DOE/CH-9209

COMBINED AIR STRIPPER/ MEMBRANE VAPOR SEPARATION SYSTEMS

Final Report

Contract No. 02112404

By
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Prepared for

Office of Research and Development
Technology Development,
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Research and Development Program Coordination Office
Chemical Technology Division, Argonne National Laboratory
9700 S. Cass Avenue, Argonne, IL 60439
under Prime Contract W-31-109-Eng-38 to the U.S. Department of Energy

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PREFACE

Currently available technology is not adequate to assess environmental contamination at Department of Energy (DOE) sites, take permanent remedial action, and eliminate or minimize the environmental impact of future operations. Technical resources to address these shortcomings exist within the DOE community and the private sector, but the involvement of the private sector in attaining permanent and cost-effective solutions has been limited.

During 1990, on behalf of DOE's Office of Technology Development, Argonne National Laboratory (ANL) conducted a competitive procurement of research and development projects addressing soil remediation, groundwater remediation, site characterization, and contaminant containment. Fifteen contracts were negotiated in these areas.

This report documents work performed as part of the Private Sector Research and Development Program sponsored by the DOE's Office of Technology Development within the Environmental Restoration and Waste Management Program. The research and development work described herein was conducted under contract to ANL.

On behalf of DOE and ANL, I wish to thank the performing contractor and especially the report authors for their cooperation and their contribution to development of new processes for characterization and remediation of DOE's environmental problems. We anticipate that the R&D investment described here will be repaid many-fold in the application of better, faster, safer, and cheaper technologies.

Details of the procurement process and status reports for all 15 of the contractors performing under this program can be found in "Applied Research and Development Private Sector Accomplishments - Interim Report" (Report No. DOE/CH-9216) by Nicholas J. Beskid, Jas S. Devgun, Mitchell D. Erickson and Margaret M. Zielke.

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ABSTRACT

Air stripping is an economical and efficient method of removing dissolved VOCs from contaminated groundwater. Air strippers, however, produce a vent air stream, which must meet the local air quality limits. If the VOC content exceeds the limits, direct discharge is not possible; therefore, a carbon adsorption VOC capture system is used to treat the vent air. This treatment step adds a cost of at least $50/lb of VOC captured. In this program, a combined air stripper/membrane vapor separation system was constructed and demonstrated in the laboratory. The membrane system captures VOCs from the stripper vent stream at a projected cost of $15/lb VOC for a water VOC content of 5 ppmw, and $75/lb VOC for a water VOC content of 1 ppmw. The VOCs are recovered as a small, concentrated liquid fraction for disposal or solvent recycling. The concept has been demonstrated in experiments with a system capable of handling up to 150,000 gpd of water. The existing demonstration system is available for field tests at a DOE facility or remediation site. Replacement of the current short air stripping tower (effective height 3 m) with a taller tower is recommended to improve VOC removal.

EXECUTIVE SUMMARY

Introduction and Objectives

Groundwater and soil contamination are problems at many DOE sites. The two most common organic contaminants are trichloroethylene (TCE) and carbon tetrachloride. Perchloroethylene and other chlorinated hydrocarbons, solvents, and fuel hydrocarbons have also been identified in groundwater and soil samples. Air stripping is the least expensive method of removing these volatile organic compounds (VOCs) from polluted groundwater. However, increasingly stringent environmental regulations require that VOCs in the resulting air stripper vent stream be captured or destroyed before discharging the stream to the atmosphere. Carbon adsorption is widely used to capture the VOC contained in the air-stripper emissions but produces a secondary waste in the form of spent carbon. The spent carbon is generally regenerated off-site, involving transportation costs. The cost of capturing VOCs by carbon adsorption is reported in the literature to be at least $50/lb of VOC.

The objective of this project was to build and operate a combined air stripper/membrane vapor separation system in which the membrane system removes the VOCs from the air stripper vent stream and recirculates the air to the stripper. The combined system is smaller than a carbon adsorption system, and has none of the problems associated with spent carbon regeneration. The economic benefits of the new system are compelling. Calculations indicate that the cost of air-stripper emissions treatment by membrane technology is about $0.60/1,000 gallons of groundwater treated. The corresponding air treatment costs per pound VOC removed from the water are $15/lb VOC for a VOC water content of 5 ppmw, and $75/lb VOC for a water VOC content of 1 ppmw. Thus, membrane vapor separation is more economical than vapor-phase carbon adsorption for VOC in water concentrations of 1 ppmw and higher. The unit built and demonstrated in this program reduced the VOC content of the water feed stream by as much as 96%. VOC removal up to 99% could be achieved with a taller air-stripping tower. The current tower is 3 m high; a tower of 6-10 m is required for optimum performance of the combined system. Use of the taller tower will result in a very small increase in the capital cost of the system because the air stripper is only about 15% of the total cost.

The demonstration system is available for field operation. Potential sites are the Hanford and Savannah River Sites.

Technology Description

A simplified flow diagram of the process is shown in Figure 1. Air and VOC-contaminated water flow countercurrent through the air stripper, producing a VOC-laden air stream and a VOC-depleted water stream. The VOC-laden air passes to a membrane vapor separation system. The VOCs are drawn through the membrane by a vacuum pump, providing a small, concentrated VOC vapor stream. This stream is cooled and condensed, to form a small volume of liquid VOC for disposal. The amount of VOC produced is extremely small; a

100,000 gpd water stream at a VOC concentration of 1 ppmw contains only 0.84 lb/day of VOC. The residual air stream from the membrane system, depleted of VOCs, is recirculated through the air stripper.

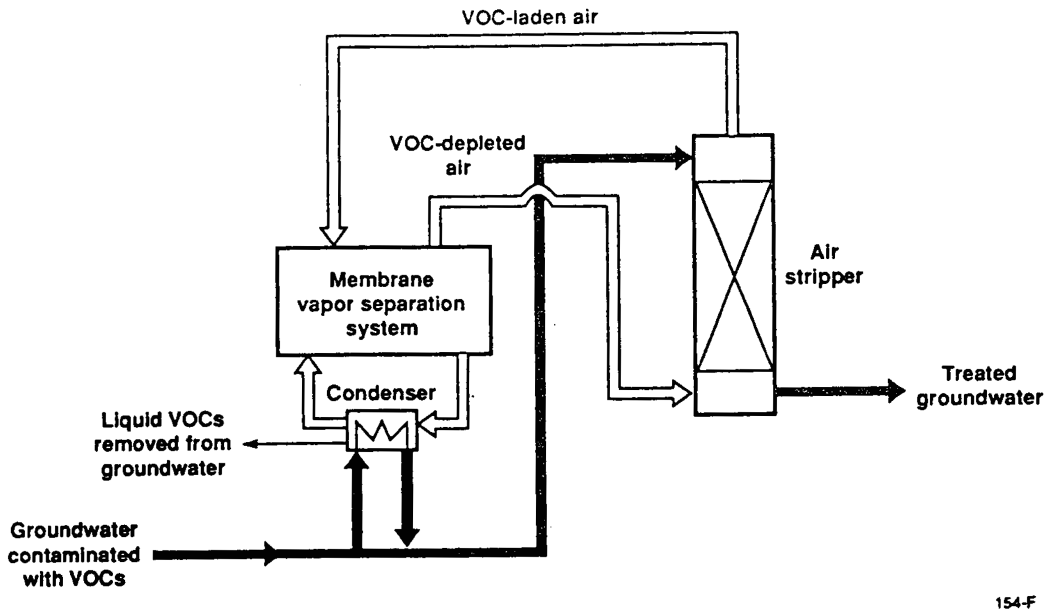

Figure 1. Simplified flow diagram of a combined air stripper/membrane vapor separation system.

Technology Performance

The combined air stripper/membrane vapor separation system that was constructed and tested by MTR treats 55-125 gpm of VOC-contaminated water; the stripper air flow rate varies from 46 to 70 scfm. The performance of the system was evaluated with four VOCs that are common groundwater contaminants: trichloroethylene, carbon tetrachloride, 1,2-dichloroethane, and chloroform. VOC removals ranged from 12% to 96%; most removals were in the range 80-90%.

Experiments with water containing trichloroethylene (TCE) as the model VOC contaminant demonstrated that the combined system removes 62-83% of the TCE present in the feed water. The membrane system removes 90-95% of the TCE reaching it from the air stripper. The combined system produces an aqueous condensate containing 6-7% TCE by weight from a water stream containing about 10 ppmw TCE. The overall concentration factor is thus well over 5,000-fold. The condensate spontaneously splits into an aqueous phase, which can be recycled to the air stripper, and an organic phase consisting of nearly pure TCE. The TCE phase can be sent for disposal or solvent reclamation.

Further experiments with carbon tetrachloride, dichloroethane, and chloroform as the model VOC contaminants showed that the membrane system removes 71-98% of the VOCs from the air leaving the air stripper. The overall removal obtained by the combined air stripper/membrane system varied from 60% to 96% for carbon tetrachloride, from 34% to 64% for chloroform, and from 12% to 29% for dichloroethane. The level of removal is determined by the Henry's law coefficient of the VOC, as is the case for conventional air-stripping operations.

The experimental data showed that a combined air stripper/membrane system is an effective and reliable way of treating contaminated groundwaters without emitting pollutants into the air. Overall VOC removal was demonstrated to be as high as 96% in pilot studies. Our results showed that significantly better removals would be obtained with a taller air stripper tower. In the present unit, VOC removal is limited by the stripper tower height of 3 m (the system is operated indoors) and not by the capacity of the membrane system. VOC removal of at least 99% could be achieved by improving the performance of the air stripper.

Remediation Costs

The combined air stripper/membrane vapor separation system has not yet been demonstrated at an actual remediation project; thus, remediation cost data are estimates. The capital costs of a membrane system to treat air emitted by an air stripper treating water at 190,000 gallon per day (132 gpm) are estimated to be $130,000, or $1,000/gpm.

The annual operating costs for the membrane system are estimated to be $33,000, which translates to $0.62/1,000 gallon of water treated. The treatment cost per pound VOC removed from the water is $15/lb VOC, if the water contains 5 ppmw VOC, and $75/lb VOC, if the water contains 1 ppmw VOC. The capital and operating costs of the membrane system are determined by the flow rate of air to be treated (and thus by the flow rate of the water treated by the air stripper) rather than by the VOC content of the air to be treated (and thus by the VOC content of the water treated by the air stripper). This characteristic makes membrane systems especially suited for the treatment of streams relatively concentrated in VOC.

