United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-78-177
August 1978

Research and Development

EPA

Demonstration of Ultrafiltration and Carbon Adsorption for Treatment of Industrial Laundering Wastewater

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/2-78-177
August 1978

DEMONSTRATION OF ULTRAFILTRATION AND CARBON ADSORPTION FOR TREATMENT OF INDUSTRIAL LAUNDERING WASTEWATER

by

Myles H. Kleper
Robert L. Goldsmith
Arye Z. Gollan
Walden Division of Abcor, Inc.
Wilmington, Massachusetts 01887

Grant No. S-804367-01

Project Officer

Ronald Turner
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

This study was conducted in cooperation with the
Institute of Industrial Launderers
Washington, D.C. 20036

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Industrial Environmental Research Laboratory-Cincinnati, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

The results of a research and demonstration project for treating industrial laundry wastewaters using ultrafiltration - activated carbon treatment processes are presented herein. The principal treatment step was ultrafiltration (UF). The UF process concentrates suspended solids and emulsified oils while producing a high quality permeate stream. A portion of the UF permeate was then treated by activated carbon for removal of residual organics and color. It is hoped that the results of this study will aid industrial launderers and municipal treatment authorities in better understanding the problems unique to this industry and will encourage further research in this area.

The Organic Chemicals and Products Branch of the Industrial Pollution Control Division Industrial Environmental Research Laboratory - Cincinnati 45268 should be contacted for further information on this subject.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

The treatment of industrial laundering wastewaters by ultrafiltration (UF) and activated carbon adsorption (ACA) has been investigated. Three program tasks were performed:

Task 1: Pilot-scale testing at Abcor, Inc. facilities

Task 2: Pilot-scale testing at a field demonstration site

Task 3: Economic analysis of full-scale treatment systems.

All experiments were conducted with non-cellulosic spiral-wound UF modules.

This study of industrial laundry wastewater treatment by ultrafiltration and activated carbon adsorption has indicated that a consistently high quality product water, potentially reusable within the laundry, can be produced. The operation of the spiral-wound ultrafiltration modules was, however, hindered by the fouling tendency of the feed stream. Average module permeate flux was therefore low. This factor, in turn, resulted in high capital and operating cost estimates for full-scale treatment systems.

Successful feasibility tests with industrial laundering effluents were performed with the spiral-wound modules during Task 1. Average flux levels of 40-50 gal/ft^2-day (125^{o}F) and stable membrane performance were realized. Adsorption isotherms conducted with composite UF permeate samples indicated that carbon adsorption capacity for color bodies was quite good, whereas TOC adsorption was marginal.

In Task 2, field demonstration experiments with a 5000 gpd (nominal capacity) treatment system were conducted. Initial tests identified the need for prefiltration to prevent plugging of the spiral-wound modules by lint. A successful, but temporary and non-commercial, prefiltration step was developed for lint removal.

Subsequently, four 2-week demonstration tests were conducted. Although plugging by lint was eliminated, severe membrane surface fouling occurred and difficulty in recovering membrane flux using standard detergent cleaning procedures was encountered. UF membrane flux at system conversions ranging from 67% to 99% averaged 14 gfd (135^{o}F).

A slip-stream of UF permeate was continuously passed through a 2-inch diameter carbon column. Overall UF/ACA removal efficiencies were 99.2% for turbidity and 98% for oils and grease. Also, BOD, COD, and TOC removals were 82%, 86%, and 82% respectively.

Capital and operating cost estimates for treatment systems employing spiral-wound UF modules are, based on the low permeate flux, understandably high. For a 100,000 gpd treatment system (assuming 14 gfd flux and 98% water recovery), operating cost for the prefiltration and UF systems is estimated to be $9.01/1000 gal. Total carbon adsorption costs of $1.07/1000 gal could be offset by credits gained from reuse of the product water within the laundry. Reuse of this product water was not demonstrated during this program.

This report was submitted in fulfillment of the original scope-of-work for Grant No. S-804367-01 by the Walden Division of Abcor, Inc. under the sponsorship of the Institute of Industrial Launderers and the U.S. Environmental Protection Agency. The original grant was twice amended to include sampling and analysis for priority pollutants at industrial laundries and an assessment of sludge disposal alternatives for industrial launderies. Work on both of these amendments is ongoing and will be reported as addenda. This report covers the period from March 15, 1976 to March 14, 1977, and work was completed as of April 8, 1977.

CONTENTS

FIGURES

TABLES

ENGLISH-METRIC CONVERSION TABLE*

To Convert From	To	Multiply by
Inch	Meter	2.54×10^{-2}
Feet	Meter	3.05×10^{-1}
Square inch	Square meter	6.45×10^{-4}
Square feet	Square meter	9.29×10^{-2}
Cubic feet	Cubic meter	2.83×10^{-2}
Gallon	Cubic meter	3.79×10^{-3}
Pound	Kilogram	4.54×10^{-1}
Pound per sq. inch	Atmosphere	6.80×10^{-2}
Horsepower	Watt	7.46×10^{2}
Gallon per day	Cubic meter per day	3.79×10^{-3}
Gallon per minute	Cubic meter per day	5.45
Gallon per sq. ft-day	Cubic meter per sq. meter-day	4.10×10^{-2}
Gallon per minute per sq. ft.	Cubic meter per sq. meter-day	5.87×10^{1}

* The units most familiar to the projected readership of this report have been maintained.

ACKNOWLEDGMENTS

The efforts and dedication of Mr. Charles E. Humphrey, Research Coordinator of the Institute of Industrial Launderers, in maintaining program direction and in providing technical assistance to the authors is acknowledged.

The technical guidance of Mr. Mervyn Sluizer, Jr., and Mr. Manfred Tidor of the Institute of Industrial Launderers, and Mr. Ron Turner of EPA throughout the entire program is also gratefully acknowledged.

Roy F. Weston, Inc.,as consultants to the Institute of Industrial Launderers, served in a review capacity for this program.

The authors thank the management and staff of all the industrial laundries that participated in this program and are particularly grateful to the employees of Standard Uniform Rental Service, Dorchester, Massachusetts, for their helpfulness and support during the field demonstration program.

Ms. Cheryl Renaud prepared the draft of this report and Ms. Sharon Collins typed the final manuscript.

SECTION 1

INTRODUCTION

NATURE OF THE PROBLEM

Industrial laundries handle a variety of items, including uniforms, shop towels, printers towels, mops, mats and gloves. The wastewaters generated from the laundering of these items are of significant environmental impact in terms of both waste volume and contaminant loading. Although wastewaters from all laundry sources are reported to account for 5% to 10% of municipal sewer discharges the portion of these wastewaters attributable to industrial laundries is in the order to 0.5% (8). Industrial laundry wastewaters can be from 3 to 20 times higher in suspended solids and BOD than average domestic sewage (1).

Representative wastewater contaminant data for a typical industrial laundry operation (1) are presented in Table 1, along with the sewer discharge limits set by the City of Chicago, where this plant is located. In addition to high suspended solids and BOD loadings, the levels of oil and grease, lead, and mercury in the plant effluent are in excess of the Municipal Discharge Standards. Other characteristics of industrial laundering effluents are:

- -- both flow and composition are highly variable, over both short-term (minutes to hours) and long-term (days to months) operations, and
- -- the emulsions are very stable chemically.

It is apparent from these observations that this industry will require a stable treatment system highly efficient in waste removal to meet sewer discharge standards.

CURRENT TREATMENT

One of the most thoroughly investigated methods of treating commercial laundry wastewaters consists of coagulation and flocculation followed by dissolved air flotation with polishing of the underflow by sand or diatomaceous earth (DE) filtration and dewatering of the flotation scum by vacuum filtration (1). Though this sequence was found acceptable for

TABLE 1. LAUNDRY WATER CONTAMINANT LEVELS FOR ONE TYPICAL PLANT AND ITS SEWER DISCHARGE STANDARDS (1)

Contaminant	Range in Waste Sampled Over 3 Mos.	Average Levels in Waste	Typical Sewer Discharge Standards
Total solids, mg/l	4,900-8,600	6,800	---
Suspended solids, mg/l	650-5,000	2,800	300*
Total dissolved solids, mg/l	---	4,000	---
BOD, mg/l	650-1,300	830	300*
TOC, mg/l	1,000-6,300	2,500	---
Hexane extractables,** mg/l	400-3,800	1,500	100*
pH, units	10.2- 11.9	---	4.5-10
Alkalinity, ppm $CaCO_3$	---	325	---
Total Chromium, mg/l	1.0- 3.6	2.3	25
Copper, mg/l	0.2- 9	4.0	3.0
Lead, mg/l	3.0- 36	12.7	0.5
Zinc, mg/l	0.6- 9	3.9	15.0
Cadmium, mg/l	0 - 0.6	0.24	2.0
Iron, mg/l	3.5-126	40	50
Nickel, mg/l	1.0- 2.5	1.6	10
Mercury, mg/l	1.2- 7.0	3.3	0.0005

* Surcharge assessed based on mass discharge above acceptable limitation and not concentration.

** Oil and Grease

uniform and linen laundry wastewater, it could not consistently produce an effluent meeting municipal sewer standards when processing industrial laundry wastes.*

The ranges of removal efficiencies by the flotation portion of the treatment system alone and the flotation/DE filter combination are given in Table 2 for industrial laundry wastewater processing. Although very good quality water can be achieved by the dissolved air flotation/filtration scheme, the inconsistency of this system in treating the highly variable industrial laundering effluents is evident from these data. Therefore, even with this method of treatment, industrial launderers might periodically incur municipal sewer surcharges for suspended solids and BOD above those normally present in domestic sewage. Heavy metals may have to be removed completely according to local ordinances and the capacity of municipal treatment facilities. Annual operating costs without these surcharges were estimated at $2.70/1000 gal if chemicals were supplied in bulk.

A dissolved air flotation scheme employing an electrolytic process that involves an electrocoagulation cell followed by an electro-flotation basin was tested at an industrial laundry for 7 days (8 hours per day) (2). Maximum suspended solids, BOD, and hexane extractible reductions of 92%, 86%, and 94%, respectively, were observed. Though reported power and chemical costs for this system are low ($0.66/1000 gal) no estimation was made of the cost for operating labor. This cost could be quite high because of the constant variability of the waste. Waste equalization can potentially lower the labor cost. A trade off must be made, however, between reduced operating costs and the high space requirement for holding tanks.

TREATMENT APPROACH SELECTED FOR EVALUATION

The overall goal of this program was to develop an economically viable wastewater treatment system which could consistently produce an effluent meeting municipal sewer discharge standards. The method of industrial laundry wastewater treatment investigated was ultrafiltration (UF) followed by activated carbon adsorption (ACA). Ultrafiltration is the principal unit process. The UF system concentrates suspended solids and high-molecular weight solutes, producing two streams: a purified product water (permeate) and a concentrate. Typically, the concentrate volume is 1% to 5% of the influent volume. Further treatment of the UF permeate, principally for removal of residual low molecular weight organics (i.e., dissolved detergent, dyes, and solvents), is achieved by adsorption on activated carbon.

---

*As defined in reference (1), an industrial laundry washes mostly shop towels, printers towels, and dust mops, which results in wastewater contamination that is abnormally high compared to other laundry types.

TABLE 2. RANGES OF WASTE TREATMENT EFFICIENCIES FOR A CONVENTIONAL INDUSTRIAL LAUNDRY WASTE TREATMENT SYSTEM (1)

Parameter	Range in Waste Sampled Over 3 Months (mg/l)	Range of % Removal by Flotation	Range of % Removal of System
BOD	650 -1,300	0-67	48-73
TOC	1,000 -6,300	0-93	54-95
Suspended Solids	650 -5,000	38-98	79-99
Total Solids	4,900 -8,600	0-54	5-57
Hexane Solubles	400 -3,800	0-95	34-99
Copper	0.2- 9	0-93	0-98
Lead	3.0- 36	17-99	40-99
Mercury	1.2- 7.0	0-91	33-91
Cadmium	0- 0.6	0-95	0-95
Zinc	0.6- 9	36-99	89-99
Total Chromium	1.0- 3.6	0-73	0-88
Iron	3.5-126	62-99	85-99
Nickel	1.0- 2.5	0-70	0-80

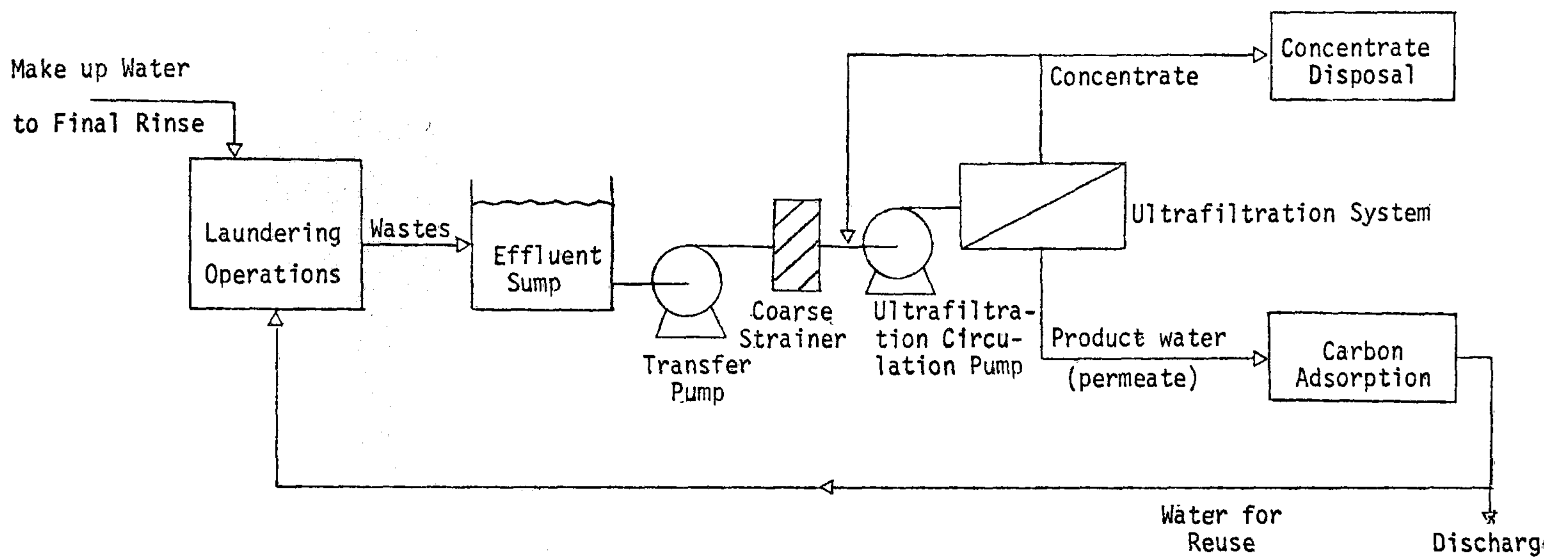


Figure 1. Generalized process flow schematic.

A generalized flow schematic of this treatment process is given in Figure 1. Laundry wastes flow into a sump and are transferred through a strainer to the ultrafiltration system. The strainer removes coarse solids and lint that could plug pumps, valves, and controllers. The strained feed stream is recirculated within the UF membrane loop. A small concentrate stream is continually bled off, and a permeate stream, essentially free of suspended solids, is continuously produced. The permeate is passed directly into a column packed with granular activated carbon. The carbon-column effluent is potentially suitable for reuse within the laundry.

Features of the ultrafiltration/activated carbon treatment approach are:

- Ultrafiltration is largely insensitive to waste shock loads. Since the bulk of the contaminant removal is in the ultrafiltration step, the overall process will be shock insensitive.
- No chemicals are added. This eliminates both chemical costs and chemical handling equipment. Also, operating and maintenance labor requirements associated with chemical addition are eliminated. Membrane systems will operate successfully in the pH range 0.5 to 13 and in the presence of free chlorine (up to 50 ppm).
- The effluent from the system will be essentially free of suspended solids and will have a low organic content. With regard to these contaminants, a reusable water will be available.
- Dissolved inorganics will tend to build up in the system to a steady state level. This will be established when the rate of addition of salts in makeup water, detergent formulations, and soiled articles equals the rate of removal in the ultrafiltration concentrate. It may be desirable to reformulate detergents to have a lower builder content and/or to demineralize the makeup water.
- Heavy metals (except hexavalent chromium and mercury) may be efficiently removed in the ultrafiltration step. This is because the metals may be insolubilized by reaction with anionic detergents and do not pass through the ultrafiltration membrane.
- There is no need to cool the waste before treatment. The hotter the effluent the better the ultrafiltration system will perform at the temperature levels encountered in laundry wastewaters. Temperature will have only a minimal effect on carbon adsorption efficiency. Thus the overall process will conserve the sensible heat of the water for reuse, providing a major process credit.
- A total package system will be compact and easy to install.

SECTION 2

CONCLUSIONS

This study of industrial laundry wastewater treatment by ultrafiltration and activated carbon adsorption has indicated that a consistently high quality product water, potentially reusable within the laundry, can be produced. However, the performance of the spiral-wound ultrafiltration modules was unacceptable due to membrane fouling by oil and grease and the ineffectiveness of standard membrane cleaning procedures. Average module permeate flux was therefore low. This factor, in turn, resulted in high capital and operating cost estimates for full-scale treatment systems.

Specific conclusions reached during this program are:

1. Contaminant Removal Efficiencies

   - The overall UF/ACA product water averaged <17 mg/l suspended solids, 190 mg/l BOD, 353 mg/l COD, 123 mg/l TOC, and <9 mg/l total freon extractibles. An effluent of this quality indicates average removal efficiencies for the treatment process of >96% for suspended solids, >97% for freon extractibles (oil and grease) and 82%, 86%, and 82% for BOD, COD, and TOC, respectively. An effluent of this quality should be acceptable for discharge to municipal sewer systems. Based on local ordinances, a surcharge may be applied if the mass discharge of BOD and suspended solids exceed acceptable limits.

   - Metals removal by the UF/ACA process was, in general, calculated from the lower detection limit values of the assays. All metals of interest, except mercury, were removed to levels below those specified in the sewer ordinances of the Metropolitan Sanitary District (MSD) of Greater Chicago.

2. Membrane Flux

   - Severe membrane fouling by free oil occurred for the three types of spiral-wound modules evaluated. A variety of membrane cleaning techniques was largely ineffective in restoring membrane flux.

   - Of the three spiral-wound module feed-side spacers and two UF membrane materials investigated, the best performance was obtained with Abcor, Inc. Type HFM membranes in open-spacer spiral-wound modules. For these, average permeate flux was 14 gal/sq. ft.-day (gfd) [135°F] during eight weeks of tests at system conversions of 67% to >99%. A flux level of this magnitude is not economically acceptable for treatment of industrial laundry wastewaters.

- It is doubtful if a spiral-wound membrane configuration can withstand prolonged operation in an industrial laundry. A membrane configuration, which is less susceptible to fouling and more amenable to cleaning, e.g., tubular, is clearly required.

3. Estimated Process Costs

- Assuming stable performance could be achieved at an average flux of 14 gfd, spiral-wound UF system and pretreatment operating costs are estimated to range from $11.82/1000 gal when processing 25,000 gpd to $9.01/1000 gal when processing 100,000 gpd.

- The activated carbon's adsorptive capacity for color bodies is greater than its adsorptive capacity for TOC. Breakthrough curves developed for color indicate a carbon replacement cost of $0.85/1000 gal.

SECTION 3

RECOMMENDATIONS

On the basis of the knowledge gained during this program, the following recommendations for future work are offered:

- No further ultrafiltration work should be conducted with spiral-wound membrane modules.
- The flux performance of tubular UF assemblies should be evaluated to verify or amend the capital and operating cost projections developed for the tubular configuration. If a flux rate of 40 gfd is assumed for tubular UF modules rather than the 14 gfd observed for spiral-wound modules, estimated operating costs become $4.88, $2.82, and $2.57/1000 gal for treatment systems of 25,000, 75,000, and 100,000 gpd, respectively. For the 100,000 gpd system, operating costs for tubular systems are predicted to be $2.39/1000 gal because of advances in membrane technology expected in the next 2 to 4 years.
- In conjunction with a tubular UF evaluation, an engineering and economic survey of UF concentrate disposal options should be performed. For higher capacity UF systems, concentrate disposal by contract hauling was calculated to be as high as 17% of the UF system operating costs. Significant reductions in this cost could greatly enhance the economics of the entire treatment system.
- Should tubular UF prove to be economically viable, the suitability of the final UF/ACA product water for reuse must be evaluated.

SECTION 4

DISCUSSION OF UNIT PROCESSES

The purpose of this section is to set forth certain principles and definitions which will be used in subsequent sections. Many general references are available which describe the relevant unit processes in more detail.

ULTRAFILTRATION

Ultrafiltration and reverse osmosis (RO) are similar processes in that both employ a semipermeable membrane as the separating agent and pressure as the driving force to achieve separation. There are important differences, however, which lead to different applications, process conditions and equipment for each of the two processes. Although the approach in this program is based on ultrafiltration, the differences between UF and RO are presented in Table 3 to aid reader understanding of the subject matter.

In an ultrafiltration process a feed solution/suspension is introduced into a membrane unit, where water and certain solutes pass through the membrane under an applied hydrostatic pressure. Solutes whose sizes are greater than the pore size of the membrane and all suspended solids are retained and concentrated. The pore structure of the membrane thus acts as a molecular filter, passing smaller size solutes and retaining the larger size solutes. The pore structure of this molecular filter is such that it does not become plugged because suspended solids are rejected at the surface and do not penetrate the membrane.

For solutions which have no rejected species, such as water, the flux through the membrane is given by:

$$J_o = \frac{\Delta P}{R_m + R_f} \qquad (1)$$

where,

J_o = Flux rate (gal/ft^2-day)

ΔP = Pressure drop across the membrane (pressure driving force) (psig)

R_m = Resistance of clean membrane (ft^2-day-psig/gal)

R_f = Resistance of fouling layer (ft^2-day-psig/gal)

TABLE 3. DIFFERENCES BETWEEN REVERSE OSMOSIS AND ULTRAFILTRATION

Item	Reverse Osmosis	Ultrafiltration
Size of solute retained	Molecular weights generally less than 500 High salt retention	Molecular weights generally over 1000 Nil salt retention
Osmotic pressures of feed solutions	Important, can range to over 1000 psig	Negligible
Operating pressures	Greater than 400 psig, up to 2000 psig	10 to 100 psig
Nature of membrane retention	Diffusive transport barrier; possibly molecular screening	Molecular screening
Chemical nature of membrane	Important in affecting transport properties	Unimportant in affecting transport properties so long as proper pore size and pore size distribution are obtained
Typical membrane flux levels	2 to 15 gal/day-ft^2	20 to 200 gal/day-ft^2

No material from the process stream builds up on the membrane surface and, therefore, for water the flux is pressure dependent and flow independent.

When ultrafiltering solutions having high concentrations of rejected material, the observed flux levels are much lower than the water flux of the clean membrane. A gel layer develops and the following equation applies:

$$J_1 = AQ^x \ln \frac{C_g}{C_b} \qquad (2)$$

where,

J_1 = Flux rate

A = A constant which is a function of feed channel dimensions and fluid properties

C_g = Concentration of rejected species in the gel layer

C_b = Concentration of rejected species in the bulk solution

Q = Circulation rate of fluid through the membrane modules (gpm)

x = Empirical constant (generally $1 < x < 2$)

ln = Natural logarithm

For solutions with high concentrations of rejected materials, the flux is pressure independent (above ~10 psig) and flow dependent.

The removal efficiency, r, of a UF module for a given species is defined by the relationship:

$$r = \frac{C_f - C_p}{C_f} \; (100\%) \qquad (3)$$

where C_f and C_p are the feed and permeate concentrations for a module operated with significant water recovery.

COMMERCIALLY AVAILABLE ULTRAFILTRATION MEMBRANES AND MODULES

Industrial ultrafiltration membranes are classified by molecular weight cut-off, and are available from either cellulosic or non-cellulosic materials. The cellulosic membranes can be employed at pH 2.5 to 9, while the ranges for others vary. For example, Abcor, Inc.'s non-cellulosic Type HFD membrane has a pH tolerance range from 3 to 12 and can withstand operating temperatures in excess of 165°F. This membrane is, however, sensitive to oxidation by free-chlorine. Abcor Inc.'s Type HFM non-cellulosic membrane can tolerate up to 50 ppm free-chlorine, has a pH range of 0.5 to 12 and can operate at up to 185°F.

Four module configurations are available commercially to house the ultrafiltration membranes. These are plate-and-frame, tubular, spiral-wound, and hollow-fine-fiber (tubeside feed) geometries. For treatment of industrial laundry wastes the tubular and spiral-wound geometries are judged to be most suitable in terms of both process reliability and system expense.

A tubular membrane, as shown in Figure 2, consists of a porous tubular support with the membrane either cast in place, or inserted into the support tube. The feed solution is pumped through the tube; the concentrate is removed downstream; and the permeate passes through the membrane/porous support composite.

A spiral-wound module is shown in Figure 3. It consists of a large membrane sheet(s) wound into a compact spiral configuration around a central permeate collector tube. The feed solution is passed over one side of the sheet, and the permeate is withdrawn from the other side.

Each module configuration has particular advantages and disadvantages which are summarized in Table 4. Tubular membranes are desirable in that they can process feeds containing high suspended solids with minimal pretreatment, and can be easily cleaned, either chemically or mechanically, if they become fouled. Spiral-wound modules are less expensive than tubular modules in dollars/sq. ft of membrane area, generally have lower power requirements, and are more compact. Spiral-wound modules are, however, more susceptible to plugging and may be difficult to clean. Because of their potential cost savings, spiral-wound modules were chosen for testing in this program.

TABLE 4. COMPARISON OF MEMBRANE CONFIGURATIONS OF INTEREST FOR INDUSTRIAL LAUNDRY WASTE TREATMENT SYSTEMS

Configuration	Advantages	Disadvantages
Tubular	1. easily cleaned chemically or mechanically if membranes become fouled	1. high holding volume required per unit membrane area
	2. can process dirty feeds with minimal pretreatment	2. moderately expensive at present
	3. individual tubes can be replaced	
Spiral-wound	1. compact-good membrane surface to volume ratio	1. susceptible to plugging by particulates
	2. less expensive than tubular membranes	2. badly fouled membranes are difficult to clean

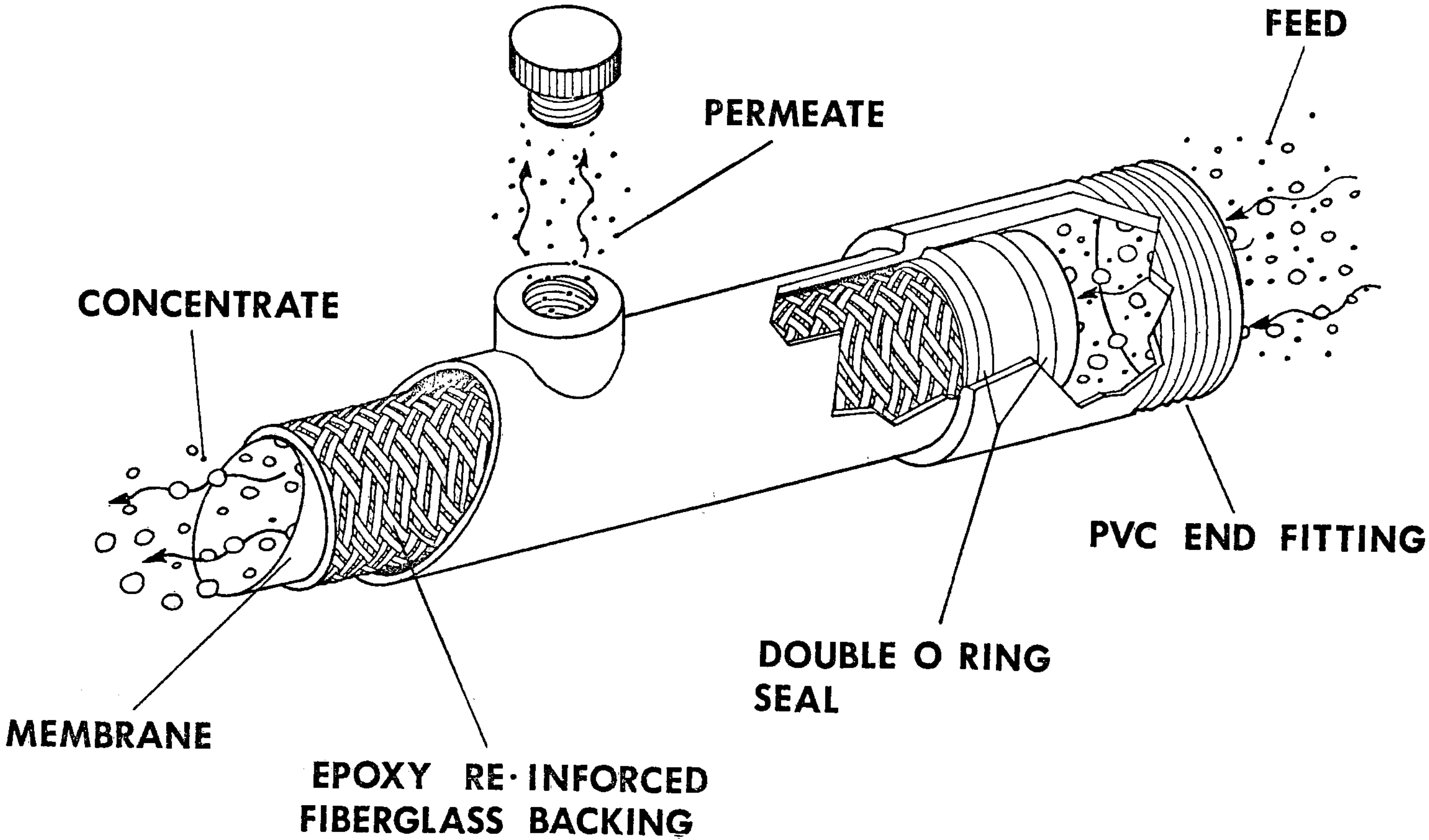


Figure 2. Cut-away view of tubular ultrafiltration assembly.

