for the concentrated contaminants.

3.3 Applications of Membrane Processes for the Treatment of Hazardous Wastes

Membrane processes have many applications in the treatment of contaminated waste streams. The most common applications involve the removal and concenuation of organic and inorganic contaminants from liquid waste streams. The waste streams can originate from industrial processes, contaminated groundwater. contaminated surface water bodies. or as by-products of other treatment processes.

Membrane and filtration processes have historically been utilized for the treatment and purification of drinking water. For this application, filtration is used to remove a wide variety of constituents, ranging from visible particulates (sand filters) to ionic species (reverse osmosis). From these conventional applications, new uses of membrane separations have recently been applied to the treatment of hazardous waste streams.

Membranes can be used to separate and concentrate organic contaminants from waste streams. In these applications, the organic contaminants are removed based on their size (molecular weight) or polarity. Size separations rely on membranes with specific pore size distributions. The smaller the pores, the greater will be the removal of small molecular weight compounds. However, as the membrane's pore size decreases, the flux (flow per unit membrane area) also decreases impacting the overall economics and efficiency of the process. The polarity of an organic constituent is a measure of it's ability to ionize in solution. Examples of polar molecules are water, alcohols, and compounds with hydroxyl (e.g. phenols) and carboxyl groups (e.g. organic acids). Aliphatic hydrocarbons and polynuclear aromatic hydrocarbons are examples on non-polar organic molecules. The chemical characteristics of the membrane can be used to separate non-polar constituents in a waste stream from polar constituents. For example, a membrane whose surface is hydrophilic will allow passage of polar components while retaining the non-polar components. These membranes can be used to separate dissolved and emulsified oils from aqueous waste streams.

Inorganic contaminants, such as salts and heavy metals, can be removed and concentrated from waste streams by membrane processes. Suspended inorganics can be easily removed through the use of microfiltration membranes. These membranes have pore sizes ranging from as low as 0.01 µm to several microns. Dissolved inorganics can be removed either through the use of hyperfiltration (reverse osmosis) membranes, or by precipitation followed by microfiltration. Conventional reverse osmosis membranes may require extensive prefiltration to avoid fouling, and therefore can only be used on relatively clean feed solutions. Chemical precipitation, followed by microfiltration, allows for the use of microfilters which exhibit higher fluxes and are not as sensitive to fouling.

Membrane processes can be helpful in solving many remediation problems at hazardous waste sites.

Contaminated Groundwater

Containment and/or remediation of contaminated aquifers typically utilizes pump and treat technologies to control contaminant plume migration and ultimately restore the quality of the groundwater. The recovered groundwater usually requires treatment prior to discharge. Treatment alternatives for the recovered groundwater are dependent on the nature and extent of the contamination. Membrane systems can be effectively used to significantly reduce the quantity of groundwater requiring costly treatment

The contaminants of concern can be isolated and concentrated into a reduced volume which can be more easily handled. Another potential benefit of the concentration process is that additional destructive treatment alternatives may become feasible. For example, the concentration of hydrocarbons from a contaminated groundwater can produce a reduced volume waste with a high BTU value allowing for fuel blending as a disposal alternative. This not only reduces the quantity of groundwater that must be treated, but also produces a more easily treatable final waste product. As another example, heavy metals can be concentrated from an aqueous stream by membrane processes and immobilized by solidification/stabilization technologies.

Membrane processes can be potentially used to recover organic and inorganic constituents for recycle/reuse. In these applications, the separation scheme must be developed to produce a high quality concentrate.

Membrane processes can be applied to the removal of many organic contaminants from waste streams. Organic contaminants that can be removed include petroleum derived hydrocarbons (benzene, toluene, ethylbenzene, xylenes), polynuclear aromatic hydrocarbons, PCBs, dioxins/furans, pesticides, and chlorinated hydrocarbons. Generally, membrane process are more easily applied to removing larger molecular weight, non-polar organic components because larger pored membranes can be utilized and surface chemistry interactions can augment size separations.

Removal of hazardous inorganic species from contaminated groundwater requires a detailed knowledge of the water chemistry in order to optimize the separation. In many cases, addition of precipitating chemicals must be added in order to induce particulate formation. Furthermore, groundwater containing high concentrations of innocuous inorganic constituents such as iron and divalent cations (egs. potassium and calcium) may compete with and interfere with the removal of toxic heavy metals. Conventional reverse osmosis membranes are fragile and must be protected from the corrosive nature of many highly contaminated aquifers.

Integration With Other Technologies

Membrane processes are particularly amenable to integration with other remedial technologies enabling applications to additional waste matrices. Ease of integration is facilitated by the modular and scalable properties of membrane systems. These systems can be readily integrated with other remedial process equipment to enhance the effectiveness and economy of these systems.

Membrane processes can be used as a final polishing tool for remedial technologies involving discharge of process water. In this capacity, the membrane system is utilized to remove contaminants from a relatively dilute waste stream. The benefit of using this polishing step is to avoid costly overdesign of the primary remedial technology. For example, a membrane system can be impiemented as a final polishing step on a bioreactor. The bioreactor can be designed to cost-effectively treat the bulk of the organic contamination, while the polishing membrane can be designed to treat the aqueous phase prior to discharge.

Membrane processes can be used as a pie-treatment step for other remedial technologies. The purpose of the pre-treatment would be to concentrate the contaminants to a level that is amenable for specific remedial technologies. For example, organic contaminants in dilute aqueous streams (e.g. groundwater, leachate) can be concentrated to a level that could support an efficient biomass for bioremediation technologies.

Membranes can be integrated with remedial technologies as a component in the process. For example, membranes can be used to recycle and recover extraction fluids used to concentrate organic and inorganic contaminants in soil extraction technologies.

3.4 Features of SEP's Hyperfiltration System

The SBP Hypetliltration system has several unique features which provides advantages over conventional membrane processes in wastewater treatment applications. The demonstration was designed to evaluate these features under actual remediation conditions.

Formed-In-Place Membrane

SBP uses a proprietary formed-in-place membrane technology. The membrane is formed on porous sintered stainless steel tubes by depositing microscopic layers of inorganic and polymeric chemicals. The properties of the formed-in-place membrane can be varied by controiling the type of membrane chemicals used, their thickness, and the number of layers. This important feature allows for customization of the membrane system to a wide variety of waste characteristics and clean-up criteria. The formed-in-place membrane can be quickly and economically reformulated in the field to accommodate changes in waste characteristics or treatment requirements.

Conventional membranes rely on rigid polymeric, ceramic, or porous stainless steel membranes. These membranes are available in discrete pore sizes and cannot be customized to the characteristics of the feed. Furthermore, once installed on-site it is difficult and costly to modify their separation properties in response to variable feed characteristics.

The formed-in-place membrane is compatible with a wide variety of contaminants often encountered in hazardous wastewaterstreams. Many conventional reverse osmosis membranes are made from materials such as cellulose acetate and exhibit poor compatibility with reactive substances often encountered in hazardous wastes. These conventional membranes will degrade and become inoperative when challenged with many organic compounds. The compatibility problem becomes more critical as the level of concentration increases. The SBP formed-in-place membrane is stable under most chemical environments and will not degrade even at high contaminant concentrations.

Fouling Control

A major limitation of many membrane systems is their propensity to irreversibly foul. Fouling is the uncontrolled build-up of materials on the surface of the membrane. Fouling leads to a loss of flux and eventually results in cessation of flow. If a membrane fouls, it must be cleaned in order to restore flux. If cleaning is unsuccessful, then the membrane is replaced.

SBP utilizes a cross-flow filtration mechanism to continuously clean the surface of the membrane, hence minimizing fouling. In this mode, the feed stream is directed parallel to the membrane's surface resulting in a cleaning action which minimizes the buildup of materials on the membrane's surface.

Since all membranes eventually foul, a cleaning cycle is necessary to restore flux and operability. Many membrane systems have limited abilities to be regenerated due to restrictions in the choice of cleaning chemicals. The SBP formed-in-place membrane is compatible with a wide range of chemical cleaning methods, enabling in-place regeneration of flux. In situations where the membrane becomes irreversibly fouled, the formed-in-place membrane can be stripped and reformulated on-site.

3.5 Demonstration Results

The results of the demonstration test program at the American Creosote Works site provides information relevant to the application of SBP's technology to other waste types and sites.

SBP's membrane technology can be used as an integral part of a remediation system to significantly reduce the volume and toxicity of contaminated wastewater. The technology is particularly suited for the treatment of contaminated groundwater as part of a pump and treat system. The technology reduces risks to human health and the environment by transferring the contaminants to a smaller volume facilitating destruction or detoxification by other technologies.

The system is simple to operate, reliable and requires a minimum of operator attention or maintenance once the membrane has been formed. The stability of the system makes it particularly suitable for long-term use as is necessary for extended pump and treat remedial programs.

The demonstration at the American Creosote Works was designed to evaluate the two most critical process parameters for membrane systems; volume reduction and contaminant reduction. A summary of the demonstration results for these critical processes parameters are presented below. A discussion of the demonstration results and process performance, as they relate to applicability to other wastes and sites, follows in the subsequent chapter.

Volume Reduction

- The claim that the system can be operated to recover 80% of the feedwater volume as permeate was achieved. Average water recovery (volume reduction) for the first five runs was 83%. The volume reduction for the extended run (day six) was 96%, and represents the maximum volume reduction capability of the unit for the waste stream tested.

Contaminant Reduction

- The process did not achieve the developer's claim of 90% overall removal of the semivolatiles present in the feedwater (on the average, a 74% reduction was achieved). However, the process does effectively remove polynuclear aromatic hydrocarbons from the feedwater and place them in the concentrate. Overall, removal of polynuclear aromatic hydrocarbons averaged 92%. Removals of individual PAHs range from 78% to well over 94% for individual two, three, and four ring PAHs.

- Other high molecular weight pollutants, such as oils and dioxins, are also rejected from the permeate with high efficiency (93% for oils and >99% for dioxins). However, removal of low molecular weight phenols is much less effective, with values between 15 and 21%.

- Depending on how a system is used, i.e.. level of volume reduction and quality of permeate, operating plus capital cost could be as low as $200/1,000 gallons. Capital cost for an averaged size system is approximately $300,000.

3.6 Discussion of Demonstration Results and Applications

The results and observations from the SITE demonstration, coupled with information supplied from the vendor, is used to discuss the applicability of SBP's membrane technology to the treatment of organic contaminated wastewater. The SITE demonstration was designed to evaluate the innovative features of SBP's process as a volume reduction technology.

The SITE demonstration took place at the American Creosote Works in Pensacola, Florida and utilized groundwater contaminated with creosote and pentachlorophenol. Creosote was chosen as a testing material for two reasons.

1. Creosote is a complex mixture of over 250 individual compounds, dominated by polynuclear aromatic hydrocarbons and phenolics, and exhibits a wide range of chemical and physical properties. The wide molecular weight distribution of the organic contaminanta is an excellent challenge material for a membrane process, allowing for analysis of removal efficiencies over a wide range of feed characteristics.

2. Wood preserving waste contaminated aquifers represent a significant and widespread environmental problem. Results from this demonstration could be directly applicable to other wood preserving waste sites.

A pumping well recovered the creosote and PCP contaminated groundwater from the site. The groundwater. which contained aqueous and dense free product fractions. was allowed to settle and the aqueous phase retained for the study. The aqueous phase was diluted with carbon-treated potable water in order to adjust the concentration of the semivolatiles in the feed to fully test the concentrating capabilities of the tiltration unit.

Contaminant Reduction

The utility of a membrane system is its ability to remove contaminants from a wastewater stream and concentrate them into a reduced volume. The contaminant reduction is the percent decrease in specific contaminants from the feed to the permeate (discharge). The higher the percent contaminant reduction, the more effective is the membrane at removing contaminants from the waste stream.

It is important to note that the applicability of the technology cannot be made solely on the percent contaminant reduction. Since contamination is reduced as a percentage of the concentration in the feed, the quality of the permeate is dependent on feed concentrations. In order to assess applicability. the predicted quality of the permeate can be estimated by calculating contaminant reductions from the feed. The estimated permeate quality can then be compared to site specific discharge standards.