Air stripping is more cost effective for water treatment than liquid-phase carbon adsorption, even if vapor-phase carbon adsorption is used to treat the stripper air effluent. Costs for treating air stripper air effluent with membrane vapor separation and with vapor-phase carbon adsorption were compared. For water streams with a VOC content of 1 ppmw or higher, membrane vapor separation yields lower treatment costs than vapor-phase carbon adsorption.

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1.0 INTRODUCTION

1.1 Technology Scope

Groundwater contamination is a major problem at many DOE facilities and waste sites. According to a recent study, the five most common contaminants, listed in order of frequency, are chlorinated hydrocarbons, radionuclides, metals, anions, and fuel hydrocarbons.[1] This list contains two classes of volatile organic contaminants: chlorinated hydrocarbons, reported at 14 of 18 DOE facilities and at 53 of 91 DOE waste sites, and fuel hydrocarbons, reported at 9 DOE facilities and at 19 DOE waste sites. Table 1 lists the 20 volatile organic contaminants (VOCs) most frequently identified at DOE facilities and includes the Henry's law coefficient for these compounds. A Henry's law coefficient of 200 atm/mole fraction or more indicates that the VOC is efficiently removed from water by air stripping.

Air stripping is the least expensive method of removing VOCs from polluted groundwater. However, increasingly stringent air pollution regulations require that VOCs in the stripper vent stream be captured or destroyed before this stream can be discharged to the atmosphere. Carbon adsorption is widely used to capture the VOC contained in the air-stripper emissions but produces spent carbon as a secondary waste. Because the amount of organic compound being discharged from any one air stripper is small, offsite regeneration is the most efficient method of handling the spent carbon. The cost of capturing VOCs by carbon adsorption is about $40-50/lb of VOC.

The objective of the project was to build and operate a combined air stripper/membrane vapor separation system in which the membrane system removes the VOCs from the stripper air vent stream. The combined system is much smaller than a carbon adsorption system, and has none of the problems associated with spent activated carbon regeneration on-site or off-site. The economic benefits of the new system are compelling. Calculations indicate that the cost of air-stripper emissions treatment by membrane technology will be about $15/lb of VOC recovered, which is one-third or less of the cost of carbon adsorption treatment. The cost of the combined air stripping/membrane vapor separation treatment will be about $0.4-0.7/1,000 gallons of groundwater treated.

Table 1. Volatile Organic Contaminants in Groundwater on DOE Facilities.[1] Total number of DOE facilities reporting is 18.

	Volatile organic compound	Henry's law coefficient (atm/mole fraction)
14	Trichloroethylene	648
11	1,1,1-Trichloroethane (Methyl chloroform)	967
11	1,2-Dichloroethylene: cis trans	409 371
10	Perchloroethylene	1,190
10	1,1-Dichloroethane	326
10	Chloroform	225
8	Toluene	353
8	Xylene: ortho meta para	233 370 337
8	1,1-Dichloroethylene	1,270
7	Benzene	309
7	1,2-Dichloroethane	65
7	Carbon tetrachloride	1,634
7	Dichloromethane	138
6	Ethylbenzene	447
6	Freon (type not specified)	26,900 (Freon-113)
5	Vinyl chloride	1,245
4	1,1,2-Trichloroethane	53
4	1,1,2,2-Tetrachloroethane	18
4	Chlorobenzene	252
2	Cyclohexane	10,700

The basic configuration of the combined system was shown in Figure 1. Groundwater contaminated with VOCs is fed into the top of an air stripper in which the water contacts a recirculating air stream. The air stripper column contains a packing material to improve the air/water contact area. VOCs are transferred from the water stream into the air stream; the VOC-laden air is sent to a membrane vapor separation system. The membrane system removes the VOCs from the recirculating air stream, concentrating the VOCs into a very small stream. The VOCs are recovered from this stream by condensation, using the cold groundwater as the coolant. The VOC-depleted air stream produced by the membrane system is returned to the air stripper, creating a closed-loop system that eliminates emission of VOCs into the atmosphere. The VOCs are recovered in liquid form for reuse or disposal.

1.2 Technology Programmatic Requirements

The Environmental Restoration and Waste Management (EM) mission adopted by the U.S. Department of Energy is to achieve and maintain full compliance with all applicable environmental laws and regulations for both current operations and previously contaminated and/or inactive facilities and sites. Within the Office of Environmental Restoration and Waste Management, the Office of Technology Development (OTD) ensures that reliable and accepted technologies will be available for DOE to achieve this goal. OTD manages a Research, Development, Demonstration, Testing and Evaluation Program that generates innovative technologies to be implemented in the EM programs. The work described in this report falls under the Groundwater and Soils Cleanup program area. The objective is to demonstrate the effectiveness and efficiency of a combined air stripper/membrane vapor separation system to treat groundwater contaminated with volatile organic contaminants. Contaminated groundwater is found at virtually all DOE facilities and sites. The developed technology is ready to be evaluated at a DOE facility or site.

2.0 METHODOLOGY AND APPROACH

During the program a combined air stripper/membrane vapor separation system was constructed. The system subsequently underwent parametric testing with water streams containing single and multiple model VOC contaminants. The system, the testing program, and the analytical procedures are described in the sections that follow. Before describing the performance of the system, however, a short description of the membrane separation technology developed at MTR is appropriate, since this is a relatively new technology.

2.1 Vapor Separation

The MTR membrane vapor separation process is illustrated schematically in Figure 2. In this process, organic vapor-laden air contacts one side of a membrane that is permeable to organic vapors but relatively impermeable to air. The high permeability of the organic vapors is a result of the high level of sorption of the vapors into the membrane material. A partial vacuum, applied to the other side, draws the organic vapor through the membrane. The permeate vapor is then compressed and condensed to recover the organic fraction. The purified air stream is removed on the feed side, as the residue.

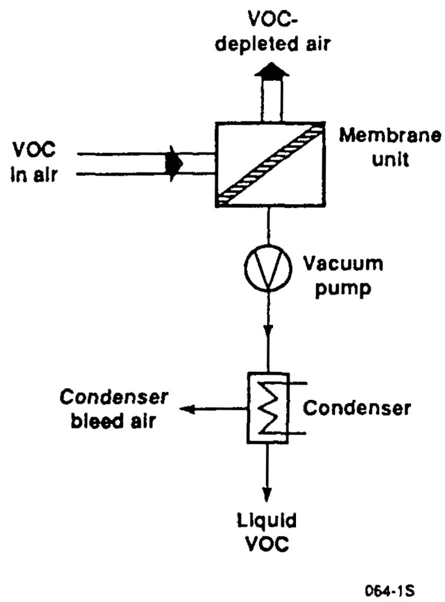

Figure 2. Diagram of the MTR membrane organic vapor separation process.

The membranes developed by MTR for the separation of organic compounds from air are composite structures, as shown schematically in Figure 3. The tough, open, microporous layer provides strength and the ultrathin permselective coating is responsible for the separation properties.

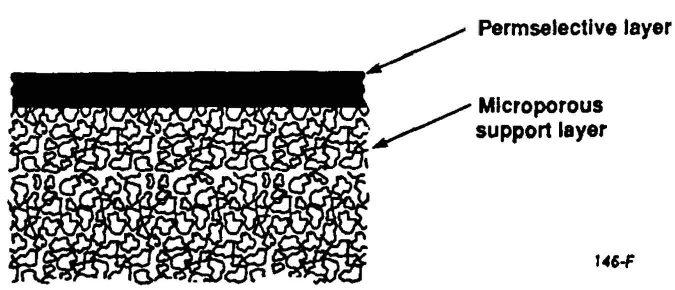

Figure 3. Schematic of an MTR composite membrane. Membranes in rolls 100-200 yards long and 40 inches wide are produced at MTR.

Certain membrane materials, particularly hydrophobic rubbery polymers, possess an intrinsically high selectivity for organic vapors over air, allowing useful separations to be performed. A measure of the ability of a membrane to separate a particular vapor from an air stream is the selectivity (α), defined as the ratio of the vapor permeability through the membrane (P_{vap}) to the air permeability through the membrane (P_{air}):

$$\alpha = \frac{P_{vap}}{P_{air}} \qquad (1)$$

Our experience has shown that a membrane selectivity of greater than 10, and preferably greater than 20, is required if a membrane process is to be economically viable. The selectivity of the MTR-100 membrane for a number of common industrial organic vapors is listed in Table 2, which shows that the selectivity varies for different vapors, but is usually greater than twenty. If multiple organic vapors are present, the individual vapors are removed according to their individual selectivity without interference by the other vapors.

Table 2. MTR-100 Membrane Selectivity for Common Industrial Organic Vapors, Measured at Ambient Temperature

Vapor	Membrane Selectivity
Octane	90 - 100
1,1,2-Trichloroethane	60
Isopentane	30 - 60
Methylene chloride	50
CFC-11 (CCl_3F)	45
1,1,1-Trichloroethane	30 - 40
Isobutane	20 - 40
Trichloroethylene	25 - 35
Perchloroethylene	25 - 35
Tetrahydrofuran	20 - 30
CFC-113 ($C_2Cl_3F_3$)	25
Acetone	15 - 25
CFC-114 ($C_2Cl_2F_4$)	10

The composite membranes are incorporated into spiral-wound modules of the type illustrated schematically in Figure 4. In operation, feed gas enters the module and flows between the membrane leaves. The component of the feed that is preferentially permeated by the membrane spirals inward to a central permeate collection pipe. The remainder of the feed flows across the membrane surface and exits as the residue.

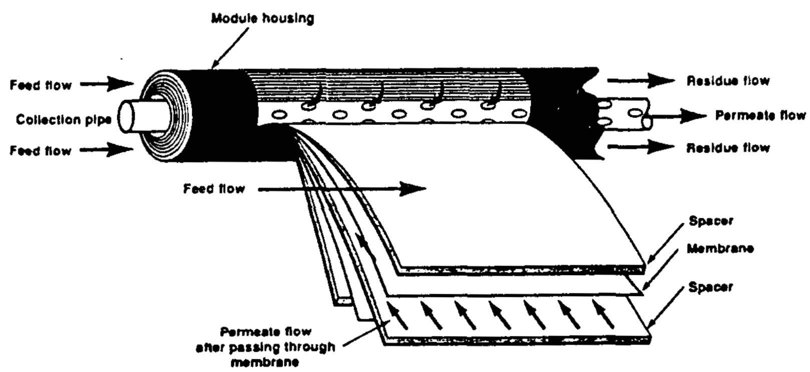

Figure 4. Schematic of a spiral-wound membrane module. The membrane area in MTR modules ranges from 0.3 m^2 for laboratory modules to 6 m^2 for commercial-sized modules.