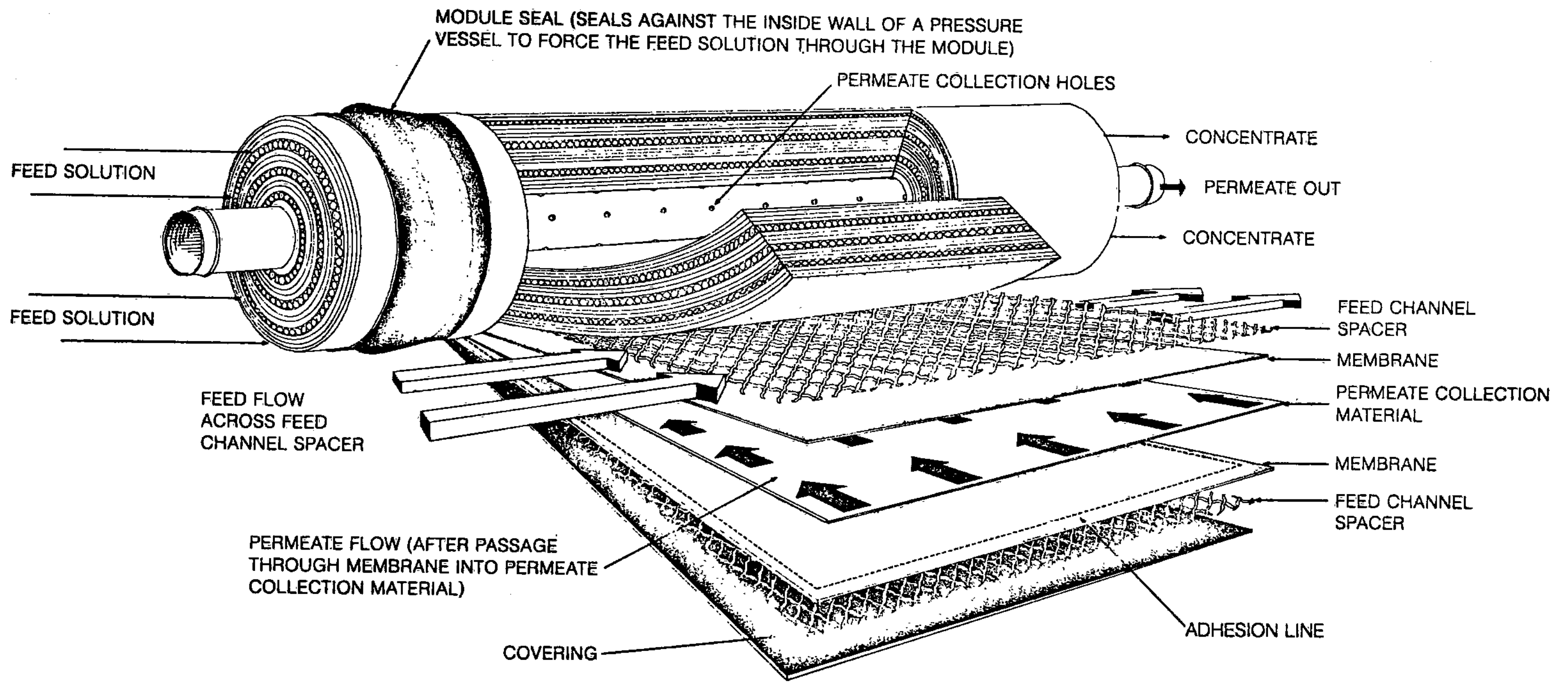


Figure 3. Cut-away view of spiral-wound ultrafiltration module .

Three different types of spiral-wound modules are currently available. The difference between them is the spacer geometry employed on the feed flow channel side. The module depicted in Figure 3 utilizes a Vexar spacer. The Vexar material is a 1 mm (nominal) turbulence promoting spacer. Corrugated spacer material consists of 2 mm (nominal) corrugation. Open-spacer feed channels have a 4 mm (nominal) mesh-like geometry similar to the Vexar design.

Of the three spacer geometries, the narrow Vexar spacing is the most susceptible to plugging by suspended solids, while the open-spacer material is the least susceptible to plugging. Should one passage within a Vexar or open-spacer module become plugged, the feed solution can bypass that passage and little effective membrane area is lost. However, with corrugated spacer modules, once a feed channel becomes plugged the entire membrane area along that channel is lost.

One significant advantage of Vexar spacer modules over the corrugated and open-spacer modules is their lower power requirement. Vexar modules operate with feed circulation rates of 10 to 20 gpm, while the other spiral-wound module types require 50 to 100 gpm circulation flow.

The three different type spacers produce different feed flow patterns within a module thus influencing ultrafiltrate flux. Also, the width of the spacer material controls the membrane surface area per module. For commercial-scale modules (4-inch diameter x 36 inches long) the membrane surface area is 40 ± 2 sq. ft. for the Vexar spacer spirals, 34 ± 2 sq. ft. for the corrugated spacer spirals and 18 ± 2 sq. ft. for the open-spacer spirals.

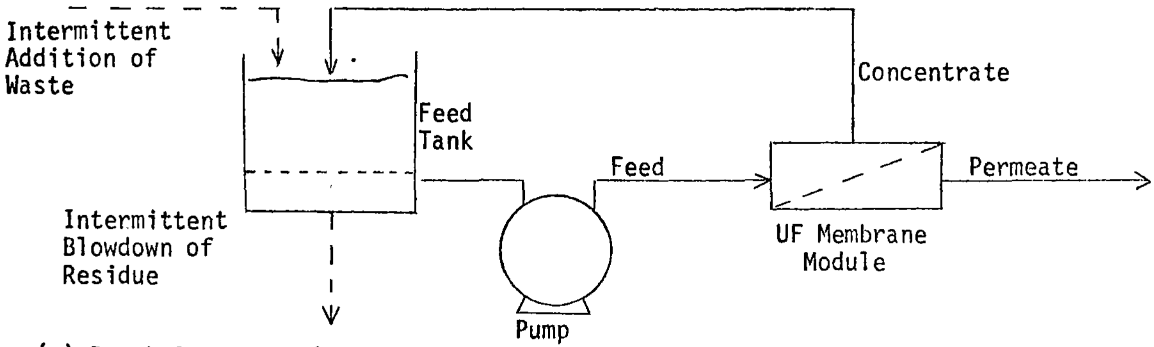
SYSTEM DESIGNS FOR ULTRAFILTRATION EQUIPMENT

Three common ultrafiltration system designs are shown in Figure 4. In the batch concentration mode of operation (Figure 4a), the feed tank is charged with waste only at the beginning of each concentration cycle. During operation the permeate is continuously withdrawn while the concentrate is recycled to the feed tank. As the run proceeds the volume of waste in the feed tank decreases, and its concentration increases. When the volume of waste is sufficiently low, it is discharged and a fresh batch of waste is charged to the feed tank. The degree of volumetric concentration is given by

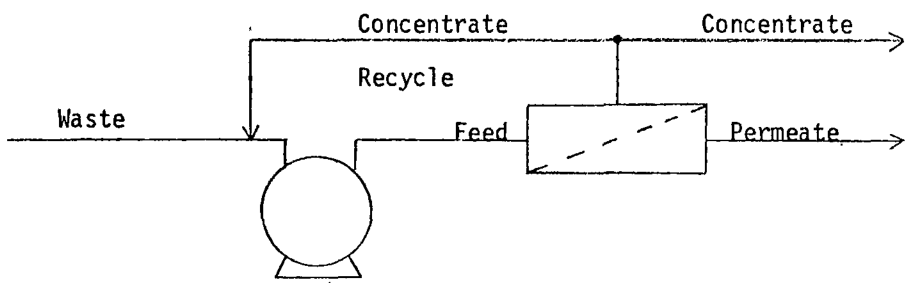
$$C_v = \frac{V_o}{V_o - V_p} \qquad (4)$$

where V_o and V_p are the initial batch volume and the collected permeate volume, respectively. The degree of volumetric concentration, C_v, is related to the overall water recovery, by the relationship

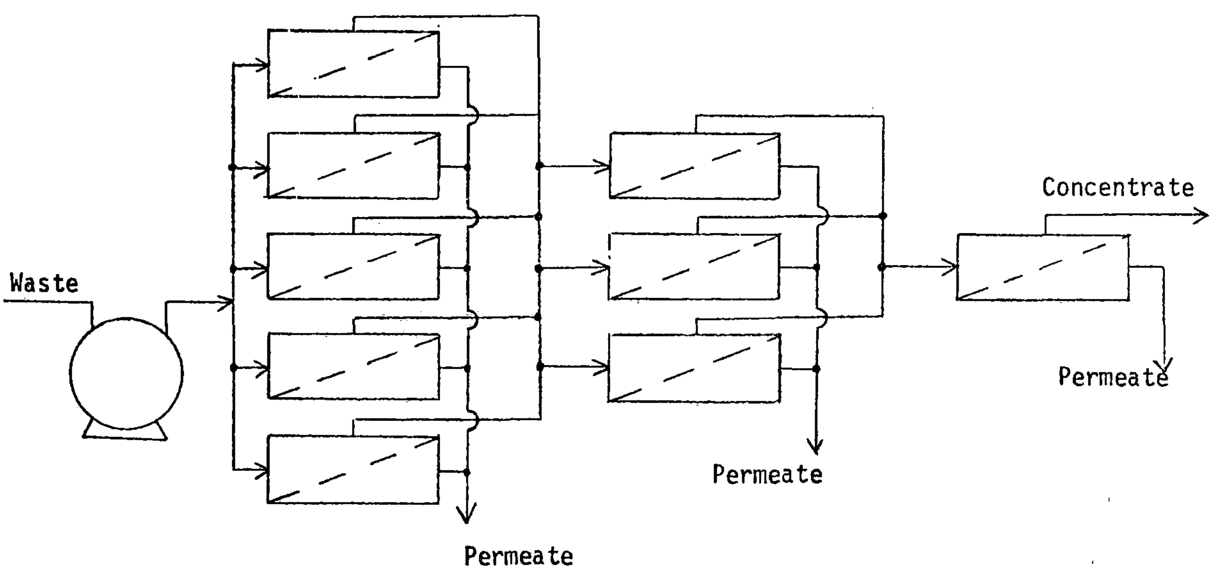
$$y\ (\%) = \left(1 - \frac{1}{C_v}\right) \quad 100 \qquad (5)$$



(a) Batch Concentration



(b) Continuous Feed and Bleed



(c) Continuous Staged; Once-Through

Figure 4. Various system designs for modular membrane equipment.

Corresponding values of the volumetric feed concentration and the system water recovery are shown below.

C_v	Equivalent Water Recovery (%)
1X ($V_p = 0$)	0
2X	50
10X	90
20X	95
50X	98
100X	99

There are three advantages to the batch concentration mode of operation:

1. Feed circulation rate within the modules can be adjusted to control membrane fouling and/or concentration polarization.
2. High system conversions can be obtained by concentrating to a very low residual volume.
3. The average feed concentration over the batch concentration is minimized (compared to other modes of operation) resulting in a maximum time-averaged module flux and rejection over the concentration cycle.

The disadvantages of this mode relate to its intermittent nature of operation. Since it is not continuous, it requires large holding tank capacity and somewhat more operator time than the other modes.

The continuous feed and bleed mode of operation is shown in Figure 4b. The advantages of this mode are:

1. It is continuous.
2. Feed circulation can be adjusted to control concentration polarization.
3. High system conversions can be obtained.

The disadvantages of this mode is that the system is operated at the concentration level of the concentrate stream. Thus, the average flux and rejection will be low relative to that of the batch concentration mode.

For sufficiently large systems continuous once-through operation, shown in Figure 4c, is preferred. This mode combines the advantages of both the batch and the feed-and-bleed modes of operation. The feed passes through each module in a single-pass which minimizes the average feed concentration and achieves maximum utilization of the modules in terms of flux and rejection. In this mode, operation is continuous and a high overall system conversion can be obtained.

The preferred mode of operation for any given application may be a modified form of one of these three more common modes. The operating mode selection depends upon UF feed flow conditions, membrane flux, water recovery desired, membrane cleaning frequency, etc.

CARBON ADSORPTION

Adsorption by activated carbon is a surface phenomenon in which dissolved organics are removed from wastewater and concentrated at the carbon-liquid interface. The degree of adsorption which occurs is a combination of solute solubility in the wastewater and the strength of the attractive forces between the solute and the carbon. The more hydrophilic the organic, the less likely it is to move toward the carbon-water interface. Thus, highly soluble organics tend to be poorly adsorbed by carbon; whereas less solute organics are more highly adsorbed.

Activated carbon is a highly porous material which is characterized by a typical surface area yield of 1000 m^2/gram. Since adsorption is a surface phenomenon, activated carbon has the potential (depending on the nature of the dissolved organics) to be a highly-effective, economical unit process for improving water quality.

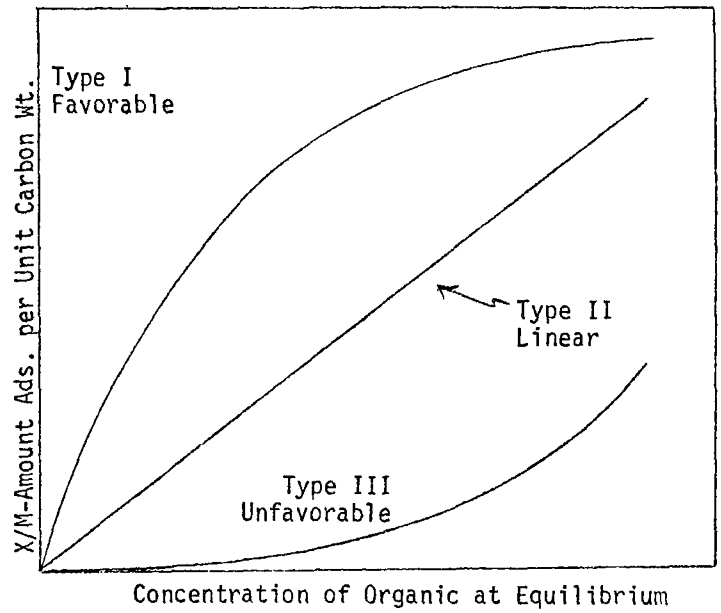
There are two important factors in the evaluation of carbon adsorption: the amount of organic adsorbed at equilibrium and the rate at which equilibrium is attained. The equilibrium uptake is usually expressed by an "adsorption isotherm". The isotherm is a plot of the weight of organic adsorbed per unit weight of carbon (X/M) versus the organic concentration in the waste (C) when equilibrium is established at a constant temperature. Three types of hypothetical isotherms are shown in Figure 5a. Type II is a linear isotherm over the region of interest. Type I is a favorable isotherm since the adsorptive capacity of the carbon remains high at low feed concentrations. This results in lower carbon dosages for a given organic removal. Type III is an unfavorable isotherm since uptake at a given concentration is low requiring a high carbon dosage for a given organic removal.

A number of mathematical expressions have been proposed (3) to describe the shape of the isotherm. The most generally applicable expression is the Freundlich adsorption equation:

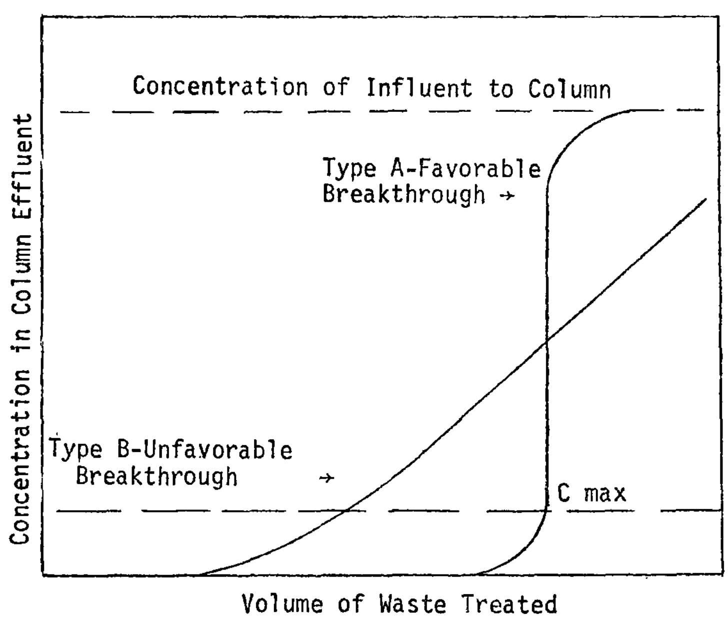
$$\frac{X}{M} = kC^{1/n} \tag{6}$$

where,

X = amount of organic adsorbed
M = weight of carbon
k = constant
n = constant
C = concentration of unadsorbed organic in surrounding solution at equilibrium



a) Types of Adsorption Isotherms



b) Types of Breakthrough Curves

Figure 5. Hypothetical isotherms and breakthrough curves for carbon adsorption.

Restating this equation in logarithmic form,

$$\log\left(\frac{X}{M}\right) = \log k + \left(\frac{1}{n}\right) \log C \quad (7)$$

A plot of X/M vs. C on logarithmic paper will yield a straight line with slope 1/n if the Freundlich isotherm is followed.

Little progress has been made for liquid systems in predicting the isotherm from the properties of the carbon and organic. Therefore, isotherms must be determined experimentally for each waste-carbon combination. The Freundlich expression given by Equations (6) and (7) is useful for correlating the experimental data.

In a practical system, the amount of contaminant removed may be limited by the rate of adsorption, in addition to the equilibrium uptake. The transport of a dissolved organic molecule from the bulk solution to attachment at an adsorption site on the carbon can be broken into three consecutive steps:

- diffusion through the liquid film surrounding the carbon particle,
- diffusion through the carbon pores to an available adsorption site, and
- adsorption.

In principle any of these sequential steps could limit the observed rate of adsorption. However, in practice, adsorption is very fast relative to diffusion. For fixed bed contactors operated at normal velocities, film diffusion is generally the rate limiting step (4).

The effect of adsorption rate on the performance of a carbon column is to govern the shape of the breakthrough curve. The breakthrough curve is a plot of the concentration of contaminant in the column effluent as a function of the volume of waste treated. Two hypothetical breakthrough curves are shown in Figure 5b. The favorable Type A curve makes much better use of the adsorptive capacity of the carbon before the quality of the effluent exceeds the maximum allowed concentration (C_{max}). A sharp breakthrough curve is obtained when the rates of film and pore diffusion are fast relative to the linear velocity of the waste through the column. Generalized correlations are available (5,6) for the prediction of the shape of the breakthrough curve. Factors influencing the shape include: linear velocity of the waste, diameter of carbon particles, film diffusion coefficient, pore diffusion coefficient, and isotherm shape. For complex wastes, such as industrial laundry wastes, the breakthrough curve must be determined experimentally.

Both the adsorption rate and capacity of the carbon can be adversely affected by the presence of particulates in the feed. These tend to coat the carbon particles reducing access to the internal porous structure. Therefore, pretreatment (usually by depth filtration) is required for suspended solids removal.

For system capacities of interest to industrial launderers carbon regeneration would be performed off-site.

SECTION 5

PROGRAM OVERVIEW

The program for evaluating ultrafiltration and carbon adsorption treatment of industrial laundry wastewaters was divided into three program tasks:

- Task 1: Pilot-scale Testing at Abcor, Inc.'s Facilities
- Task 2: Pilot-scale Testing at a Field Demonstration Site
- Task 3: Economic Analysis of Full-scale Treatment Systems

All UF experiments were performed with spiral-wound modules manufactured by Abcor, Inc. Carbon adsorption testing was conducted with Filtrasorb 400, a general purpose granular activated carbon, produced by Calgon Corporation.

In Task 1 three actual industrial laundry wastewaters, each from a different source and each representing a different strength industrial load, were processed by ultrafiltration modules at Abcor's pilot laboratory. Two membrane types and two module feed-side spacers were evaluated to select the preferred membrane/module combination for field testing. Composite samples of the ultrafiltrates were further treated with granular activated carbon in isotherm experiments.

The Task 2 field demonstration was conducted at Standard Uniform Rental Service, Dorchester, Massachusetts. The average wastewater from this plant was considered to be of a "light" to "medium" industrial loading. Initial work under Task 2 consisted of test system design, construction, installation, and shakedown testing. Several preliminary experiments and four two-week concentration cycles were performed with the 5000 gpd (nominal) test system. A slip stream of UF permeate was continuously drawn off and passed through a two-inch diameter column for ACA treatment.

Based on the results of the Task 2 studies, the economics of full-scale treatment systems were analyzed. This third program task developed capital and operating cost estimates for industrial laundries discharging 25,000, 75,000 and 100,000 gpd.

SECTION 6

TEST SYSTEMS, PROCEDURES, AND ANALYSES

ULTRAFILTRATION

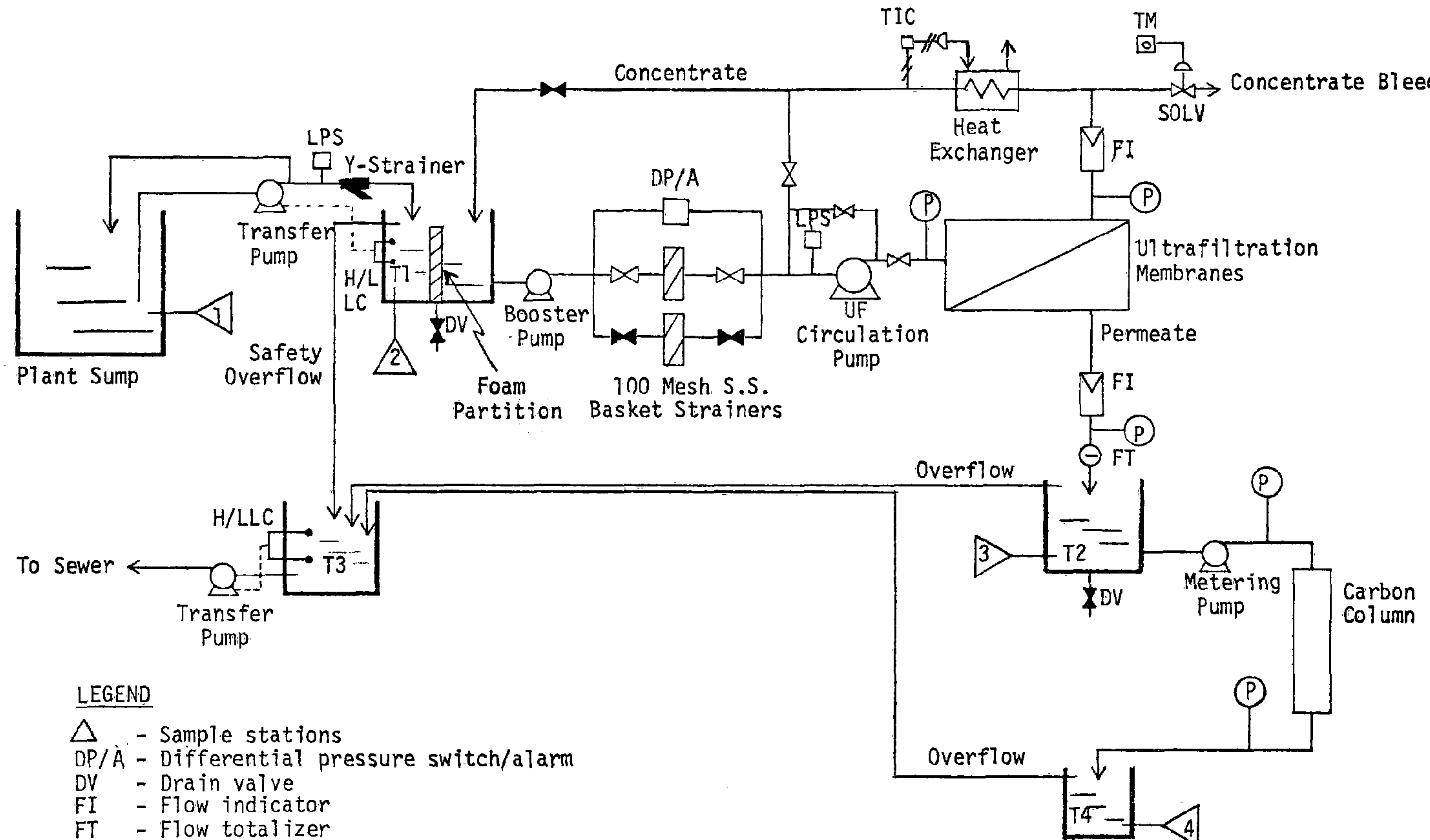
Test System

The basic operation of the UF test system employed during the in-house tests is similar to that of the field demonstration test system; therefore, only the latter will be described. The field test system, including the carbon column, is shown schematically in Figure 6. Plant wastewater was collected in an existing sump and delivered to the UF feed tank (T1) by a transfer pump. The suction line of the pump was connected to a float and withdrew liquid from ~15 inches below the surface, minimizing free oil content in the feed. The transfer pump was equipped with a low pressure switch and a bypass loop. A Y-strainer on the discharge line removed gross solids.

The plant wastewater was fed into the UF feed tank (T1) as signalled by a high/low level switch mounted within the tank. The average volume in T1 was maintained at 75 gallons. A polyurethane foam partition, 3 inches in thickness, was positioned vertically within the feed tank. This partition was not originally incorporated into the test unit; it was devised during preliminary testing when lint breakthrough to the UF modules proved troublesome. Besides effectively trapping lint particles within its pore structure, it also served as an oil coalescer.

Feed was withdrawn from the side of T1 and passed by a booster pump through one of two parallel 100 mesh stainless steel basket strainers. A differential pressure switch measured the pressure drop across the strainer in use and indicated when the second strainer should be brought on-line and the first strainer cleaned. A check valve prevented any back pressure at the strainer outlet.

The feed entered the suction of a centrifugal circulation pump and was delivered in parallel to the inlet of the two module housings. The circulation pump was equipped with a low pressure switch/alarm (LPS) to protect it against running dry and a temperature indicator/alarm to protect the system against excessive temperatures.



LEGEND

△ - Sample stations
DP/A - Differential pressure switch/alarm
DV - Drain valve
FI - Flow indicator
FT - Flow totalizer
H/LLC- High/low level controller
LPS - Low pressure switch
P - Pressure gauge
SOLV - Solenoid Valve
T - Tank
TIC - Temperature indicator/controller
TM - Timer

Figure 6. Flow schematic of field demonstration test system.

Each module housing was equipped with two spiral-wound UF cartridges in a series arrangement. The type of spiral-wound modules within each housing is identified in the Results and Discussion Section. The feed flow through each housing was indicated and could be controlled by butterfly valves at the housing inlets and by a ball valve on the bypass loop. Pressures before and after each housing were measured. The main portion of the concentrated waste was returned to the suction of the circulation pump while the remainder was bled from the system to maintain the desired conversion. When very high conversions (i.e., very low concentrate bleed flows) were being investigated a timer controlled the operation of a solenoid valve to maintain the proper concentrate discharge.

The UF permeate flow rate from each housing was measured before the permeates were combined. The overall permeate pressure was indicated and a flow totalizer on the permeate line recorded the cumulative volume of permeate produced.

The UF permeate flowed into a 50 gallon surge tank (T2) which served as the carbon column feed reservoir. The overflow from T2 was delivered to holding tank T3 and pumped to the sewer.

A metering pump provided a constant feed flow through the carbon columns which were operated in the upflow mode. The feed pressures at the inlet and outlet of the carbon columns were measured. The carbon effluent flowed into a four gallon surge tank (T4) which also overflowed to T3.

Test Procedures

Task 1 Experiments--

Task 1 in-house tests were conducted on samples (250 gallons each) from the wastewater sumps of three different industrial laundries. Prior to discharge of wastewater on the day of sampling the waste collection pits at each site were drained. Also, all accumulated sediment was removed from the pit before sampling at one of the three sampling sites ("light" loading wastewater). The 250 gallon sample was returned to Abcor and pumped into a 500 gallon holding tank for next-day processing.