For the demonstration at the ACW site, the total concentrations of semivolatile contaminants for each run are summarized in Table 1 for the feedwater and permeate. The system was evaluated by comparing the total concentrations of these compounds in the feedwater against the permeate. Over the six day period. an average overall rejection of 74% was achieved. Thus, starting with a feedwater containing on the average 90 mg/L of total designated semivolatile components. the cornposited permeate, accounting for 80% of the original feedwater volume, contained on the average 23 mg/L. This did not meet the vendor's claim for 90% removal, largely because of the noted inefficiency with phenolics. This is not totally unexpected since the membrane, as formulated, was not expected to remove species with molecular weights less than 200.

TABLE 1. Feed and Permeate Semivolatiles - Total Concentrations and Contaminant Reductions

	Total Semivolatile Concentrations mg/L		
	Feed	Permeate	Contaminant Reduction (%)
Run1	104	18	83
Run2	91	24	74
Run3	92	26	72
Run4	104	22	79
Run5	85	23	73
Run6	60	24	60

A summary of the average concentrations for individual semivolatile compounds in the feed and permeate, along with the associated rejections, for the six day demonstration are presented in Table 2. The results of the demonstration indicated that the pilot unit was capable of removing over 94% of some PAHs but only 15 - 21% of the phenoiics. The permeate generated during the process was discharged directly to the local POTW.

These results indicate. as expected, that the membrane is more effective in removing larger molecular weight components (PAHs) than the smaller molecular weight molecules (phenoiics). With a complex feed such as creosote, it is difficult to achieve high reductions of all components and at the same time deliver adequate throughput. In this application, the membrane was formulated to maximize reduction of the more toxic poiynuclear aromatic hydrocarbons. Passage of the phenolic compounds into the permeate did not pose a significant disposal problem since the local POTW could accept the phenols in their treatment system. At other sites, careful attention should be made to local discharge requirements and available treatment facilities.

The SBP membrane process would be most applicable to wastewaters containing large molecular weight organic compounds (PAHs, dioxins/furans, polychlorinated biphenyls, and certain pesticides/herbicides). The system can remove smaller weight molecular compounds (phenols, benzene, toluene, ethylbenzene, xylenes) if larger molecular weight compounds are not abundantly present. Removal of smaller weight molecular compounds can be accomplished by modifying the structure of the formed-in-place membrane. For these applications the pores of the membrane are reduced, resulting in higher retentions of smaller components as well as a reduction in the flux (throughput) of the system. To compensate for the reduced flux, either additional membrane modules can be added or more time will be required to accomplish the remediation. In either case, the overall cost may be higher.

The SBP system may be most suitable to treating relatively dilute, but toxic, wastestreams in which the percent reduction of contaminants will allow discharge of the permeate without further treatment. This feature makes the unit highly suitable for polishing effluents as part of a multi-technology treatment tram. In this system, the primary treatment technology can be utilized to remove the bulk of the contamination, with the filtration unit being used as a final polishing step.

If the concentration of contaminants in the permeate does not meet clean-up requirements, then the permeate can be recycled back through the membrane to achieve the targeted effluent quality. Recycling of the permeate has the disadvantage of requiring additional membrane modules, or additional time, both of which increase treatment costs.

A number of mechanisms could explain the contaminant reduction results, including rejection by the membrane on the basis of molecular weight or molecular size, rejection and coalescence of dispersed oil in which specific components are soluble, or even rejection simply by adsorption of the PAHs on inert suspended solids.

Examination of the results for the conventional parameters tested in the feed and permeate (Table 3) provides some insight into the separation mechanism. High concentrations of oil and grease found in the feedwater suggests that considerable oil remained in a dispersed or colloidal form. This oil would be removed by a membrane with ultrafiltration or hyperfiltration characteristics. Since the PAHs are more soluble in oil than in water, concurrent removal of the PAHs entrained within the oil may have occurred. The phenols with relatively high solubility in water are, also as expected, removed more poorly. This also is reflected in the poor rejections calculated for TOC and COD. Other contaminants, not quantified by the semivolatile analysis, also may contribute to the high TOC and COD in the permeate.

TABLE 2. Individual Semivolatile Concentrations and Rejections (average of six daily runs)

ANALYTE	FEED (mg/L)	PERMEATE (mg/L)	REJECTION (%)
Phenol	4.90	3.66	20.6
2-Methyl phenol	2.31	1.93	16.5
4-Methyl phenol	6.92	5.75	16.9
2,4-Dimethyl phenol	1.82	1.54	15.4
Benzoic Acid	(1.42)	2.16	a
Pentachlorophenol	(2.42)	1.88	a
Naphthalene	12.67	2.87	77.7
2-Methyl Naphthalene	4.52	0.46	89.6
Acenaphthylene	(0.14)	(0.02)	a
Acenaphthene	6.64	0.51	91.7
Dibenzofuran	4.86	0.41	91.6
Fluorene	5.92	0.37	93.6
Phenanthrene	17.06	0.59	96.6
Anthracene	1.96	0.07	36.5
Fluoranthene	7.01	0.10	96.6
Pyrene	4.70	0.05	36.9
Benzo(a)anthracene	1.24	'0.03	>97.6
Chrysene	1.13	'0.03	>97.4
Benzo(b)fluoranthene	(0.46)	'0.03	a
Benzo(k)fluoranthene	(0.43)	'0.03	a
Benzo(a)pyrene	(0.31)	'0.03	a

Values in parentheses represent analytes with estimated values that are above instrument ■ limits but below quantitation limits

' - Analytes not detected are presented by an ', and the values represent one-half the quantitation limit.

a - Individual rejections not calculated due to estimated values.

TABLE 3. Conventional Parameters

Analyte	Feed (mq/L)	Permeate (mg/L)	Rejection %
	Average of six runs		
TDS	237	190	20
TSS	34	<4	>88
OIL/GREASE	191	14	94
TOC	121	92	24
COD	379	362	7

Volume Reduction

The utility of a membrane separation system for treating hazardous wastestreams is also dependent on the magnitude of volume reduction. The volume reduction is a measure of the percent of the feed water that can be generated as cleaner permeate. The higher the volume reduction, the greater the potential utility of the membrane system. Volume reduction cannot be solely used as an indicator of membrane performance. The quality of the permeate must also be considered when evaluating the applicability of the technology. A high volume reduction with low permeate quality is not acceptable since the permeate will not be dischargeable and will require further treatment. When designing a membrane separation system, volume reduction and permeate quality must be balanced in order to develop a cost-effective treatment meeting site-specific clean-up criteria.

For the six-day demonstration at the American Creosote Works an 80% volume reduction was achieved each day. This level of volume reduction was set as a target prior to the demonstration and was easily attained. The level of volume reduction was achieved by continuously recirculating the concentrate through the system. On the last day of operation the process was allowed to run until the unit could no longer function, representing the maximum volume reduction for that feed. The maximum volume reduction was 96%.

The relationship between volume reduction and permeate quality is exemplified by results from the demonstration. During the six day demonstration, grab samples of the permeate stream were collected at the beginning, middle. and end of each run. The purpose of these samples is to document changes in permeate quality during the course of the batch filtration. The analysis of the data reveals an increase in total semivolatile content of the permeate from the beginning to the end of each run. Six day average permeate concentrations of total semivolatiles were 19.24

mg/L at the beginning of the run, 24.17 mg/L in the middle, and 29.95 mg/L at the end of the run. In addition, on day six, when the unit was allowed to run to a maximal volume reduction of 96%, the final permeate semivolatile concentration was 47.25 mg/L.

These changes in permeate quality during the filtration are due to increasing semivolatile contents of the recirculating concentrate. As the batch filtration proceeds, the surface of the membrane is challenged with progressively higher concentration of contaminants. Since the membrane can only reject a certain proportion of the feed stream, the concentration of contamination in the permeate will increase.

When applying a membrane solution to a wastewater problem it is crucial to evaluate the balance between permeate quality and volume reduction. Maximizing volume reduction is important since it impacts economics by minimizing the volume of wastewater requiring treatment. However, the quality of the discharged water is critical and must be maintained during the filtration process. Treatability testing is necessary to determine the optimal balance between permeate quality and volume reduction.

Fouling Control

Fouling is the loss of flux due to the buildup of components on the surface of the membrane. All membranes exhibit some degree of fouling and eventually require cleaning to restore flux. Many membranes foul readily and are not amenable to cleaning for flux restoration. If flux cannot be restored, then the membrane must be replaced resulting in considerable expense and downtime.

A major attribute of the SBP system is its ability to minimize fouling. SBP effectively controlled excessive fouling, in spite of the problematical nature of the wood preserving waste feed, through a combination of cross-flow operation and membrane cleaning. Flux and pressure data collected during the demonstration indicated gradual and slight fouling of the membrane. This slight fouling was reversed after each two-run cycle by a membrane cleaning procedure. Analysis of the washwaters from the cleaning process indicated that approximately 8% of the mass of semivolatiles remained in the system and were removed during the washing process. The membrane cleaning process effectively regenerated the membrane to its original clean permeate flux conditions. This enabled the membrane to be reused, without the necessity to reformulate.

The ability to repeatedly regenerate the flux after the cleaning procedure is a good indication that the formed-in-place membrane is stable and can be used over an extended length of time. In the unlikely event of an irreversible fouling, the membrane can be cost-effectively and easily reformed on-site with a minimum of downtime.

Operational Reliability and Implementability

Operational reliability and implementability is important in deciding the applicability of the technology to other wastestreams and sites. Experiences from the Demonstration represent the most extensive compilation of operability data for the SBP system at a hazardous waste site.

The system proved to be quite stable and required a minimum of attention over the six days of study. System performance was relatively constant during the six day test. With feed concentrations of total semivolatiles ranging from 60.4 to 103.8 mg/L, the percent rejection averaged 74%., with a narrow standard deviation of 7.5. SBP Technologies was able to reproducibly achieve targeted volume reductions of 80%. Other than adjustment of the pressure to maintain flux and the cleaning of the unit, which consumed about 2 hours every other day, there was little need for an operator. In a commercial installation some means of on-line monitoring (eg.. changes in pressure, contaminant concentration, etc.) could alert the operator to out-of-specification operation or out-of-compliance permeate. It is estimated that the unit could be run by two operators (health and safety requirements). Additional units could easily be operated by the existing personnel.

Other than the cleaning operation every other day, there was no downtime during the demonstration. With the exception of the pump there are no moving parts to break down or require service.

The process equipment and supplies for the system are commercially available. This includes the filtration modules. membrane forming chemicals, pumps. tanks. process controls, gauges, and flowmeters.

The membrane formation procedure requires a high level of expertise and may require trial and error methods to achieve the desired separation characteristics. However, these are not obstacles to implementation since the process is inexpensive and rapid.

The process is easily scalable and can be modified by adding or deleting modules in response to processing requirements.

The addition of modules does not affect the mode of operation, except for additional support equipment (pumps, tanks, plumbing).

Based on the observations from the demonstration, it is feasible that the membrane system can be effectively and reliably operated over an extended time period as would be necessary for pump and treat remediations.

3.7 Applicable Wastes

While this study of the SBP Hype&ration Unit was limited to a single wastewater, the groundwater available at the American Creosote Works site, the results of the study along with other results provided by the vendor suggest that the technology would have applicability to other contaminated groundwaters and process waters. The developer believes the system can treat wastes with 100 to 500 mg/L of COD where the molecular weight of the contaminants to be concentrated are over about 200. However, the characteristics of the membrane can be modified to treat smaller molecular weight compounds. More dilute feedwater will necessitate additional cycles to achieve the desired concentrations in permeate and concentrate streams. However, the more dilute feedwaters would also allow for higher fluxes. Other than having an impact on cost and throughput, this should not adversely affect operation.

Wastestreams exceeding the target concentration range (100 - 500 mg/L COD) would require reduced cycling to achieve the required level of concentration. The effect of elevated feedwater concentrations on the rejection of individual components may also need to be determined by laboratory resting. Data from this study indicates ,a reduction in permeate quality as the concentration of the feed increases.