Banks of membrane modules can be incorporated into various system designs. A single-stage system, consisting of one set of membrane modules, may produce adequate VOC removal from the feed but the VOC concentration in the permeate may be too low for condensation to occur. In this case, a two-stage system, in which the permeate from the first stage becomes the feed to the second stage, is used. The second-stage membrane area is only 10-15% of the first, because the volume of the stream is low. If the second-stage is still too dilute for VOC removal by condensation, a very small third stage may be added.

2.2 Combined Air Stripper/Membrane Vapor Separation System

The overall flow diagram of the combined air stripper/membrane vapor separation system built and tested in the program is given in Figure 5. Air and water are continuously brought into contact in an air stripper. The air stripper operates under countercurrent conditions and contains packing material to improve the air/water contact area. The water stream entering the air stripper at the top contains a volatile organic compound (VOC) that is removed in the stripper tower. The VOC leaves the air stripper as a vapor in the air vent stream. This air stream is fed into a three-stage membrane separation system, which removes most of the VOC from the air by first concentrating the VOC, then condensing it in the third membrane stage.

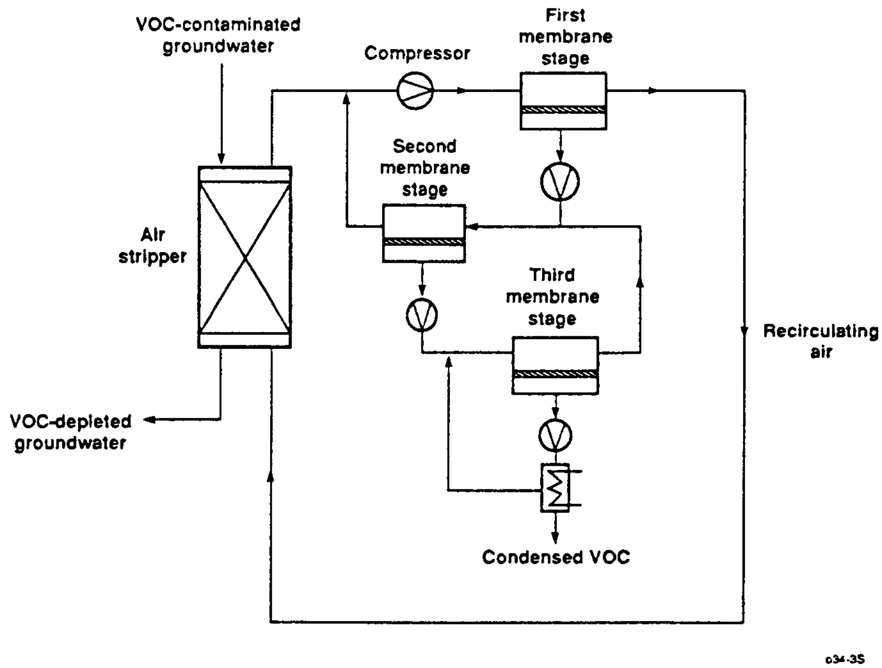

Figure 5. Flow diagram of the combined air stripping/membrane separation system to remove VOCs from contaminated groundwater.

A three-stage membrane separation system is required because the vent stream from the air stripper has a low VOC concentration and adequate enrichment of the permeate stream for VOC recovery cannot be attained in one separation step. The three-stage system raises the VOC concentration from 10-1,000 ppmv* in the feed air stream to 2-5% by volume in the permeate. At this concentration, the VOC is easily condensed.

The air stream leaving the air stripper is first compressed to 15 psig. Since the air stream is saturated with water vapor, some water is condensed out in the compressor aftercooler. The compressed air stream is fed into the first membrane stage, which contains 63 m^2 membrane area. Since the membrane is more permeable to the VOC than to air, most of the VOC permeates the membrane. The first-stage residue stream, with a much reduced VOC concentration, is recirculated to the air stripper. The permeate side of the membrane system is maintained at a reduced pressure by a vacuum pump. The recompressed permeate is fed into a condenser (not shown) operating at ambient temperature, to remove water vapor. The first- stage permeate is then fed into the second membrane stage, containing 20 m^2 membrane area, in which the VOC is concentrated for the second time. The second-stage residue stream is recirculated to the first membrane stage and the second-stage permeate is fed into the third membrane stage, again via a water-vapor condenser (not shown). The third stage contains 2.5 m^2 membrane area

*Concentrations of VOC in air are expressed in % by volume or ppm by volume (ppmv). Concentrations of VOC in water are expressed by % by weight or ppm by weight (ppmw).

and produces a permeate with a VOC concentration high enough to allow condensation at 5°C. The bleed from the third-stage condenser is recirculated to the front of the third membrane stage; the third-stage residue is recirculated to the second membrane stage.

During the laboratory testing, the demonstration system was operated as a closed loop. The water stream exiting the air stripper was mixed with the liquid VOC condensed in the membrane system, to produce the VOC-containing water stream that was fed into the air stripper. Under steady-state conditions, the amount of VOC removed from the water stream by the air stripper was equal to the amount of VOC removed from the air stream by the membrane system. In actual use, of course, the system will be operated in a different way: the condensed VOC will be collected for disposal and the treated water stream will be discharged, or possibly further treated in an additional air stripper, to obtain very low VOC discharge levels.

A number of parameters can be measured during operation of the demonstration system. A schematic of the demonstration system, as operated in the laboratory, is shown in Figure 6. The figure shows the locations at which the system parameters are measured. Each quantitative parameter is identified by a code consisting of a capital letter or letters followed by a numeral. The letter(s) specify whether the parameter is a flow rate (Q), a pressure (P), a temperature (T), a gas chromatograph reading (GC), or a oxygen analyzer reading (OX). The numeral is a running number to distinguish between the various parameters of the same kind.

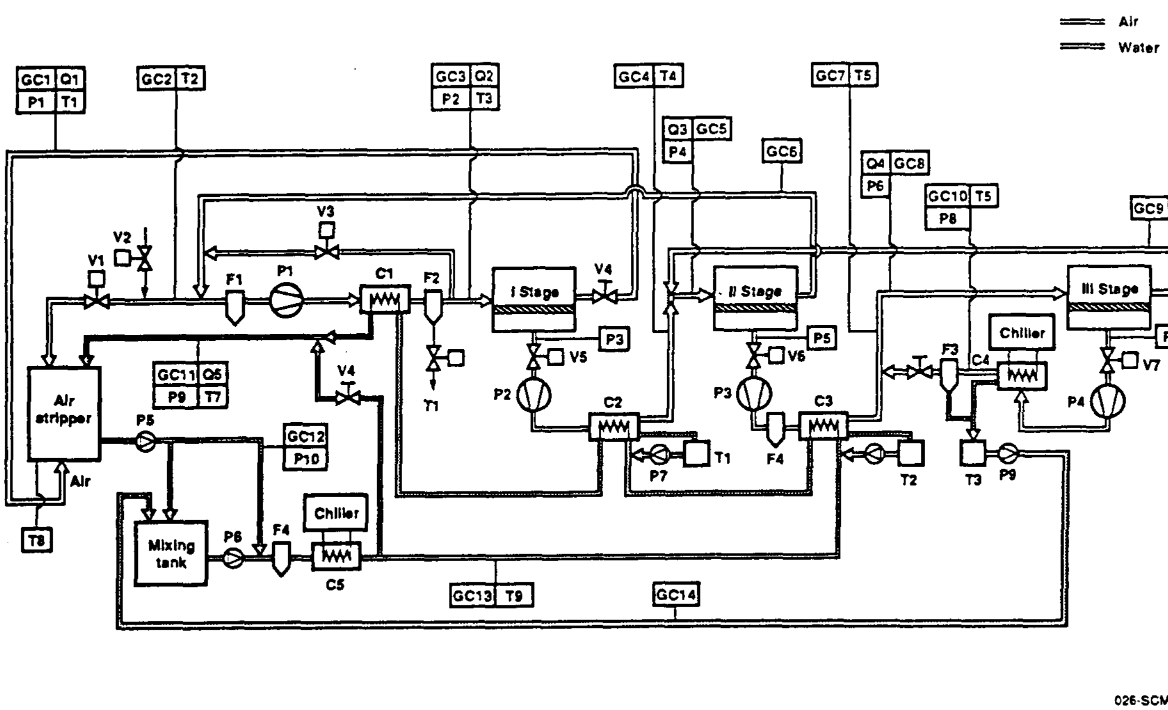

Figure 6. Configuration of the air stripper/membrane vapor separation demonstration system identifying the various system parameters.

2.3 Experimental Design

The effect of four system variables on the performance of the combined air stripper/membrane vapor separation system was evaluated during parametric testing at MTR's laboratories. Membrane system parameters, such as feed and permeate pressure, were not varied. These are determined by the capacity of the installed compressor and vacuum pumps. The membrane system design was based on our experience with other membrane pilot units; therefore, optimum capacities were selected.

The four parameters studies were: (1) the VOC type in the feed water, (2) the VOC concentration in the feed water, (3) the air-to-water volume ratio, and (4) the air flow rate. A brief discussion of each parameter follows.

(1) VOC Contaminant

Based on the frequency of occurrence of VOCs as listed in Table 1, four model VOC contaminants were selected for the experiments. The four VOCs, characterized in Table 3, represent a 25-fold variation in Henry's law coefficient, the main determinant of air stripper performance. The model compounds cover the range from a very volatile VOC, carbon tetrachloride, to a relatively nonvolatile VOC, 1,2-dichloroethane.

Table 3. VOCs Used in the Parametric Testing of the Demonstration System

VOC contaminant	Boiling point (°C)	Vapor pressure at 20°C (torr)	Henry's law coefficient (atm/ mole fraction)
Trichloroethylene (TCE)	87	56	650
Carbon tetrachloride (CCl_4)	77	91	1,600
1,2 Dichloroethane (DCE)	84	62	65
Chloroform ($CHCl_3$)	61	160	225

A total of 32 experiments were carried out in which the water stream entering the air stripper contained a single VOC contaminant. In five further experiments, the stream entering the air stripper contained a mixture of trichloroethylene, carbon tetrachloride, and chloroform.