The wastewaters were processed in the batch concentration mode (i.e., concentrate returned to the feed tank and permeate continuously withdrawn). The UF module pressure drop and the UF permeate flux vs. feed concentration and time were monitored. Initial feed, final concentrate and composite permeate samples were analyzed for a number of constituents (see below).

Operating conditions for these tests were:

Feed Circulation Rate

Open-Spacer Modules:	60-95 gpm
Corrugated Spacer Modules:	45-90 gpm

Inlet Pressure:	45-50 psig
Feed Temperature:	125°F
Feed pH:	Actual

Upon completion of each batch concentration experiment, proportionate amounts of UF permeate and concentrate were combined to provide a 5X feed for total recycle processing by the UF system. A 5X feed volumetric concentration (80% conversion) corresponds to the average feed concentration within the membrane loop during an entire batch concentration to a volumetric feed concentration of 50X. In experiments of this type, both the concentrate and permeate are returned to the feed tank. Thus, the feed concentration remains the same throughout the test allowing permeate flux to be monitored as a function of time. The total recycle tests were conducted for ten day periods and feed and permeate samples were collected on the first and tenth days.

Task 2 Experiments--

Field experiments were conducted with the UF system operated in the feed-and-bleed mode. The UF system was maintained at each of four different system conversions for a period of two weeks. System operation was continuous, 24-hours/day.

At the start of each experiment, the UF feed tank was filled with laundry waste and the system was started. Until the desired system conversion was reached all concentrate was returned to the suction of the circulation pump. When the concentration within the membrane loop reached the proper level, the concentrate bleed timer was engaged and concentrate was periodically ejected through a solenoid valve to drain. The amount of concentrate removed was controlled by the timer which was set in proportion to the total permeate flow, maintaining the proper system conversion.

Task 2 UF system operating conditions were:

Feed Circulation Rate	
Open-Spacer Modules:	45-90 gpm
Corrugated Spacer Modules:	55-75 gpm
Vexar Spacer Modules:	15-20 gpm
Inlet Pressure:	45-60 psig
Feed Temperature:	135°F
Feed pH:	Actual

UF permeate flux and the standard operating data were monitored daily. During each 24-hour period composite samples of the feed, ultrafiltrate, and carbon effluent were collected using a metering pump. In addition, a grab sample of UF concentrate was taken each day. Corresponding daily samples were combined to form a weekly composite sample for analysis. Additional assays were performed on "two-week" composites.

UF Membrane Cleaning--

Various chemical formulations were employed during the UF membrane detergent cleaning cycles. These formulations and the entire cleaning operation are discussed in more detail in Section 7. A generalized procedure for cleaning the spiral-wound UF membranes is presented below.

1. The concentrated waste was drained from the system.
2. Clean water was passed through the system at a low flowrate (~ 20 gpm) to flush out the residual concentrate.
3. A 1%, by weight, solution of Abcor, Inc.'s "Ultra-clean" was recirculated through the system for 30 minutes under the following operating conditions:

Recirculation Flowrate:	20-25 gpm
Inlet Pressure:	20-25 psig
Temperature:	115-120^{o}F

   The "Ultra-clean" was dissolved in warm water then added to tap water being circulated through the system under the proper operating conditions.
4. Clean water was passed through the system for 20-30 minutes at low flow and low pressure to flush out all traces of the detergent.
5. The water flux of the clean membranes was determined.

CARBON ADSORPTION

Isotherm Procedures

The carbon adsorption isotherm tests were conducted using the following procedure.

1. Filtrasorb 400 granular activated carbon was ground with a mortar and pestle and sifted through a 335 mesh screen.
2. Seven samples of dried carbon were weighted out: 2 mg, 5 mg, 10 mg, 20 mg, 50 mg, 100 mg, and 500 mg.
3. Each sample of dried carbon was placed in a separate erlenmeyer flask.
4. 100 (±1) ml of ultrafiltrate were added to each flask.
5. The flasks were stoppered and placed on a Burrel Wrist Action Shaker for 24-48 hours.
6. The flask contents were filtered through a 0.22 micron Millipore Filter, and the center portion of filtrate was collected for analysis.

7. The seven carbon treated samples, an original feed sample taken through all procedures except for carbon addition, an original feed sample not taken through the isotherm procedures, and a high purity water sample are analyzed. Isotherms were developed for both TOC and color.

Carbon Column Operation

A slip stream of UF permeate was continuously fed into a 2-inch diameter carbon column during the field demonstration tests. A flow diagram showing the carbon column's operation is given in Figure 7. The column contained 2400 grams of Filtrasorb 400 (Calgon Corp) granular activated carbon and had a residence time of 11.3 minutes. The column was operated in an upflow mode at a flowrate of 6.7 gpm/ft^2 (480 cc/min). The carbon effluent flowed into a 4-gallon surge tank from which a composite sample was continuously withdrawn. Excess liquid overflowed to drain.

ANALYSES

Table 5 lists the assays routinely performed during both the in-house and field demonstration experiments. Also indicated are the methods employed during each analysis. All assays, except mercury, were performed by Abcor's Analytical Laboratory. The mercury analyses were conducted by Environmental Research and Technology, Concord, Massachusetts.

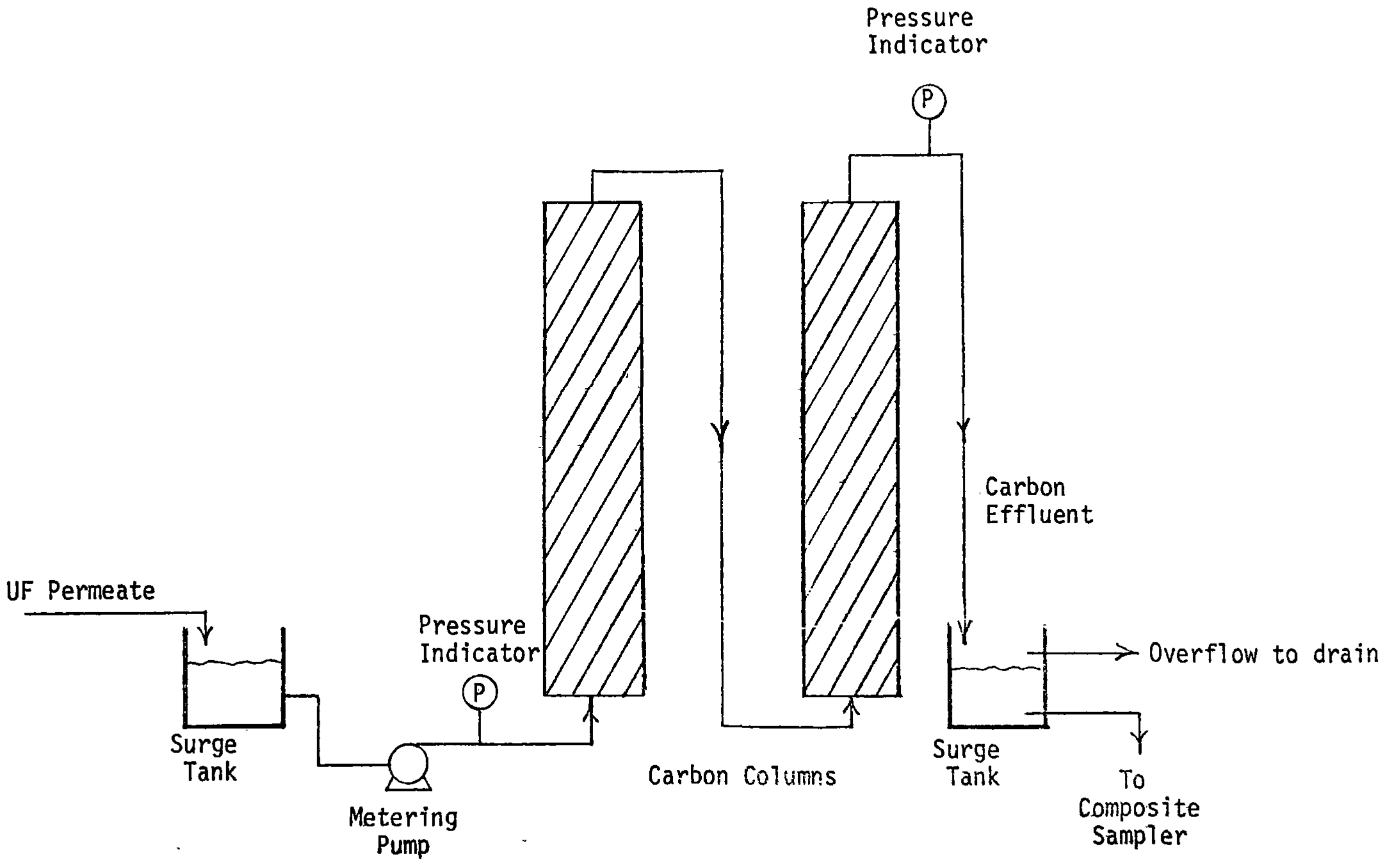


Figure 7. Flow schematic of carbon column.

TABLE 5. CHEMICAL ANALYSES ROUTINELY PERFORMED DURING IN-HOUSE AND FIELD DEMONSTRATION EXPERIMENTS

Constituent	Assay Method	Reference
Alkalinity as $CaCO_3$	HCl Titration	SM 403*
BOD	5 Day Incubation, Electrode	SM 507, 422F, 422B
Cadmium	Atomic Absorption	SM 301A
Chromium	Atomic Absorption	SM 301A
COD	Dichromate Reflux	SM 508; EPA, p. 21**
Color	Visual Comparison	SM 204A
Iron	Atomic Absorption	SM 301A
Lead	Atomic Absorption	SM 301A
Mercury	Atomic Absorption	SM 301A VI
Nickel	Atomic Absorption	SM 301A
pH	Meter Reading	Manufacturer's Manual
Suspended Solids	Glass Fiber Filtration	SM 208D
TOC	Combustion-Methane Detection	EPA, p. 236
Total Freon Extractibles	Separatory Funnel Extraction	SM 502A, EPA, p. 229
Total Solids	Gravimetric	SM 208A
Turbidity	Meter Reading	SM 214A
Zinc	Atomic Absorption	SM 301A

*SM 403 (etc) refers to procedure number in "Standard Methods for the Examination of Water and Wastewater," 14th Edition, APHA, 1975.

**EPA refers to "Manual of Methods for Chemical Analysis of Water and Wastes," U.S. EPA, 1974.

SECTION 7

RESULTS AND DISCUSSION

PILOT SCALE TESTING AT ABCOR INC.'S FACILITIES

Introduction

The Task 1 tests were designed to determine whether spiral-wound UF processing of industrial laundry wastewaters is feasible, and if so, to determine the preferred membrane type and module spacer. Each of the three laundry wastewaters tested was of a different industrial strength and was classified by the Institute of Industrial Launderers as either a light, medium, or heavy industrial load.

Four membrane/spacer combinations were tested during these in-house experiments. These combinations are summarized below:

Membrane Type	Spacer Configuration
Abcor, Inc. Type HFD	Corrugated
Abcor, Inc. Type HFD	Open-Spacer
Abcor, Inc. Type HFM	Corrugated
Abcor, Inc. Type HFM	Open-Spacer

Vexar spacer modules were not tested since at this stage of the program it was felt the very narrow channel Vexar spacer would be plugged by lint.

Washroom production schedules for the time periods during which sampling occurred are given in Appendix A.

Ultrafiltration

UF Membrane Flux--

Average UF membrane flux levels during the batch pumpdown and total recycle experiments are given in Table 6 (the permeate flux vs. time curves for each test are presented in Figures A1 through A6 in Appendix A). These data indicate slightly better flux performance for the Type HFM membrane as opposed to the Type HFD membrane.

TABLE 6. AVERAGE UF MEMBRANE FLUX LEVELS DURING IN-HOUSE EXPERIMENTS (Values given in gfd @ 125°F)

Wastewater Loading	Operating Mode	Membrane/Spacer Combination* HFD Corrugated	HFD Open	HFM Corrugated	HFM Open	Comments
Light	Batch	30	†	†	40	Final Concentration Reached = 13.6X
	Total Recycle	17	†	†	38	5X feed diluted to 3X after 2 days due to loss of feed.
Medium	Batch	35	†	†	30	Final Concentration Reached = 17.1X
	Total Recycle	25	†	†	27 ††	Modules fouled by free oil, test terminated after 2 days
Heavy	Batch	†	45-50	45-50	†	Final Concentration Reached = 11X Feed Circulation Rates 90-95 gpm Free oil removed
	Total Recycle	†	40	45	†	Test duration 14 days No module cleaning performed between batch pumpdown and total recycle tests.

* Two membrane/spacer combinations used during each experiment.

† No tests made in these instances.

†† As noted in comments, run was of a short duration. See Figure A4 for flux vs. time curve.

The final volumetric concentration achieved was limited by the sample size and the dead volume of the UF system. For the three batch pumpdowns, with an average final concentration factor of 13.9X (92.8% water recovery) the HFM membrane modules averaged ~40 gfd (125°F) and the HFD membrane modules averaged ~38 gfd (125°F). During the total recycle experiments, however, the average flux levels were 37 gfd (125°F) for the HFM modules and 27 gfd (125°F) for the HFD modules.

The duration of the total recycle experiments with the "light" and "heavy" loading waste streams was 10 days. The total recycle test with the "medium" loading wastewater was curtailed after two days due to a sharp decline in the permeate flux for both modules. A review of membrane module performance before this flux decline and during subsequent operations is presented in Table 7. As the data of Table 7 indicate, the standard cleaning cycle with "Ultra-clean" recovered the flux for both membrane modules to acceptable levels following the batch pumpdown. When the low membrane flux levels were observed during this total recycle test, a second washing with "Ultra-clean" was performed, resulting in flux recoveries to 47 gfd (69% of initial flux) for the HFM module and 21 gfd (29% of initial flux) for the HFD module. These flux levels were not considered acceptable.

"Dishmate" (Calgon Corporation), a detergent containing free-available-chlorine, was used during the next cleaning cycle. Because of the susceptibility of the HFD membrane to chemical attack by free chlorine, only the HFM membrane module could be cleaned with "Dishmate". The resultant HFM water flux was 76 gfd (112% of initial flux). As discussed in the following paragraph, the validity of this flux measurement is in question.

Since the HFD module remained fouled, a 10% kerosene in water mixture was circulated through the modules. Little change in water flux occurred for either membrane type. The flux for the HFM membrane module was acceptable, and therefore, the extended recycle experiment was reinitiated with only the HFM open-spacer module. Upon system startup a leak was detected in the HFM module which caused feed to enter the permeate stream. Since it is not known precisely when this leak developed, the water flux measurements for the HFM module following the last two cleaning cycles are questionable.

The HFM module was removed from its housing, carefully cut open, and unwound. A coating of free oil was observed on the membrane surface. The leak in the module occurred at the interior glue seam where the membrane and spacer material begin to wrap around the permeate collection tube. The spacer material was inserted slightly askew during manufacture, placing excess stress on the glue seam and causing it to fail. The module failure was attributed entirely to this manufacturing defect.

It is suspected that the flux decline observed with the "medium" loading sample was related to the free oil found in this wastewater. As the ultrafiltration process proceeds, oil droplets may progressively adhere to the membrane surface to form a water impervious coating. In a properly

TABLE 7. HISTORY OF MEMBRANE MODULE PERFORMANCE DURING EXPERIMENTATION WITH "MEDIUM" LOADING INDUSTRIAL LAUNDRY WASTEWATER SAMPLE *

Membrane/ Spacer Geometry	Event	Membrane Flux at 125°F, (gfd)
HFM/ Open-Spacer	Prior to batch pumpdown	68.0
	Following 4 hour batch pumpdown, 10 minute "Ultra-clean" and 50 minute "Ultra-clean"	67.7
	Total recycle experiment at 5X, flux after 1 hour	38.5
	Total recycle experiment at 5X, flux after 24 hours	13.2
	½-hour "Ultra-clean"	46.7
	½-hour "Dishmate"	75.8
	½-hour 10% kerosene (by volume) in water; 10 minute "Ultra-clean", 50 minute "Ultra-clean"	79.3
	Leak developed in HFM membrane upon restart in total recycle, membrane cut open for inspection	----
HFD/ Corrugated Spacer	Prior to batch pumpdown	73.0
	Following 4 hour batch pumpdown, 10 minute "Ultra-clean" and 50 minute "Ultra-clean"	65.2
	Total recycle experiment at 5X, flux after 1 hour	36.4
	Total recycle experiment at 5X, flux after 24 hours	9.9
	½-hour "Ultra-clean"	21.2
	½-hour, 10% kerosene (by volume) in water; 10 minute "Ultra-clean", 50 minute "Ultra-clean"	29.2
	Subsequent cleaning postponed until completion of third wastewater experimentation	----

* Similar data is not given for "light" and "heavy" loading wastewater samples since routine cleaning methods effectively recovered membrane flux.

designed system, free oil droplets would be removed from the feed prior to its introduction to the membrane system. The treatment of the "light" and "medium" loading wastewater was performed without the inclusion of oil removal in an attempt to eliminate the oil separation step. The severe fouling encountered during the total recycle test with the "medium" loading wastewater suggests that this would not be a preferred mode of operation.

The removal of free oil from industrial laundry wastewater can be accomplished by a number of commercially available oil skimmers. In lieu of an oil skimmer, testing with the "heavy" loading wastewater sample was conducted in the following manner. The wastewater sample was pumped into the 1500-gallon feed tank, and, one hour prior to processing by the UF system, was well-agitated for 15 minutes. Feed was drawn into a 55-gallon feed tank from the bottom of the 1500-gallon tank allowing free oil to remain floating in the larger tank. The concentrate from the membrane loop was returned to the 55-gallon tank, preventing any mixing of the free oil into the feed stream. Comparison of the flux data for this test with the previous experiments (see Table 6) shows the advantage of free oil flotation (or skimming). The average flux for both membrane modules was 45-50 gfd (125^{o}F) while processing the wastewater with the heaviest loading.

Module Pressure Drop--

The two types of spacer materials used in constructing the spiral-wound modules tested during the Task 1 experiments create different feed flow patterns within each module. Variations in the feed transport through the modules results in different pressure drops across each spiral and thus significantly affects the UF system power requirement.

The power requirement for a UF system is determined almost entirely by the power input to the feed circulation pump. This power input is directly proportional to the product of the volumetric output of the pump and the pressure drop across the membrane system. Table 8 presents the projected horsepower requirements for each type of spiral-wound module evaluated from the data obtained during the batch pumpdown and the total recycle experiments with each industrial laundry wastewater. The horsepower requirement per module was higher for the corrugated spacer module during all experiments with the exception of the "medium" loading batch pumpdown. For this test the open-spacer and corrugated spacer modules had essentially identical horsepower requirements.

The horsepower requirement, per gallon of product per day, favors the use of corrugated spacer modules because of their increased membrane surface area over open-spacer modules. The corrugated flow channels are, however, more susceptible to plugging than the open-spacer flow channels. Therefore, preference for one feed-side spacer geometry over the other was not clearly demonstrated.

TABLE 8. PROJECTED POWER REQUIREMENTS FOR UF SPIRAL-WOUND MODULES OPERATING ON INDUSTRIAL LAUNDRY WASTEWATERS DURING IN-HOUSE EXPERIMENTS

Wastewater Loading	Spiral Wound Module Spacer Geometry	Mode of Operation	Average Feed Flowrate (gpm)	Average Pressure Drop (psi)	Projected Horsepower per Module (hp)	Average Productivity per Module (gpd)	Projected Horsepower per gallon of product per Day (hp/gpd)
"Light"	Corrugated	Batch Pumpdown	45	11	0.29	960	3.02×10^{-4}
	Open Mesh	Batch Pumpdown	60	6	0.21	720	2.92×10^{-4}
	Corrugated	Total Recycle	45	15	0.39	608	6.40×10^{-4}
	Open Mesh	Total Recycle	60	6	0.21	630	3.33×10^{-4}
"Medium"	Corrugated	Batch Pumpdown	65	10	0.38	1,088	3.49×10^{-4}
	Open Mesh	Batch Pumpdown	75	9	0.39	540	7.22×10^{-4}
"Heavy"	Corrugated	Batch Pumpdown	95	12	0.66	1,530	4.31×10^{-4}
	Open Mesh	Batch Pumpdown	90	11	0.57	810	7.04×10^{-4}
	Corrugated	Total Recycle	95	13	0.71	1,530	4.64×10^{-4}
	Open Mesh	Total Recycle	90	12	0.62	720	8.61×10^{-4}

UF Membrane Flux Recovery--

The measurement of the flux of tap water through UF membranes, under standardized conditions, indicates the water transport properties of the membrane and is one means of detecting membrane degradation due to compaction, plugging, biological fouling and/or chemical attack. This measurement is always performed after membrane cleaning. Except for the one instance of severe membrane fouling after exposure to free oil (the "medium" loading wastewater test), reasonable membrane flux recoveries were obtained after up to 330 hours of accumulated exposure to industrial laundry wastewater. Thus, free oil must be removed prior to the ultrafiltration process so membrane cleaning can be performed effectively using straight-forward, standardized cleaning procedures.

UF Membrane Removal Efficiency--

Initial feed, composite permeate, and final concentrate samples were taken during each batch pumpdown and analyzed for a wide range of contaminants. The composite permeate analyses were made on a mixed sample of the total ultrafiltrate produced by both the HFD and HFM membranes. Detailed analytical results for the "light", "medium", and "heavy" wastewaters are presented in Tables A4, A5, and A6 of Appendix A. These results are summarized, in terms of membrane removal efficiency, in Table 9.

Nearly complete removal of suspended solids and freon extractibles (i.e., oil and grease) was obtained for all three wastewaters. Overall removal efficiencies for BOD ranged from 66.5%-88%, averaging 80.6%. Composite permeate BOD analyses ranged from 360 mg/l for the "light" wastewater to 930 mg/l for the "heavy" loading sample. In all three cases, COD and TOC rejections of >80% were noted. It is thus apparent that a significant contribution to the organic pollutant loading in industrial laundry wastewater is associated with suspended matter. Based on the individual test results, the UF rejection of metals (and metallic compounds) generally ranged from >70 to 98% during the in-house experiments. Only the rejection for mercury (20% for the "medium" loading waste and 11.1% for the "heavy" loading sample) was low. The average mercury concentration in both the initial feed and final composite permeate was, however, <0.001 mg/l.

Rejection of dissolved solids is not characteristic of ultrafiltration membranes, and therefore, low removal efficiencies for dissolved solids and alkalinity are expected. Post treatment by carbon absorption can be employed to remove dissolved organic species.

Feed and individual permeate grab samples were also collected at the beginning and end of the total recycle experiments. These data are presented in Table 10. Due to the short duration of the "medium" loading wastewater recycle experiment, no samples were analyzed for this run.

TABLE 9. AVERAGE CONTAMINANT ANALYSES AND MEMBRANE REMOVAL EFFICIENCIES FOR UF BATCH CONCENTRATIONS OF "LIGHT," "MEDIUM," AND "HEAVY" LOADING INDUSTRIAL LAUNDRY WASTEWATERS

Assay	Average Initial Feed	Average Final Concentrate	Average Mixed Composite Permeate	Average Removal Efficiency, % *†
Total Solids (mg/l)	4,910	32,870	1,750	54.0
Suspended Solids (mg/l)	1,960	19,400	<4	>99.6
Dissolved Solids (mg/l)	2,950	13,470	1,746	30.6
Turbidity (NTU)	--- ††	--- ††	4	---
BOD (mg/l)	4,100	37,200	614	80.6
TOC (mg/l)	3,030	22,900	347	85.4
COD (mg/l)	12,200	96,400	1,280	86.4
Freon Extractibles (mg/l)	3,140	22,600	25.2	98.2
Alkalinity (ppm $CaCO_3$)	1,320	2,320	1,230	5.5
pH (units)	11.2	11.2	11.4	---
Chromium (mg/l)	<3.3	---	<1.3	67.0
Copper (mg/l)	4.6	---	<0.7	>73.0
Lead (mg/l)	9.3	---	<1.0	>74.1
Zinc (mg/l)	4.8	---	<0.29	>85.7
Cadmium (mg/l)	0.77	---	<0.008	>83.3
Iron (mg/l)	37.8	---	1.3	>92.2
Nickel (mg/l)	<0.58	---	<0.5	>32.4
Mercury (mg/l)	<0.001	---	<0.001	15.6

*Removal Efficiency, $r = \frac{\text{Feed Concentration-Composite Permeate Concentration}}{\text{Feed Concentration}} \times 100$

†Average removal efficiency is based on individual test results and not on average feed and permeate concentrations.

††Very high.

NOTE: See Appendix A for detailed data from each experiment.

As shown in Table 10, the permeate quality of the two membrane types was quite similar. For the "light" loading wastewater the average removal efficiency for total solids was 59% and for TOC, 84%. Ultrafiltration of the "heavy" loading wastewater resulted in average removal efficiencies over the ten day period of 92% and 97% for total solids and TOC, respectively.

Carbon Adsorption

Equilibrium adsorption isotherms at 20°C were determined for each UF composite permeate for both TOC removal and color removal. Figure 8 presents the equilibrium isotherms for the "medium" loading industrial laundry waste. This figure is representative of the data obtained from all waste samples. The isotherms for the "light" and "heavy" loading wastes can be found in Appendix A. The points in most curves fall reasonably close (within experimental error) to straight lines indicating agreement with the Freundlich isotherm expression. Similar curves for TOC removal were obtained in all cases. Likewise, the adsorptive capacity for color followed the same trend for all three permeates.

The steep slope of the TOC isotherms indicates that as the TOC concentration decreases, the loading drops off very rapidly. For a two-fold decrease in concentration (see Figure 8) the adsorptive capacity of the carbon decreased by over an order of magnitude. This indicates that the TOC content of the waste is composed of a small amount of strongly adsorbed material and a larger amount of weakly adsorbed material. Isotherms of this nature indicate that a rapid breakthrough of TOC will occur during processing of industrial laundry ultrafiltrates through a carbon column.

The adsorption isotherms for color removal exhibit much more gradual slopes than the TOC isotherms. This indicates that the carbon's adsorptive capacity for color producing compounds remains high even as the color of the UF permeate becomes reduced.

For the "heavy" loading wastewater, an additional isotherm was performed to determine the effect of neutralization of the sample pH on the carbon's adsorptive capacity. This isotherm is also presented in Appendix A. If a substantial improvement in organic adsorption occurred, then a trade off study between pH adjustment costs and increased carbon efficiency would be warranted. However, performing the adsorption isotherm test on a neutralized industrial laundry UF permeate (pH = 7.1) had little, if any, affect on the carbon's adsorptive properties for either TOC or color.

From the above discussion, it appears that activated carbon treatment of industrial laundry UF permeates will prove very beneficial in terms of color removal, but will only marginally lower the TOC of the ultrafiltrate.

Task 1 Conclusions

Based on the Task 1 experimental results, the following conclusions can be drawn relative to UF/activated carbon treatment of industrial laundering effluents.