Based on the results obtained at the ACW site with the membrane formulated to treat wood preserving wastes, the composition of the groundwater can determine the applicability of the system. Groundwater rich in PAHs would probably be suitable while feedwater where smaller molecular weight compounds are a major pollutant would probably not be appropriate. However. the vendor claims that membranes could be formulated to separate small molecular weight species (BTEX) such as those found in hydrocarbon contaminated wastewaters (see Appendix B). Since the former wood-preserving facility had not used the newer chromated copper arsenate preservative, no information on the removal of metallic contaminants was obtained.

Cross-flow filtration using the formed-in-place membrane may also be applicable to other wastestreams containing different high molecular weight organic contaminants. This might include polychlorinated biphenyls (PCBs) as might be encountered from a spill from a PCB transformer leak, particularly since the same preferential solubility in oil noted earlier may prevail. On the same basis, the system may be useful for separating other emulsified or dispersed organics which do not lend themselves to simple physical phase separation. The system is also well suited to significantly reduce the concentration of dioxins and furans in wastewater. Reduction of dioxins/furans encountered in this demonstration was greater than 99.9%.

The developer believes the membrane can be customized to achieve different rejection characteristics that could be applied to a wide range of contaminants (see Appendix B).

3.8 Site Characteristics

The pilot-plant unit used in the demonstration program required a level base large enough to accommodate the unit, and storage tanks for the feed, concentrate, and washwater. As was used for the SITE demonstration, a covered concrete pad is recommended to protect the equipment from the elements as well as contain the accidental release of contaminated materials.

Clean water and power were the only utilities needed. If necessary, the relativeiy small amount of clean water needed for washing of the membrane could be trucked in and power for the compressor could be provided by an on-site generator. While it was not studied, it may be practical to use permeate for washing. Where the unit was being used to treat groundwater, power also would have to be provided for the well pumps.

Acquisition of groundwater for the unit may require the development of an extraction well network. consisting of the appropriate pumps, regulators, and plumbing.

Permit requirements and the mode in which the filtration unit is operated may make it necessary to have additional space for storage tanks for equalization of the permeate until analyses can confirm acceptability for the POTW or surface water body discharge.

3.9 Environmental Regulation Requirements

Anticipating that the SBP system would be used on groundwater at a contaminated site, concerns would be local well-drilling requirements and storage of pumped groundwater. Depending on the size of these wells, their productivity, and the capacity of the treatment system being installed, storage tanks may be needed as a reservoir, to separate free oil (if needed), and to provide equalization of feed and permeate. Such tanks must meet regulatory requirements for design (permits, materials, etc.), consistent with their size and placement.

Discharge of the permeate to a POTW would certainly require a NPDES/pretreatment permit (or state equivalent). Depending on the operational mode used, the permit may require continuous monitoring. This would prevent averaging of high concentrations of contaminants in the permeate late in a cycle with the low concentrations during the early stages. Permits that allow equalization or cornpositing of permeate during a cycle would be less restrictive.

The reject stream (concentrate) from the filtration process will contain elevated concentrations of the higher molecular weight contaminants. In the case *of* creosote, these will largely be PAHs. several of which are considered carcinogenic. Consequently, the concentrate will probably have to be considered hazardous and any subsequent treatment could require that the facility have a "Treatment, Storage, and Disposal" permit.

The washwater generated will also need to be addressed. Since it contains me same PAH (and phenolic) constituents, it too will be hazardous. Because of the chemicals added, recycle into the concentrate or disposal with the concentrate may not be possible unless pretreated.

Additional regulations approved in 1991 under the "Third third" rule of the Resource Conservation and Recovery Act of 1976 (RCRA) and the Hazardous and Solid Waste Amendments of 1984 (HSWA) lists certain wood preserving wastes as hazardous (F032, F034. FO35). Required treatment for these wastes has not yet been defined. In addition, RCRA and HSWA could also designate the permeate, the concentrate, the washwater. and any other wastes subsequently generated as a residual from a hazardous waste under the "derived from regulation". Consequently, these streams also would be considered hazardous. A recent court decision leaves the interpretation of this matter unclear at this time.

Under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and the Superfund Amendments and Reauthorization Act of 1986 (SARA), EPA is responsible for determining the methods and criteria for the removal of contamination from a Superfund site. The utility and cost-effectiveness of the SBP filtration unit as *one* segment of a treatment system would, to an extent, be dependent on the final level of remediation deemed appropriate and necessary at a particular site by EPA. However, since the use of remedial actions by treatment that ". ..permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances" is strongly recommended (Section 121 of SARA). inclusion of the SBP filtration system could be attractive as part of the remediation for a site contaminated with wood preserving chemicals.

Chlorinated dioxins/furans are known to be produced during pentachlorophenol manufacture. Limited testing during this demonstration indicated that low concentrations of certain of these materials, particularly the octa isomers, were present in the groundwater and were concentrated in the concentrate. The highly toxic 2.3,7,8-tetrachlorodioxin (TCDD) was not found. Subsequent treatment or disposal of the concentrate would need to address this matter in more detail.

3.10 Materials Handling Requirements

Materials handling requirements for the SBP unit involve 1) the acquisition of feed material for the unit, 2) pretreatment. and 3) residuals (permeate and concentrate) management.

Acquisition of Feed

If the SBP filtration unit is part of a system used to treat groundwater, the first need is a well drilling rig to provide the well(s) from which the feedwater is to be obtained. Once the wells are drilled and developed, each must be equipped with a pump to draw up the necessary feed water. Local well drilling requirements would have to be taken into consideration.

Pretreatment

At some sites pretreatment may be necessary (as it was at this site) to remove free oil and even suspended solids. Since the developer has indicated that the filtration unit is most effective when operating with a feed water having a COD range of 100 - 500 mg/L and is most effective in rejecting materials with molecular weights greater than about 200. pre-testing will be necessary to assure that these requirements are consistently met. If the vendor's system is provided with relatively clean ground- or process water. no pretreatment may be necessary.

Permeate Disposal Options

The applicability of this membrane technology at a site is dependent on the quality of the permeate, site-specific discharge criteria, and the availability and accessibility of local public or industrial wastewater treatment facilities. It is important to conduct a treatability study to assess the quality of the permeate and to determine options for disposal. If the permeate quality is not amenable for discharge to surface waters or local treatment facilities, then the technology is not applicable to the site.

Prior to the initiation of the demonstration at the ACW site in Pensacola, a limited filterability test was conducted on contaminated groundwater to determine if the permeate would be accepted by the local POTW. The permeate was subjected to biological testing *(Ceriodaphnia)* and chemical analysis to determine its suitability for discharge. The permeate passed the local POTW's criteria and was directly discharged to a local sewer hook-up.

Several additional options are available for permeate disposal and are dependent on waste and site conditions, as well as local discharge regulations and treatment options.

- The permeate quality may meet local standards for direct discharge to local surface water bodies. This would occur only if the level of contaminants in the permeate was extremely low and meeting the strict requirements for surface discharge.

- The permeate could be treated on-site with additional treatment equipment to reduce contaminant levels for either surface water body discharge or sewer discharge. Treatment, such as with activated carbon, may be necessary to reduce contamination to acceptable limits. The use of additional treatment equipment will increase remediation costs and may necessitate additional disposal requirements.

- The permeate may be recycled through the filtration unit, or processed through a smaller unit, to further reduce contaminants for surface water body or sewer discharge. The secondary filtration unit may have different membrane characteristics as the primary unit to remove species that were not retained or require greater reductions. This option would also add to the overall cost of the remediation since additional equipment and time would be required.

- If it is not feasible to reduce contaminant concentrations to levels adequate for on-site discharge, and if no local sewer hook-up is accessible, then it may be necessary to transport the permeate by tanker truck to an acceptable treatment facility. This option would only be economically feasible if the membrane process drastically reduced the volume of a wastestream that is very costly or difficult to treat (e.g. dioxin contaminated wastewater).

Concentrate Disposal Options

The SBP membrane process minimizes the quantity of waste requiring extensive treatment by concenuating the contaminants into a reduced volume while producing a cleaner permeate for discharge. Since the contaminants are not desuoyed by the process it is necessary to consider disposal options for the reduced volume concentrate stream. If the treatment options for the concentrate stream do not reduce overall treatment costs or provide a reduction in risk to human health and the environment. then the membrane system is not a feasible remedial technology.

Optimally, a disposal option that can permanently destroy or immobilize the contaminants in the concentrate stream on-site is preferable to off-site transportation and disposal.

A portion of the concentrate from the SITE demonstration was utilized by SBP to develop a bioremediation technology that could be coupled co the filtration unit to produce a treatment system for on-site destruction of a major portion of the waste. The system uses a two-stage bioreactor containing several naturally occurring strains of soil bacteria capable of mediating PAH and PCP contamination. SBP uses the membrane system' to reduce the quantity of wastewater input into the bioreactors and to optimize contaminant concentrations to support the biomass. The use of the concentrate as a feed to the bioreactors extends the utility of this volume limiting technology by reducing the volume of wastewater that must be processed, therefore reducing equipment costs and site space requirements. The results from SBP's bioremediation studies are presented in Appendix B.

Additional disposal options available for the concentrate stream are discussed below.

- The concentration process enhances the calorific value of most organic wastes. This enables the utilization of thermal technologies as a means of destroying the organic contaminants. The feasibility of using and choosing a thermal technology is based on the nature of the organic contaminants. Concentrates from petroleum based contamination could be readily used for fuel blending, while concentrates from other sources (such as wood preserving wastes) would require careful testing to determine selection of the appropriate thermal technology. Thermal destruction could be accomplished on-site (mobile units) or transported off-site.

- Concentrates containing highly toxic constituents, such as PCBs and dioxins/furans. which are not amenable to biodegradation or thermal treatments, can be chemically neutralized by processes such as dechlorination. The neutralized waste could then be disposed of in a conventional manner.

3.71 Personnel Issues

The system requires little attention once operation is underway. Flux must be maintained by manually adjusting pressure. In a larger-scale system, this could be accomplished automatically. Similarly, the transfer of concentrate back to the feed side of the unit would be automated, requiring an operator only to monitor the permeate quality and flux. Washing of the system with clean water every two days required about 2 hours. The frequency of washing can vary with the waste and the operating mode. It is estimated that two operators would be necessary, primarily for health and safety concerns.

In order to assure protection of workers during the remediation. all on-site personnel should have an OSHA 40 hour health and safety training and an annual 8-hour refresher course.

3.72 Potential Community Exposures

Contaminant exposure to the community from the SBP filtration unit is minimal. Potential community exposure may occur during the filtration of volatile organic compounds and can be contained through the implementation of emission control equipment. Potential exposure of contaminants could occur from the accidental discharge of waste and process water from the equipment and well distribution network. This could be minimized by placing all tanks and equipment on containment structures, and utilizing leak detection systems for plumbing.

SECTION 4

ECONOMIC ANALYSIS

4.7 Introduction

The primary purpose of this economic analysis is to estimate costs (excluding profit) for commercial-scale remediation using the SBP filtration unit. With realistic costs and a knowledge of the bases for their determination, it should be possible to estimate the economics for operating similar-sized systems at other sites utilizing scale-up cost formulas. Among such scale-up cost formulas available in the literature for chemical process plant equipment is the "six-tenths rule". The six-tenths rule is an exponential method for estimating capital costs from existing equipment costs. If the cost of a piece of equipment of size or capacity q, is C,, then the cost of a similar piece of equipment of size or capacity q2 can be calculated from:

$$C_2 = C_1(q_2/q_1)^n$$

The value for n in this study was taken as 0.6.

it was assumed that the performance of commercial-scale equipment will be the same as that demonstrated here. This economic analysis is based on assumptions and costs provided by SBP, on results and experiences from this SITE demonstration, and on best engineering judgement as practiced by the authors. The results are presented in such a manner that if the reader disagrees with any of the assumptions made here. other conclusions can be derived irom such other assumptions.

Certain actual or potential costs were omitted because site-specific engineering aspects beyond the scope of this SITE project would be required. Certain functions were assumed to be the obligation of the responsible party or site owner and also were not included in the estimates.

Cost figures provided here are "order-of-magnitude" estimates, generally +50%/-30%, and are representative of charges typically assessed to the client by the vendor, exclusive of profit.