(2) Water VOC Concentration (GC11)

The amount of VOC in the feed water stream is a key parameter determining system performance. The lower the VOC concentration in the water stream, the lower is the VOC concentration in the air stream to be treated by the membrane system. The lower the VOC concentration in the membrane system feed air, the harder it is to recover the VOC by condensation after the third stage and the lower is the removal efficiency of the membrane system. It is, therefore, important to determine the performance of the system at low water VOC concentrations. During the parametric testing, most of the experiments were carried out with VOC concentrations in the feed water ranging from 0.15 to 10 ppmw (μg/g).

(3) Air-to-Water Volume Ratio (A/W)

This is the most important parameter distinguishing this air stripper unit from conventional systems. Air strippers usually operate at large air-to-water (A/W) volume ratios ranging from 20 to 200. A large A/W ratio maximizes the driving force for VOC removal from the aqueous stream, but makes membrane treatment of the air stream more difficult because of the large volume and low concentration of the stream to be treated. A membrane air-treatment system would benefit from a small air flow rate and from a high VOC-in-air concentration: both conditions are achieved by reducing the A/W ratio. The air stripper VOC removal efficiency will, however, decrease with a decreasing A/W ratio. Since reducing the A/W is a trade-off, the influence of the A/W ratio on the combined stripper/membrane system was evaluated. The A/W ratio was varied from 2.9 to 8.1.

(4) Air Recirculation Flow Rate (Q1)

Variation of the air recirculation flow rate will influence the performance of both the membrane system and the air stripper. The VOC removal obtained in the air stripper increases with increasing air flow rate, whereas the VOC removal obtained by the membrane system decreases with increasing air flow rate. Variations in air flow rate were carried out at a constant air-to-water volume ratio. Varying the air flow rate, **Q1**, also requires varying the water flow rate, **Q5**. The air flow rate was varied from 46 to 70 scfm.

2.4 Data Reduction and Interpretation

The performance of the combined air stripper/membrane system is characterized by two parameters that quantify the VOC removal achieved. The first parameter is the VOC removal achieved by the air stripper, R_A, defined as

$$R_A = 1 - \left(\frac{ppmw\ VOC\ in\ water\ effluent}{ppmw\ VOC\ in\ water\ influent}\right) \cdot 100\% \qquad (2)$$

Since VOC removal from water is the overall objective of the combined system, R_A is a measure of the overall effectiveness of the combined system. The second parameter is the VOC removal achieved by the membrane system, R_M, defined as

$$R_M = 1 - \left(\frac{ppmv\ VOC\ in\ air\ effluent}{ppmv\ VOC\ in\ air\ influent}\right) \cdot 100\% \qquad (3)$$

2.5 Software Development

Two computer programs were developed: one calculates performance of the air stripper; the other calculates performance of the membrane vapor separation system. Combination of the two programs allows the calculation of the performance of a combined air stripper/membrane system under varying operating conditions, as well as the design of a combined air stripper/membrane system for specific applications. A description of the programs follows.

2.5.1 Air Stripper Program

The program that models the air stripper performance is based on software written by D.W. Hand and J.C. Crittenden of Michigan Technological University.[2] The "Packed Tower Aeration Design" program is written in the Basic programming language and is available in the open literature. A discussion of the model equations used in the computer program can be found in the literature.[3] We converted this program into the Pascal programming language and added several options to the program. The most significant modification is that the new program allows for recirculation of the air stream, i.e., the VOC concentration in the inlet air stream is not necessarily zero. This is accomplished by simply rewriting the equation for the logarithmic mean driving force for VOC removal as:

$$\frac{(C_{water\text{-}inlet} - C_{air\text{-}outlet}/H) - (C_{water\text{-}outlet} - C_{air\text{-}inlet}/H)}{ln\ [(C_{water\text{-}inlet} - C_{air\text{-}outlet}/H)\ /\ (C_{water\text{-}outlet} - C_{air\text{-}inlet}/H)]} \qquad (4)$$

where C is the mole concentration of the VOC and H is the dimensionless Henry's law coefficient (concentration in air/concentration in water).

The original program automatically assumes that $C_{air\text{-}inlet}$ equals zero, as is the case in conventional air stripping. The new program has the following options available:

(1) calculation of tower dimensions based on specifiable VOC removal requirements,

(2) calculation of VOC removal based on tower dimensions and specifiable inlet VOC concentrations,

(3) calculation of VOC removal based on tower dimensions, specifiable water inlet VOC concentration, and specifiable percentage VOC removal in recirculating air stream, and

(4) calculation of the effective mass transfer coefficient in the tower based on tower dimensions and specifiable VOC removal.

The new program has been checked for errors and the output compared with that obtained with the original Hand and Crittenden program. The new program has proven to be reliable. Copies of the new program are available free of charge by writing to MTR.

2.5.2 Membrane System Program

Over the past five years, MTR has developed various computer programs that model membrane vapor separation systems. We extended the modeling capabilities to include a three-stage membrane system, including the condensers that remove water and VOC from the VOC-enriched streams.

The membrane performance calculations are based on the basic membrane gas permeation equations adapted for cross-flow conditions. Three different options are available for the calculation of the performance of the condensers in the system: (a) using Raoult's law (the condensables form ideal mixtures), (b) using the van Laar equation of state (the condensables form non-ideal mixtures), and (c) assuming the condensables are completely immiscible. The program for the three-stage system can calculate the VOC removal achieved by a specific membrane system under varying operating conditions. It can also calculate the size of a membrane system required to achieve any specified VOC removal.

The three-stage membrane system program was checked for errors by using the existing single-stage program to check the calculated performance of each individual stage. The calculated performance of the condensers was also checked.

2.6 Quality Assurance

The goal of the work was to determine the feasibility of combining an air stripper with a membrane vapor separation system. The key performance parameters are the VOC removal efficiencies of the air stripper and the membrane system, respectively. Accurate measurement of the VOC concentrations in the water influent and effluent streams, as well as in the air influent and effluent streams, were required. The procedures used for the measurements were in accordance with the detailed quality assurance plan prepared as part of the program. The VOC concentrations in both water and air streams were determined by gas chromatography, after concentrating the sample in a purge-and-trap system.

The trap used in the purge-and-trap concentrator (OI Analytical, model 4460A) was a Tenax/Silicagel/Charcoal trap. The operating conditions used were those of EPA Method 601:

Purge time:	11 min
Trap temperature:	25°C
Dry purge time:	0 min
Desorb time:	4 min
Desorb temperature:	180°C
Bake time:	7 min
Bake temperature:	180°C

The gas chromatograph (Hach-Carle, Series 100) was equipped with a flame ionization detector. The column used in the gas chromatograph was a 20% SP2100 + 0.1% Carbowax 1500 on 80/100 Chromosorb WHP (10 foot length, 1/8 inch diameter). The column was operated at 140°C for single component VOC analysis and at 110°C for multiple component VOC analysis. Chromatograms were recorded on a recorder/integrator (Shimadzu, model CR601). The detection limits in water and in air of the VOCs used in the experiments are listed in Table 4.

Table 4. Detection Limits of the Model VOCs in Water and in Air

Volatile organic compound	VOC detection limit in water for a 50 ml sample (ppmw)	VOC detection limit in air for a 5 ml sample (ppmv)
Dichloroethane	0.006	0.20
Trichloroethylene	0.010	0.20
Chloroform	0.020	0.50
Carbon tetrachloride	0.035	0.60

3.0 RESULTS AND DISCUSSION

The performance of the air stripper/membrane vapor separation system for groundwater treatment is measured by the overall VOC removal achieved. The VOC removal efficiency of the combined system is determined by the performance of the two subsystems. Overall VOC removal depends on:

(1) the efficiency with which the air stripper removes the VOC from the feed water, and

(2) the efficiency with which the membrane system removes the VOC from the recirculating air stream.

The operating parameters that affect the removal efficiency of the systems were discussed in section 2.3. The parameters are: VOC type and concentration, air-to-water ratio, and air flow rate. The effect of these parameters on VOC removal efficiency was examined in a series of 37 experiments. The first 13 were with TCE as model VOC: all three remaining parameters were varied, according to the parametric test plan. Eleven similar experiments were conducted with carbon tetrachloride. Fewer experiments (4 each) were done with 1,2-dichloroethane and chloroform because the effect of air flow rate had been established in the previous experiments. In the remaining five experiments, a mixed VOC stream was used: the behavior of the individual components was monitored. A complete record of the results of all 37 experiments is given in Appendix A, Tables A1 through A5.

In the following sections, the results are analyzed and discussed. The overall VOC removal shows that the system removes VOCs from model groundwater streams efficiently. The experimental results also provide important information about system design requirements and operating conditions for field demonstration.

3.1 Effect of VOC Type and VOC Concentration on VOC Removal by the Combined System

The VOC removal achieved by the combined air stripper/membrane vapor separation system is shown in Figure 7, as a function of the VOC concentration in the water stream entering the air stripper. The figure shows data for four model VOCs: carbon tetrachloride (CCl_4), trichloroethylene (TCE), chloroform ($CHCl_3$), and 1,2-dichloroethane (DCE). The Henry's law coefficients of these VOCs range from 65 to 1,600 atm/mole fraction.

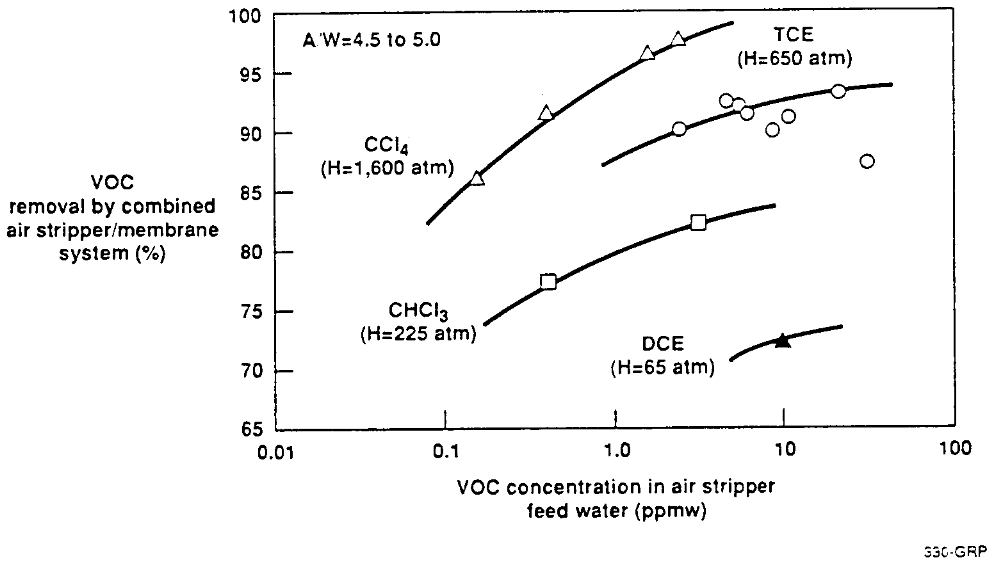

Figure 7. VOC removal achieved by the combined air stripper/membrane vapor separation system as a function of the VOC concentration in the air stripper feed water. All data were obtained with an air-to-water ratio of 4.5-5.0.