TABLE 10. CONTAMINANT ANALYSES DURING UF TOTAL RECYCLE EXPERIMENTATION

a). "LIGHT" LOADING INDUSTRIAL LAUNDRY WASTEWATER

Assay	Sampled after 53 hours Feed	Sampled after 53 hours HFD Permeate	Sampled after 53 hours HFM Permeate	Sampled after 239 hours Feed	Sampled after 239 hours HFD Permeate	Sampled after 239 hours HFM Permeate
Total Solids (mg/l)	4,660	1,820	1,570	4,260	2,040	1,820
TOC (mg/l)	2,740	362	310	2,280	456	432
Turbidity (NTU)	--	5.3	4.7	--	5.2	5.5
pH (units)	--	10.4	10.4	9.4	9.4	9.4

b). "HEAVY" LOADING INDUSTRIAL LAUNDRY WASTEWATER

Assay	Sampled after 19.4 hours Feed	Sampled after 19.4 hours HFD Permeate	Sampled after 19.4 hours HFM Permeate	Sampled after 242 hours Feed	Sampled after 242 hours HFD Permeate	Sampled after 242 hours HFM Permeate
Total Solids (mg/l)	39,000	2,990	3,060	38,900	3,100	3,200
TOC (mg/l)	32,800	808	716	36,200	1,070	1,120
Turbidity (NTU)	--	2.8	2.7	--	4.8	4.6
pH (units)	11.8	12.0	11.9	9.7	9.7	9.7

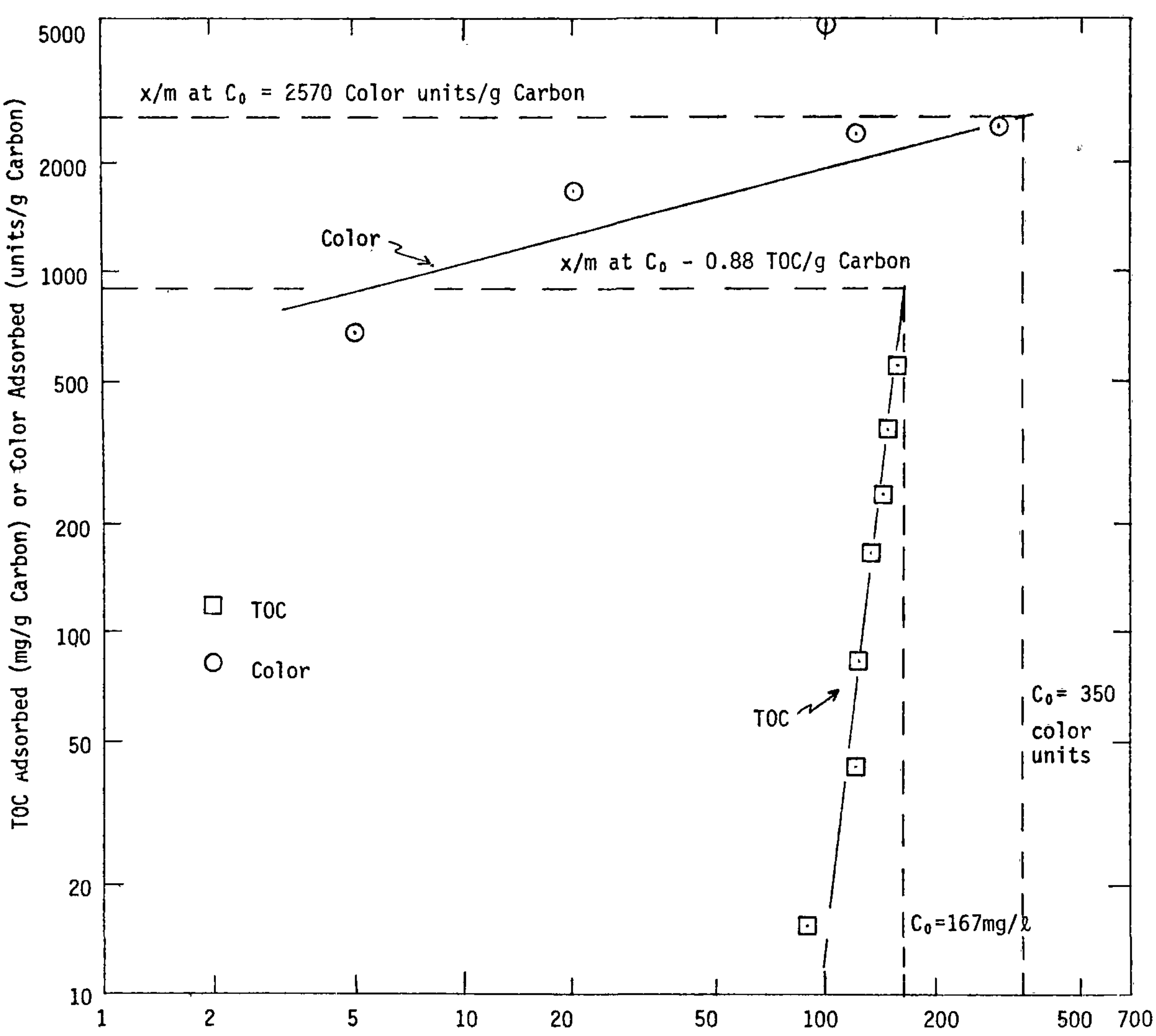


Figure 8. Equilibrium adsorption isotherms for TOC and color removal from "medium loading" industrial laundry waste UF permeate.

- The Type HFM membrane is preferred over the HFD membrane because of its higher flux level, its greater resistance to environmental attack, and its tolerance to free chlorine (for cleaning purposes).
- It appears from the limited test data that average flux levels of 40-50 gfd (125^{o}F) can be maintained if the feed is pretreated for free oil removal.
- Both membrane spacer types, corrugated and open-spacer, appear applicable for processing industrial laundry wastes. Field tests with both feed-side channel spacers will determine the preferred option.
- Membrane rejection for suspended solids was >99%, and for freon extractibles, >98%. BOD, COD, and TOC rejections were typically >80%. Rejections for all metals except mercury generally ranged from >70-98%.
- If free oil is removed from the feed prior to UF treatment, the membrane flux should be recoverable by standard detergent formulation and cleaning procedures.
- Based on the projected power requirements for the spiral-wound modules, and a power cost of $0.04/kw-hr, power costs of $0.25/1000 gal and $0.52/1000 gal are predicted for operation of the corrugated and open-spacer modules, respectively. Power costs of the magnitude are considered acceptable for spiral-wound module UF systems.
- Carbon adsorption treatment is technically feasible for color removal from the UF permeate; however, only marginal TOC removal is anticipated.

PRELIMINARY FIELD DEMONSTRATION EXPERIMENTS

Introduction

Four experiments were conducted at the field demonstration site prior to the initiation of the formal test program. These preliminary experiments served as shakedown runs for the UF/ACA system and were designed to obtain data on a number of parameters:

- effectiveness of pretreatment in preventing lint breakthrough to the membrane system circulation loop;
- membrane flux vs. time relationships at low (67%) and high (99%) conversions;

-- comparative flux levels for open-spacer and corrugated spacer spiral-wound modules;

-- feasibility of employing Vexar spacer spiral-wound modules;

-- contaminant removal efficiencies for UF membranes and activated carbon over an extended time period; and

-- effectiveness of establishing cleaning procedures in recovering membrane water flux.

The results of these experiments and their implications for the formal test program are discussed below.

Ultrafiltration

UF Membrane Flux, Tests P1 and P2--

The first preliminary test (P1) was conducted with the feed transfer pump suction line inadvertently placed 15 inches from the bottom of the sump rather than 15 inches beneath the liquid surface. A 20 mesh Y-strainer was located on the discharge of the transfer pump and a wooden board was situated in the UF feed tank to provide a quiescent region (~15 minute residence time) from which feed to the UF system was withdrawn. The feed was then screened through 30 mesh basket strainers. Type HFM membrane corrugated spacer and open-spacer modules were tested in parallel housings. Each housing contained two membrane cartridges.

With a system conversion of 65-70% (~3X concentration factor) the flux of the corrugated modules averaged 33 gfd (135°F), and the flux for the open-spacer modules averaged 36 gfd (135°F). Although no severe membrane fouling was observed, the test was concluded after four hours due to plugging of the 30 mesh basket strainers with lint. The permeate flux vs. time curve for this test is shown in Appendix B.

Prior to the second preliminary experiment (P2) the suction line from the sump was raised to the proper height. This action had little, if any, effect on the rate at which the basket strainers became plugged. The second test also had to be terminated early (after 5 hours operation) and, as evidenced by the reduced circulation flow through the modules during P2, plugging of the spiral-wound feed-side spacers was occurring. During P1 the feed circulation rate was 70-75 gpm. In P2 this rate was reduced to 55-69 gpm.

The open-spacer module flux was similar for Tests P1 and P2 until the final hour of operation, at which point it began to decline more rapidly for Test P2. For the corrugated module the permeate flux during P2 was lower than in the first test by as much as 50%. These losses in flux are probably a result of the lower feed velocity through the cartridges, and in the case of the corrugated module, loss of membrane exposure due to channel plugging. The flux curve for Test P2 is also given in Appendix B.

Improved Pretreatment--*

System operation was clearly limited by the plugging of both basket strainers and modules with lint particles and threads. To provide improved lint removal a new tank partition, constructed of reticulated polyurethane foam, was positioned in the center of the UF feed tank. The foam is highly porous and had been shown during pilot studies on other programs (7) to be an effective depth filter. It was also anticipated that the foam partition would act as an oil coalescer. Once the foam becomes loaded with suspended solids and/or oil, it can be removed from the tank and regenerated (a limited number of times) by surface cleaning and squeezing.

Grab samples of the feed from the sump, the feed prior to the foam partition and the feed after the foam partition were analyzed for suspended solids content. These assays are shown below.

Assay	Feed from Sump	Feed Prior to Foam Partition	Feed After Foam Partition
Suspended Solids (mg/l)	1940	2610	976

It is clear from these data that the foam acted mainly as a surface filter, concentrating the suspended solids in the first portion of the tank. Regardless of the mechanism of filtration, the foam's potential for suspended solids removal was evident.

A further demonstration of the effectiveness of lint removal by the foam partition was the continuous operation of <u>100 mesh</u> basket strainers in the ultrafiltration system. With both strainers in line, overnight operation was successfully achieved.

UF Membrane Flux, Tests P3 and P4--

After installing the foam partition, two more preliminary experiments were performed. Run P3 began with testing of open-spacer modules at a 67% (3X concentration factor) system conversion; however, the conversion increased during an unattended overnight shift. The average conversion over the first 70 hours of Test P3 was determined from analytical data (see below) to be 97% (30X concentration factor). The 99% (100X) system conversion aimed for during the final 100 hours of the test was determined by sample analysis to be from 99.5-99.8% (200-500X concentration factor). Variations in the concentrate flow with time account for the discrepancies between the planned and the actual system conversions.

The flux data for Test P3 are plotted in Figure 9. The open-spacer flux through the first five hours declined from 35 to 22 gfd (135°F). At this point, the system was left unattended overnight and the feed concentration within the loop increased beyond a 3X concentration factor. As a result of the increased concentration, the flux declined to 14 gfd (135°F). When the system conversion was corrected to 67% the flux returned to 22 gfd and remained stable for 20 hours.

* This pretreatment method was instituted for these pilot studies only. It is not a commercially-available process. For full-scale spiral module operation further investigation of pretreatment alternatives is necessary.

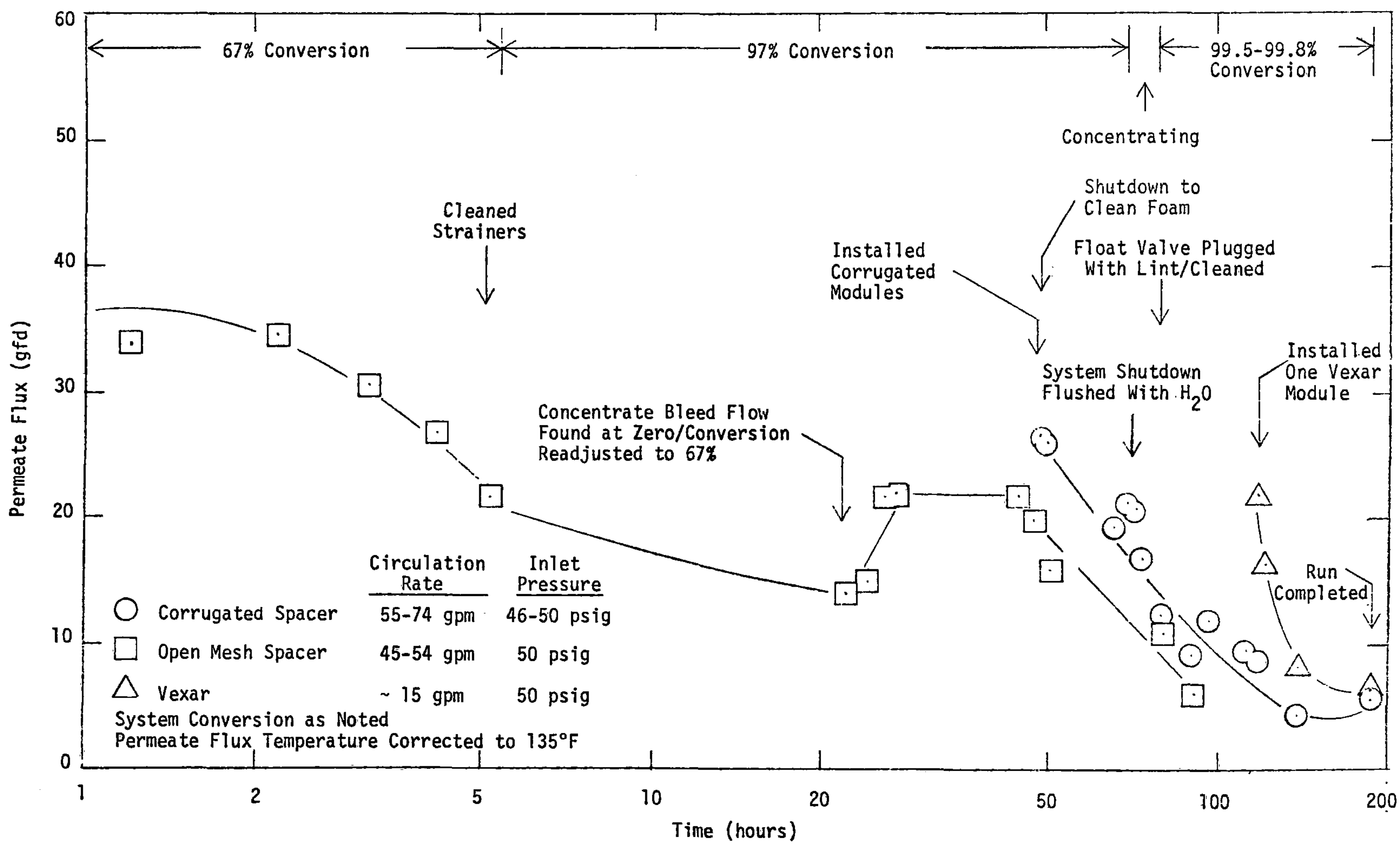


Figure 9. UF permeate flux vs. time for third preliminary field demonstration experiment (Test P3).

Two corrugated modules were operated in parallel with the open-spacer modules beginning at the start of the third day. The flux for both module types declined steadily and continued to decline as the system conversion was increased. As mentioned above, the conversion achieved inadvertently exceeded 99%.

With about two-thirds of the test completed, the open-spacer modules were replaced with a single Vexar module. The flux of this module declined over three days to the level of the corrugated modules. The final process flux at 135°F and 99.5-99.8% conversion was about 5 gfd for each module type.

The fourth preliminary test was conducted to compare the Vexar and open-spacer configurations. The laundry wastewater was concentrated to a 100X concentration factor and then the UF system was operated in the feed-and-bleed mode to maintain this conversion. The flux for the open-spacer module remained stable from 20 to 75 hours operating time; the flux for the Vexar module constantly declined with time (see flux curve, Appendix B). The final flux levels were 20 gfd (135°F) for the open-spacer module and 6 gfd (135°F) for the Vexar module.

UF Membrane Flux Recovery--

Recovery of the UF membrane water flux to acceptable levels was achieved following each preliminary test; however, the cleaning procedure was, at times, lengthy. Multiple detergent cleanings were always required, and frequently, from 5 to 7 cleaning cycles had to be performed. A tabulation of the flux recovery data is given in Appendix B.

Module Pressure Drop--

The installation of the foam partition within the UF feed tank eliminated the plugging of the feed-side spacer channels of the UF modules with lint. No increase in pressure drop was observed across any of the module types, including Vexar.

The projected horsepower requirements for each module type are presented in Table 11. Clearly the low flow rate required by a Vexar module enhances its power requirement relative to the corrugated and open-spacer modules. The higher membrane area per Vexar module (40 sq. ft. vs. 34 sq. ft. and 18 sq. ft. for the corrugated and open-spacer modules, respectively) makes its use even more economically attractive. The power cost for processing 20,000 gallons per day of laundry wastewater at a 67% conversion is roughly 6 times less for Vexar modules than corrugated modules, and nearly 13 times less for Vexar modules than open-spacer modules.

UF Membrane Rejection--

Twice during Test P3 samples of the feed (from the sump), the UF concentrate and the UF permeate were analyzed. These samples were collected on a continuous basis each day and then combined into either two-or four-day composite samples. The first series of samples was taken at a 97%

TABLE 11. PROJECTED HORSEPOWER REQUIREMENTS FOR UF SPIRAL-WOUND MODULES OPERATING ON INDUSTRIAL LAUNDRY WASTEWATERS DURING PRELIMINARY FIELD DEMONSTRATION TESTS

Spiral Wound Module Spacer Geometry	Average Feed Flowrate (gpm)	Average Pressure Drop (psi)	Projected Horsepower per Module (hp)	Average Productivity per Module @ 67% Conversion (gpd)	Projected Horsepower per Gallon of Product per Day (hp/gpd)	Horse Power-Hours per Day for Processing 20,000 gal.	Kilowatt-Hours per Day for Processing 20,000 gal.	Dollars per day for Processing 20,000 gal @ $0.04/KWH
Open Spacer	70	15	0.606	540	1.12×10^{-3}	537.6	401	16
Corrugated	70	15	0.606	1020	0.59×10^{-3}	238.2	178	7.12
Vexar	15	15	0.130	1500	0.087×10^{-3}	41.8	31.2	1.25

conversion, a composite sample of the carbon column effluent was also analyzed.

Table 12 presents the analytical data from the 97% conversion test period. Essentially complete suspended solids and turbidity removals were achieved. BOD, COD, and TOC removals ranged from 70 to 82% in the UF permeate and from 88 to 94% in the carbon effluent. The total freon extractibles analyses reported are in error on the high side due to contamination of the freon used in the analysis. Note, the concentration of oils and grease in the permeate should be closer to the levels reported for the permeate in the industrial laundry wastewaters (28, 10, and 38 mg/l) processed during in-house tests. Exact values of metals removals are, again, generally limited by the lower detection limits of the assays. Color removal increased from 70% after the UF processing to 98% following carbon adsorption.

The analytical data from the 99.5-99.8% conversion period of Test P3 are given in Table 13. The feed assays are very similar to the data shown in Table 12 indicating little change in the overall feed composition. Suspended solids and turbidity removals were not affected by the increased system conversion. However, BOD, COD, TOC, and color removals all decreased somewhat, as expected, since the concentration of the feed within the circulation loop at 99.5-99.8% conversion was nearly an order of magnitude higher than at 97% conversion.

Carbon Adsorption

Partial breakthrough of color occurred in the carbon column effluent after 200 hours of preliminary testing; however, complete breakthrough was not achieved. Due to the long duration of the preliminary tests and the high conversions achieved, fresh carbon was placed in the columns prior to start-up of the formal tests. As noted in Table 12, the carbon was quite effective in removing color from the UF permeate, and it also enhanced the overall system BOD, COD, and TOC removal efficiencies.

Conclusions

On the basis of the preliminary field demonstration tests the following conclusions are drawn:

- Effective pretreatment to remove lint particles has been demonstrated; however, practical pretreatment options for full-scale units must be chosen, tested, and economically evaluated.
- Processing with Vexar modules is feasible with proper feed pretreatment. Comparative testing with both open-spacer and Vexar modules is warranted to further detail their flux characteristics at very high conversions and their amenability to cleaning.

TABLE 12. CONTAMINANT ANALYSES AND UF AND CARBON REMOVAL EFFICIENCIES DURING 97% CONVERSION PERIOD OF THIRD PRELIMINARY FIELD-EXPERIMENT (TEST P3)

Assay	Feed From Sump	UF Concentrate	UF Permeate	UF Removal Efficiency,% *	Carbon Effluent	Overall Removal Efficiency,% *
Total Solids (mg/l)	2,240	21,100	1,640	26.8	---	---
Suspended Solids (mg/l)	336	8,450	8	97.6	---	---
Dissolved Solids (mg/l)	1,900	12,600	1,630	14.2	---	---
BOD (mg/l)	1,100	33,000	330	70.0	132	88.0
COD (mg/l)	2,680	78,200	520	80.6	159	94.1
TOC (mg/l)	832	19,000	148	82.2	55	93.4
pH (units)	11.8	11.3	11.6	----	11.8	---
Turbidity (NTU)	750	30,000	6.0	99.2	3.0	99.6
Color (units)	1,000	---	300	70.0	20	98.0
Total Freon Extractibles (mg/l)	(1,260) †	(11,000) †	(116) †	90.8	(82) †	93.5
Alkalinity (mg/l as $CaCO_3$)	930	---	---	----	880	5.4
Cadmium (mg/l)	<0.2	---	---	----	<0.2	---
Chromium (mg/l)	<0.5	---	---	----	<0.5	---
Iron (mg/l)	9.5	---	---	----	<1	>89.5
Lead (mg/l)	1.4	---	---	----	<1	>28.6
Nickel (mg/l)	<0.5	---	---	----	<0.5	---
Zinc (mg/l)	2.2	---	---	----	0.13	94.1

$$* \text{ Removal Efficiency, } r = \frac{\text{Feed Concentration - UF Permeate (or Carbon Effluent) Concentration}}{\text{Feed Concentration}} \times 100$$

† Suspected error in analysis

TABLE 13. CONTAMINANT ANALYSES AND UF REMOVAL EFFICIENCIES DURING 99.5-99.8% CONVERSION PERIOD OF THIRD PRELIMINARY FIELD EXPERIMENT (TEST P3)

Assay	Feed From Sump	UF Concentrate	UF Permeate	UF Removal Efficiency,%*
Total Solids (mg/l)	2,500	145,000	2,200	12.0
Suspended Solids (mg/l)	360	92,300	5	98.6
Dissolved Solids (mg/l)	2,140	52,700	2,190	----
BOD (mg/l)	1,290	71,000	580	55.0
COD (mg/l)	3,050	617,000	929	69.5
TOC (mg/l)	820	128,000	292	64.4
pH (units)	11.7	11.0	11.7	----
Turbidity (NTU)	1,000	150,000	4.5	99.6
Color (units)	2,000	----	1,000	50.0
Total Freon Extractibles (mg/l)	(957)†	(103,000)†	(234)†	----
Alkalinity (mg/l as $CaCO_3$)	840	---	---	----
Cadmium (mg/l)	<0.2	---	---	----
Chromium (mg/l)	<0.5	---	---	----
Iron (mg/l)	10	---	---	----
Lead (mg/l)	2.6	---	---	----
Nickel (mg/l)	<0.5	---	---	----
Zinc (mg/l)	2.5	---	---	----

* Removal Efficiency, $r = \frac{\text{Feed Concentration} - \text{Permeate Concentration}}{\text{Feed Concentration}} \times 100$

† ( ) Indicates Suspected Error in Analysis due to Freon Contamination

-- Testing with corrugated modules is no longer warranted. Their operation is limited to temperatures ≤125°F, they are not as compact as Vexar modules; and they are more difficult to clean than the open-spacer modules.

-- Conversions as high as 99.8% (500X) can be achieved with process flux levels ranging from 4-10 gfd (135°F).

-- At a conversion of 97% UF removal efficiencies of 70% for BOD, 80% for COD, and 82% for TOC can be expected.

-- Optimization of cleaning procedures is a necessary step before scale-up of the pilot unit.

FORMAL FIELD DEMONSTRATION PROGRAM

Introduction

The formal field demonstration program was designed to provide simulation of system conversions typical in a four-stage ultrafiltration system. These system conversions and their corresponding feed volumetric concentrations are:

System Conversion, %	Volumetric Feed Concentration
67	3X
90	10X
97	30X
99	100X

These system conversions were skewed toward the higher concentrations because performance characteristics at these levels will have a major impact on the process economics. That is, if concentrations of 100X or higher could be achieved the costs associated with concentrate disposal would be greatly reduced. Note that since most of the permeate will be produced by the first stages in a full-scale system, flux data for these stages are as critical as for the latter stages in determining membrane area requirements.

By operating the UF pilot system in the feed-and-bleed mode, each system conversion listed above was maintained for a two-week period, and between each test the membranes were chemically cleaned. Two open-spacer modules and two Vexar spacer modules, containing Type HFM membranes, were evaluated simultaneously.

Ultrafiltration

UF Membrane Flux--

The UF permeate flux vs. time curves for the field demonstration tests conducted at 67%, 90%, 97%, and 99% conversion are presented in Figures 10, 11, 12, and 13, respectively. Average flux levels are summarized below.

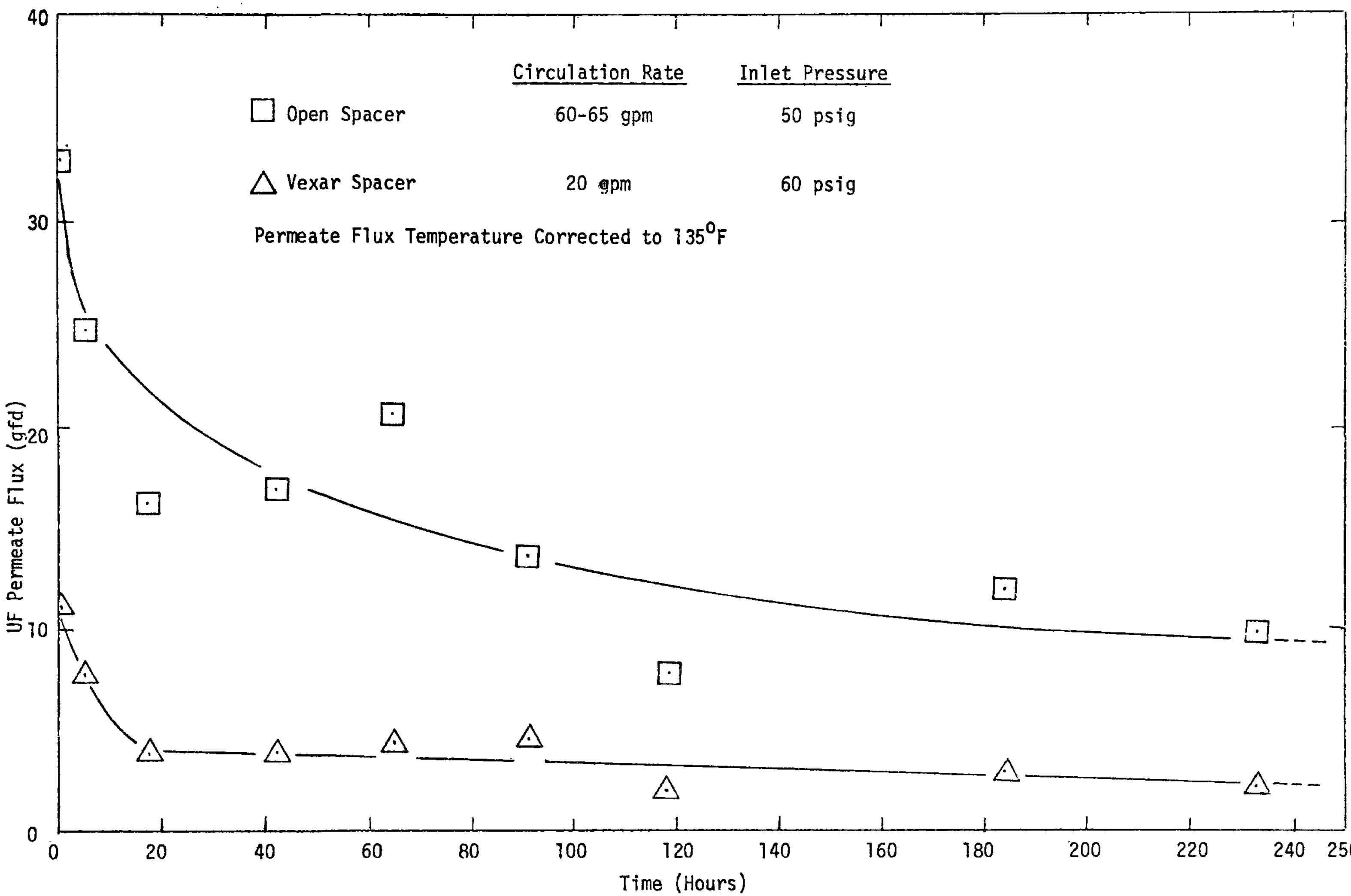


Figure 10. UF permeate flux vs. time for 67% conversion field demonstration test.