An economic analysis for the remediation of a hypothetical site is presented in sub-section 4.6. This exercise demonstrates the application of the costing information derived from this study to a realistic remediation scenario.

4.2 Conclusions

The total annual cost to operate a 12-module filtration unit ranges between 35 14.180 and $1,209,700, depending on whether effluent treatment and costs are considered, the flow rate through the unit. the cleanup requirements, and the cost of effluent treatment and disposal (if required).

Effluent treatment and disposal costs. if considered, could account for up to 60% of the total cost. Labor can account for up to 40% of total annual costs. Processing costs are more dependent on labor costs than equipment costs.

The cost per 1,000 gallons can be broken down by flow rate as follows (for with and without effluent treatment and disposal costs):

With Effluent Treatment Costs

24 cpm	12 gpm	7.2 gpm
$228-522/1,000 gal	$456-1,044/1,000 gal	$760-1,739/1,000 gal

Without Effluent Treatment Costs

24 gpm	12 gpm	7.2 gpm
$222/1.000 gal	$444/1,000 gal	$739/1,000 gal

As expected, the cost category having the largest impact and variability on total cost was effluent treatment and disposal.

4.3 Issues and Assumptions

This section summarizes the major issues and assumptions used to evaluate the cost of SBP's filtration unit. In general, assumptions are based on information provided by SBP. Certain assumptions were made to account for variable site and waste parameters and will, undoubtedly, have to be refined to reflect site-specific conditions.

System Design and Performance Factors

The SITE demonstration used a four-module filtration unit. For a full-scale remediation, twelve of the same modules instead of four would be used with a portable generator for power, a mix tank, and a single pump and motor.

No assumptions as to the site size or volume of waste to be treated were made. It was assumed that the same unit would be operated at different flow rates for a one year period to obtain the desired results. For example, at the maximum assumed flow rate of 24 gpm, 2.6 million gallons of waste would be treated in 230 days of operation. The annual cost was then divided by the volume of waste that would be treated at a particular flow rate to obtain $/1000 gal.

System Operating Requirements

No assumptions regarding percent rejection or outlet contaminanr concentrations were made. Based on results from the SITE demonstration, a volume reduction of 80% between waste and concentrate was assumed. Costs per 1000 gal. treated were calculated for 24. 12 and 7.2 gpm flow rates: the last corresponding to what was demonstrated in the SITE program. Flow rates, the amount of recycle, and the initial concentration of contaminants may impact costs significantly.

One equipment operator/supervisor and one technician will operate the unit and be on-site eight hours per day, although the system will be operated only seven hours per day, five days per week. The extra hour each day will be used for cleaning and maintaining the unit. A site supervisor will visit the site for approximately two to three days each month for oversight purposes. The two-person crew could operate up to three 12-module systems. If more modules are required, additional manpower would be needed.

Utilization Rates and IMaintenance Schedules

The filtration unit was assumed to be utilized for 230 days out of a possible 365 days a year. Scheduled maintenance was assumed to be performed during normal operating hours.

Financial Assumptions

For the purpose of this analysis, capital equipment costs were amortized over a 7-year period with no salvage value. Interest rates, time-value of money, etc. were not taken into account.

The following is a list of additional assumptions used in this study.

- Access to the site is available.
- Utilities, such as electricity, water, telephone, is easily accessible.
- The permeate stream will not require further treatment.
- A hook-up to the appropriate outlet (sanitary sewer, storm sewer, surface water body) is available on or near the site.
- There are no wastewater pre-treatment requirements.

4.4 Basis for Economic Analysis

In order to compare the cost-effectiveness of technologies in the SITE program, EPA breaks down costs into 12 categories shown in Table 4 using the assumptions already described. The assumptions used for each cost factor are described in more detail beiow.

Site Preparation Costs

The amount of preliminary preparation will depend on the site and is assumed to be performed by the responsible party (or site owner). Site preparation responsibilities include site design and layout. surveys and site logistics, legal searches. access rights and roads. and preparations for support facilities. decontamination facilities, utility connections. and auxiliary buildings. These preparation activities are assumed to be completed in 500 staff hours, At a labor rate of $50/hr. this would equal $25,000.

Other significant costs associated with site preparation include construction of a pad and cover, well drilling as well as buying and installing a groundwater pump, holding tanks, and associated plumbing.

The cost to construct a concrete pad and cover to support the unit and protect the unit from the elements is estimated to be 520,000.

Based on the SITE demonstration, the cost to drill a well was assumed to be $5,000. To achieve the appropriate maximum groundwater extraction rate of 24 gpm. three recovery wells are required, resulting in a cost of approximately $15,000. A 5200 gal. holding tank cost 55,000. Using the "six-tenths rule" to scale-up, the cost of a 10,000 gal. tank for a full-scale remediation was assumed to cost $7,400. Three tanks will be required, resulting in a cost of $22,200. A 1/2 horse-power pump cost $1,035 for the SITE demonstration. A pump for each well would cost a total of $3,105. These additional costs amount to about $40,000.

Therefore, the total site preparation costs for a full-scale remediation would be about 385,000 as shown in Table 4.

Permitting and Regulatorv Costs

Permitting and regulatory costs include actual permit costs, system health/safety monitoring, and analytical protocols. Permitting and regulatory costs can vary greatly because they are very site- and waste-specific. For this cost estimate, permitting and regulatory costs are assumed to be 5% of the equipment costs. This assumption is based on operation at a Superfund site. At RCRA corrective action sites permitting and regulatory costs may be higher and an additional 5% of the equipment cost should be added.

Equipment Costs

Capital equipment costs are for a twelve-module filtration (unit equipped with a portable generator for power, a mix tank, and a single pump and motor ail mounted on a trailer with associated instrumentation, alarms and controls. Variation in equipment costs from site to site should not be significant. However, based on the cleanup requirements and the material being treated. the flow rate through the system may vary dramatically resulting in a wide range of costs per unit treated.

Based on SBP's capital cost estimate of $300,000 for 12 modules, each module would cost $25,000.

As recommended by SBP, equipment costs were amortized over 7 years, with no salvage value at the end of that time period. giving an annual cost of $42,850 as shown in Table 4, without any interest factor.

Startup

SBP's filtration units are mobile and are designed to move from site to site. Transportation costs are only charged to the client for one direction of travel and are usually included with mobilization rather than demobilization. Transportation costs are variable and dependent on site location as well as on applicable oversize/overweight load permits. which vary from state to state. The total cost will depend on how many and which state lines are crossed.

The system is designed to be ready to operate as mounted on the trailer so mobilization costs should be primarily the cost of travel and the time to connect the plumbing and adjust the membranes if necessary. The startup labor cost is included in the total labor cost component and includes relocation and or hiring expenses.

The cost of health monitoring programs has been broken down into two components - OSHA training, estimated at $1,000/person. and medical surveillance, estimated at $500/person for a total cost of $1,500/person. For two people, on-site, this would be $3,000 Depending on the site, however, local authorities may impose specific guidelines for monitoring programs. The stringency and frequency of monitoring required may have significant impact on the project cost. A conservative estimate of $5,000 was assumed as shown in Table 4.

Labor

Labor costs may be broken down into two major categories: salaries and living expenses. SBP estimates that the equipment will require two on-site personnel for operation and maintenance. Due to the extended time requirements for major groundwater restoration projects, SBP plans for hire local operators or relocate personnel to the site. These actions would minimize costs associated with living expenses. A cost of $5,000 is estimated for hiring and or relocation.

TABLE 4 Estimated Costs for SBP Filtration Unit

COST COMPONENT	TOTAL
1. Site Preparation Costs *	$85,000
2. Permitting & Regulatory Costs *	$15,000
3. Equipment Costs (amortized over 7 years)	$42.850
4. startup *	$5,000
5. Labor	$199,080
6. Consumables and Supplies	
Health & Safety Gear	$3,000
Maintenance Supplies	$500
7. Utilities	
Telephone	$6,600
Electricity	$2,000
Sewer/Water	$2,000
8. Effluent Treatment & Disposal (Concentrate)	$13,915-$695,520
9. Residuals/Waste Shipping, Handling and Transport Costs	$46,000
10. Analytical Costs	$60,000
11. Facility Modification, Repair & Replacement	$37,150
12. Demobilization Costs *	$10,000
TOTAL (WITHOUT CONCENTRATE DISPOSAL)	$514,180
TOTAL (WITH CONCENTRATE DISPOSAL)	$528,095-$1,209,700

* one-time costs

Site supervision will require periodic visits from the main or regional office to oversee the progress of the remediation. Per diem is assumed to be $125 per day per person, but may vary widely by location. This rate is a liberal estimate assuming that cleanups may occur in some of the more expensive areas of the country. Travel to and from the site (periodic supervision) is estimated to be $800/visit. One rental car is assumed to be obtained at a rate of $55/day.

Supervisory and administrative staff will consist of an off-site program manager at $75/hour. The SBP filtration system will operate 7 hours per day, 5 days per week. One equipment operator/ supervisor at $50/hr. and one technician at $35/hr. will be on-site 8 hr./day. The labor requirements and rates are detailed in Table 5.

Consumables and Supplies

There are two items to consider under this cost category. The first is health and safety gear which include hard hats, safety glasses, respirators and cartridges. protective clothing, gloves, safety boots, and a photoionization detector monitor, all estimated at $1,500/person. For two people this totals $3,000.

The second item is maintenance supplies (spare parts. oils, greases and other lubricants, etc.) estimated at 1% of the annual amortized capital costs or approximately $500. The cost of membrane forming chemicals are inconsequential (less than $200).

Utilities

Telephone charges are estimated at $500/month plus an additional 10% for fax service or $550/month. This will total $6,600 annually.

Electric usage is estimated by SBP to cost about $10/day or 52.000 annually. Combined sewer and water usage costs is assumed to be about $0.05/1000 L ($0.20 per 1000 gal). Based on the SITE demonstration results, approximately 150 gallons of water were used to flush a 4-module system. Hence a 12-module system was assumed to use three times as much water or about 500 gallons/day. This would cost about $10/day or $2,000 a year as well. This does not consider discharge of permeate, which may incur additional cost.

TABLE 5. SBP Labor Requirements and Rates

Living and Travelling Expanses: 3 days/month for 12 months		
Per Diem $125/day/person x 1 person x 3 days/week x 12 weeks	=	$4,500
Rental Car $55/day x 7 days/week x 52 weeks	=	$1,980
Travel $800/trip x 12 months	=	$9,600
Salaries:		
Program Manager - S75/hr(1) x 8 hr/day x 36 days	=	$21,600
Operator/Supervisor - $50/hr(1) x 8 hr/day x 230 days	=	$92,000
Technician - $35/hr(1) x 8 hr/day x 230 days	=	$64,000
Relocation/Hiring	=	$5,000
Total Labor	**=**	**$199,080**

(1) Includes salary, benefits, and administration/overhead costs but excludes profit.

Effluent Treatment and Disposal

Two process streams are produced by the filtration unit. The permeate is considered to be essentially free of contaminants and is assumed to meet standards appropriate for discharge to a POTW. The concentrate is the reduced-volume portion of the waste stream containing the enriched contaminants. This stream would require further treatment such as biological degradation, incineration, fuel-blending. or some other process appropriate to the type and concentration of contaminants.

The filtration system being evaluated is a volume reduction technology, and as such minimizes the volume of wastewater that would require treatment. For this demonstration, the technology was demonstrated as a method to reduce the volume of wood preserving waste contaminated groundwater. Therefore, treatment of the concentrate is not part of the demonstrated technology and it is not necessarily appropriate to consider costing for this parameter. However, the cost for ueating these effluents can be a substantial factor in designing a remediation program. Based on these issues, overall costing wiil be calculated both with and without effluent treatment and disposal costs.

Two concentrate disposal options are considered in this exercise. The first. bioremediation, is a system developed by SBP Technologies. SBP claims that their biodegradation system provides on-site destruction of PAH contaminants. At this time, the bioremediation system has not been tested as a full-scale process. SBP has provided a projected cost estimate of 10-40 cents per gallon of groundwater contaminated with 100-2000 ppm of PAHs for its full-scale bioremediation system.

The second disposal option for the concentrate is more conventional and was derived from the demonstration. Based on the characteristics of the concentrate, fuel blending is considered a viable disposal option, resulting in a cost of $1.50/gallon.