Figure 7 illustrates how the efficiency of each subsystem influences the overall removal. First, the overall VOC removal decreases with decreasing Henry's law coefficient because the driving force for VOC removal decreases. This is observed for all conventional air-stripping operations. Second, the overall VOC removal decreases with decreasing VOC concentration because the ability of the membrane system to recover liquid VOC from the recirculating air stream is reduced, as the VOC concentration in that stream decreases. The dependence on the VOC concentration is not very strong: if the VOC concentration is reduced by a factor of ten, the VOC removal is reduced by a factor of only 1.5.

The data shown in Figure 7 were obtained with a combined air stripper/membrane system of a fixed size. Any desired overall VOC removal can be obtained by changing the capacities of the air stripper and/or the membrane system. As a general rule, the capacity requirement for both the air stripper and the membrane system increases with decreasing Henry's law coefficient. The capacity requirement for the membrane system increases with decreasing VOC concentration.

Four experiments were carried out with a mixture of carbon tetrachloride, trichloroethylene, and chloroform as the model VOC contaminant. The performance of the combined air stripper/membrane system is given in Table A5 in Appendix A. Overall removal by the combined system for the individual VOCs ranks as carbon tetrachloride > trichloroethylene > chloroform, which is in order of decreasing Henry's law coefficient. The transfer of one VOC from the aqueous phase into the air stream is not affected by the presence of other VOCs. This greatly simplifies the design studies for multiple VOC removal.

3.2 Effect of Air-To-Water Volume Ratio on the VOC Removal by the Combined System

Figure 8 presents the TCE removal achieved by the combined air stripper/membrane system as a function of the air-to-water (A/W) volume ratio of the air stripper. In the experiments, the A/W ratio was varied by changing the water flow rate and keeping the air flow rate more or less constant. The figure contains two sets of data: one set at a 46-48 scfm air flow rate and one set at a 65-68 scfm air flow rate. The TCE removal increases with increasing A/W ratio and does not seem to be a strong function of the air flow rate.

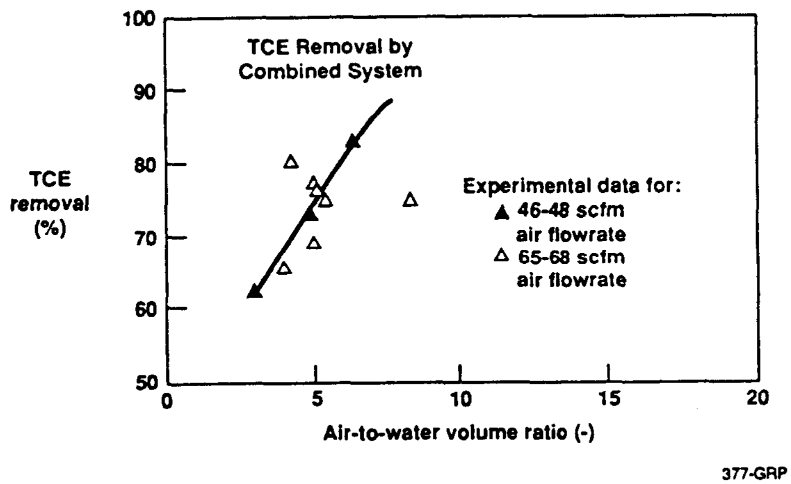

Figure 8. TCE removal by the combined air stripper/membrane system as a function of the air-to-water volume ratio.

The combined air stripper/membrane system responds to variation in A/W ratio as follows:

(1) Increase in A/W ratio at constant air flow rate, (i.e. a decrease in the water flow rate): the VOC removal by the air stripper increases, while the VOC removal obtained by the membrane system remains constant. The net result for the combined system is an increase in VOC removal, which is confirmed by the experimental data given in Figure 8.

(2) Increase in A/W ratio at constant water flow rate, (i.e. an increase in air flow rate): the VOC removal by the air stripper increases whereas the VOC removal by the membrane system decreases. These two counteracting effects may thus increase or decrease the VOC removal obtained by the combined system. The data in Figure 8 show that a 40% variation in air flow rate, in the case of TCE removal, does not change the overall removal. This reflects the two competing effects.

Figure 8 demonstrates that, at a constant air flow rate, the removal obtained by the combined system increases as the air-to-water volume ratio increases. However, an increase in A/W ratio at constant air flow rate means a decrease in water flow rate, that is, a decrease in the capacity of the combined system. Therefore, we face a trade-off: an increase in air flow rate improves VOC removal in the air stripper but reduces VOC removal in the membrane system. Considerations regarding capital and operating costs of the combined system will determine the optimum system configuration. This is discussed in more detail in Section 3.6.

3.3 Effect of VOC Type and Concentration on VOC Removal by Membrane System

The removal of VOC from the recirculating air stream by the membrane system varies from 71% to 98%. The VOC removal achieved by the membrane system was 90% or higher in 30 out of 37 experiments. This compares favorably with the performance of the air stripper, which has low levels of VOC removal if the Henry's law coefficient is low. The VOC removal achieved by the membrane system is determined by three parameters:

(1) the air flow rate entering the membrane system,

(2) the VOC concentration in the feed air stream, and

(3) the condensability of the VOC present in the air stream.

Figures A1 through A4 in Appendix A show the removal of the four model VOCs by the membrane system, as a function of the VOC concentration in the air stream for one or two different ranges of feed air flow rates. Two observations can be made from Figures A1 through A4: (1) the VOC removal decreases with increasing air flow rate (for a membrane system of fixed size), and (2) the VOC removal decreases with decreasing VOC concentration because condensation of the VOC in the third membrane stage becomes more difficult. Figure 9 summarizes the VOC removal achieved by the membrane system as a function of the VOC saturation percentage in the air stream for all four VOCs used in the experiments. VOC saturation percentage is defined as the VOC partial pressure in the air stream divided by the VOC saturation pressure, times 100%. The fact that the data for the different VOCs lie on a single curve indicates that the membrane system concentrates the different VOCs with the same efficiency. The removal by the membrane system flattens out at approximately 93%. This maximum level of removal is determined by the size of the membrane system and the flow rate of air entering the membrane system. Higher removal can be obtained by increasing the capacity of the membrane system and/or decreasing the air flow rate. See also Section 3.4 and Figure 10.

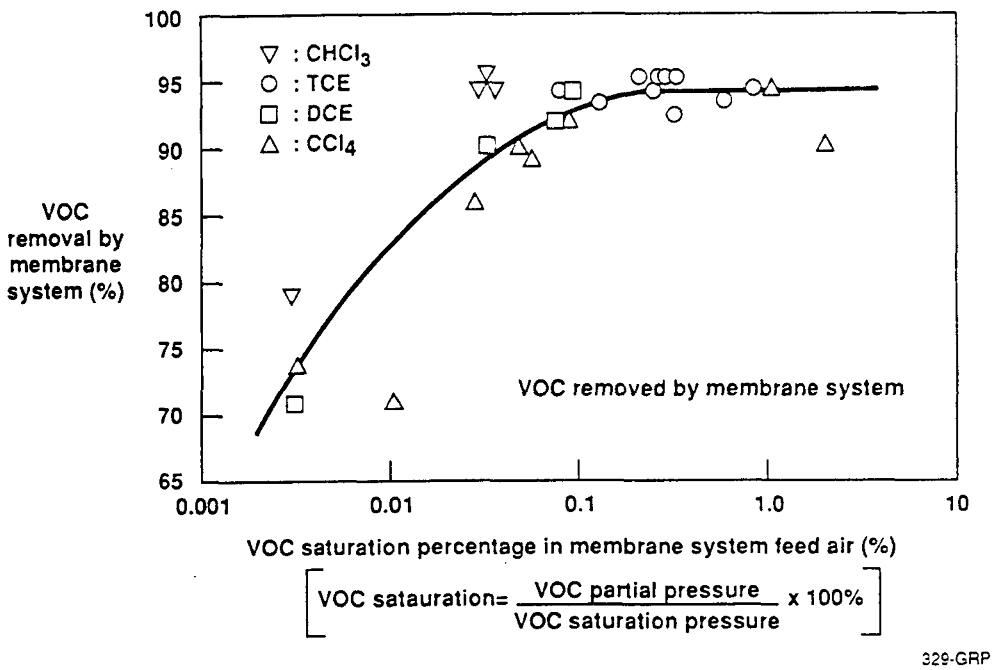

Figure 9. VOC removal by membrane system as a function of VOC saturation percentage in the membrane system feed air. The data include measurements with trichloroethylene, chloroform, dichlorethane, and carbon tetrachloride at feed air flow rates ranging from 60 to 70 scfm.

The membrane system removes multiple VOCs from the recirculating air stream very efficiently. In the liquid state, essentially all VOCs are miscible with each other, which favors condensation. Thus, it is easier to remove VOC from an air stream containing 1% carbon tetrachloride and 1% trichloroethylene than to remove VOC from an air stream containing 1% of either VOC. The high VOC removals obtained with the membrane system at low VOC in air concentrations (see Table A5) support this observation.

3.4 Effect of Air Flow Rate on VOC Removal by Membrane System

The VOC removal obtained by a membrane vapor separation system of a certain fixed size will depend on the flow rate of the air stream to be treated. Figure 10 shows that the TCE removal by the membrane system decreases as the air flow rate increases. Thus, it is preferable to minimize the air flow rate to maximize VOC removal by the membrane. This means that, to maximize the amount of water treated by the combined system, it becomes important to operate the air stripper at an air-to-water ratio that is as low as possible. As discussed below, in Section 3.5, it is important that the air stripper is not limited by transfer area to ensure that, for any given A/W ratio, the maximum VOC removal is obtained.