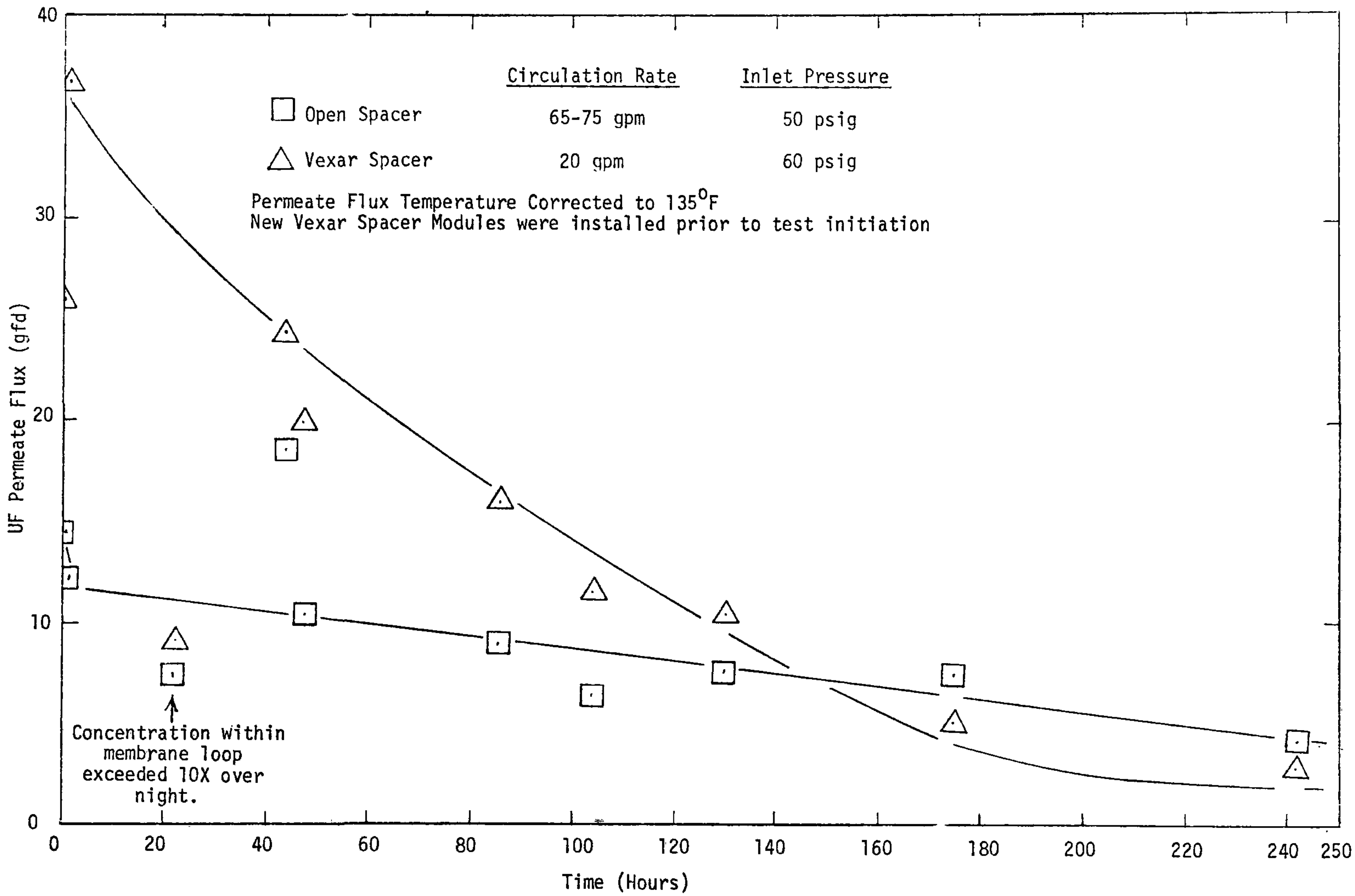


Figure 11. UF permeate flux vs. time for 90% conversion field demonstration test.

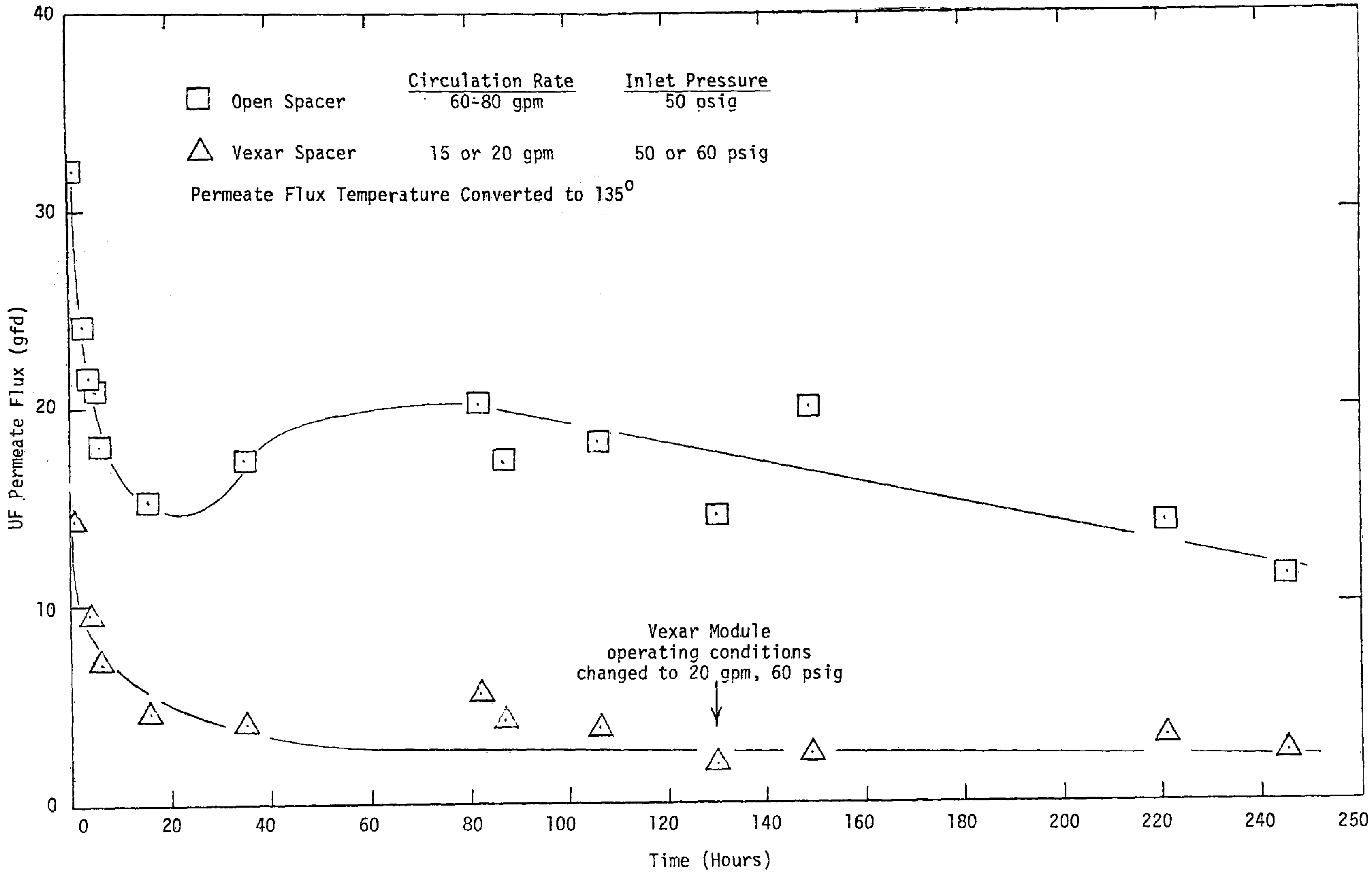


Figure 12. UF permeate flux vs. time for 97% conversion field demonstration test.

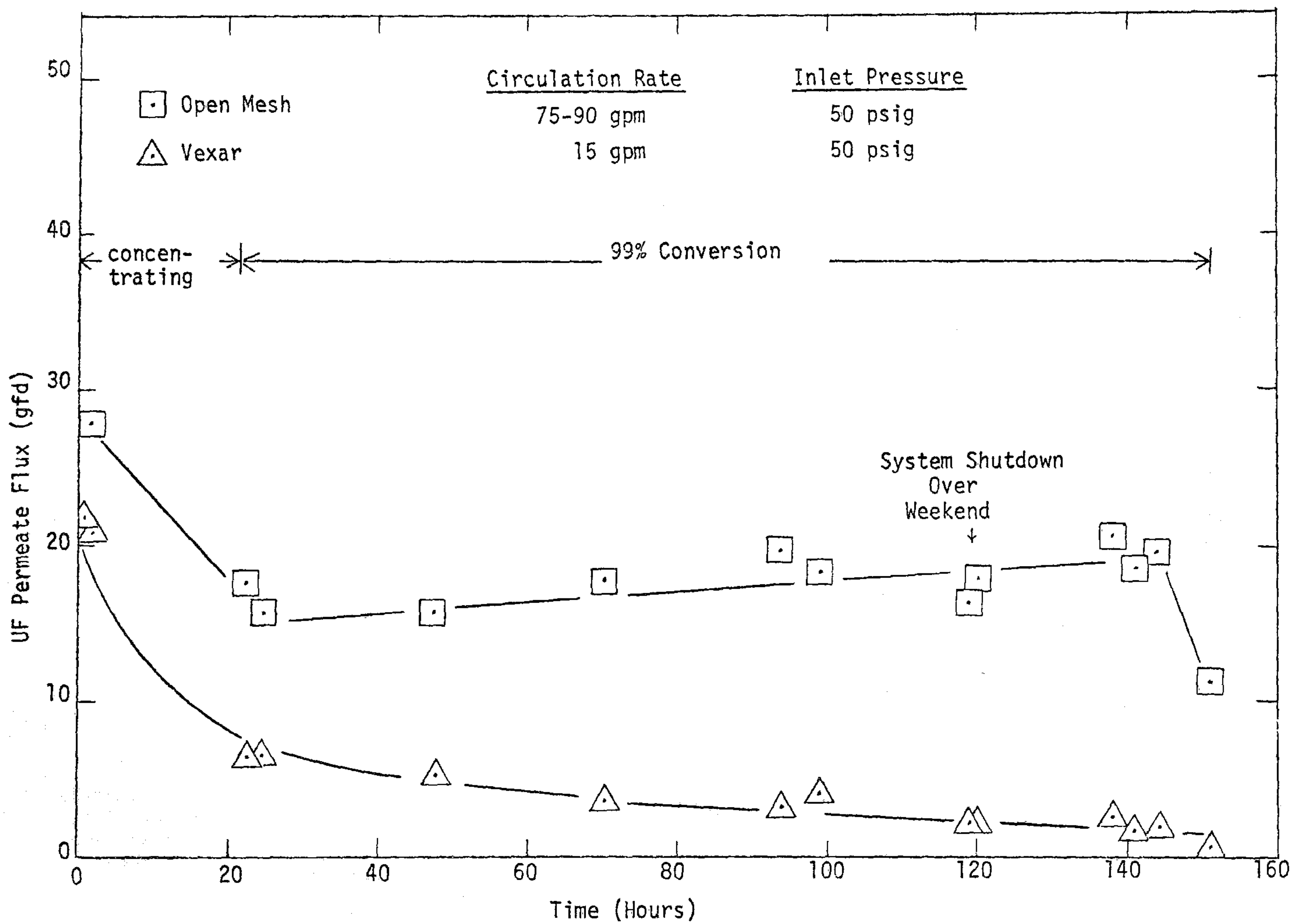


Figure 13. UF permeate flux vs. time for 99% conversion field demonstration test.

System Conversion, %	Average UF Permeate Flux (gfd @ 135°F) Vexar Spacer	Open-Spacer
67	3	12
90	15	8
97	3	17.5
99	3.5	17.5

The apparent inconsistencies in the trends for these data are readily explainable. First, the tests were conducted sequentially from highest conversion to lowest conversion. Therefore, a reduction in flux recovery following cleaning, or a gradual degradation of the membrane modules due to increased exposure to industrial laundry wastes could adversely affect the flux in the latter (lower conversion) tests. Secondly, for the open spacer modules, the formation of a thin oil layer on the membrane surface during the 90% conversion test limited the average permeate level to 8 gfd (135°F). The oil film reduced the passage of water through the membrane, while permeating oil (see below) into the product stream. The exact nature of this oil film and why it had a greater affect on the open-spacer, rather than the Vexar modules, has not been clearly defined.

A third factor influencing the average module flux levels is that after the 97% conversion experiment the water flux of the Vexar modules could not be recovered. Thus, new Vexar spacer modules were installed in the test unit for the 90% conversion experiment. While these new membranes exhibited high flux initially (see Figure 11), the flux curve has a steep slope throughout the first 175 hours of the test. At this point the permeate flux stabilizes within the 2-5 gfd (135°F) range. Once having been exposed to industrial laundry wastewater, as shown in Figure 10, the Vexar modules exhibit the same magnitude of permeate flux (2-5 gfd) as observed in the higher conversion experiments.

With the exception of the sharp flux decline for the Vexar modules during the 90% conversion experiment, the spiral-wound modules exhibited very stable flux performance. The average values of the permeate flux were 14 gfd for the open-spacer modules and 3 gfd (excluding the initial portion of the 90% conversion test) for the Vexar spacer modules. The open-spacer module flux during the formal field tests was, however, substantially below the Task 1, in-house test values. Also, the flux levels for both the open-spacer and Vexar spacer modules were below what would be predicted from the preliminary field tests. The reasons for these differences in membrane module flux performance include:

- The in-house tests were conducted with a limited volume of wastewater, and therefore, the membranes were exposed to only a relatively low fixed level of foulants.
- The first two preliminary field tests had a total duration of only 9 hours; therefore, no long-term fouling effects were observed.

-- All modules used in the first formal field test had already accumulated between 100 and 200 hours exposure to the industrial laundry wastewater during the preliminary tests.

UF Membrane Flux Recovery--

Table 14 presents the UF membrane flux recovery data during all field demonstration tests. (The corrugated modules were eliminated from evaluation after the preliminary testing and are not discussed below.) The same two open-spacer spiral-wound modules were used throughout the preliminary and formal test programs. They each accumulated over 1000 hours exposure to industrial laundry wastes and typically recovered 70% of their initial water flux after detergent cleaning. The final water flux for these modules was, however, only 53.5 gfd (135°F). As the tests proceeded, recovery of the water flux became more difficult for these modules. After 4 hours exposure to the waste (Test P1), two detergent cleaning cycles were required for satisfactory flux recovery. After 169 hours accumulated exposure (following all preliminary tests) 7 detergent cleaning cycles were required. During the formal field testing the number of detergent washings required to recover the flux of the open-spacer modules increased progressively from 3 to 6. When the formal field tests began, a reducing agent for iron foulant removal was added to the cleaning formulation. Although the extent of membrane iron fouling was not precisely determined, this change in the formulation of the cleaning solution was beneficial.

The Vexar spacer modules proved much more difficult to clean. In fact, following the second field test (533 hours cumulative exposure) the water flux of the Vexar modules could only be recovered to 11.3 gfd (135°F). These modules were discarded and new modules were installed in the test system. Following the final experiment (488 hours of exposure to the waste) the flux for these modules was recovered to only 17.6 gfd (135°F).

Clearly, the rate of irreversible flux decline for the Vexar modules is unacceptable. Also, the number of detergent cycles needed to clean the open-spacer modules or even partially clean the Vexar modules is excessive. Optimization of the module cleaning formulations and procedures is therefore required either before, or in conjunction with, any further testing of spiral-wound modules for the treatment of industrial laundry wastes.

Preferred UF Module Spacer Geometry--

As discussed above, the flux of the open-spacer module averaged 14 gfd (135°F) while the flux for the Vexar spacer module averaged 3 gfd (135°F) throughout the formal field test program. Vexar modules contain 40 sq. ft. of active membrane area while open-spacer modules contain 18 sq. ft. of active membrane area. Daily module productivity is calculated by multiplying square feet of membrane area in a given module type by the average module flux. Average module productivity, in terms of gallons per day is therefore 252 gpd and 120 gpd for the open-spacer and Vexar configurations, respectively.

TABLE 14. FLUX RECOVERY AND ACCUMULATED OPERATING TIMES FOR UF MEMBRANES OPERATED ON INDUSTRIAL LAUNDRY WASTEWATERS DURING FIELD DEMONSTRATION TESTS

Membrane Type/Spacer	Designation	Accumulated Exposure Time (Hours)	Water Flux at 135°F (gfd)	Comments
HFM/Corrugated	MC1	334	75.6	Used during Task 1
	MC2	0	200	New Module, Preliminary Testing
	MC1 and MC2	4	54.8	2 detergent cleanings
		11	---	Corrugated modules developed leaks due to high temperature
	MC3 and MC4	0	---	Water flux not recorded
		139	45.6	5 detergent cleanings
HFM/Open Spacer	MO2 and MO3	0	100	New Modules, Preliminary Testing
		4	79.8	2 detergent cleanings
		11	94.9	3 detergent cleanings
		101	86.4	-----------------------
		169	63.0	7 detergent cleanings
		320	75.0	Following first field test, 3 detergent cleanings, iron fouling treatment
		566	72.0	Following second field test, 4 detergent cleanings, iron fouling treatment
		808	73.1	Following third field test, 5 detergent cleanings, iron fouling treatment
		1054	53.5	Following fourth field test, 6 detergent cleanings, iron fouling treatment
HFM/Vexar	MV1	0	162	New Module
	MV1 and MV2	68	74.6	5 detergent cleanings, initial water flux not recorded for MV2
		136	55.1	7 detergent cleanings
		287	33.8	Following first field test, 3 detergent cleanings, iron fouling treatment
		533	11.3	Following second field test, 4 detergent cleanings, iron fouling treatment
	MV3 and MV4	0	140	New Modules
		242	31.4	Following third field test, 10 detergent cleanings, iron fouling treatment
		488	17.6	Following fourth field test, 5 detergent cleanings, iron fouling treatment

Power considerations for each are also based on the average module flux levels and active membrane areas just given. The theoretical horsepower requirements per gallon of product per day are 2.4 x 10^{-3} hp/gpd for open-spacer modules and 1.9 x 10^{-3} hp/gpd for Vexar modules. Thus, the power requirements for the two types of modules are much closer than observed during the preliminary field tests (see Table 11). One reason that these values are closer is that the Vexar module power was calculated with a feed flowrate of 20 gpm and a pressure drop of 20 psig. This circulation rate and its resulting pressure drop were used during the final two field tests in an effort to improve the Vexar module flux performance from that observed at 15 gpm (ΔP = 15 psig) circulation rate.

Another factor which must be considered before selecting the preferred module type is the relative response of the modules to cleaning. As noted above, the open-spacer modules showed considerably greater flux recovery than the Vexar modules.

Therefore, with regard to process flux, daily module productivity, and flux recovery, the open-spacer module is preferred to the Vexar spacer module. Since the power savings for the two module types are reasonably close in terms of hp/gpd, the open-spacer configuration is clearly preferred.

UF Membrane Removal Efficiency--

Tables 15 through 18 present the entire analytical data sets for the four field demonstration tests. Any deviations from the standard sampling procedures are noted in the footnotes to each table. Also, oil permeation through the membranes of the open-spacer modules resulted in abnormally low removal efficiencies for suspended solids and total freon extractibles during the 90% conversion test. With the exception of the data obtained during that particular test, the average UF removal efficiencies are:

Assay	Average UF Removal Efficiency, %
Total Solids	41.8
Suspended Solids	>96.2
Dissolved Solids	28.9
BOD	76.4
COD	82.2
TOC	78.4
Turbidity	95.4
Total Freon Extractibles	95.1

The UF process removed >95% of suspended solids, turbidity, and total freon extractibles. These values are somewhat lower than the corresponding Task 1 data. This suggests that although severe oil permeation was experienced in only one instance, minor oil permeation was a regular occurrence. This was probably the result of small quantities of free oil in the feed stream continuously adhering to the membrane surface and diffusing through it. In a full-scale operation this problem can be eliminated by installing a free-oil skimmer or coalescer upstream of the UF modules.

TABLE 15. CONTAMINANT ANALYSES AND UF AND CARBON REMOVAL EFFICIENCIES DURING 67% CONVERSION FIELD TEST

ASSAY	FEED FROM SUMP			UF CONCENTRATE			UF PERMEATE			UF REMOVAL EFFICIENCY, %[1]			CARBON EFFLUENT			OVERALL REMOVAL EFFICIENCY, %[1]		
	Week #1	Week #2	Composite	Week #1	Week #2	Composite	Week #1	Week #2	Composite	Week #1	Week #2	Composite	Week #1	Week #2	Composite	Week #1	Week #2	Composite
Total Solids (mg/ℓ)	2,140	3,140	---	5,660	3,700	---	1,160	1,240	---	45.8	60.5	---	---	---	---	---	---	---
Suspended Solids (mg/ℓ)	512	590	---	2,310	1,020	---	12	24	---	97.7	95.9	---	---	---	---	---	---	---
Dissolved Solids (mg/ℓ)	1,638	2,550	---	3,350	2,680	---	1,148	1,216	---	29.9	52.3	---	---	---	---	---	---	---
BOD (mg/ℓ)	1,200	1,300	---	3,600	2,300	---	200	340	---	83.3	73.8	---	150	88	---	87.5	93.2	---
COD (mg/ℓ)	---	---	3,220	---	---	10,640	---	---	600	---	---	81.4	---	---	160	---	---	95.0
TOC (mg/ℓ)	720	1,060	---	3,460	1,960	---	112	162	---	84.4	84.7	---	62	62	---	91.4	94.2	---
pH (units)	10.9	9.8	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Turbidity (NTU)	700	850	---	3,600	2,000	---	37	50	---	94.7	94.1	---	---	---	---	---	---	---
Total Freon Extractibles (mg/ℓ)	574	630	---	2,560	1,470	---	8	32	---	98.6	94.9	---	7	<5	---	98.8	>99.2	---
Alkalinity (mg/ℓ as $CaCO_3$)	---	---	1,080	---	---	---	---	---	---	---	---	---	---	---	980	---	---	9.3
Cadmium (mg/ℓ)	---	---	<0.2	---	---	---	---	---	---	---	---	---	---	---	<0.2	---	---	---
Chromium (mg/ℓ)	---	---	<0.5	---	---	---	---	---	---	---	---	---	---	---	<0.5	---	---	---
Copper (mg/ℓ)	---	---	0.8	---	---	---	---	---	---	---	---	---	---	---	<0.5	---	---	>37.5
Iron (mg/ℓ)	---	---	7.0	---	---	---	---	---	---	---	---	---	---	---	<1.0	---	---	>85.7
Lead (mg/ℓ)	---	---	1.7	---	---	---	---	---	---	---	---	---	---	---	<1.0	---	---	>41.2
Mercury (mg/ℓ)	---	---	0.0015	---	---	---	---	---	---	---	---	---	---	---	0.001	---	---	33.3
Nickel (mg/ℓ)	---	---	<0.5	---	---	---	---	---	---	---	---	---	---	---	<0.5	---	---	---
Zinc (mg/ℓ)	---	---	1.6	---	---	---	---	---	---	---	---	---	---	---	<0.1	---	---	>93.8

[1] Removal Efficiency, $r = \frac{\text{Feed Concentration} - \text{UF Permeate (or Carbon Effluent) Concentration}}{\text{Feed Concentration}} \times 100$

TABLE 16. CONTAMINANT ANALYSES AND UF AND CARBON REMOVAL EFFICIENCIES DURING 90% CONVERSION FIELD TEST

ASSAY	FEED FROM SUMP		UF CONCENTRATE		UF PERMEATE[3,4]		UF REMOVAL EFFICIENCY, %[1]		CARBON EFFLUENT[4]		OVERALL REMOVAL EFFICIENCY, %[1]	
	Week #1	Week #2	Week #1	Week #2	Week #1	Week #2	Week #1	Week #2	Week #1	Week #2	Week #1	Week #2
Total Solids (mg/ℓ)	2,240	1,040	9,690	2,790	1,360	---	39.3	---	---	---	---	---
Suspended Solids (mg/ℓ)	680	324	5,020	504	174	---	74.4	---	---	---	---	---
Dissolved Solids (mg/ℓ)	1,560	716	4,670	2,286	1,126	---	27.8	---	---	---	---	---
BOD (mg/ℓ)	1,100	(270)[2]	6,000	1,500	350	520	68.2	---	220	100	80.0	(54.5)[2]
COD (mg/ℓ)	---	---	---	---	---	948	---	---	---	216	---	---
TOC (mg/ℓ)	940	---	7,120	---	322	251	65.7	---	102	72	89.1	---
pH (units)	11.0	7.6	---	---	---	---	---	---	---	---	---	---
Turbidity (NTU)	1,000	360	8,000	1,600	100	15	90.0	95.8	---	2.8	---	99.7
Total Freon Extractibles (mg/ℓ)	916	345	6,100	1,300	363	36	60.4	89.6	5	12	99.5	96.5
Color (units)	---	---	---	---	---	400	---	---	---	20	---	---

[1] Removal Efficiency, r = $\frac{\text{Feed Concentration-UF Permeate (or Carbon Effluent) Concentration}}{\text{Feed Concentration}} \times 100$

[2] ( ) indicates suspected error in analysis.

[3] Week #2 UF Permeate taken from vexar modules only, grab sample.

[4] During Week #1 one sample of UF Permeate was invertantly placed in carbon effluent sample bottle and vice versa.

TABLE 17. CONTAMINANT ANALYSES AND UF AND CARBON REMOVAL EFFICIENCIES DURING 97% CONVERSION FIELD TEST

ASSAY	FEED FROM SUMP			UF CONCENTRATE		UF PERMEATE		UF REMOVAL EFFICIENCY, %[1]		CARBON EFFLUENT[2]			OVERALL REMOVAL EFFICIENCY, %[1]		
	Week #1	Week #2	Composite	Week #1	Week #2	Week #1	Week #2	Week #1	Week #2	Week #1	Week #2	Composite	Week #1	Week #2	Composite
Total Solids (mg/l)	( )[3]	1990	-----	( )[3]	11,300	( )[3]	1330	----	33.2	---	---	-----	----	----	------
Suspended Solids (mg/l)	( )[3]	500	-----	( )[3]	3,580	( )[3]	35	----	93.0	---	---	-----	----	----	------
Dissolved Solids (mg/l)	( )[3]	1490	-----	( )[3]	7,720	( )[3]	1295	----	13.1	---	---	-----	----	----	------
BOD (mg/l)	790	910	-----	26,500	14,300	220	160	72.2	82.4	230	110	-----	70.9	87.9	------
COD (mg/l)	---	----	2,530	---- 65,400[4]	----	--- 397[4]	----	---- 84.3[4]	----	---	---	445	----	----	82.4
TOC (mg/l)	750	440	-----	18,600	7,900	212	85	71.7	80.7	188	94	-----	74.9	78.6	------
PH (units)	( )[3]	9.3	-----	----	----	---	----	----	----	---	---	-----	----	----	------
Turbidity (NTU)	( )[3]	500	-----	( )[3]	9.000	( )[3]	30	----	94.0	---	---	-----	----	----	------
Total Freon Extractibles (mg/l)	320	630	-----	15,100	7,500	20	13	93.8	97.9	22	8	-----	93.1	98.7	------
Alkalinity (mg/l as $CaCO_3$)	---	----	580	----	----	---	----	----	----	---	---	582	----	----	------
Cadmium (mg/l)	---	----	< 0.2	----	----	---	----	----	----	---	---	< 0.2	----	----	------
Chromium (mg/l)	---	----	< 0.5	----	----	---	----	----	----	---	---	< 0.5	----	----	------
Copper (mg/l)	---	----	0.9	----	----	---	----	----	----	---	---	< 0.5	----	----	> 44.4
Iron (mg/l)	---	----	4.9	----	----	---	----	----	----	---	---	< 1	----	----	> 79.6
Lead (mg/l)	---	----	1.5	----	----	---	----	----	----	---	---	< 1	----	----	> 33.3
Mercury (mg/l)	---	----	0.001	----	----	---	----	----	----	---	---	0.001	----	----	------
Nickel (mg/l)	---	----	< 0.5	----	----	-	----	----	----	---	---	< 0.5	----	----	------
Zinc (mg/l)	---	----	1.6	----	----	----	----	----	----	---	---	0.6	----	----	62.5

[1] Removal Efficiency, r, = $\frac{\text{Feed Concentration-UF Permeate (or Carbon Effluent) Concentration}}{\text{Feed Concentration}} \times 100$

[2] Carbon Column nearing breakthrough

[3] Samples inadvertantly disposed of prior to complete analysis

[4] Composite Samples

TABLE 18. CONTAMINANT ANALYSES AND UF AND CARBON REMOVAL EFFICIENCIES DURING 99% CONVERSION FIELD EXPERIMENT

Assay	Feed from Sump Week #1[2]	UF Concentrate Week #1	UF Concentrate Week #2	UF Permeate Week #1	UF Permeate Week #2	UF Removal Efficiency,%[1] Week #1	Carbon Effluent Week #1	Carbon Effluent Week #2	Overall Removal Efficiency,%[1] Week #1
Total Solids (mg/ℓ)	2,840	73,000	37,700	2,050	1,740	27.8	2,350	--	17.3
Suspended Solids (mg/ℓ)	270	36,100	21,600	<5	8	>98.1	<5	--	>98.1
Dissolved Solids (mg/ℓ)	2,570	36,900	16,100	2,045	1,732	20.4	2,345	--	8.8
BOD (mg/ℓ)	880	87,900	31,000	260	363	70.5	260	363	70.5
COD (mg/ℓ)	3,120	276,000	---	592	---	81.0	592	--	81.0
TOC (mg/ℓ)	675	54,400	31,500	198	208	70.7	202	202	70.1
pH (units)	11.6	10.6	11.3	11.4	10.8	---	11.6	11.2	---
Turbidity (NTU)	700	70,000	40,000	7.7	4.0	98.9	9.3	--	98.7
Total Freon Extractibles (mg/ℓ)	505	36,000	20,600	20	14	96.0	8	<5	98.4
Alkalinity (mg/ℓ as $CaCO_3$)	1,010	---	---	---	---	---	1,040	--	---
Cadmium (mg/ℓ)	<0.2	---	---	---	---	---	<0.2	--	---
Chromium (mg/ℓ)	<0.5	---	---	---	---	---	<0.5	--	---
Copper (mg/ℓ)	0.99	---	---	---	---	---	<0.5	--	>49.5
Iron (mg/ℓ)	5.7	---	---	---	---	---	<1.0	--	>82.5
Lead (mg/ℓ)	2.2	---	---	---	---	---	<1.0	--	>54.5
Mercury (mg/ℓ)	0.002	---	---	---	---	---	0.001	--	50.0
Nickel (mg/ℓ)	<0.5	---	---	---	---	---	<0.5	--	---
Zinc (mg/ℓ)	2.0	---	---	---	---	---	0.57	--	71.5

[1] Removal Efficiency, r, $= \frac{\text{Feed Concentration - UF Permeate (or Carbon Effluent) Concentration}}{\text{Feed Concentration}} \times 100$

[2] No feed sample collected during second week due to pump malfunction.