It is important to note that effluent treatment costs can be very high and are dependent on specific waste and site conditions. Cost estimates for this exercise were based on waste and site characteristics of the demonstration.

Based on the SITE demonstration, the concentrate accounts for 20% by volume of the contaminated groundwater influent stream to the filtration unit. The volume of concentrate generated each day and the range of costs for the three different flow rates suggested by SBP are shown in me following table for the bioremediation system and conventional disposal:

	24gpm	12gpm	7.2gpm
Gallons of Waste Treated/Day	10.060	5,040	3,024
Gallons of Concentrate Generated/Day (assumes 20%)	2.016	1,008	605
Annual Treatment Costs Eioremediation	$46,370 $185,470	$23,169 $92,736	$13,915 $66,660
Annual Treatment Costs Conventional	$696.520	$347,760	$208,725

Effluent treatment and disposal costs can range from $14,000-$700,000 depending on the flow rate through the filtration unit, the mode of treatment, and the cost of treatment in SBP's bioremediation system. The reader is cautioned that SBP's bioremediation process was not investigated here and the effectiveness and costs of this process have not been independently verified.

Residuals/Waste Shipping, Handling and Transport Costs

Waste disposal costs including storage. transportation and treatment costs are assumed to be the obligation of the responsible party (or site owner). it is assumed that residual or solid wastes generated from this process would consist only of contaminated health and safety gear, used materials, etc. Landtilling is the anticipated disposal method for this material and costs were once again derived from the demonstration test. Twenty-six 208 L (55 gal) drums of waste were generated during the demonstration test. This resulted in approximately four drums of solid waste generated each day of operation. However, due to intensive sampling activities during the demonstration, excessive solid waste was generated. Under actual remediation conditions, substantially less waste would be generated. It is estimated that approximately one drum of solid waste would be generated each day of operation. At a disposal cost of $200/drum, the total yearly cost of disposal is estimated to be $46,000.

Analyticai Costs

Standard operating procedures do not require planned sampling and analytical activities. Periodic spot checks may be executed at SBP's discretion to verify that equipment is performing properly and that cleanup criteria are being met, but costs incurred from these actions are not assessed to the client. The client may elect, or may be required by local authorities. to initiate a sampling and analytical program at their own expense.

For this cost analysis, one sample per day for 100 days at $600/sample was assumed to be required by local authorities for monitoring and permitting purposes. This would total approximately $60.000.

Facility Modification Repair and Replacement Costs

Since site preparation costs were assumed to be borne by the responsible patty (or site owner), any modification, repair, or replacement to the site was also assumed to be done by the responsible party (or site owner). The annual cost of repairs and maintenance was estimated by SBP to be $37,150.

Demobilization Costs

Site demobilization will include shutdown of the operation, final decontamination and removal of equipment, site cleanup and restoration, permanent storage costs, and site security. Site demobilization costs will vary depending on whether the treatment operation occurs at a Superfund site or at a RCRA-corrective action site. Demobilization at the latter type of site will require detailed closure and post-closure plans and permits. Demobilization at a Superfund site does not require as extensive post-closure care; for example, 30-year monitoring is not required. This analysis assumed site demobilization costs are limited to the removal of all equipment and facilities from the site. It is estimated that demobilization would take about two weeks and consist primarily of labor charges. Labor costs include salary and living expenses. See "Labor Costs" for information on labor rates. Demobilization is estimated to be $10,000.

Grading or recompaction requirements of the soil will vary depending on the future use of the site and are assumed to be the obligation of the responsible party (or site owner).

4.5 Results

Table 4 shows the total annual cleanup cost to range between $514,180 and $1,209,700. This is based on me assumption that the remediation will take one year. Most applications for this technology will require several years, as in pump-and-treat remedial projects. Since many of the cost factors are one-time, the overall $/gallon cost will go down as the length of the project increases. This is illustrated in the hypothetical site example in the subsequent sub-section. The total cost is also highly dependent on whether concentrate treatment and disposal is considered as part of SBP's technology and responsibility. Concentrate disposal costs can vary widely, and are dependent on technical and regulatory issues related to the waste characteristics. Therefore, if concentrate disposal costs are considered, this category could account for up to 60% of the total costs. Without concentrate disposal, labor is the dominant cost, accounting for approximately 40% of the cost. Equipment costs represent a relatively minor component. Furthermore, the system can be easily scaled-up by adding 12-module units. SBP indicates that up to three 12-module units could be operated without adding additional labor. This would significantly reduce overall treatment costs. The smallest cost categories appear to be those associated with startup, and consumables and supplies. All other cost categories appear to contribute to the total cost about equally (i.e. 5-10%).

The costs per 1,000 gal is dependent on the flow rate. the duration of the project, whether concentrate disposal is being considered, and the cost of effluent treatment and disposal. These ranges are shown below and are based on a one year project.

	24 gpm	12 gpm	7.2 gpm
	Cost par thousand gallons of feed		
With Concentration Disposal	$228 $522	$456 $1,044	$760 $1,739
Without Concentrate Disposal	$222	$444	$739

In all of the above analyses, it should be remembered that costs for 10 out of the 12 cost components were considered. One of the cost components not included here was permitting and regulatory expenses. Additional effluent treatment and disposal for the permeate was assumed to be not required. If these factors are taken into account. costs could significantly increase.

4.6 Remediation of a Hypothetical Site

The economic analysis presented in the preceding sections is based on costs for a one year remedial project. The dominant application of the membrane system is expected to be for groundwater restoration projects. Since groundwater restoration projects can last for ten to twenty years, a hypothetical economic analysis is presented to illustrate the application of the twelve factors in developing a multi-year project.

The hypothetical site contains groundwater contaminated with wood preserving wastes (creosote and PCP) in composition and concentrations similar to the feedwater tested in this demonstration. The remedial plan calls for containment of the groundwater plume, with eventual aquifer restoration. A hypothetical model predicts that approximately two million gallons of groundwater is contaminated, and that 10 pore volumes of groundwater (twenty million gallons) must be treated to restore the aquifer. The groundwater will be extracted from me shallow aquifer (ten to thirty feet below surface) through three wells.

The remedial design will utilize three 12-module filtration units operating at 7.2 gpm/unit for a combined throughput of 2 1.6 gpm. Treatability testing identified that an 80% volume reduction could be achieved, with the permeate meeting discharge standards to me local POTW. The concentrate from the process will be treated on-site by a bioremediation technology similar to SBP's proposed system at a cost of 40 cents/gallon. [see Appendix B.) Based on these conditions. and the economic assumptions previously stated, the remedial time-frame will be ten years. Approximately 2.100.000 gallons of groundwater will be treated each year by the filtration unit, and 420,000 gallons of concentrate by the bioremediation system. The total volume of groundwater *to* be treated for the ten year project is 21 million gallons.

Table 6 is a summary of the costs for each of the twelve criteria as they relate to the conditions set forth in the hypothetical analysis. Based on the requirements of the hypothetical site, the overall treatment costs for the remediation is $300/1,000 gallons. It is important to note the overall $/gallon treatment cost is highly dependent on the length of the remediation project. The longer the project. the lower the $/gallon treatment cost.

TABLE 6. Hypothetical Site Cost Analysis

Ten Year Project (1993 Dollars)

1. Site Preparation	$85,000
2. Permitting and Regulatory	$15,000
3. Equipment	$900,000
4. Startup	55,000
5. Labor	$1,990,800
6. Consumables and Supplies	535,000
7. Utilities	$106,000
8. Effluent Treatment and Disposal	S1,669.248
9. Residuals	$460,000
10. Analytical	$600,000
11. Facility Modification Repair and Replacement	$371,500
12. Demobilization	310.000
	$6,247,548

APPENDIX A

PROCESS DESCRIPTION

A.1 Introduction

This section of the report presents a concise description of the SBP Filtration Unit and its operation at the American Creosote Works site. Factors involved in site and waste selection are presented in this section or in the body of the report to assist engineers and scientists in evaluating the suitability of the process for their own needs at Superfund and other hazardous waste sites. Results of the demonstration, including summaries of analytical test results, are presented in Appendix C.

A.2 Process Description

Membranes are being used increasingly for the removal of dissolved and colloidal contaminants in wastewater streams. Reverse osmosis (hyperfiltration) is well known for its ability to concentrate ionic species while ultrafiltration has found broad utility for the removal of dispersed colloidal oil, non-settlable suspended solids, and larger organic chemical molecules. One of the major problems these processes have faced is the fouling or blinding of the membranes after limited use. Various approaches have been developed in an effort to minimize this deterrent. Cross-flow filtration. where the contaminants are constantly flushed or washed from the membrane surface by the feedwater stream. is one of these approaches. The SBP unit goes further. Rather than a thin polymeric membrane requiring careful handling to avoid perforation, a membrane is created on a stainless steel microfilter support by the introduction of a mixture of carefully selected (and proprietary) chemicals. This approach imparts special properties and allows a degree of customization that may be difficult to achieve with conventional membranes. The resulting "formed-in-place" membrane can be designed to provide properties similar to conventional hyperfiltration or ultrafiltration. as needed for a specific application.

The filtration unit consists of porous sintered stainless steel tubes arranged in a modular, shell-and-tube configuration. Multi-layered inorganic and polymeric "formed-in-place" membranes are coated at microscopic thickness on the inside diameter of the stainless steel tubing by the recirculation of an aqueous slurry of membrane formation chemicals. This "formed-in-place" membrane functionally acts as a hyperfilter. rejecting species with molecular weights as low as 200. in addition, surface chemistry interactions between the membrane matrix and the components in the feed play a role in the separation process. A relatively clean stream, called the "permeate", passes through the membrane while a smaller portion of the feedwater, retaining those species that do not pass through the membrane, is retained in a stream called the "concentrate" or "reject".

For efficient operation of a membrane filtration system. it is necessary to prevent the buildup of dissolved and particulate species on the surface of the membrane and in the membrane pores. The buildup of contaminants, termed "fouling", can lead to a steady decline in the permeate flux (flow per unit area of membrane surface), eventually causing cessation of flow. To prevent or retard excessive fouling, the SBP filtration unit is operated in a cross-flow mode (Figure 1). In cross-flow mode the feed stream is directed parallel to the surface of the membrane. Material larger than the surface porosity is temporarily retarded on the membrane surface and then swept clean by the cross-flow action - if the fluid velocity is sufficient. Meanwhile, the portion of the stream containing the smaller species passes through the membrane. The goal of cross-flow filtration is not to trap components within the pore structure of the membrane.

The SBP test unit used in this demonstration operates with four modules aligned in parallel. The filtration unit is approximately 13 feet long, 5 feet wide, and 7 feet high and contains an estimated total membrane area of up to 300 square feet. Automatic level controls provide for unattended operation with continuous feed to the tank. Concentrate recycle flow also can be controlled automatically. Figure 2 provides a schematic of the filtration unit.

At the American Creosote Works site, groundwater was pumped from a well to an aboveground storage tank where a quiescent period of several hours allowed oil and suspended solids to coalesce and separate. The feedwater stream to the filtration unit was drawn from the mid-section of the storage tank to minimize introduction of these materials. The pump that drew material from the tank also provided the compression for the system to operate, approximately 750 psig.

The permeate leaving the filtration unit was sampled as required and then discharged in accordance with permit requirements. The concentrate was collected in a smaller tank until the desired volume was accumulated. It is then recycled as feed until the desired final concentration and volume are achieved. This mode of operation was selected for the demonstration in anticipation of a companion study of a proprietary biodegradation process for the concentrate. Alternate operating modes can be used to achieve other goals, depending on disposal plans and options for the permeate and the concentrate.