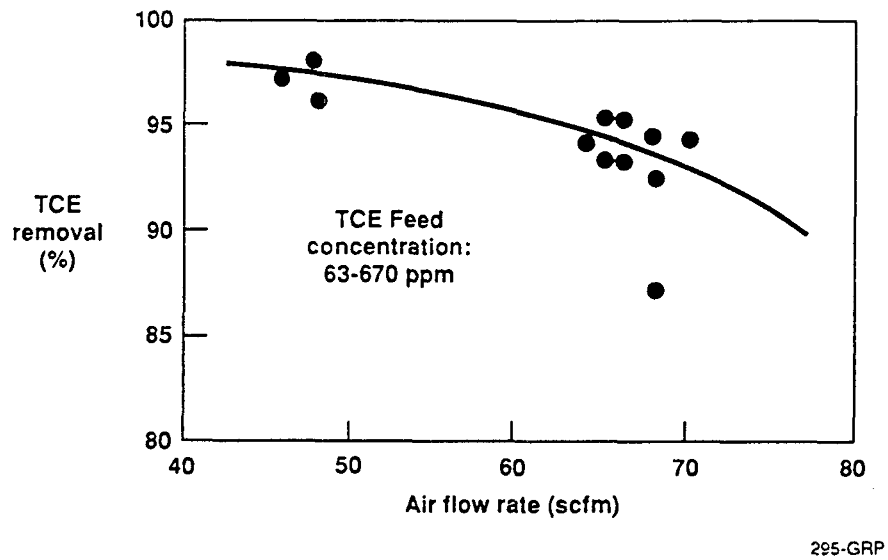

Figure 10. TCE removal by the membrane system as a function of the air flow rate entering the membrane system.

3.5 Discussion of Mass Transfer in the Air Stripper

To check the performance of the air stripper, we calculated the effective mass transfer coefficient in the packed tower from the experimental data obtained with TCE. Figure 11 shows the calculated coefficients as a function of the air stripper water flow rate and compares the experimental values with those predicted by the Onda correlation for packed contactors.[4] The experimental values are, on average, 30% lower than the predicted values, but the experimental values show the same dependence on the water flow rate as predicted by the Onda correlation. This degree of agreement between experimentally determined mass transfer coefficients and those predicted by dimensionless correlation is very good.

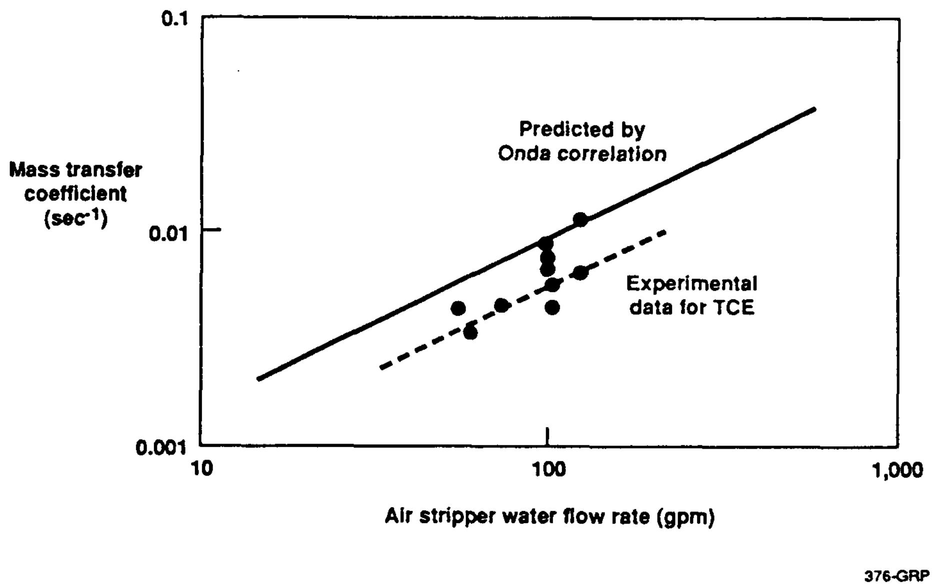

Figure 11. Mass transfer coefficient for packed towers as a function of the water flow rate. Data points are calculated from experimental data obtained for TCE. The solid line was obtained using the Onda correlation.[4]

The VOC removal achieved by the air stripper depends strongly on the Henry's law coefficient of the VOC. The removal varies from a low of 20% for dichloroethane (H = 65 atm/1 mole fraction) to 95% for carbon tetrachloride (H = 1,600 atm/1 mole fraction). Although this dependence on the Henry's law coefficient cannot be eliminated, the VOC removal achieved for each VOC can be improved by simply increasing the height of the stripping tower. The total height of the tower used in the parametric testing at MTR's laboratories was limited to 4 m giving an effective packed column height of 3 m. The height limitation resulted from the system being operated indoors. In actual field applications, where there is no height limitation, it will be possible to use a taller tower. Most air strippers operated outdoors are 5-10 m tall. The air stripper computer program, described in Section 2.5.1, was used to calculate the performance of the combined air stripper/membrane system as a function of tower height. The starting point for the calculations was an actual experiment carried out with TCE (Experiment 3, Table A1), in which 80% removal was achieved. Figure 12 shows the improvement in TCE removal obtained if the tower height is increased, while keeping all other conditions constant.

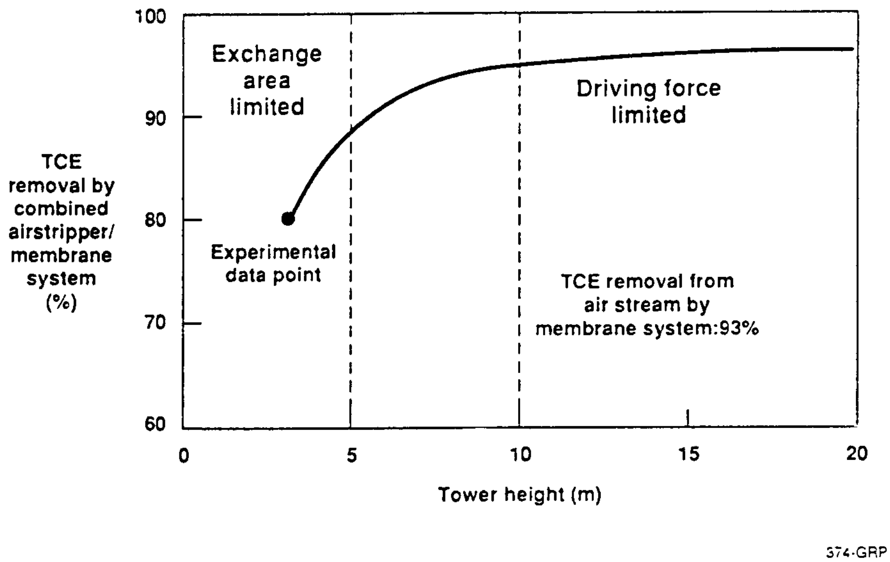

Figure 12. TCE removal obtained by the combined air stripper/membrane system as function of the height of the air stripper. The experimental data point was obtained with TCE (see Table A1, Experiment #3), with a tower height of 3 m. The TCE removal at other tower heights was calculated with the air stripper computer program. The TCE removal from the air stream by the membrane system was 93% both in the actual experiment and in the calculations.

Initially, the TCE removal increases sharply with increasing tower height, but then reaches a limiting value of about 95% for heights of 10 or more. This result shows that, at a height of 3 the removal obtained by the air stripper is limited by the area available for mass transfer rather then by the driving force, whereas at a height of 10 m or higher the removal obtained is limited by the driving force. There are two compelling reasons for operating a combined air stripper/membrane system in such a way that the removal in the air stripper is limited by driving force rather than transfer area:

(1) increasing the tower height will have a minor effect on the capital cost of the combined system because the air stripper represents less than 15% of the capital costs, and

(2) the air stripper can be operated at an air-to-water volume ratio close to the minimum. This minimizes the flow rate and maximizes the VOC concentration in the air stream to be treated by the membrane system. Both conditions reduce the size requirements for the membrane system, decreasing capital and operating costs of the combined system.

3.6 Balancing the Two Subsystems

The performance of the combined air stripper/membrane vapor separation system is determined by the performance of the two subsystems: (1) the air stripper which removes VOC from the water stream, and (2) the membrane system which removes VOC from the recirculating air stream. The VOC removals achieved in each subsystem must be balanced, because it is inefficient to operate a combined system in which one subsystem has a significantly higher VOC removal than the other. Figure 13 shows the VOC reduction factor achieved by the combined air stripper/membrane system, as a function of the VOC reduction factor achieved by the membrane system. VOC reduction factor is defined as the VOC inlet concentration divided by the VOC outlet concentration, i.e., a reduction factor of 100 corresponds to 99% VOC removal.

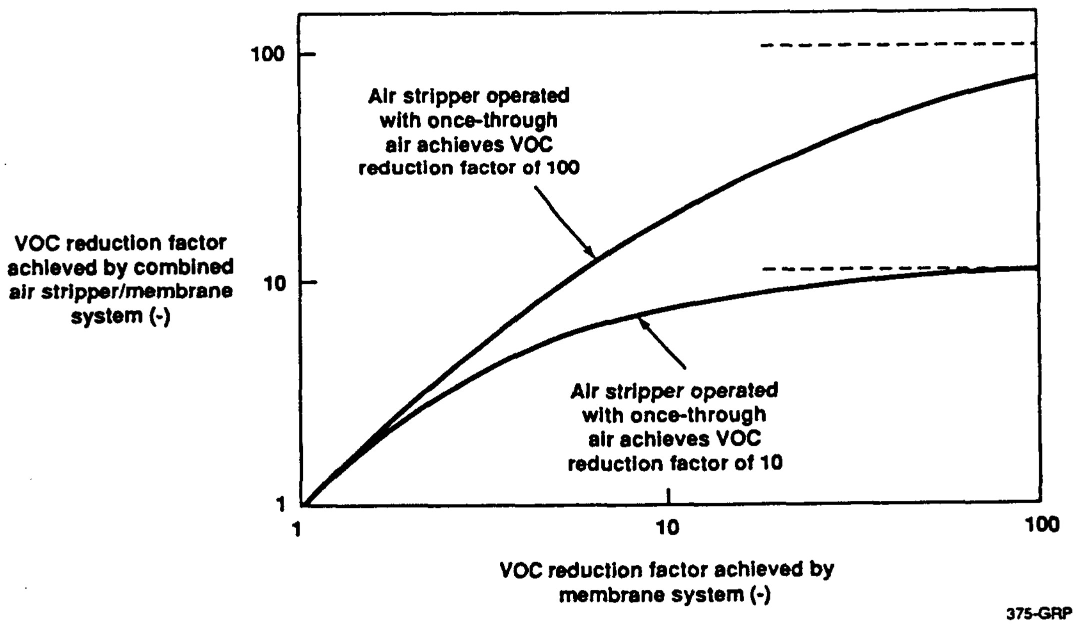

Figure 13. VOC reduction factor achieved by the combined air stripper/membrane system as a function of the VOC reduction factor achieved by the membrane system. Results are calculated for two different air strippers which, when operated with once-through air, achieve VOC reduction factors equal to respectively 10 and 100.