The range of BOD, COD, and TOC removal efficiencies - 76, 82, and 78% respectively - are consistent with previous results and indicate that no membrane or module failures occurred. These values would, however, have been slightly improved if the free-oil had been completely eliminated from the feed stream. In terms of actual permeate quality, average BOD was 302 mg/l; COD, 634 mg/l; and TOC 194 mg/l.

Mass balance calculations performed with the data presented in Tables 15 through 18 indicate that the system conversion was not maintained at exactly the desired level throughout each test. For example, during week #1 of the 97% conversion test a system conversion of 96-98% (25-50X concentration factor) is indicated from the analytical data. For the second week of this test, conversions of 80-94% (5-18X concentration factor) are indicated. The lower conversion during the second week is attributed to a slight mismatch between total permeate flow and possible concentrate bleed settings. The timer-solenoid valve arrangement used for withdrawing a constant flowrate of concentrate was only adjustable in increments of 18 ml/min and therefore precise control at the desired conversion was not always attainable.

Carbon Adsorption

Carbon Removal Efficiency--

Throughout the four field demonstration experiments a slip-stream of UF permeate was continuously fed to a 2-inch diameter carbon column. The assays performed on the carbon effluent composite samples are presented along with the initial feed, UF concentrate and UF permeate analyses in Tables 15 through 18. Table 19 condenses these data giving average values for the feed, UF permeate, carbon effluent and carbon removal efficiency based on the UF permeate quality. Overall UF/ACA removal efficiencies are discussed in a subsequent section.

As observed in Table 19 the activated carbon reduced the UF permeate organic loading and oxygen demand by ~40%. Freon extractibles were decreased by over 55%. All of these removal efficiencies are based on weekly or biweekly composite samples indicating that the activated carbon consistently improved the UF permeate quality.

Adsorptive Capacity of Carbon--

The adsorptive capacity (maximum loading) of a particular carbon column for a given contaminant is determined by measuring the volume of liquid processed before the concentration of that contaminant in the carbon column effluent approaches or equals its concentration in the feed stream. When these concentrations approach each other complete "breakthrough" is said to have occurred. By analyzing periodic grab samples for TOC and color, breakthrough curves for these contaminants were developed for the field demonstration tests.

TABLE 19. AVERAGE CARBON REMOVAL EFFICIENCY DATA
(UF Permeate as Feed, Basis)

Assay	Average Feed Concentration	Average UF Permeate Concentration	Average Carbon Effluent Concentration	Average Carbon Removal Efficiency, % *†
BOD (mg/l)	1030	302	190	37.1
COD (mg/l)	2960	634	353	44.3
TOC (mg/l)	764	194	123	36.6
Total Freon extractibles (mg/l)	596	20.4	<9	>55.9

$$* \text{ Removal Efficiency, } r, = \frac{\text{UF Permeate Concentration} - \text{Carbon Effluent Concentration}}{\text{UF Permeate Concentration}} \times 100\%$$

† Based on average UF permeate and carbon effluent concentrations

Two sets of breakthrough curves were generated: One set was generated during the 67 and 90% conversion tests; the other, during the 97 and 99% conversion tests. These data are shown in Figures 14 and 15, respectively. New carbon was placed in the columns prior to the collection of each data set. The average UF permeate color and TOC concentrations were 195 color units and 143 mg/l in one test compared to 750 color units and 213 mg/l TOC in the test at the higher UF system conversions. The substantial difference in average ultrafiltrate color concentration, while attributable in part to changes in system conversion, may also be the result of variations in the mix of articles laundered.

For TOC, both curves indicate that the carbon effluent concentration approaches the UF permeate concentration at ~2250 gallons processed. After this point the concentration of TOC in the carbon effluent increased above the average UF permeate concentration in one case and returned to ~50% of the average UF permeate concentration in the other. In the former instance, the increase can be attributed to desorption of contaminants from the fully loaded carbon. In the latter case, the low final TOC concentration may be the result of biological activity within the column. Breakthrough after 2250 gallons were processed through the column corresponds to a carbon replacement cost of $1.32/1000 gal (at a carbon cost of 56¢/lb).

A lower carbon replacement cost may be indicated if column operation is dictated by effluent color concentration only. While color breakthrough occurred at approximately the same time as TOC breakthrough in the test at the higher UF system conversions, complete color breakthrough did not occur during the test at the lower UF system conversions. At the time when these UF tests were completed, 3234 gallons of ultrafiltrate had already been processed through the carbon column. Since color breakthrough was in no way indicated at this point (see Figure 14), a conservative estimate for the carbon replacement frequency would be after the processing of 3500 gallons through the 2-inch column. This corresponds to a carbon replacement cost of $0.85/1000 gallon.

Without performing similar tests on other laundry wastewaters, it is difficult to assess the degree to which these costs are representative of all industrial laundering operations. Furthermore, it is possible that carbon treatment of UF permeates for color removal may not be necessary for launderies which wash colored articles.

<u>Overall UF/ACA Removal Efficiency</u>

The overall contaminant removal efficiency of the ultrafiltration/activated carbon adsorption treatment combination was quite good. These data were presented for the individual field tests in Tables 15 through 18 and are summarized in Table 20. Turbidity removal averaged 99.2%, and suspended solids removal, determined by the UF permeate concentration, was > 96.2%. Most of the suspended solids which did pass the UF process were eliminated from the final effluent by the depth filter characteristics of the carbon column. The average reduction in total freon extractibles was > 97.7%. Overall removal efficiencies for BOD, COD, and TOC averaged 82%, 86% and 82%, respectively.

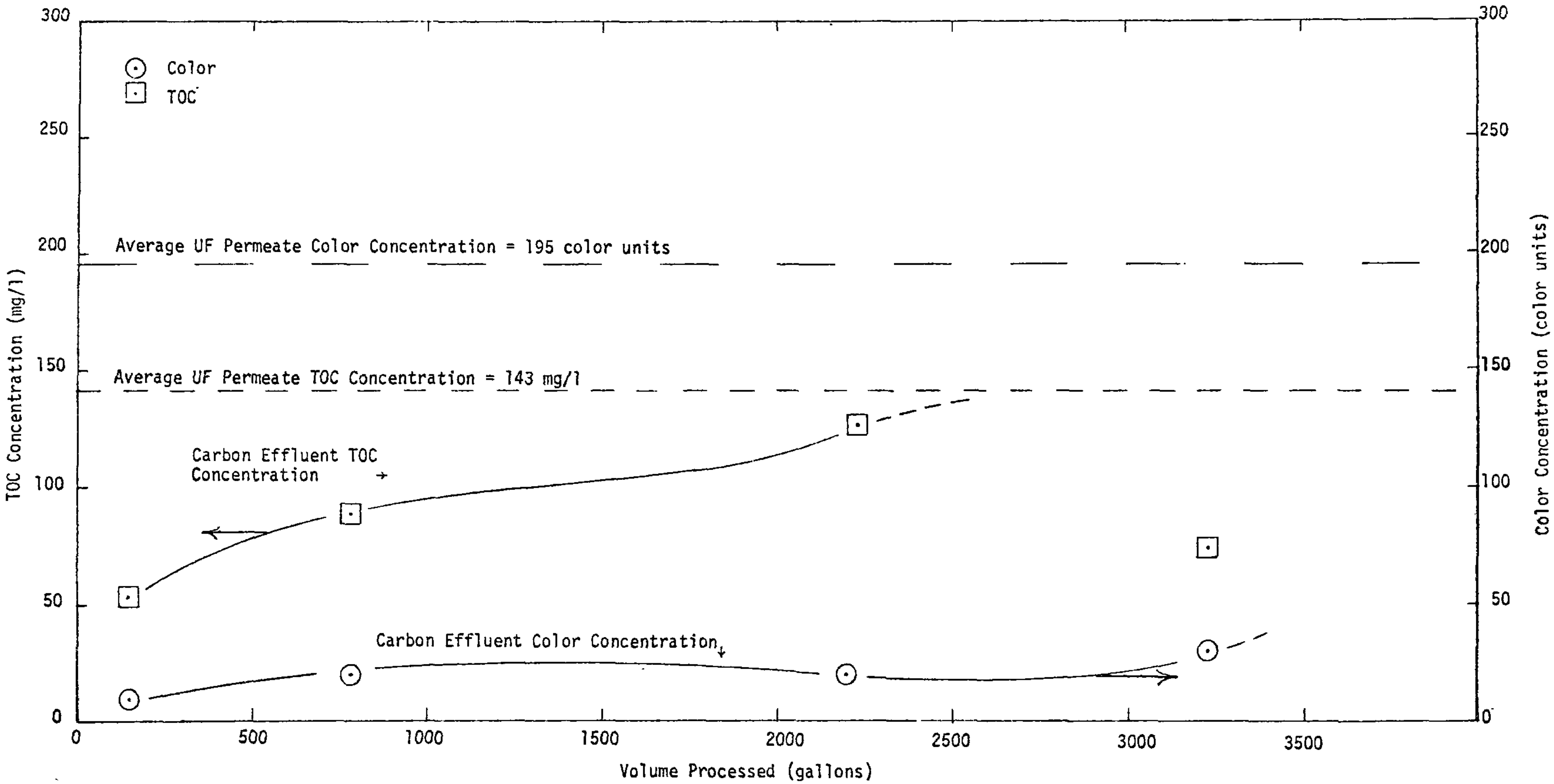


Figure 14. Carbon column breakthrough curves for color and TOC during 67 and 90% conversion field demonstration tests.

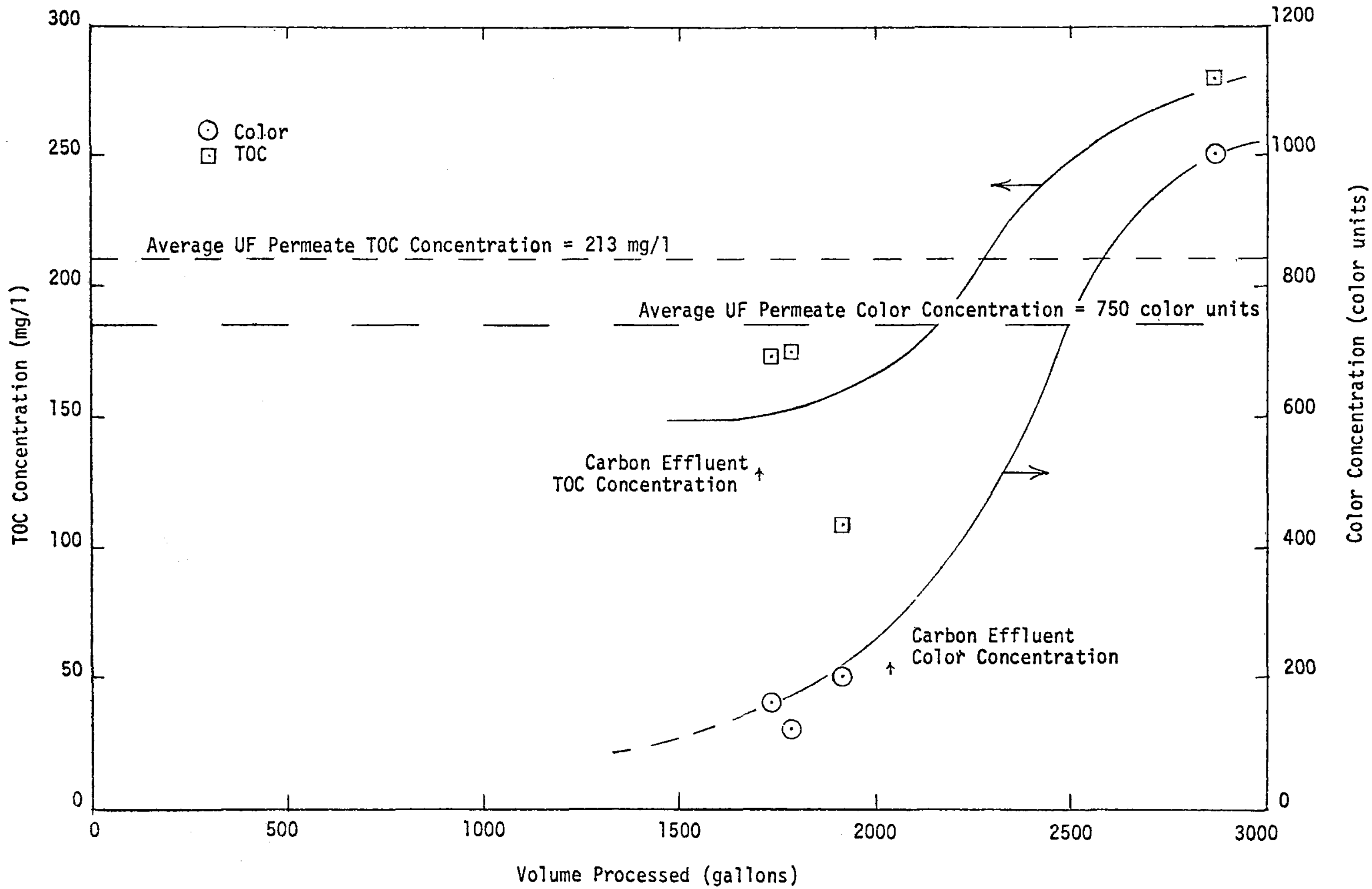


Figure 15. Carbon column breakthrough curves for color and TOC during 97 and 99% conversion field demonstration test.

TABLE 20. SUMMARY OF AVERAGE UF/ACA PRODUCT WATER QUALITY AND REMOVAL EFFICIENCIES DURING FIELD DEMONSTRATION TESTS

Assay	Average Feed Concentration	Average UF/ACA Effluent Concentration	Average UF/ACA Removal Efficiency, %*†
Total Solids (mg/l)	2230	1480**	41.8**
Suspended Solids (mg/l)	479	<16.8**	>96.2**
Dissolved Solids (mg/l)	1750	1463**	28.9**
BOD (mg/l)	1030	190	81.7
COD (mg/l)	2960	353	86.1
TOC (mg/l)	764	123	81.8
Turbidity (NTU)	685	6.1	99.2
Total Freon Extractibles (mg/l)	596	<9	>97.7
Alkalinity (mg/l as $CaCO_3$)	890	867	3.1
Cadmium (mg/l)	<0.2	<0.2	---
Chromium (mg/l)	<0.5	<0.5	---
Copper (mg/l)	0.9	<0.5	>43.8
Iron (mg/l)	5.9	<1	>82.6
Lead (mg/l)	1.8	<1	>43.0
Mercury (mg/l)	0.0015	0.001	41.5
Nickel (mg/l)	<0.5	<0.5	---
Zinc (mg/l)	1.7	0.42	>75.9

* Removal efficiency, $r = \frac{\text{Feed Concentration - UF/ACA Effluent Concentration}}{\text{Feed Concentration}} \times 100$

† Average removal efficiency is based on individual test results and not on average feed and permeate concentrations.

**Carbon effluent sample not analyzed for this constituent. UF permeate concentration and UF system removal efficiency are given.

Industrial laundries are typically surcharged by municipal treatment authorities on the mass of BOD and suspended solids discharged. The minimum allowable discharge before a surcharge is assessed varies between localities; however, it is clear from these data that the UF/ACA process will eliminate or greatly reduce these charges. The effluent oil and grease level of <9 mg/l should satisfy all sewer discharge standards.

As discussed previously, the metals removal efficiencies for the combined treatment process were generally limited by the lower detection limit of the assays. The MSD of Greater Chicago Sewer Discharge Standards were easily met for all metals, except mercury. For mercury, an average removal efficiency of 41.5% was achieved with an average effluent concentration of 0.001 mg/l. The MSD's standard for mercury, 0.005 mg/l, is quite low. A survey of 20 municipal sewer discharge standards has indicated a range of 0.005 - 1.5 mg/l for the allowable concentration of mercury in industrial effluents (1).

Conclusions

With the conclusion of the formal field demonstration experiments, the entire test program was completed. On the basis of these experiments, conclusions derived relative to UF/ACA treatment of industrial laundry wastewaters are:

-- Open-spacer, spiral-wound, UF modules are preferred to Vexar spacer modules since they offer higher permeate flux rates and higher daily productivities. Open-spacer modules are also more easily cleaned than Vexar modules. The small savings in power cost per gallon of product per day offered by Vexar modules is far outweighed by the open-spacer modules' advantages.

-- Average permeate flux for the open-spacer modules was 14 gfd (135°F); for the Vexar modules the average flux was 3 gfd (135°F). Flux levels of this magnitude are not economically acceptable for treatment of industrial laundry wastewaters.

-- Free oil in the waste stream can seriously effect the performance of the UF membranes. Both permeate flux and permeate quality deteriorate rapidly if a free oil layer coats the membrane surface.

-- Optimization of UF module cleaning formulations and procedures is required in conjunction with any further testing of spiral-wound modules for the treatment of industrial laundry wastewaters. In fact, it is doubtful if a spiral-wound membrane configuration can withstand prolonged operation in an industrial laundry. A membrane configuration, which is less susceptible to fouling e.g., tubular, is clearly required.

- -- The overall UF/ACA product water averaged <17 mg/l suspended solids, 190 mg/l BOD, 353 mg/l COD, 123 mg/l TOC, and <9 mg/l total freon extractibles. An effluent of this quality indicates average removal efficiencies for the treatment process of >96% for suspended solids, >97% for freon extractibles and 82%, 86%, and 82% for BOD, COD, and TOC, respectively. An effluent of this quality should be acceptable for discharge to municipal sewer systems. Based on local ordinances, a surcharge may be applied if the mass discharge of BOD and suspended solids exceed acceptable limits.

- -- Metals removed by the UF/ACA process was, in general, calculated from the lower detection limit values of the assays. All metals of interest, except mercury, were removed to levels below those specified in the sewer ordinances of the Metropolitan Sanitary District (MSD) of greater Chicago.

- -- Activated carbon treatment improved UF permeate quality substantially. Further reductions in the BOD, COD, and TOC of the wastewater averaged ~40%.

- -- The carbon's adsorptive capacity for color bodies is greater than its adsorptive capacity for TOC. Breakthrough curves developed for color indicate a carbon replacement cost of $0.85/1000 gal.

SECTION 8

ECONOMIC SCALE-UP ANALYSIS

INTRODUCTION

In this section purchased equipment (capital) costs and operating costs are projected for UF/ACA systems treating industrial laundry wastewaters. Cases are presented for launderies discharging 25,000, 75,000 and 100,000 gpd of waste.

A generalized flow schematic for the waste treatment system is shown in Figure 16. Two basic alternatives have been examined: waste treatment for discharge to the sewer and waste treatment with water reuse. The latter alternative requires post-treatment of the UF permeate by carbon adsorption and the installation of a large product water holding tank.

Figure 16 assumes a 100,000 gpd waste discharge. The waste is transferred from the plant sump to a 75,000 gal surge tank. This surge capacity permits 24 hour/day operation of the UF system even though the plant has an 8 hour/day waste generation cycle. Waste pretreatment before the UF system will consist of three steps:

(1) Microstraining for lint removal (e.g. Sweco vibrating screen or Bauer Hydrasieve).

(2) Skimming for free oil removal in the surge tank (e.g. rope skimmer).

(3) Filtration for additional suspended solids removal. The type of filter to be used has not yet been specified. This step requires additional investigation, the degree of which was not anticipated at the start of this program.

The ultrafiltration system costs are based on Abcor, Inc. Type HFM membranes in open-spacer, spiral-wound modules. Since the average permeate flux was not strongly dependent on the system conversions, the use of a single-stage rather than a multi-stage system is preferred.

Key design bases are outlined below:

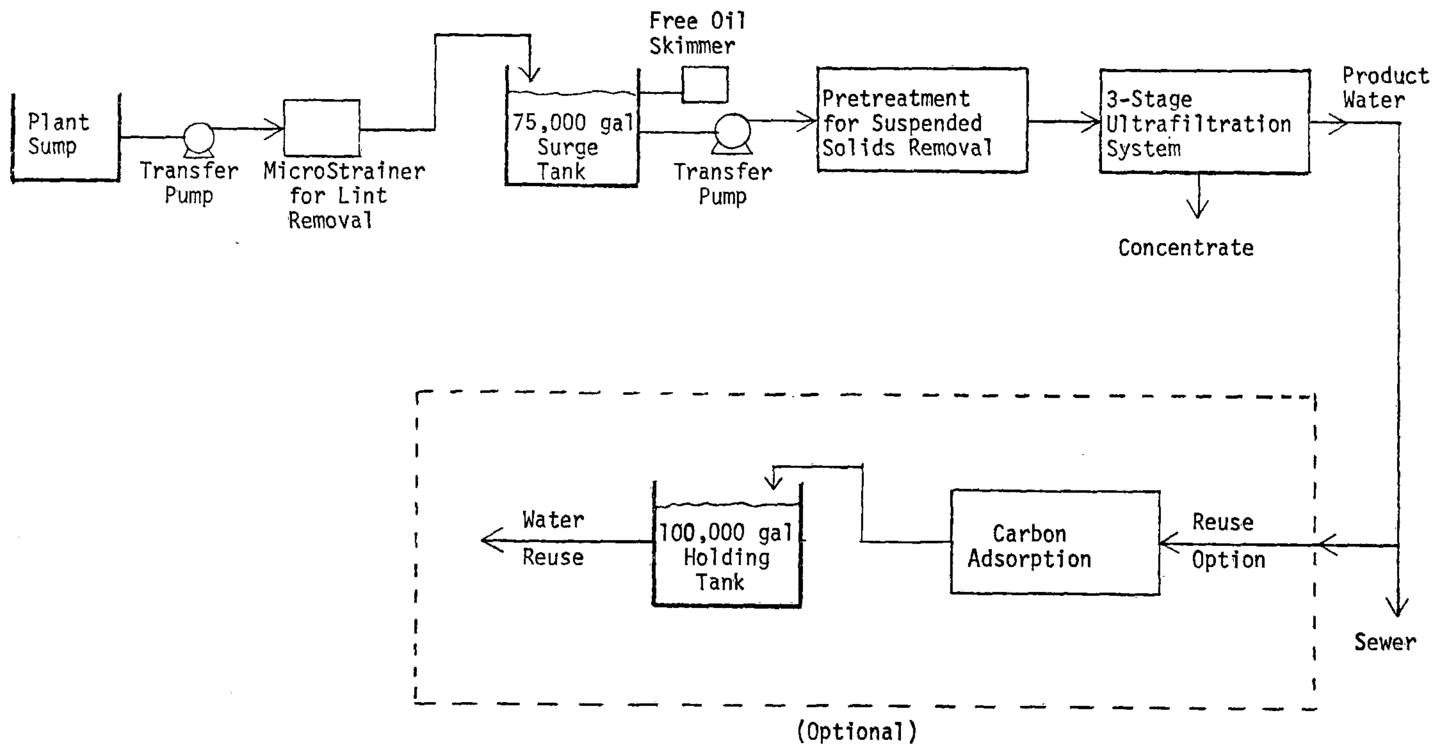


Figure 16. Flow schematic of 100,000 gpd waste treatment system.

Assumed Membrane Flux, gfd	14
Membrane Life, yrs	1
Membrane System Costs, $/ft^2	50
Membrane Replacement Costs, $/ft^2	20

Based on the average flux of 14 gfd, membrane area requirements for the three systems are:

Capacity, gpd	Membrane Area Requirement, ft^2
25,000	1,786
75,000	5,357
100,000	7,143

PURCHASED EQUIPMENT COSTS FOR PRETREATMENT AND ULTRAFILTRATION SYSTEMS

Purchased equipment costs for the three system capacities are given in Table 21. The purchased equipment cost per gallon of wasted treated per day ranges from $4 to $4.65. The Table 21 costs are based on carbon steel systems containing all necessary monitors and controllers for unattended operation, a temperature control loop, a product water turbidity monitor and a central control panel. These costs exclude costs for an activated carbon adsorption system, which is addressed separately in a subsequent section. Also excluded is installation cost which will be highly site specific. If all utilities (power, water, and sewer connections, etc.) are in place, and no new facility must be constructed, installation costs might be as low as $25,000 to $50,000. If not, installation costs may be as high as 100% of the system cost. Installation costs must be calculated on an individual, site-by-site basis.

ANNUAL OPERATING COST FOR PRETREATMENT AND ULTRAFILTRATION SYSTEMS

Table 22 contains operating cost projections for the three system capacities. These do not include capital-related costs such as amortization, interest, and taxes. Also, carbon adsorption operating costs and water reuse credits are addressed in a subsequent section. Details of the power cost estimates are given in Table 23. All UF system costs are based on system operation six days per week with system cleaning taking place on the seventh day. Pre-treatment system costs are based on operation six days per week only. The operating costs range from $11.82/1000 gal when processing 25,000 gpd to $9.01/1000 gal when processing 100,000 gpd. These costs are clearly impractical and necessitate the evaluation of an alternative UF approach, presented at the end of this section, which is predicted to significantly lower the operating expenses.

PURCHASED EQUIPMENT AND ANNUAL OPERATING COSTS FOR ACTIVATED CARBON TREATMENT AND COMPLETE WATER REUSE

Pretreatment and ultrafiltration system costs have been discussed thus far with the assumption that all UF permeate would be discharged to municipal sewers. However, it is possible that some, if not all, of the UF permeate

TABLE 21. ESTIMATED PURCHASED EQUIPMENT COSTS FOR WASTEWATER TREATMENT SYSTEMS OF VARIOUS CAPACITIES (Thousands of Dollars)

ITEM	UF SYSTEM CAPACITY (gpd)		
	25,000	75,000	100,000
PRETREATMENT			
1. Holding tank and controls with a capacity of 75% of system capacity.	10	20	25
2. Prefiltration for lint and suspended solids removal	15	18	20
3. Oil skimmer for free oil removal	2	3	4
	27	41	49
ULTRAFILTRATION SYSTEM			
1. UF System including controls, monitors and engineering design costs	89.3	267.9	357.2
	89.3	267.9	357.2
TOTAL ESTIMATED PURCHASED EQUIPMENT COSTS	116.3	308.9	406.2
PURCHASED EQUIPMENT COST PER GALLON OF WASTE TREATED PER DAY	\$4.65	\$4.12	\$4.06

NOTES: 1. This cost analysis does not include installation costs which will vary considerably from site to site depending on availability of utility connections, space, etc.

2. This analysis assumes discharge of UF permeate to the sewer and therefore carbon adsorption and product water storage costs are omitted.

TABLE 22. ESTIMATED ANNUAL OPERATING COSTS FOR WASTEWATER TREATMENT SYSTEMS OF VARIOUS CAPACITIES (Thousands of dollars)*

ITEM	UF SYSTEM CAPACITY (gpd)		
	25,000	75,000	100,000
PRETREATMENT			
1. Labor, Operating & Maintenance, 2 hrs/day @ $5.00/hr plus 75% fringe benefits and overhead	5.5	5.5	5.5
2. Supervisory Labor, 1 hr/day @ $10/hr plus 75% fringe benefits and overhead	5.5	5.5	5.5
3. Power, 5 or 10 hp (27,900 or 55,800 kw-hr @ 4¢/kw-hr)	0.8	1.7	1.7
	11.8	12.7	12.7
ULTRAFILTRATION SYSTEM			
1. Labor, Operating & Maintenance, 3 hr/day @ $5.00 plus 75% fringe benefits and overhead	9.6	9.6	9.6
2. Supervisory Labor, 1 hr/day @ $10/hr plus 75% fringe benefits and overhead	6.4	6.4	6.4
3. Membrane Replacement	35.7	107.1	142.9
4. Power, see breakdown in Table 23	22.4	67.2	89.6
5. Cleaning Chemicals, 1 cleaning per week, 25, 35 or 45 lbs @ $1.85/lb	2.4	3.4	4.3
6. UF Concentrate Disposal, 250, 750 or 1000 gpd, 312 days/yr (contract hauling @ 5¢/gal)	3.9	11.7	15.6
	80.4	205.4	268.4
TOTAL ANNUAL OPERATING COSTS	92.2	218.1	281.1
TREATMENT COSTS, $/1000 gal	$11.82	$9.32	$9.01

* Annual operating cost analysis does not include capital related costs such as amortization, interest and taxes.

TABLE 23. ESTIMATED POWER REQUIREMENTS FOR WASTEWATER TREATMENT SYSTEMS OF VARIOUS CAPACITIES

System Capacity	No. of Spiral-Wound Cartridges	No. of Parallel Passes	Total Flow, gpm	ΔP per pass, psig	Actual Horsepower, hp	kw-hr per 1000 gal	Cost per year, $
25,000	99	33	2310	45	86	61.4	22,400
75,000	298	99	6930	45	257	61.4	67,200
100,000	397	132	9240	45	343	61.4	89,600

Notes:
1. Open-spacer module membrane area is 18 sq. ft., 3 modules per parallel pass.
2. Flow rate per pass is 70 gpm.
3. Horsepower requirement assumes 70% pump efficiency.
4. Power costs based on 4¢ per kw-hr.

could be reused directly within a laundry which handles a minimum of white articles. Nevertheless, because of the questionability of UF permeate reuse, no projections of water reuse credits were made.