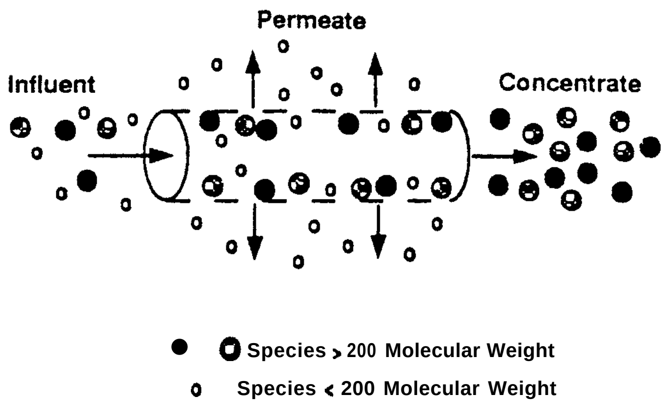

Figure 1. Cross-Flow Filtration

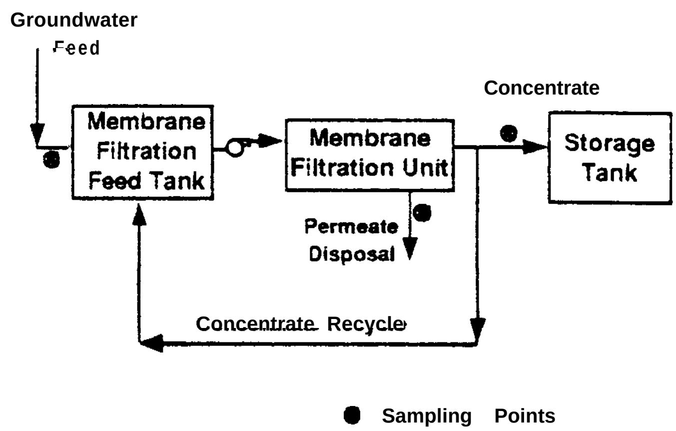

Figure 2. Schematic of SBP Filtration System

APPENDIX B

VENDOR CLAIMS AND CASE STUDIES

Note: Information contained in this appendix was provided by SBP Technologies, Inc. and has not been independently verified by the SITE Program.

B.1 *Introduction - Hyperfiltration System*

SBP's hyperfiltration system, which consists of porous stainless steel tubes internally coated with specially formulated chemical membranes, has been demonstrated to successfully treat water contaminated with a number of hazardous or toxic materials. In this system, contaminated ground and surface waters are pumped through the filtration system tubes and contaminants are collected inside the tube membrane while "clean" water permeates the membrane and tubes. The system has been shown to be highly versatile and able to effectively remove a variety of materials from contaminated waste streams, including petroleum hydrocarbons, benzene, toluene, ethylbenzene. xylene. chlorinated dioxins. chlorinated furans, and heavy metals. This extent of versatility is provided largely by the application of several types of chemical membranes with distinct permeability and ion exchange capabilities.

As discussed in this Applications Analysis Report, SBP used this hyperfiltration technology in a pilot-scale field study, performed in conjunction with the U.S. EPA Superfund Innovative Technology Evaluation (SITE) Program. At the American Creosote Works (ACW) site in Pensacola, Florida. groundwater has been encountered with significant wood preserving waste contamination, of which a significant percentage is high molecular weight carcinogenic polynuclear aromatic hydrocarbons (PAHs) and pentachlorophenol (PCP), typically associated with the wood treatment industry.

In this field study, one type of chemical membrane was used to coat the porous stainless steel tubing, with an aim to provide the optimal separation efficiencies for the higher molecular weight contaminants. These are generally ;egarded to be most "hazardous" molecules and are generally more resistant to degradation in the environment. The results confirmed that this membrane system was very effective in removing >95% (w/v) of the high molecular weight polynudear aromatic hydrocarbon (PAH) contaminants, the most carcinogenic components, during the monitored demonstration run. However, on the average, approximately 20% of the lower molecular weight phenolic contaminants were removed by this membrane type. SBP feels that this percentage can be improved by adjusting membranes and flows in the field. The iatitude to tinker with the system was not available during the formal demonstration period.

In the ACW study, the relatively heavy concentrations of contaminants in the feed material for the hyperfiltration unit precluded effective use of other "tighter" types of membranes as the first pass barrier due to the potential for fouiing. Optimally, a combination system employing the initial membrane used here to remove high molecular weight contaminants, followed by a "tighter" membrane to remove lower weight phenoiics from the permeate of the first membrane would have been more likely to provide the full spectrum of contaminant removal desired.

B.2 Results BTEX/Petroleum Hydrocarbon Hyperfiltration

A. BTEX/Gasoline Contaminated Waste Stream

Other waste streams, highly contaminated with lower molecular weight molecules, have been successfully hyperfiltered and concentrated using alternate chemical membrane types than that used in the ACW field site demonstration. One example has been the hyperfiltration of waste water from certain oil refining operations containing significant amounts of benzene, toluene. ethylbenzene. and xylenes (BTEX), as well as other petroleum hydrocarbons.

A summary of the hyperfiltration results of this treatment is as follows:

Contaminant	Original Feed Sample	Permeate Sample	% Removal
Benzene	2200 ppb	34 ppb	98.5%
Toluene	7640 ppb	92 ppb	98.9%
Ethyl-benzene	2590 ppb	15 ppb	99.4%
Xylenes	12200 ppb	100 ppb	99.2%
TPH	483 ppm	3.5 ppm	99.3%

B. Contaminated Landfill Liquids

In a separate study, condensate from a methane-recovery operation at a municipal landfill was treated for the removal and concentration of a large spectrum of contaminants, including naphthalene, heavy metals, and BTEX. The results of this are:

Contaminant	Original Feed Sample	Permeate Sample[1]	% Removal
Toluene	177 ppm	<5 ppm	>97.2%
Ethyl-benzene	268 ppm	<5 ppm	>98.1%
Xylenes	561 ppm	<10 ppm	>98.2%
Naphthalene	90.4 ppm	<10 ppm	>89.0%

[1]All permeate readings were below the detectable limits for the analysis method used in this study.

B.3 Conclusions - Hyperfiltration System

These results demonstrate the capacity and versatility of the hyperfiltration system in treating a variety of waste streams and achieving effective volume reduction in removal of contamination from groundwater. municipal landfill leachates, or contaminated petroleum waste streams. The vaiue of this technology can be further enhanced by coupling it with a biodegradation process. This can be achieved by usmg the hyperfiltration concentrate as a biorcactor feed stream, as well as by using the hyperfiltration system to polish bioreactor effluent to yield two streams: one, a clean stream suitable for discharge; and the other, a polished concentrate to feed to the bioreactor. This creates a closed loop for targeted contaminants, and provides for an efficient continuous flow remediation design.

B.4 Introduction - Bioremediation System

In addition to the application of hyperfiltration technology to the remediation of creosotecontaminated groundwater from the American Creosote Works (ACW) site, effective biodegradation of creosote and pentachlorophenol has also been achieved at this site by SBP using specially selected, non-engineered microorganisms in a pilot-scale bioreactor system. The combination of these two systems, hyperfiltration and bioremediation. provides a novel and reliable means to first concentrate the waste feed to the bioreactor to an optimal level for efficient bioremediation activity, as well as to provide for a final polishing step using hyperfiltration of bioreactor effluent.

For this study on the ACW site, a bi-phasic bioreactor design was utilized, operating in a semi-continuous flow process. having a hydraulic retention time of four days. Groundwater, with contaminant concentrations as high as 7.000 ppm creosote, was ueated on-site. This demonstration achieved a removal efficiency of greater than 99% for total polynuclear aromatic hydrocarbons (PAHs). This includes a removal rate of 98% for the most recalcitrant, and most hazardous fraction of the PAHs and 88% for PCP. The field test proved that SBP's biotechnology application for hazardous waste remediation can be effective at an actual waste site. SBP is ready to apply this bioremediation approach for on-site treatment of PCP and PAH-contaminated soil, sludge and water.

B.5 PAH and PCP Contamination and Bioremediation

PAHs are a widespread contaminant of soil and groundwater typical of creosote wood treating facilities, manufactured gas plants, refineries and related industries. Bioremediation has been attempted for PAH constituents in several studies and field applications. but until now. biodegradation using indigenous bacterial strains has been able to achieve only 50% to 75% removal of PAHs. The untreated portion is generally comprised of the recalcitrant high molecular weight (HMW) PAHs which are those compounds with 4. 5 or 6 fused rings and are the PAH components which are known or suspected carcinogens (see Table 7). Similarly.

PCP, a common wood preservative, has proven difficult to biodegrade under field conditions.

TABLE 7. Classes and Characteristics of PAHs

Low Molecular Weight PAHs - relatively non-hazardous, relatively easy to degrade.
naphthalene
2-methylnaphthalene
1-methylnaphthalene
biphenyl
2.6-dimethylnaphthalene
2.3-dimethylnaphthalene

Medium Molecular Weight PAHs - some potentially hazardous to human health, more complex but still biodegradable by many bioremediation systems.
acenaphthylene
anthacene
fluorene
phenanthrene
2-methylanthracene
anthraquinone

High Molecular Weight PAHs - several carcinogens, very slow rates of biodegradation without specialized microbes.
fluoranthene
pyrene
benzo(b)fluorene
chtysene
benzo(a)pyrene
benzo(a)anthracene
bento(b)fluoranthene
benzo(k)fluoranthene
indeno(l,2.3-c,d)pyrene

Since 1987, SBP, in collaboration with USEPA scientists at the Gulf Breeze (Florida) Environmental Research Laboratory (GBERL), has isolated and identified several strains of naturally occurring soil bacteria capable of mediating PAH and PCP degradation at rates in excess of those achieved by undifferentiated communities of indigenous microbes. The strains are identified as:

CRE I-13: low and medium weight PAH degraders comprised of an assemblage of 13 Pseudomonads.

EPA *505:* a strain of *Pseudomonas paucimobilis* capable of high rate degradation of HMW PAH constituents.

SR3: a strain of *Pseudomonas* sp. which degrades PCP.

All organisms have been shown to mineralize their target contaminants. Additionally, EPA 505 has been patented for use in the degradation of high molecular weight PAH. Through a Cooperative Research and Development Agreement with EPA, SBP has the exclusive license to market the PAH degraders along with rights to certain other environmental biotechnology developed at GBERL.

The SBP bioremediation process was tested on groundwater from the ACW Superfund Site in Pensacola, Florida. The ACW site was an active wood treatment facility from 1902 to 1981. Both creosote and PCP were used as wood preserving agents during the site's operation. Waste liquids from the process were placed in unlined surface impoundments on-site. These impoundments often overflowed into drainage ditches which discharged into local waterways. In addition. wastes have migrated into the shallow aquifer. contaminating both soil and groundwater.

The ACW Superfund site has large volumes of shallow groundwater contaminated by creosote and PCP. In order to prove the capability of the SBP organisms to degrade these contaminants under field conditions, a highly contaminated groundwater was chosen as the test matrix.

Groundwater was pumped from the aquifer via an existing monitoring well. The extracted groundwater was stored in an equalization tank prior to the test From this tank, the contaminated feed was pumped to the two-stage bioreactor treatment system (see Figure 3). Each bioreactor had a hydraulic capacity of 200 gallons and was designed to provide mixing and up-lift type aeration.

The bioreactors were operated sequentially, i.e., the contaminated water was transferred to Bioreactor 1 (BRl) at a pre-set flow rate of four days. After four days, when BRl was full, the water was allowed to overflow into Bioreactor 2 (BR2). Laboratory grown concentrates of CRE 1-13 (specialized degraders for the low and medium weight PAHs) were added to BRl, along with nutrients and sparged air, and the tank was mixed. Similarly, BR2 was inoculated with EPA 505 (HMW PAH-degrading strain) and SR3 (PCP degrader) during its eight days of operation. Treated flow from BR2 was held in a tank for testing; after testing, the water was discharged to the city sanitary sewer.