Figure 13 shows data for two air strippers, which, when operated with once-through air, achieve VOC reduction factors equal to 10 and 100, respectively. In a combined system, the air strippers will only achieve these reduction factors if the membrane system removes all the VOC from the recirculating air stream. In practice, this will not be the case, so the VOC removal achieved by the combined system will be less. The data show that the VOC reduction factor achieved by the membrane system should approach the reduction factor of the stand-alone air stripper to maximize the VOC reduction obtained by the combined system. It is preferable to minimize the size of the membrane system because the membrane system has higher capital and operating costs than the air stripper. Thus, if an overall removal of 95% is desired for the combined system, the best approach would be to operate the membrane system at 90-95% VOC removal and to use an air stripper that, under conventional once-through air conditions, would remove 95-99% of the VOC from the aqueous phase.

4.0 TECHNOLOGY STATUS

A combined air stripper/membrane vapor separation system is a technically and economically competitive approach to the removal of VOCs from groundwater and surface waters. The combined system eliminates the air emissions associated with conventional air strippers. The concept has been demonstrated successfully in pilot-scale experiments with a system capable of handling up to 150,000 gpd. The technology is ready to be demonstrated at a DOE facility or a DOE waste site. The existing demonstration system is available for field tests but we recommend replacement of the relatively short air stripping tower (effective height 3 m) with a taller tower to further improve VOC removal.

4.1 Technology Development Evaluation

A combined air stripper/membrane vapor separation system couples two existing technologies. Air stripping is a well established technology; membrane vapor separation is a relatively new technology, but it is being used commercially for the removal of VOCs from air streams. The goal of the program was, therefore, to demonstrate that the two technologies can be combined successfully, while eliminating VOC emissions into the atmosphere. Experiments with a 150,000-gpd system using trichloroethylene, carbon tetrachloride, chloroform, and dichloroethane as model groundwater contaminants fulfilled this goal. As in conventional air-stripping operations, the VOC removal efficiency depends mainly on the Henry's law coefficient of the VOC.

The VOC transferred from the water stream into the air stream is recovered in the liquid state by the membrane vapor separation system. The volume of the recovered VOC is extremely small. For example, treatment of a 100,000 gpd stream containing 1 ppmw VOC produces only 0.8 lb VOC per day for disposal by incineration or for solvent reclamation. The use of a membrane system to treat the stripper air eliminates the secondary wastes associated with carbon adsorption systems.

The combined air stripper/membrane vapor separation system has not yet been demonstrated at an actual remediation project; thus, remediation cost data are estimates. The capital costs of a membrane system to treat air emitted by an air stripper treating water at 190,000 gallon per day (132 gpm) is estimated to be $130,000, or $1,000/gpm.

The annual operating costs for the membrane system are estimated to be $33,000, which translates to $0.62/1,000 gallon of water treated. The treatment cost per pound VOC removed from the water is \$15/lb VOC, if the water contains 5 ppmw VOC, and \$75/lb VOC, if the water contains 1 ppmw VOC. The capital and operating costs of the membrane system are determined by the flow rate of air to be treated (and thus by the flow rate of the water treated by the air stripper) rather than by the VOC content of the air to be treated (and thus by the VOC content of the water treated by the air stripper). This characteristic makes membrane systems especially suited for the treatment of streams relatively concentrated in VOC.

Adams and Clark have performed a cost analysis that compares three different water treatment methods: (1) packed-tower air stripping, (2) packed-tower air stripping with vapor-phase activated carbon as air emission control, and (3) liquid-phase activated carbon treatment.[5] For most of the VOC contaminants examined, air stripping appears to be more cost effective than liquid-phase carbon treatment, even if vapor-phase carbon is used to treat the stripper air effluent. We will therefore compare membrane vapor separation with vapor-phase carbon adsorption as treatment techniques for air stripper air effluent streams.

The lowest vapor-phase carbon treatment costs are for carbon tetrachloride, with the estimates ranging from \$430/lb, if 0.084 lb/day is removed, to \$55/lb, if 84 lb/day is removed.[5] Figure 14 shows the cost of VOC removal from an air stripper effluent as a function of the VOC content of a 100,000 gpd water stream and compares vapor-phase carbon adsorption with membrane vapor separation. The carbon adsorption data are those estimated for carbon tetrachloride removal and thus represent minimum costs. The concentration range of 0.1 to 100 ppmw at 100,000 gpd corresponds to 0.084 to 84 lb/day. From Figure 14, it can be seen that membrane vapor separation yields lower treatment costs than carbon adsorption if the VOC content in the water stream is 1 ppmw or higher.

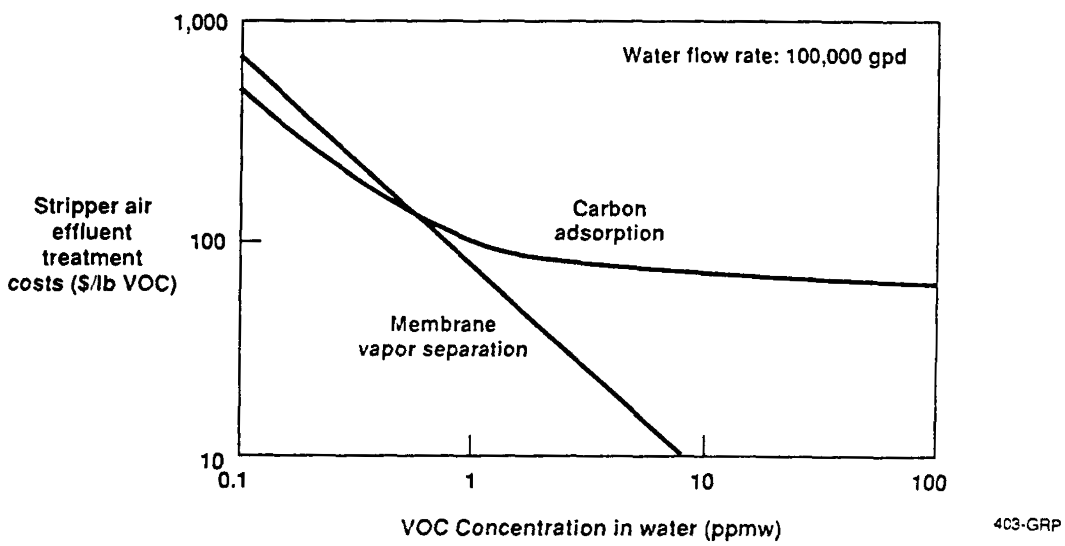

Figure 14. Cost of VOC removal from air stripper effluent as a function of the VOC content in a 100,000-gpd water stream. Data for the membrane system were determined by MTR; data for vapor-phase carbon adsorption are from Adams and Clark.[5]

4.2 Technology Integration Evaluation

The combined air stripper/membrane vapor separation concept has been demonstrated successfully in the pilot-scale experiments and is ready to be evaluated in the field. The development of the new technology is essentially completed.

Combined air stripper/membrane systems are an extension of conventional air strippers, which are the most cost-effective means of treating groundwater and surface waters contaminated with VOCs. The new technology can be used in two ways. First, a complete combined system can be installed at the start of a remediation project. Second, membrane vapor separation systems can be added to existing air strippers that are producing effluent air streams not in compliance with air-quality regulations.

Treatment of groundwater contaminated with VOCs is a common and ever-increasing necessity at DOE facilities and DOE sites, as well as many industrial sites. The results presented in this report justify further demonstration and evaluation of combined air stripper/membrane vapor separation systems as an efficient and cost-effective treatment method.

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6.0 ACKNOWLEDGEMENTS

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APPENDIX A.

EXPERIMENTAL RESULTS OBTAINED WITH COMBINED AIR STRIPPER/MEMBRANE SYSTEM

Table A1. Performance Data of Combined Air Stripper/Membrane Vapor Separation System Operating with Trichloroethylene (TCE) as Model Contaminant

Exp. no.	Param. setting	Air flow rate (scfm)	Water flow rate (gpm)	A/W volume ratio (-)	Water inlet conc. (ppmw)	Removal by stripper (%)	Air outlet conc. (ppmv)	Removal by membrane (%)
1	-	68	104	4.9	8.6	69	200	94
2	-	68	98	5.2	5.6	75	230	87
3	-	68	120	4.2	9.2	80	250	92
4	1	65	100	4.8	11	73	210	95
5	2	65	125	3.9	11	66	240	95
6	3	65	60	8.1	7.1	75	95	93
7	8	66	100	4.9	21	77	450	93
8	4	48	74	4.8	6.3	73	120	96
9	5	48	120	2.9	7.9	62	200	98
10	6	46	55	6.2	4.0	83	69	97
11	7	64	100	4.8	2.4	71	63	94
12	9	70	105	4.9	30	62	670	94
13	11	66	98	5.0	4.6	76	160	95

Table A2. Performance Data of Combined Air Stripper/Membrane Vapor Separation System Operating with Carbon Tetrachloride (CCl_4) as Model Contaminant.

Exp. no.	Param. setting	Air flow rate (scfm)	Water flow rate (gpm)	A/W volume ratio (-)	Water inlet conc. (ppmw)	Removal by stripper (%)	Air outlet conc. (ppmv)	Removal by membrane (%)
14	15	65	100	4.8	2.3	91	72	89
15	21	66	101	4.9	1.6	88	35	86
16	19	65	125	3.9	3.0	83	110	92
17	17	65	60	8.0	3.7	96	61	90
18	21	65	102	4.7	0.40	75	13	71
19	21	63	100	4.7	0.15	60	3.8	74
20	18	50	100	3.7	1.9	80	80	93
21	20	50	60	6.2	3.0	91	80	93
22	19	50	125	3.0	1.8	80	80	93
36	-	64	60	8.0	168	90	2,580	90
37	-	66	11	50	500	93	1,350	94

Table A3. Performance Data of Combined Air Stripper/Membrane Vapor Separation System Operating with 1,2-Dichloroethane (DCE) as Model Contaminant.