As water discharge standards become more stringent and if "closed-loop" treatment systems become mandatory, activated carbon treatment of the UF permeate for color removal will be a logical continuation of the waste treatment sequence. It is anticipated that the additional capital investment necessary to meet any zero discharge limitation will depend largely on the nature of the effluent guidelines which may be promulgated for the industrial launderers. These additional capital costs, associated annual operating costs, and water reuse credits are discussed below.

Estimated additional purchased equipment costs for complete water reuse are detailed in Table 24. A carbon adsorption system and a product water storage tank with a capacity equal to one day's discharge would be required. The carbon system costs are based on a projected carbon capacity of ~3 color units/mg carbon, an average removal of 500 color units per liter, and a bed service time of two months. The purchased equipment costs total $17,300 for the 25,000 gpd system, $40,800 for the 75,000 gpd system, and $51,000 for the 100,000 gpd system.

Operating costs for the carbon adsorption system are also given in Table 24. These costs range from $1.09 to $1.68/1000 gal of treated water. Carbon replacement costs account for 50% to 80% of these annual operating expense estimates.

Certain credits for water reuse within the laundry may be applied to the annual system operating costs to arrive at a significantly reduced net treatment cost. These credits are summarized in Table 25. The exact amount of credit possible for any particular industrial laundry depends upon the water consumption and sewer use charges in the city where it is located. High, low, and average values of potential water reuse credits were calculated using published data (1). The water reuse credits range from $0.55 to $2.8/1000 gal of water reused with an average credit of $1.08/1000 gal of water. All of these estimated credits are based on charges prevailing in 1971. Charges for consumption for water have undoubtedly risen while sewer surcharges are now in effect in more areas. Therefore, these figures should be considered as conservative estimates of potential water reuse savings. Even at the 1971 levels, however, these credits offset the cost of carbon adsorption treatment.

PROJECTED ECONOMICS FOR TUBULAR ULTRAFILTRATION SYSTEMS

Introduction

Two factors contributed most significantly to the capital and operating costs for open-spacer, spiral-wound-module, UF systems. First, the average UF permeate flux was low (14 gfd) causing membrane area requirements at any given capacity to be high. Since UF system capital costs are calculated on

TABLE 24. ESTIMATED ADDITIONAL PURCHASED EQUIPMENT AND OPERATING COSTS FOR COMPLETE WATER REUSE (Thousands of dollars)

ITEM	TREATMENT SYSTEM CAPACITY (gpd)		
	25,000	75,000	100,000
PURCHASED EQUIPMENT COSTS			
1. Carbon Column; 70, 210 or 280 ft^2 @ $60/$ft^3$	4.2	12.6	16.8
2. Engineering design costs for carbon column @ 25%	1.1	3.2	4.2
3. Product water storage tank, same capacity as treatment system	12	25	30
TOTAL ESTIMATED PURCHASED EQUIPMENT COSTS	17.3	40.8	51.0
PURCHASED EQUIPMENT COST PER GALLON OF WASTE TREATED PER DAY	0.69	0.54	0.51
OPERATING COSTS			
1. Labor, Operating and Maintenance 1 hour/day @ $5/hour, plus 75% for fringe benefits and overhead	2.7	2.7	2.7
2. Supervisory Labor, 0.5 hr/day @ $10/hour plus 75% for finge benefits and overhead	2.7	2.7	2.7
3. Carbon Replacement, @ 56¢/lb	6.6	19.7	26.4
4. Power, 5 or 10 hp (27,900 or 55,800 kw-hr @ 4¢/kw-hr)	1.1	2.3	2.3
TOTAL ANNUAL OPERATING EXPENSE	13.1	27.4	34.1
TREATMENT COSTS, $/1000 GAL	1.68	1.17	1.09

NOTES: 1. Purchased equipment costs do not include installation costs, which will vary considerably from site to site.

2. Annual operating costs do not include capital related costs such as amortization, interest and taxes.

TABLE 25. ESTIMATED ANNUAL CREDITS FOR REUSE OF TREATED WATER

Current Laundry Operating Costs *	Credits, Dollars/1000 gal Treated		
	Low	High	Typical
1. Influent water	0.12	0.70	0.28
2. Heating requirements (Assumes a $20^{o}F$ increase in water temperature resulting from reuse as opposed to use of waste water heat in a heat exchanger) (1.66 $x10^6$ BTU/1000 gal-day, 260 days/yr operation, @ \$3.00/10^6 BTU)	0.41	0.41	0.41
3. Sewer use charges	0.02	1.12	0.22
4. Sewer surcharges	0.00	0.60	0.17
	0.55	2.83	1.08

* Items #1, 3 and 4 are given in 1971 dollars, and are based on information from: Douglas, Gary, "Modular Wastewater Treatment System Demonstration for the Textile Maintenance Industry," EPA-600/2-73-037, January 1974.

a $\$/ft^2$ basis, these costs became quite substantial. Also, the more modules in the system, the more pumping power required. As shown in Table 22, for a 100,000 gpd treatment system power costs were >$89,000/yr. A second factor, affecting operating expense only, is membrane life. The replacement cycle for the spiral-wound modules is estimated to be one year. At a replacement cost of $\$20/ft^2$, this amounts to ~$143,000/year for a 100,000 gpd system. Since only a modest improvement in the performance of spiral-wound modules can be expected by changing the operating conditions, cost projections have been developed for an alternative UF module geometry, namely, tubular assemblies.

The tubular configuration, as discussed in Section 4, is preferred over the spiral-wound configuration from a technical standpoint: It is easier to clean (either chemically or mechanically) and would not be susceptible to plugging by lint. The spiral-wound configuration was chosen for this program since it was potentially a lower-cost geometry. However, for this particular application, the disadvantages of spiral-wound modules predominate their cost advantage, and tubular systems are projected to be more cost effective as discussed below.

<u>Projected Purchased Equipment and Annual Operating Costs for Tubular Ultrafiltration Systems</u>

Cost estimates for tubular UF systems were developed for the three system capacities of interest. For each capacity two system options were costed: The first option is based on typical current prices of tubular UF systems from Abcor, Inc. and a projected membrane flux of 40 gfd; the second option is an optimistic case which assumes that improvements in tubular membrane technology over the next 2-4 years will increase membrane flux (from 40 to 50 gfd), increase life (from 2 years to 3 years), reduce system costs (from $\$65/ft^2$ to $\$45/ft^2$) and reduce membrane replacement costs (from $\$15/ft^2$ to $\$10/ft^2$). All four sources of potential cost reduction are considered realistic and achievable.

A summary of purchased equipment and annual operating costs for tubular UF systems is presented in Table 26. A breakdown of these costs and a listing of the design bases used in their calculation is given in Appendix C. Capital costs are ~50% lower for tubular UF systems using costs for current technology than for open-spacer, spiral-wound systems of comparable capacity. These costs range from $1.97 to $2.22 per gallon of waste treated per day. Future technological advances should reduce these costs to $1.31 to $1.62 per gallon of waste treated per day.

Estimated system operating costs are reduced from the $9 to $12/1000 gal estimated for the spiral module systems to $2.6 to $5/1000 gal when current technology UF is employed. For the 25,000 gpd treatment capacity today's costs are $4.88/1000 gal. At this low capacity technological advances are not predicted to keep pace with inflation and future costs become $5.18/1000 gal. Treatment costs at the 75,000 gal capacity fall from $2.82/gal to $2.69/1000 gal as lower cost tubular UF systems are developed. The effect of these technological advances on the 100,000 gpd treatment system are to lower costs from $2.57 to $2.39/1000 gal.

TABLE 26. SUMMARY OF ESTIMATED CAPITAL AND OPERATING COSTS FOR WASTEWATER TREATMENT SYSTEMS EMPLOYING TUBULAR ULTRAFILTRATION MODULES

ITEM	UF SYSTEM CAPACITY (gpd) TODAY'S COSTS 25,000	TODAY'S COSTS 75,000	TODAY'S COSTS 100,000	FUTURE COSTS 25,000	FUTURE COSTS 75,000	FUTURE COSTS 100,000
Total estimated purchased equipment costs, $	55,600	148,900	196,500	40,500	99,900	130,800
Purchased equipment cost per gallon of waste treated per day, $	2.22	1.99	1.97	1.62	1.33	1.31
Total annual operating costs, $	38,100	65,900	80,200	40,400	62,900	74,600
Treatment costs, $/1000 gal	4.88	2.82	2.57	5.18	2.69	2.39

NOTES: 1. Purchased equipment costs do not include installation costs and will vary considerably from site to site.

2. Operating costs do not include capital related costs such as amortization, interest and taxes.

3. These costs assume discharge of UF permeate to the sewer and therefore carbon adsorption and product water storage costs are omitted.

The tubular UF configuration will produce an effluent similar in quality to the spiral-wound configuration since both configurations are available with Type HFM membranes. Since the treatment costs for the higher capacity tubular UF systems are competitive with the currently employed dissolved air flotation systems, tubular UF should be investigated for the treatment of industrial laundry wastes. Such an investigation would allow the cost estimates presented herein to be revised on the basis of actual permeate flux measurements.

REFERENCES

1. Douglas, Gary. "Modular Wastewater Treatment System Demonstration for the Textile Maintenance Industry". EPA-660/2-73-037, January 1974.

2. Ramirez, Ernest. "LectroClear™ Treatment of Industrial Laundering Wastewaters". Swift Environmental Systems Company, November 20, 1975.

3. Thomas, J.M. and Thomas, W.S. Introduction to the Principles of Heterogenous Catalysis. Academic Press, New York, p. 32 (1967).

4. Weber, W.J. Physiochemical Processes for Water Quality Control. Wiley-Interscience, New York, p. 213 (1972).

5. Vermeulen, T. "Separation by Adsorption Methods", in Advances in Chemical Engineering, Vol. II, T.B. Drew and J.W. Hooper, eds. Academic Press, New York, p. 148 (1958).

6. Hiester, N.K., Vermeulen, T., and Klein, G. "Adsorption and Ion Exchange", in Chemical Engineers' Handbook, J.H. Perry, ed., 4th Ed. McGraw-Hill, New York, Section 16 (1963).

7. Walden Division of Abcor, Inc. Internal Report. February, 1976.

8. Sluizer, Mervyn Jr., Letter from Institute of Industrial Launderers to Office of Analyses and Evaluation (WH-586), Environmental Protection Agency, Washington, D.C., May 16, 1977.

APPENDIX A. ADDITIONAL DATA FROM IN-HOUSE PILOT-SCALE EXPERIMENTATION

TABLE A1. WASHROOM PRODUCTION SCHEDULE ON DAY OF "LIGHT" LOADING WASTEWATER SAMPLING *

MACHINE # 1			MACHINE # 2			MACHINE # 3		
TIME Start	TIME Finish	Article Laundered	TIME Start	TIME Finish	Article Laundered	TIME Start	TIME Finish	Article Laundered
	0610	Rugs	0615	0700	Shirts	0620	0705	Shirts
0625	0715	Cotton shirts and pants	0710	0820	Shirts and pants	0720	0805	Shirts
0725	0830	Roll towels	0840	0945	Shirts and pants	0810	0905	Shirts
0850	0950	Wipers (rags)	1005	1040	Rugs	0910	1010	Shirts
0955	1055	Wipers	1050	1210	Wipers	1015	1100	Rugs
1110	1200	Shirts and pants	1220	1330	Shirts and pants	1115	1200	Rags
1215	1315	Wipers	1340	1430	Shirts and pants	1205	1305	Wipers
1325	1440	Shirts and pants	1520		Shirts	1335	1425	Shirts
1445	1535	Cotton shirts and pants				1435		Shirts

* Wastewater sample collected between 1100 and 1200 hours.

TABLE A2. WASHROOM PRODUCTION SCHEDULE ON DAY OF "MEDIUM LOADING" WASTEWATER SAMPLING*

MACHINE # 1			MACHINE # 2			MACHINE # 3		
Time Start/Finish		Article Laundered	Time Start/Finish		Article Laundered	Time Start/Finish		Article Laundered
0603	0712	Colored Garments	0608	0717	Colored Garments	0623	0800	White Garments
0728	0817	Mats	0740	0848	Mops	0813	0945	White Garments
0843	1030	Wipers	0916	1100	Wipers			
1055	1245	Wipers	1122	1307	Wipers			
1258	1415	Rags	1327	1508	Wipers			

* Wastewater sample collected between 0955 and 1055 hours.

TABLE A3. WASHROOM PRODUCTION SCHEDULE ON DAY OF "HEAVY" LOADING WASTEWATER SAMPLING *

Machine #1		Machine #2		Machine #3		Machine #4		Machine #5	
Time Out	Article Laundered	Time Out	Article Laundered	Time Out	Article Laundered	Time Out	Article Laundered	Time Out	Article Laundered
0842	Paint Towels	0845	Paint Towels	0748	Machine Towels	0751	Machine Towels	0828	Rags
1029	Paint Towels	1044	Paint Towels	1050	Machine Towels	0920	Machine Towels	1035	Paint Towels
						1028	Machine Towels		

*Wastewater sample collected between 0920 and 1010 hours

TABLE A4. CONTAMINANT ANALYSES AND MEMBRANE REMOVAL EFFICIENCIES FOR UF BATCH CONCENTRATION OF "LIGHT LOADING" INDUSTRIAL LAUNDRY WASTEWATER

Assay	Initial Feed	Final Concentrate	Mixed Composite Permeate	Removal Efficiency, %*
Total Solids (mg/l)	2,610	20,700	1,620	37.9
Suspended Solids (mg/l)	700	9,150	<4	>99.4
Dissolved Solids (mg/l)	1,910	11,500	1,616	15.4
Turbidity (NTU)	- †	- †	3.7	-
BOD (mg/l)	2,800	20,000	360	87.1
TOC (mg/l)	1,100	13,700	202	81.6
COD (mg/l)	3,780	57,300	672	82.2
Freon Extractibles (mg/l)	749	4,080	27.7	96.3
Alkalinity, (ppm $CaCO_3$)	875	1,500	(934)††	-
pH (units)	11.8	11.6	11.7	-
Chromium (mg/l)	<0.5	-	<0.5	-
Copper (mg/l)	1.7	-	<0.5	>70.6
Lead (mg/l)	3.9	-	<1.0	>74.4
Zinc (mg/l)	3.9	-	0.2	94.9
Cadmium (mg/l)	0.05	-	<0.005	>90.0
Iron (mg/l)	17	-	<1.0	>94.1
Nickel (mg/l)	<0.5	-	<0.5	-
Mercury (mg/l)	<0.002	-	<0.002	-

$$* \text{ Removal efficiency, } r = \frac{\text{Feed Concentration - Composite Permeate Concentration}}{\text{Feed Concentration}} \times 100$$

† Very high

†† ( ) indicates suspected error in analysis

TABLE A5. CONTAMINANT ANALYSES AND MEMBRANE REMOVAL EFFICIENCIES FOR UF BATCH CONCENTRATION OF "MEDIUM LOADING" INDUSTRIAL LAUNDRY WASTEWATER

Assay	Initial Feed	Final Concentrate	Mixed Composite Permeate	Removal Efficiency, % *
Total Solids (mg/l)	1,920	13,200	954	50.3
Suspended Solids (mg/l)	675	7,270	2.4	99.6
Dissolved Solids (mg/l)	1,240	5,970	952	23.5
Turbidity (NTU)	-- †	-- †	3.6	--
BOD (mg/l)	1,650	9,800	553	66.5
TOC (mg/l)	1,240	9,590	196	84.2
COD (mg/l)	5,480	43,800	796	85.5
Freon Extractibles (mg/l)	795	12,200	10	98.7
Alkalinity (ppm $CaCO_3$)	740	1,380	710	--
pH (units)	10.2	10.7	10.9	--
Chromium (mg/l)	< 0.5	--	< 0.5	--
Copper (mg/l)	1.2	--	< 0.5	> 58.3
Lead (mg/l)	2.1	--	< 1.0	> 52.4
Zinc (mg/l)	1.4	--	< 0.5	> 64.3
Cadmium (mg/l)	0.03	--	< 0.01	> 66.7
Iron (mg/l)	6.5	--	< 1.0	> 84.6
Nickel (mg/l)	< 0.5	--	< 0.5	--
Mercury (mg/l)	0.0005	--	0.0004	20.0

$$* \text{ Removal efficiency, } r = \frac{\text{Feed Concentration - Composite Permeate Concentration}}{\text{Feed Concentration}}$$

† Very high

TABLE A6. CONTAMINANT ANALYSES AND MEMBRANE REMOVAL EFFICIENCIES FOR UF BATCH CONCENTRATION OF "HEAVY LOADING" INDUSTRIAL LAUNDRY WASTEWATER

Assay	Initial Feed	Final Concentrate	Mixed Composite Permeate	Removal Efficiency, %*
Total Solids (mg/l)	10,200	64,700	2,680	73.7
Suspended Solids (mg/l)	4,500	41,800	<5	99.9
Dissolved Solids (mg/l)	5,700	22,900	2,680	53.0
Turbidity (NTU)	--†	--†	4.7	--
BOD (mg/l)	7,850	81,900	930	88.2
TOC (mg/l)	6,750	45,400	642	90.5
COD (mg/l)	27,400	188,000	2,370	91.4
Freon Extractibles (mg/l)	7,890	51,650	38	99.5
Alkalinity (ppm $CaCO_3$)	2,350	4,080	2,060	12.3
pH (units)	11.7	11.4	11.5	--
Chromium (mg/l)	8.8	--	2.9	67.0
Copper (mg/l)	11	--	1.1	90.0
Lead (mg/l)	22	--	<1	>95.5
Zinc (mg/l)	9.0	--	0.18	98.0
Cadmium (mg/l)	0.15	--	<0.01	93.3
Iron (mg/l)	90	--	1.8	98.0
Nickel (mg/l)	0.74	--	<0.5	>32.4
Mercury (mg/l)	0.0009	--	0.0008	11.1

$$* \text{ Removal efficiency, } r = \frac{\text{Feed Concentration} - \text{Composite Permeate Concentration}}{\text{Feed Concentration}}$$

† Very high

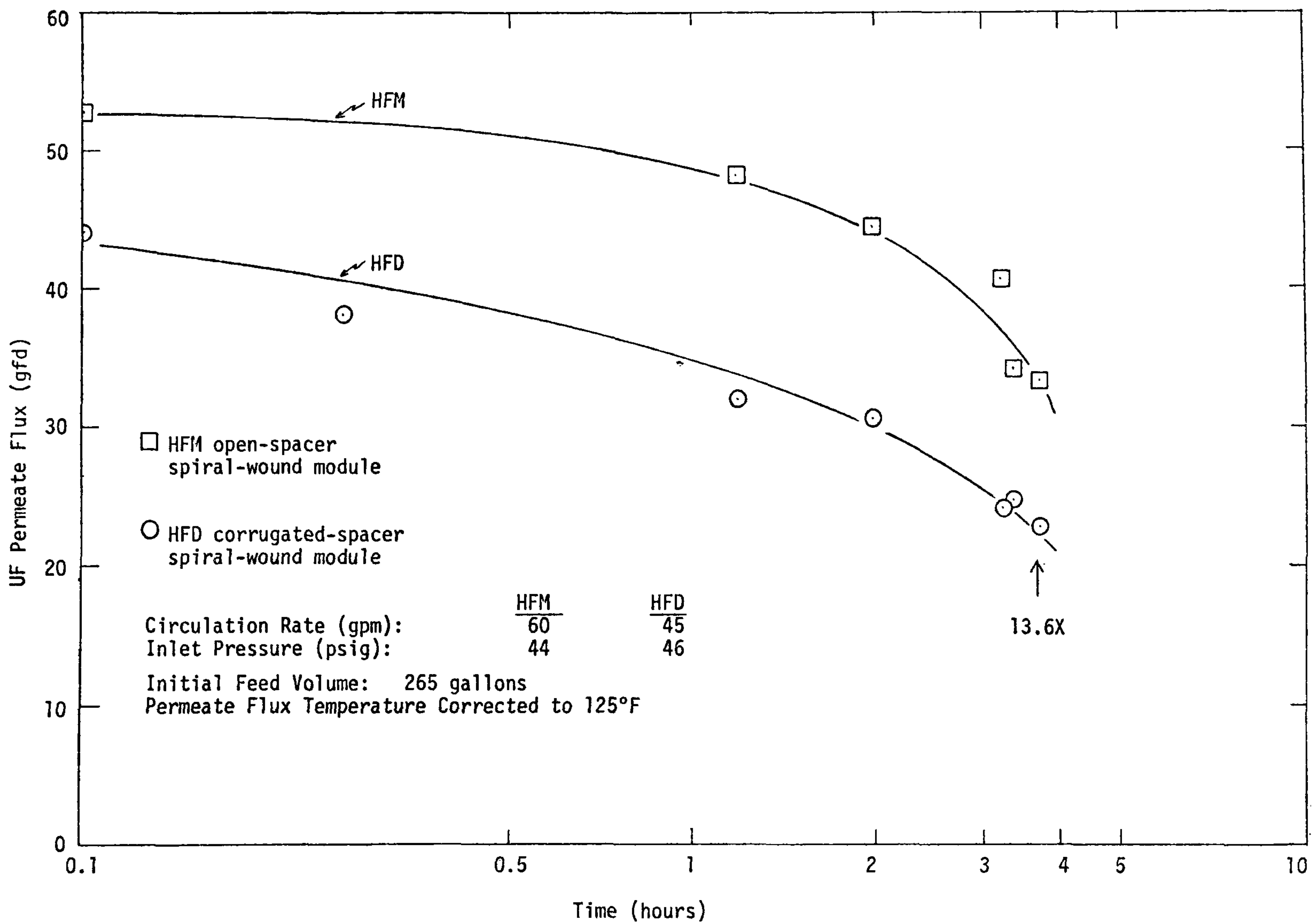


Figure A1. UF permeate flux vs. time for batch concentration of "light loading" industrial laundry wastewater.

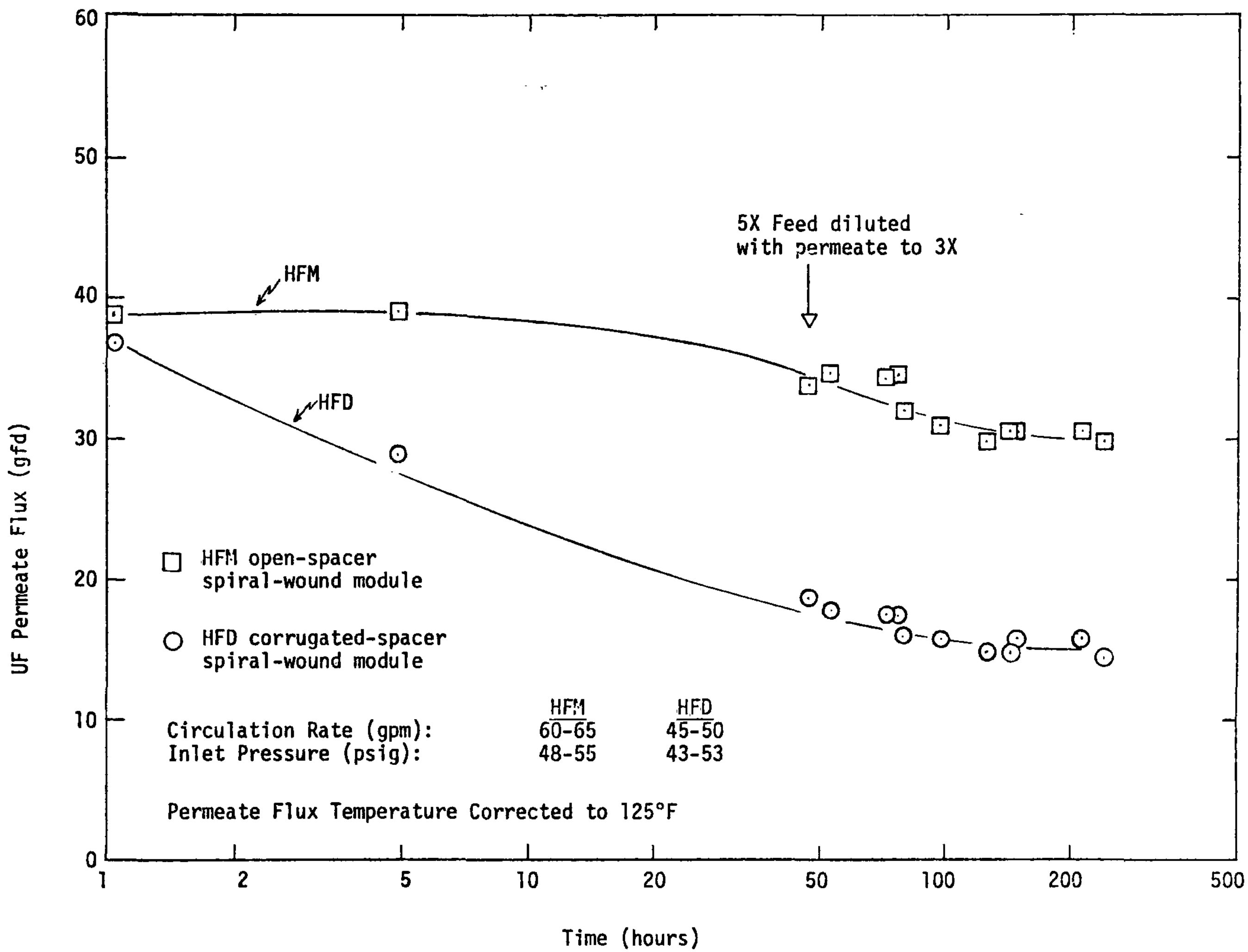


Figure A2. UF permeate flux vs. time for extended exposure test with "light loading" industrial laundry wastewater.

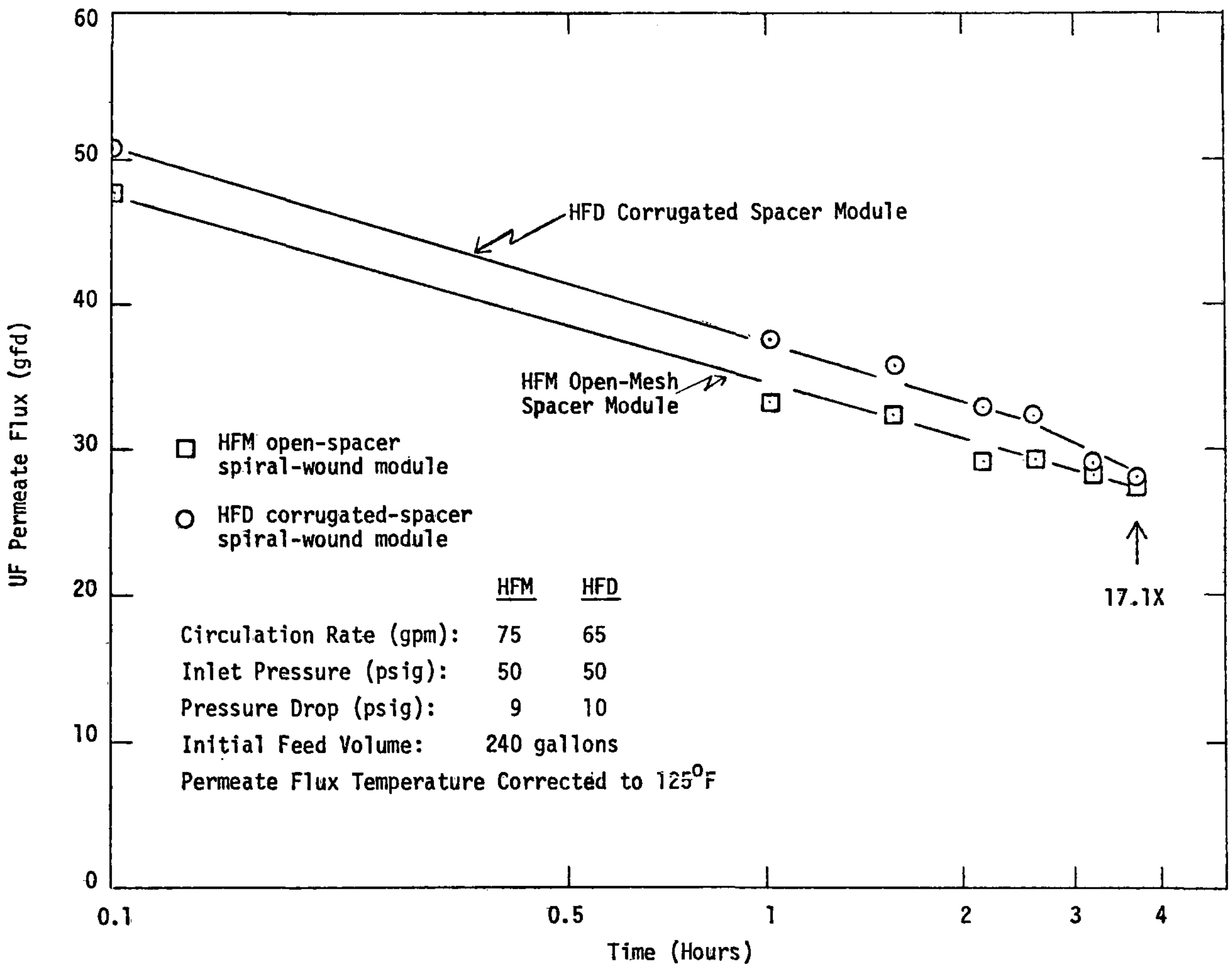


Figure A3. UF permeate flux vs. time for batch concentration of "medium loading" industrial laundry wastewater.