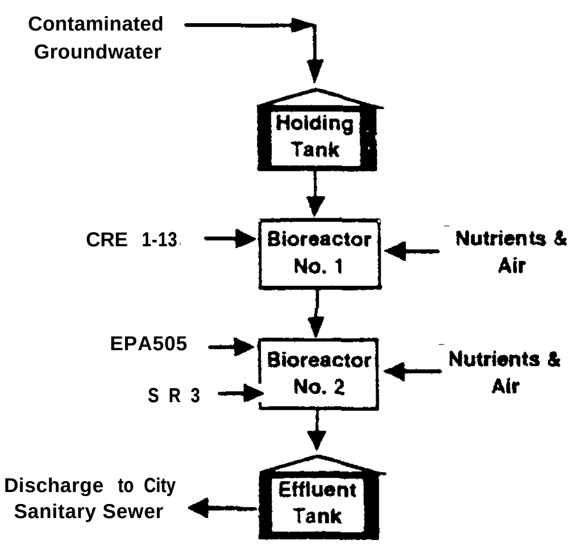

Figure 3. Simplified Process Flow for SBP Technologies Inc.'s Bioreactor System

During operation of the bioreactors, samples were collected for the analysis of key operating parameters. such as dissolved oxygen, nutrient levels. total organic carbon and suspended solids. Microbial analysis was performed to assess the cell concentration of the specialized bacteria being added. All cultures were prepared in advance and added to the bioreactors to obtain a final concentration of approximately 1 X 10^6cfu/mL. Additional samples were collected to measure the contaminant concentration across the bioreactor, as well as in rhe various portions of the treatment system, in order to calculate a mass balance.

B.6 Bioremediation Results

The overall PAH and PCP degradation performance of SBP's treatment system is shown below.

TABLE 8. Summary of Bioremediation Results of PAH and PCP Removal

Contaminant	Influent (mg/L)	Effluent (mg/L)	% Removal
Low Molecular Weight PAHs	31	8.1	<99
Med Molecular Weight PAHs	539	1.6	>98
High Molecular Weight PAHs	368	52	98
Pentachlorophenol	256	31	88

These results represent a significant advancement in PAH bioremediation. Not only has the total PAH been reduced to <1% of its original concentrations. the HMW PAH. a class of compounds which are typically not removed in biological remediation systems, have been reduced by 98-plus percent. This removal has the additional significant characteristic of having been mediated by an organism specially and specifically isolated, cultured and introduced into the bioremediation system to remove this class of compounds, and this has been accomplished under typical field remediation conditions.

To further validate the treatment technology, the contaminated groundwater was subjected to tests for toxicity and teratogenicity before and after treatment (sampled before carbon treatment). As determined by MicrotoxTM, embryonic *Menidia beryllina*, *Mysydopsis bahia*, and *Ceriodaphnia dubia* bioassays, these indicators of potential threat to human health and the environment were significantly reduced. These data show that the treatment system was effective in removing the hazardous properties of the waste material, while simultaneously demonstrating that no metabolic by-products or toxic intermediates were created by the microbial biotransformation of the waste constituents.

A mass balance was performed by comparing the total influent loading of PAHs to the residual PAHs left in the treatment system at shutdown. The HMW PAHs were found to be 80% removed (20% remained in the residual). In a scaled-up system with higher volume of waste water mated. the removal efficiently at steady state would approach the percent removal from influent to effluent (98%).

B.7 Technology Application

SBP's approach to bioremediation of hazardous waste sites is a "multi-phase" strategy, meaning that the technology is adaptable to the treatment of soil, sludges. leachates, groundwater and surface water. By the multi-phase approach. the waste matrix is modified and managed :o support the greatest level of specialized organisms survival and highest biodegradation rates. Examples are given below.

Bioremediation is applicable to a wide range of organic contamination. SBP has focused on research, development and field implementation of biotechnology-based approaches to some of the more difficult hazardous waste constituents. in particular wood preserving wastes and solvent contamination. SBP has bioremediation solutions for:

PAHs (e.g., creosote, coal tar)
Chlorinated Aliphatic (e.g.. TCE)

Pentachlorophenol
Petroleum Hydrocarbons

Treatment of contaminated liquids such as water. leachate, filtrate, groundwater, storm water, surface water and industrial process waste water can be accomplished by several of SBP's technologies. Certain waste streams can be concentrated by our hyperfiltration units; the permeate is clean water and the "concentrate" contains the reduced volume of the pollutants. These concentrated contaminants can often be bioremediated. thus minimizing the waste stream. Other liquids may be treated directly, either by biological processes, or in the case of volatiles, air stripping with biotreatment of the pollutants in a gas phase bioreactor, or "biofilter".

SBP has developed several approaches for the handling of contaminated soil. Solid phase systems are used when biostimulation of indigenous bacteria is appropriate. Slurry phase reactors, either in-vessel or *in situ* are used for soils or sludges requiring better control of microbial systems. A multi-phase approach combining soil washing and hyperfiltration to reduce volume and bioreactor treatment of the washwater is appropriate for heavily contaminated wastes.

APPENDIX C

SITE DEMONSTRATION RESULTS

C.1 Introduction

The goal of this demonstration project was to study the effectiveness of the SBP formed-in-place hypefiltration membrane unit, operating in a cross-flow mode, for the concentration of PAHs (and PCP) from contaminated groundwater found at a wood treating site. The original plans called for a companion study of a proprietary biodegradation process for the concentrate: however, a decision was made during this study not to carry out that portion of the study.

Based on available information, including a Remedial Investigation/Feasibility Study (RI/FS), the American Creosote Works site in Pensacola, Florida was selected for the investigation. The site was included on the National Priorities List on the basis of the RI/FS study which suggested that the groundwater under the site was heavily contaminated with both PAHs and PCP.

The American Creosote Works site had been used for wood treatment from 1902 to 1981. Creosote was the preservative used until the 1970's when a shift was made to pentachlorophenol in a light oil. Over the years, wood impregnation was carried out in open troughs, resulting in spills and drippage which seeped into the ground. Figure 4 presents the general layout of the facility and indicates the location of the well that was drilled to assess the suitability of the site for the SITE demonstration project. This well was selected as the source of groundwater for this demonstration.

The well yielded sufficient groundwater voiume and flow but the output was contaminated with free product. Field COD tests were used to determine that five-fold dilution of the groundwater with city water was necessary to meet the 100 - 500 mg/L COD input guideline for feedwater to the pilot filtration unit. Approximately 700 gallons of the groundwater was pumped from the well on alternate days. The groundwater was allowed to settle for several hours, and the aqueous phase pumped to a separate tank. The contaminated aqueous phase was diluted with 2,800 gallons of carbon-treated city water to bring the contaminated level of the feed in the desired range of 100 to 500 mg/L COD. Approximately 1,000 gallons of this diluted stream was used as the feedwater to the filtration unit per day. The average characteristics of this feed stream are shown in Table 9, and are based on composite samples taken on each day over the six days of the demonstration.

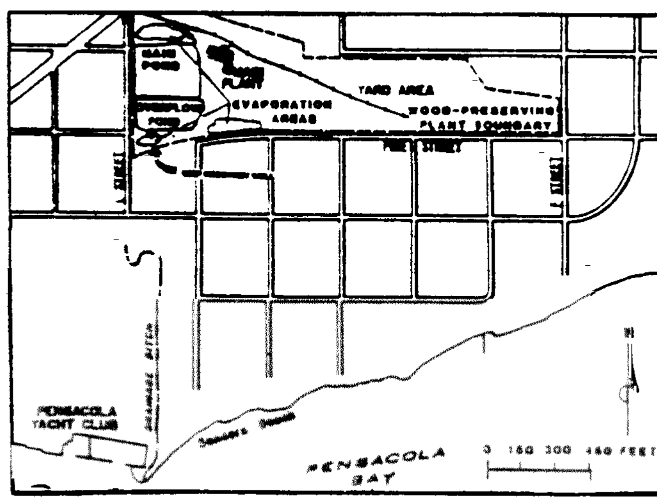

Figure 4. American Creosote Works Site

TABLE 9. **Average Characteristics** of Feed Stream to the SBP Filtration Unit

Analyte	Average
TDS (ppm)	237
TSS (ppm)	34
TOC (ppm)	121
COD (ppm)	379
Oil/Grease (ppm)	199
Semivolatiles (ppb)	
Phenol	4,900
2-Methylphenol	2,308
4-Methylphenol	6.917
2,4-Dimethylphenol	1,817
Pentachlorophenol	(2,425)
Benzoic Acid	(1,421)
Naphthalene	12,867
2-Methylnapthalene	4.525
Acenaphthylene	(138)
Acenaphthene	6.842
Dibenzofuran	4,875
fluorene	5.925
Phenanthrene	17.083
Anthracene	1,983
Fluoranthene	7,008
Pyrene	4,700
Benzo(a)Anthracene	1,235
Chrysene	1.127
Benzo(b)Fluoranthene	(460)
Benzo(k)Fluoranthene	(428)
Benzo(a)Pyrene	(312)

( ) estimated value

To achieve the desired volumes and concentrations, the feedwater was introduced during the first two hours (approximately) of each day's run. For the remainder of each day's run, the reject (concentrate) was recycled, becoming the feed, while the permeate was continuously removed and discharged to the POTW after samples were composited for analysis. Each day's run was terminated when the flowmeters indicated that the desired 800 gallons of permeate had been discharged, leaving approximately 200 gallons of concentrate.

Samples were analyzed for oil and grease, dissolved and suspended solids, volatile organics, TOC. COD, and dioxins/furans in addition to the list of designated semivolatile organics used in evaluating the developer's claims.

C2 Field Activities

SBP personnel were responsible for preparing the membrane, operating the system over the test period (six days), and washing of the unit on alternate days. Separation of the oil and other readily separable material and dilution of the groundwater with city water were field decisions that were agreed to by SBP and EPA to meet the operational requirements of the filtration unit. EPA's contractor personnel monitored flow rates and sampled feed, permeate, concentrate, and washwater while the system was operating.

While some leaks were encountered during the shakedown of the filtration unit, no breakdowns occurred during the six days of testing. The flux (transport of liquid across the membrane) did have a tendency to decrease during each day of operation, but this was accommodated by manually increasing the pressure.

C.3 Test Procedures

As noted earlier, the system was operated by introducing approximately 1,900 gallons of the diluted feedwater (about 1 volume of groundwater to 4 volumes of city water) over a two hour period at a rate of about 8 gpm. At that time, recycle of the concentrate was initiated and continued until approximately 800 gallons of permeate was generated and approximately 200 gallons of concentrate was collected.

Based on operational parameters (flux, pressure), the developer determined that washing of the unit was necessary every other day. At the end of the second day, the fourth day, and the sixth day approximately 200 gallons of city water, to which cleaning chemicals had been added, was flushed through the system and collected. This material was also analyzed.

Grab samples of the feed stream were collected every 15 minutes during the initial two-hour single pass phase, while permeate grab samples were collected every 45 minutes over the whole run. Laboratory samples were prepared by compositing the grab samples on a flow proportional basis. After the initial single pass, the concentrate was recycled for approximately four hours in each test and one composite sample was taken at the end of each run. All samples were transferred to bottles, inhibited or preserved as called for by the individual test methods, labelled. sealed, and shipped in ice-tilled coolers to off-site laboratories by overnight express.

Instantaneous flow and accumulated volumes of feed and permeate were measured automatically using calibrated flowmeters. Volume of the final concentrate was determined by the difference between the feed and permeate volumes. The temperature and pH in the three streams were measured in the field and recorded to assure that there was no gross change in characteristics that could affect filtration effectiveness. Sampling points are indicated on the schematic of the system, shown in Figure 2. The sampling schedule, analytical protocols and results, and QA/QC protocols are described fully in the Technology Evaluation Report. The ongoing QA program allowed for the collection and reporting of high quality data.

At the end of the sixth day of operation, after all the required samples had been taken, the process was allowed to continue for several hours, further concentrating the contaminants. Additional samples of the permeate were taken about every 25 gallons to observe whether there was a fall-off in contaminant rejection rate.

C.4 Results

The following results are all based on the composite analytical results and field data obtained on each day. The Technology Evaluation Report presents the complete data for grab and composite samples taken each day of feed, permeate, reject, and washwater.

Operation of Unit

The filtration unit operated in a batch mode for six hours each day, for six days, and processed approximately 1,000 gal!ons of feed per day. Over the six day test period, permeate flux was a relatively constant 0.0085 galions/min/ft2 (coefficient of variation < 10%). Based on a total membrane area of 300 ft2 for the system, the permeate flow rate for the four-module filtration unit averaged 2.6 gpm.