Exp. no.	Param. setting	Air flow rate (scfm)	Water flow rate (gpm)	A/W volume ratio (-)	Water inlet conc. (ppmw)	Removal by stripper (%)	Air outlet conc. (ppmv)	Removal by membrane (%)
23	-	67	100	5.0	9.6	18	77	94
24	-	65	60	8.1	7.8	29	63	92
25	-	63	62	7.6	3.5	21	26	90
26	-	63	62	7.6	0.5	12	2.8	71

Table A4. Performance Data of Combined Air Stripper/Membrane Vapor Separation System Operating with Chloroform ($CHCl_3$) as Model Contaminant.

Exp. no.	Param. setting	Air flow rate (scfm)	Water flow rate (gpm)	A/W volume ratio (-)	Water inlet conc. (ppmw)	Removal by stripper (%)	Air outlet conc. (ppmv)	Removal by membrane (%)
27	-	60	97	4.6	3.0	47	64	94
28	-	60	123	3.6	3.3	40	79	94
29	-	61	60	7.6	4.5	64	71	95
30	-	61	100	4.5	0.38	34	6.8	79

Table A5. Performance Data of Combined Air Stripper/Membrane Vapor Separation System Operating with Chloroform ($CHCl_3$)/Carbon tetrachloride (CCl_4)/Trichloroethylene (TCE) mixtures as Model Contaminant.

Exp. no.	Param. setting	Air flow rate (scfm)	Water flow rate (gpm)	A/W volume ratio (-)	Water inlet conc. (ppmw)	Removal by stripper (%)	Air outlet conc. (ppmv)	Removal by membrane (%)
31	49	60	100	4.5				
$CHCl_3$					0.62	24	16	89
CCl_4					0.14	83	6.3	92
TCE					0.26	58	9.4	95
TOTAL					1.0	41	32	91
32	43	60	100	4.5				
$CHCl_3$					2.2	36	46	92
CCl_4					0.85	86	30	92
TCE					1.5	64	43	92
TOTAL					4.5	55	119	92
33	44	57	123	3.5				
$CHCl_3$					3.4	33	62	94
CCl_4					1.0	83	42	94
TCE					1.8	59	58	93
TOTAL					6.3	49	162	94
34	45	57	59	7.2				
$CHCl_3$					2.1	63	35	94
CCl_4					1.2	97	23	94
TCE					1.8	88	34	94
TOTAL					5.1	79	92	94
35	-	70	100	5.2				
$CHCl_3$					2.7	36	43	90
CCl_4					1.1	80	30	90
TCE					1.8	53	41	89
TOTAL					5.6	50	114	90

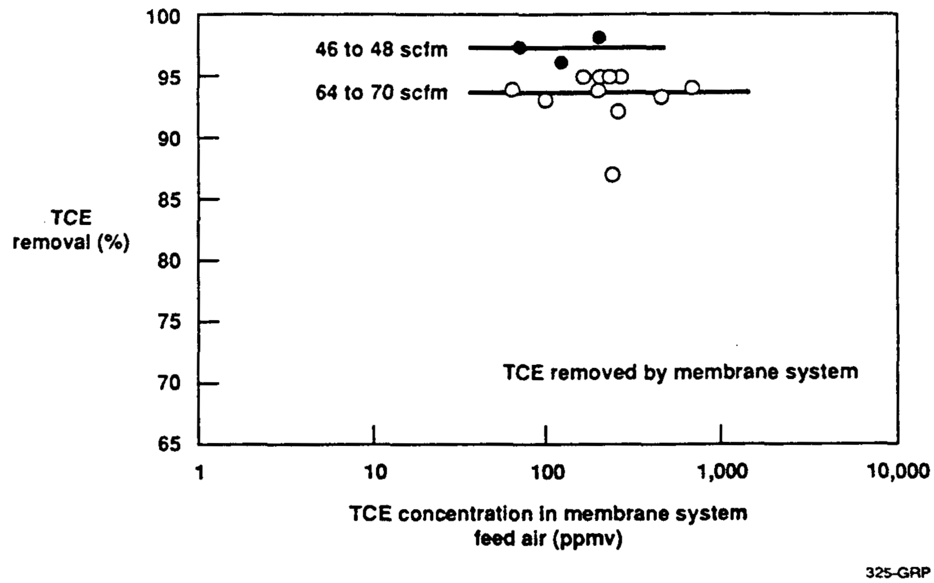

Figure A1. Trichloroethylene removal by membrane system as a function of the TCE concentration in the membrane system feed air for two different ranges of feed air flow rates.

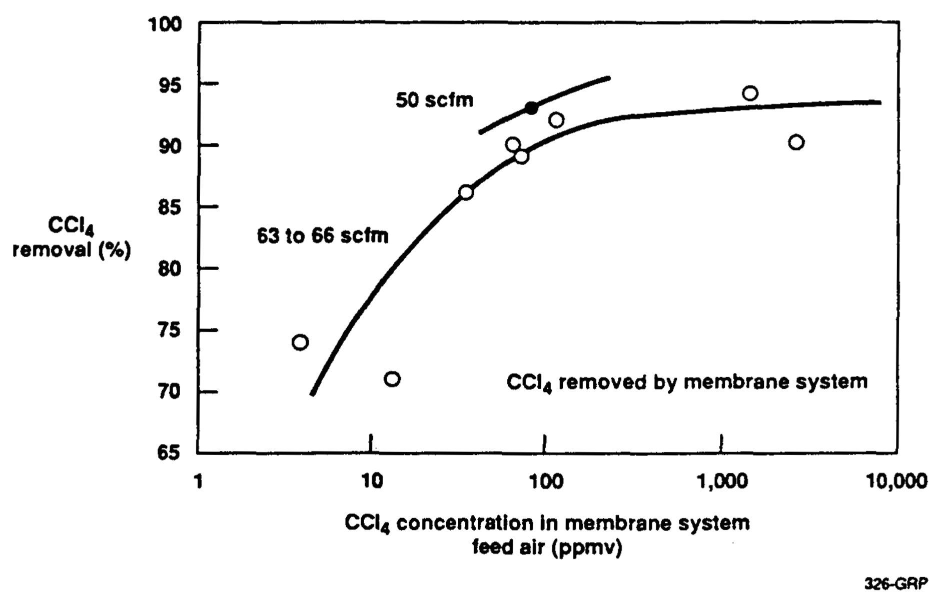

Figure A2. Carbon tetrachloride removal by membrane system as a function of the CCl_4 concentration in the membrane system feed air for two different ranges of feed air flow rates.

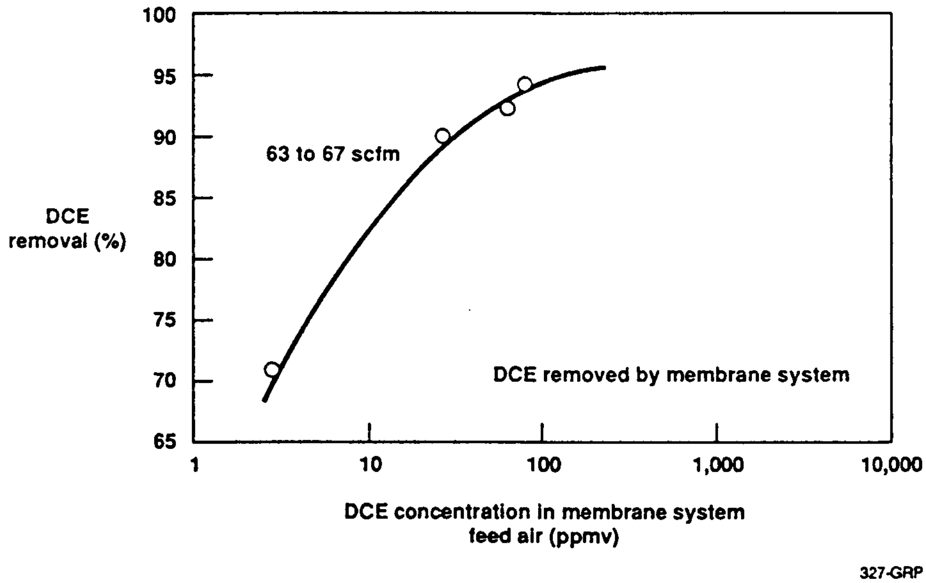

Figure A3. Dichloroethane removal by membrane system as a function of the DCE concentration in the membrane system feed air for one range of feed air flow rates.

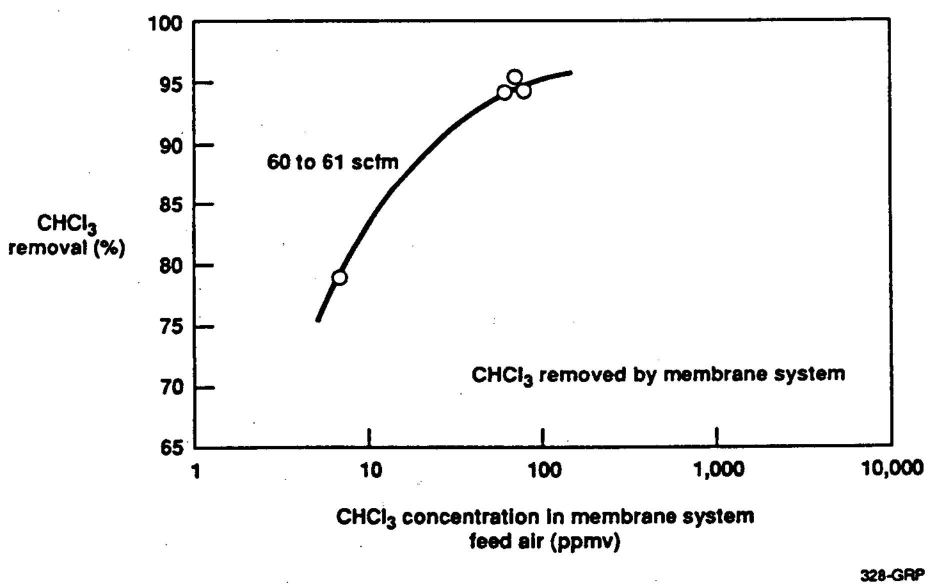

Figure A4. Chloroform removal by membrane system as a function of the $CHCl_3$ concentration in the membrane system feed air for one range of feed air flow rates.

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