The unit was cleaned every two days with approximately 200 gallons of city water and membrane cleaning materials. Over the two day period, the surface of the membrane gradually fouled. requiring an increase in feed pressure in order to maintain a constant permeate flux. The cleaning at the end of each two-day period was sufficient to restore the original flux. Figure 5 depicts the pressure adjustment over each two day period necessary to maintain the constant flux (Figure 6).

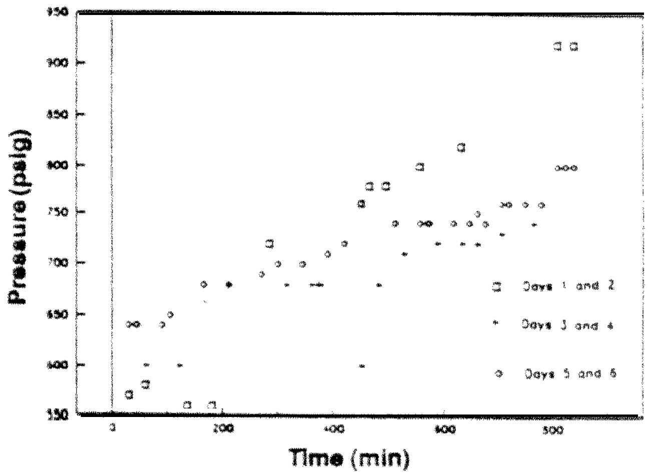

Figure 5. Feed Pressure vs. Run Time

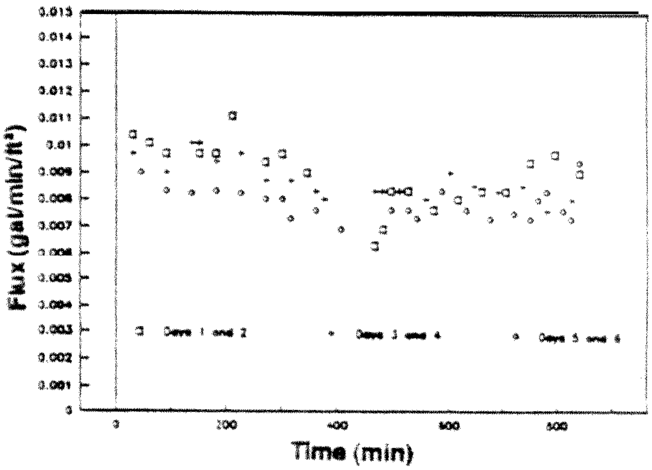

Figure 6. Flux vs. Run Time

Semivolatile Contaminant Analvsis

Contaminant Reduction

It was agreed between SBP and EP.4 that a selected list of semivolatile organic compounds would be used to assess the effectiveness of ihe Filtration Unit. The analytes consisted of all quantifiable semivolatile compounds (Method 8270) detected in the feed.

Rejection efficiency was defined as the change in total concentration for these contaminants between the feed and the permeate:

% Rejection $= 100 - \frac{C_p}{C_f} x$

where

C_f = total concentration of contaminants in feed

C_p = total concentration of contaminants in permeate

On the basis of composite samples, rejection for the total designated contaminants averaged 74% over the six days, as shown in Table 10.

Analysis of the data reveals that the system is very effective for the rejection of polynuclear aromatic hydrocarbons and much less effective for phenols. Separated in this fashion, rejection for the PAHs averaged 92% over the six days while rejection for the phenols averaged 18%.

TABLE 10. Overall Semivolatile Rejection for the SBP Filtration Unit

Day	Feed (ppm)	Permeate (ppm)	Concentrate (ppm)	Rejection %
1	104	18	206	83
2	91	24	585	74
3	92	26	248	72
4	104	22	242	79
5	85	23	199	73
6	60	24	538	60

A more accurate means of quantifying and graphically representing rejection is to calculate the reductions on a logarithmic basis. For exatnple. attempting to graph differences between 90% and 99% rejections does not fully depict the fact that a ten-fold reduction has occurred. In order to accurately represent this process, it is necessary to calculate the order of magnitude of rejection (ORD) as the log value of the ratio of the contaminants concentration in the feed to the concentration in the permeate. The equation is written as:

$$ORD = \text{Log}\ Cf/Cp)$$

Therefore, an ORD of 2.0 means that a 100 fold decrease in contamination has occurred in the permeate relative to the feed. An ORD of 1.0 means a 10-fold decrease has occurred.

For the semivolatile constituents. it appears that rejection follows the molecular weight of the chemical. Figure 7 presents the average ORD over the six days versus the molecular weight of the individual compounds.

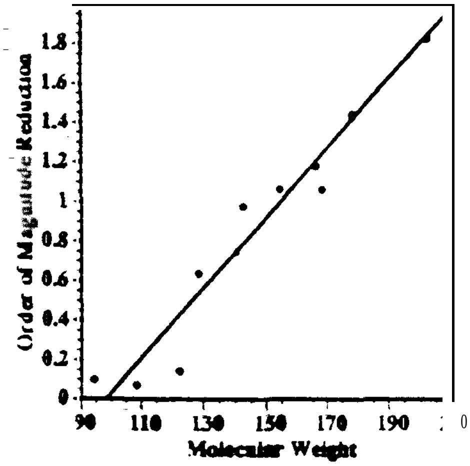

Figure 7. Molecular Weight vs. Order of Magnitude Reduction (ORD)

Mass Balance

Combining the masses of pollutants in the permeate and the concentrate on a daily basis did not provide a good material balance, relative to the feed. Only when the material in the washwater was also included was all the material accounted for. Based on the volume of washwater used in each washing operation, approximately 200 gallons, about 8% of the masses of the designated pollutants are retained on the membrane or in the liquid in the system. Table 11 provides a summary of the contribution of the different streams for each two-day period between wash operations. The relative distribution of pollutants in the washwater was very similar to that in the concentrate, with PAHs far exceeding the phenols. However, the concentration of pollutants in the washwater was similar to the feedwater.

TABLE 11. Mass Contribution of Total Semivolatiles in all Streams (2 day totals)

Days	Feed (Influent) gms	Perm gms	Conc gms	Wash gms	Total Effluent gms	Recovery %
1 & 2	777	140	556	46	742	95
3 & 4	778	159	320	84	563	72
5 & 6	581	151	i n	32	710	122
						6 day recovery = 94%

Extended Operation

After the system yielded the desired 200 gallons of concentrate on the sixth (last day) of the test and all necessary samples had been taken, operation of the system was continued with further recycle of the concentrate as long as possible to observe the behavior of the unit (i.e., the rate of fouling and the quality of the permeate). The extended operation resulted in only thirty seven gallons of concentrate remaining, representing a 97% volume reduction. However, during this time the rejection efficiency decreased, as expected, as concentration continued (Table 12).

TABLE 12 Behavior on Extended Fiibation

Additional Gallons of Permeate Produced	Semivolatile Rejection (calculated from initial % Feed)
25	47.5
50	48.5
75	60.0
100	32.3
150	21.7

Conventional Parameters

In addition to the designated semivolatile pollutants, the removal of several conventional parameters from the feedwater was also evaluated. These included total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), total organic carbon (TOC), and oil and grease (O&G). Comparison of feed and permeate confirm that the membrane is capable of removing larger molecules such as oil and suspended solids, but is not nearly as efficient in the removal of dissolved material (TDS) or otherwise-unidentified organic species (COD and TOC). Such results, summarized in Table 3, suggest that the membrane is operating predominantly as a hyperfiltration membrane. In addition, considerable concentrations of organics remain in the permeate even though the PAHs are efficiently removed. For example, the ratio of semivolatiles/COD decreases significantly, from about 0.2 in the feedwater to about 0.07 in the permeate, demonstrating that semivolatiles are not the major contributor to the COD, and that significant unidentified, smaller molecular weight compounds can pass through the membrane.

Polvchlorinated Dibenzo-p-Dioxins/Dibenzofurans

Polychlorinated dioxins (PCDDs) and furans (PCDFs) are often encountered in the manufacture of pentachlorophenol and can remain with the commercial product. To investigate this matter, selected samples of the three streams taken on the first, second, and sixth day of the demonstration were scanned for the various dioxins and furans using high resolution GC coupled with low resolution MS. A number of the more highly chlorinated dioxin and furan species were found in the feed water and in the reject at significantly higher concentrations, but analyses of the permeate indicated efficient removal of these pollutants. The 2,3,7,8-TCDD isomer was not found above the detection limit in any sample of feed, permeate, or concentrate. The 2,3,7,8-TCDF isomer was found in only one sample of feed and one sample of concentrate, in both cases the value was <0.5 ng/L (ppt). The major dioxins and furans were the octa species. These results are consistent with rejection by molecular weight or oil solubility, but not by number of rings.

TABLE 13. **Dioxins/furans** in Process **Streams**

Day 1

	Feed (ng/L)	Perm. (ng/L)	Conc. (ng/L)	Removal %
2378 TCCD	•	•	•	
12378 PeCDD	•	•	•	
123478 HxCDD	•	•	•	
123678 HxCDD	53.0	•	277.7	
123789 HxCDD	74.6	•	13.3	
1234678 HpCDD	1980	1.6	3836	99.9
OCDD	14670	38.9	42365	99.7
2378 TCDF	•	•	.21	
12378 PeCDF	•	•	-	
23478 PeCDF	•	•	•	
123478 HxCDF	11.2	•	52	
123678 HxCDF	3.2	•	8.7	
234678 HxCDF	8.5	•	30.4	
123789 HxCDF	•	.	•	
1234678 HpCDF	346	•	1066	
1234789 HpCDF	28.3	•	76	
OCDF	1030	3.3	2596	99.7

• An '-' indicates the isomer was absent or below detection limits in stream.

Day 3

	Feed (ng/L)	Perm. (ng/L)	Conc. (ng/L)	Removal %
2378 TCDD	•	•		
12378 HxCDD	•	•		
123478 HxCDD	2.4	•		
123678 HxCDD	47.7	•	116	
123789 HxCDD	6.7	•	9.9	
1234678 HpCDD	1460	•	3630	
OCDD	13250	7.9	34135	99.9
2378 TCDF	.37	•		
12378 PeCDF	•	•		
23478 PeCDF	•	•		
123478 HxCDF	8.1	•	28.4	
123678 HxCDF	•	•	4.2	
234678 HxCDF	•	•	17.0	
123789 HxCDF	•	•		
1234678 HpCDF	300	•	689	
1234789 HpCDF	•	•	40.1	
OCDF	224	•	1223	

• An '-' indicates the isomer was absent or below detection limits in stream.

Day 6

	Feed (ng/L)	Perm. (ng/L)	Conc. (ng/L)	Removal %
2378 TCDD	•	•	•	
12378PCDD	•	•	•	
123478 HxCDD	1.9	•	8.1	
123678 HxCDD	30.6	•	334	
123789 HxCDD	4.4	-	27.6	
1234678 HpCDD	1370	.36	8950	99.97
OCDD	9200	8.8	90400	99.90
2378 TCDF	.39	•	1.5	
12378 PeCDF	•	•	•	
23478 PeCDF	•	•	1.7	
123478 HxCDF	5.1	•	111.7	
123678 HxCDF	1.5	•	34.2	
234678 HxCDF	5.1	•	42.6	
123789 HxCDF	•	•	•	
1234678 HpCDF	196	•	2055	
1234789 HpCDF	14.1	•	126.2	
OCDF	473	.50	5235	99.89

• An '-' indicates the isomer was absent or bebw detection limits in stream.

Volatile Organics

Analyses for volatile organics (VOCs) were carried out during the runs on days 1, 3, and 6 because the developer was somewhat concerned that the high pressures used in the system might force volatiles through the membrane into the permeate. All VOC concentrations were low in the feedwater; the same species were also found in the permeate and the concentrate but at lower concentrations. The principal VOC was acetone, but the expected BTEX species were also present.

TABLE 14. **Volatiles** in **Process Streams**

	Feed µg/L	Permeate µg/L	Concentrate µg/L
Methylene Chloride	*	*	*
Acetone	.	.	.
Carbon Disulfide	2	<5	<5
2-Butanone	32	31	32
Benzene	16	7	<5
Toluene	20	16	<5
Ethyl Benzene	12	(7)	<5
Styrene	18	7	<5
Xylenes	43	26	<5

* probable laboratory contamination
( ) estimated value