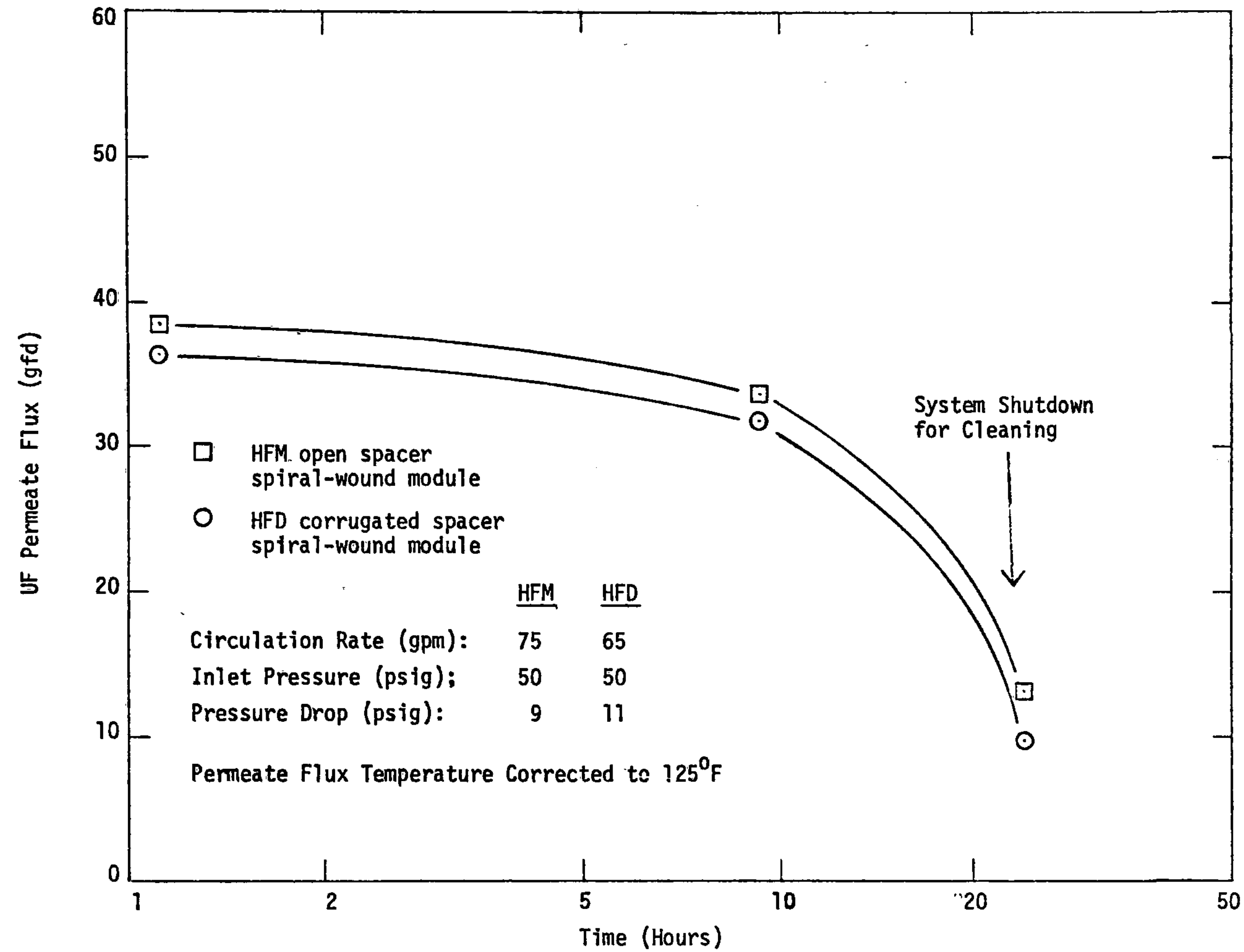


Figure A4. UF permeate flux vs. time for extended exposure test with "medium loading" industrial laundry wastewater.

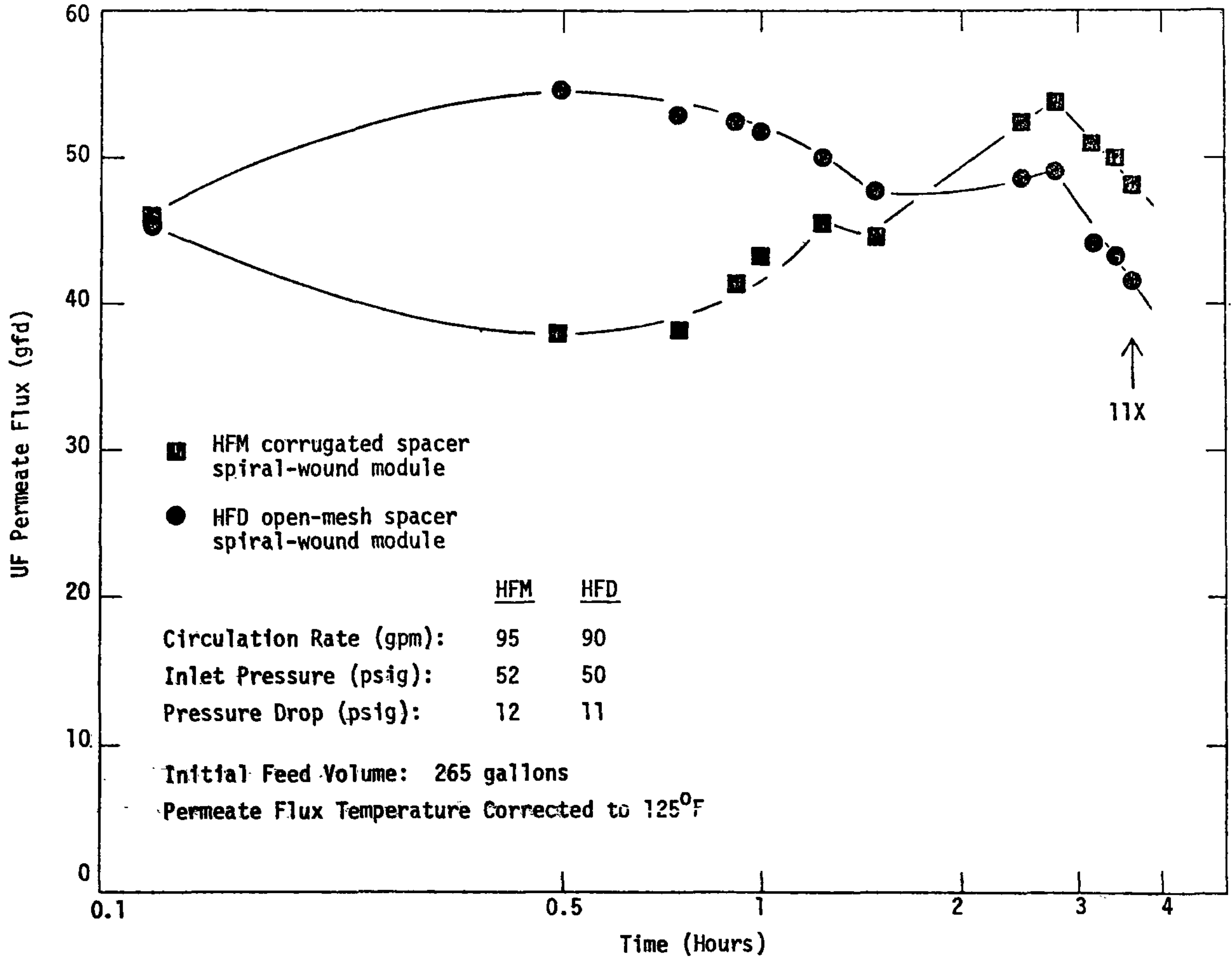


Figure A5. UF permeate flux vs. time for batch concentration of "heavy loading" industrial laundry wastewater.

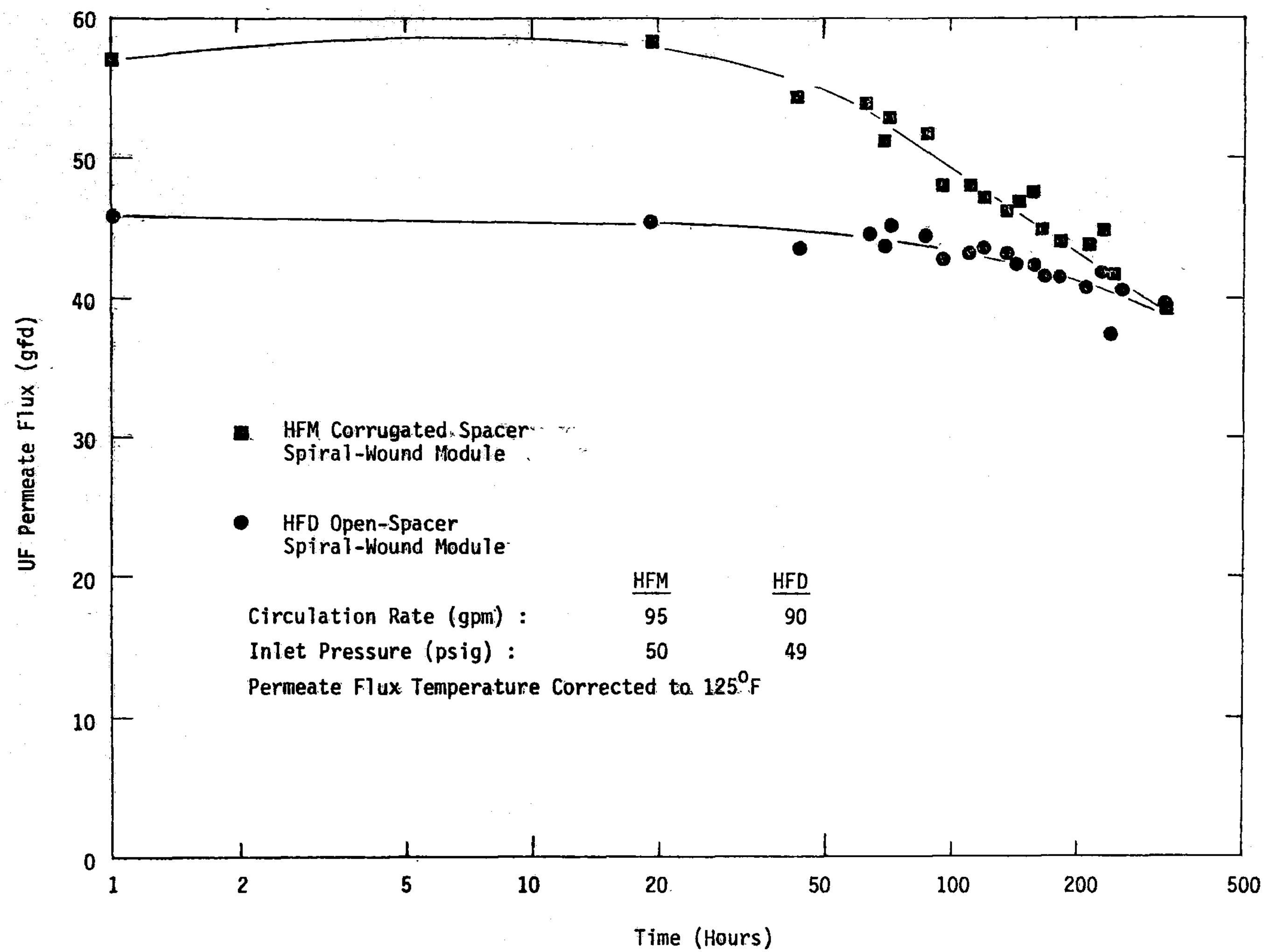


Figure A6. UF permeate flux vs. time for extended exposure test with "heavy loading" industrial laundry wastewater.

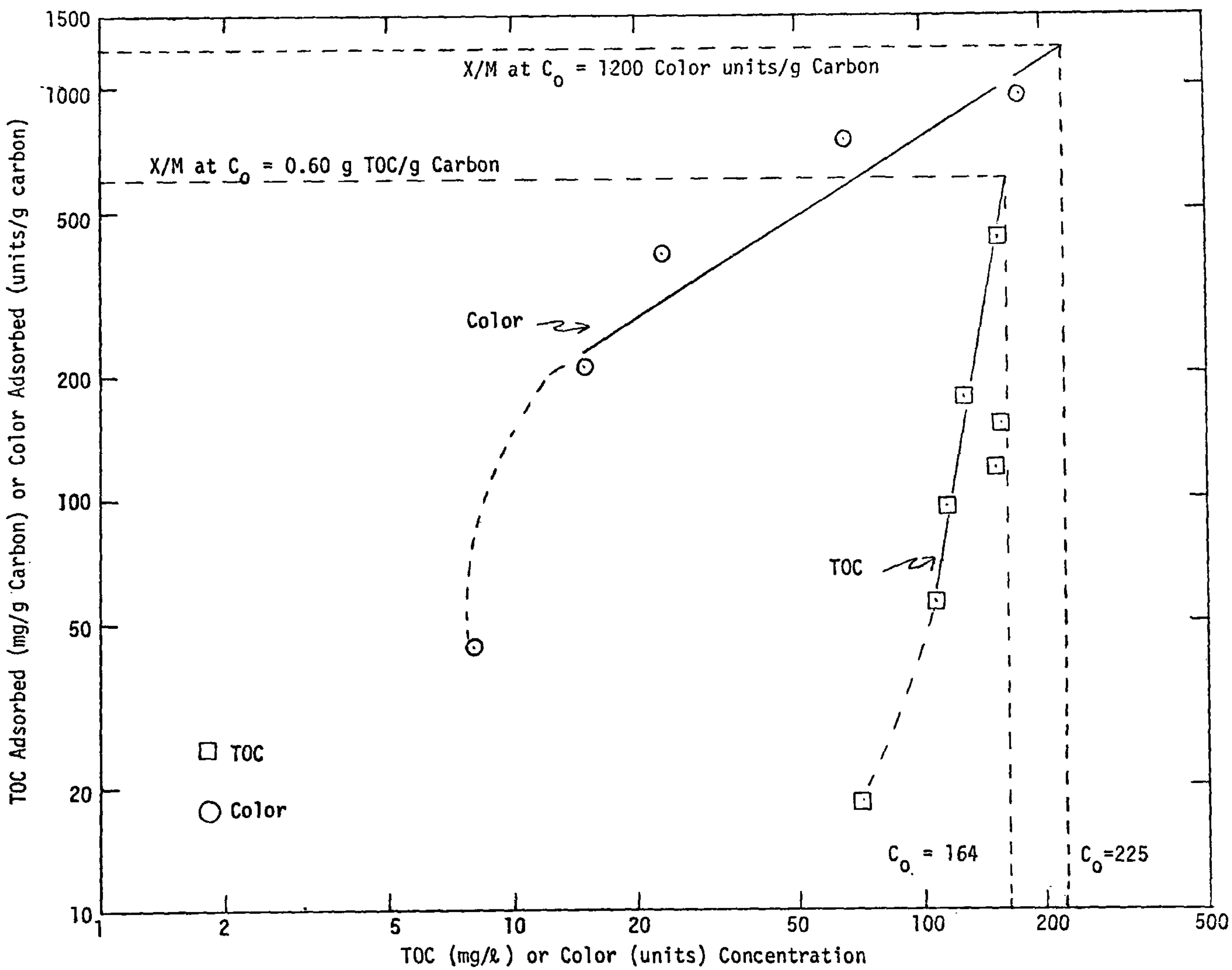


Figure A7. Equilibrium adsorption isotherm for TOC and color removal from "light loading" industrial laundry waste UF permeate

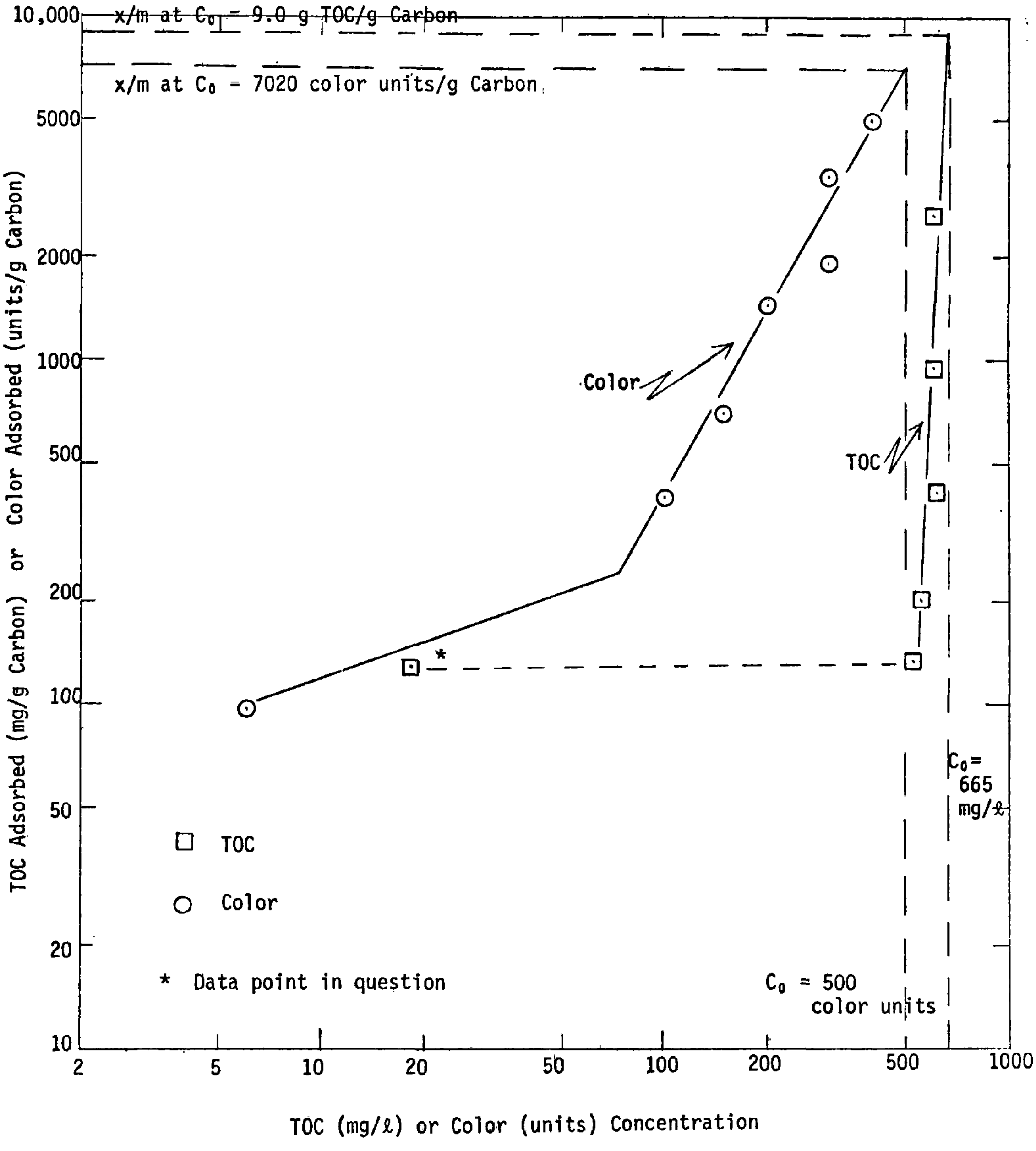


Figure A8. Equilibrium adsorption isotherm for TOC and color removal from "heavy loading" industrial laundry waste UF permeate, actual pH.

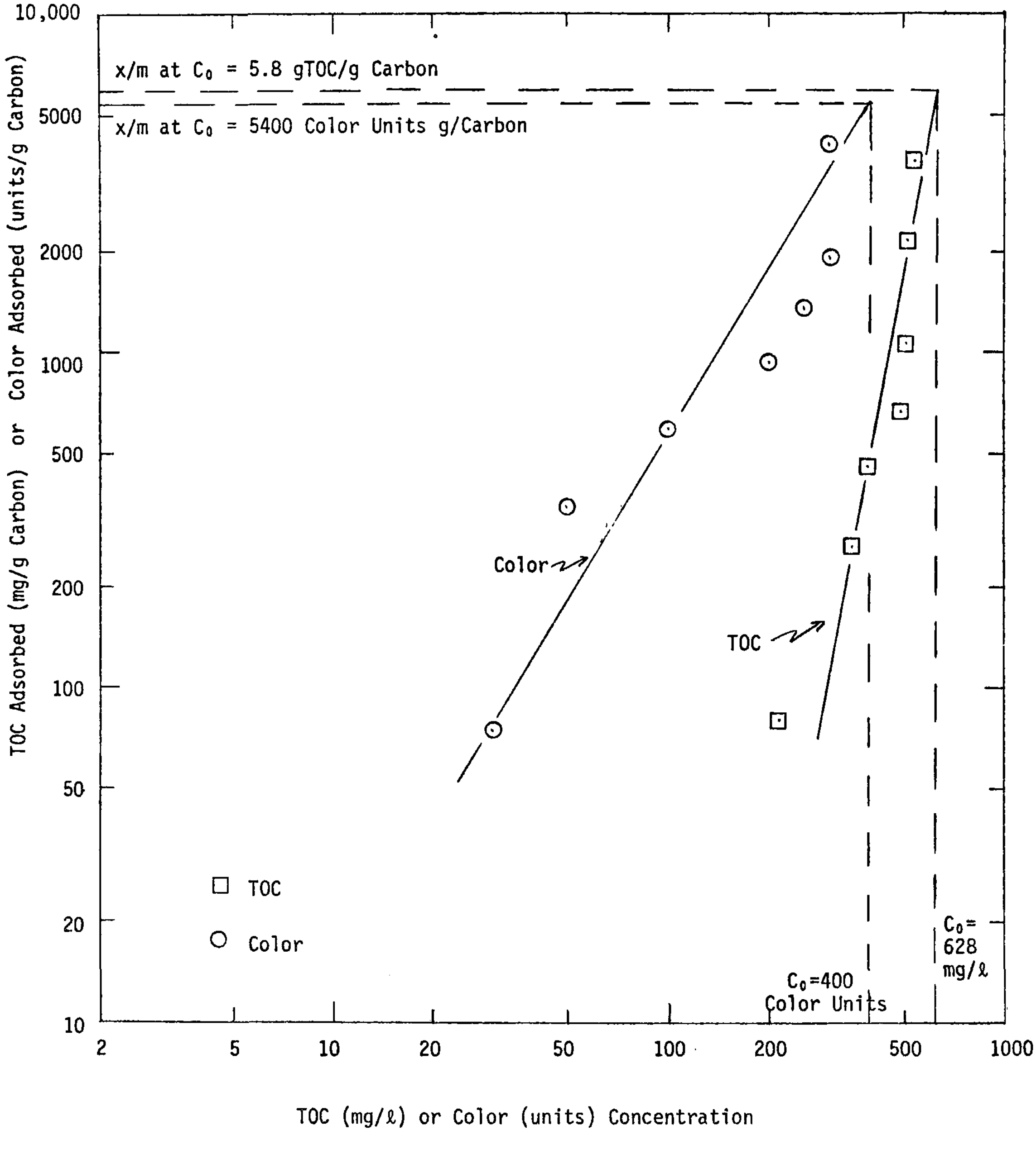


Figure A9. Equilibrium adsportion isotherm for TOC and color removal from "heavy loading" industrial laundry waste UF permeate, pH adjusted to 7.1.

APPENDIX B. ADDITIONAL DATA FROM PRELIMINARY FIELD DEMONSTRATION EXPERIMENTATION

TABLE B1. FLUX RECOVERY AND ACCUMULATED OPERATING TIMES FOR UF MEMBRANES OPERATED ON INDUSTRIAL LAUNDRY WASTEWATERS DURING PRELIMINARY FIELD TESTS

Membrane Type/Spacer	Designation	Accumulated Exposure Time (Hours)	Water Flux at 135°F (gfd)	Comments
HFM/Corrugated	MC1	334	75.6	Used during Task 1
	MC2	0	200	New Module
	MC1 and MC2	4	54.8	2 detergent cleanings
		11	--	Corrugated modules developed leaks due to high temperature
	MC3 and MC4	0	--	Water flux not recorded
		139	45.6	5 detergent cleanings
HFM/Open Spacer	MO2 and MO3	0	100	New Modules
		4	79.8	2 detergent cleanings
		11	94.9	3 detergent cleanings
		101	86.4	-----------
		169	63.0	7 detergent cleanings
HFM/Vexar	MV1	0	162	New Module
		68	74.6	5 detergent cleanings
		136	55.1	7 detergent cleanings

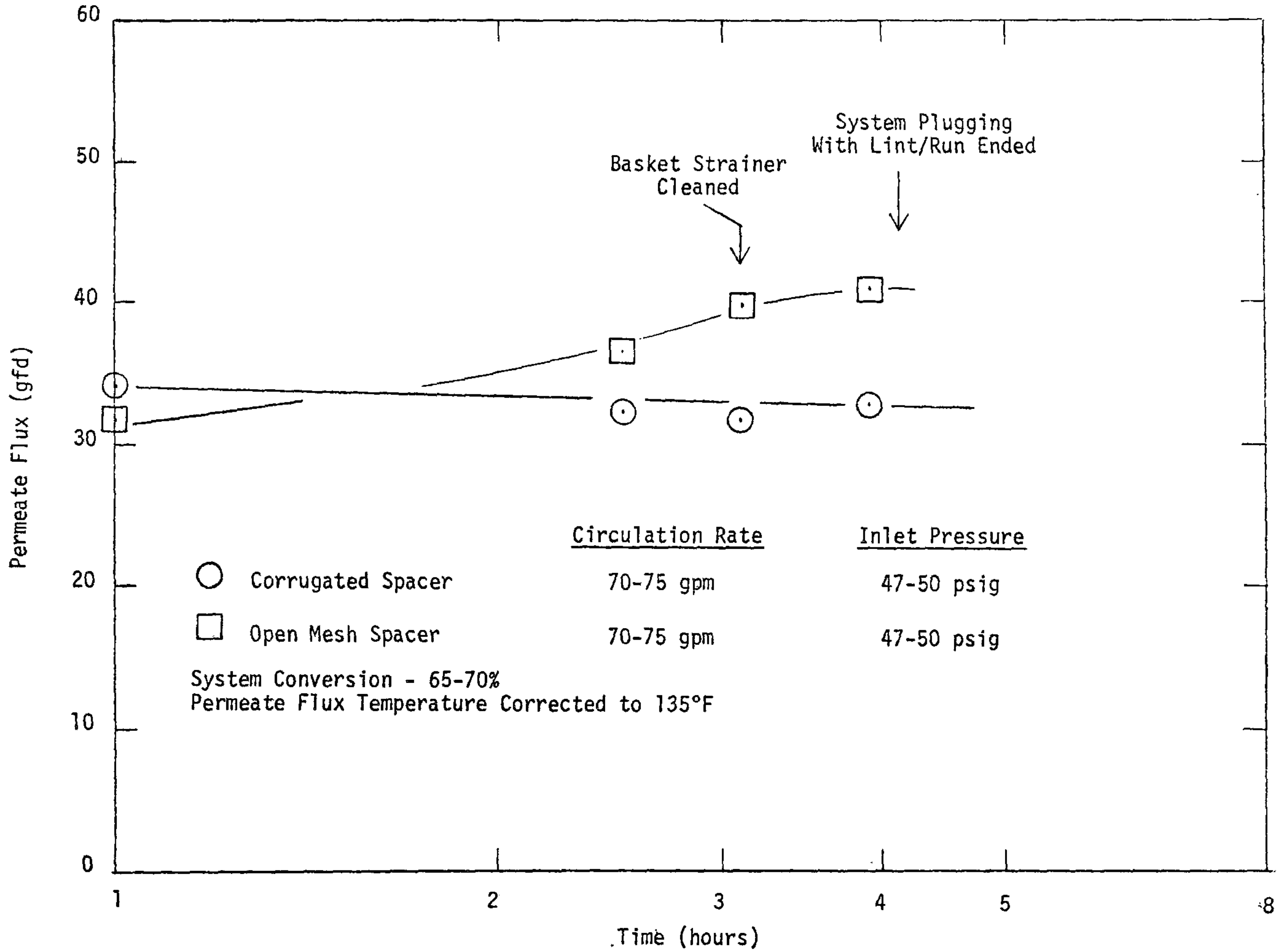


Figure B1. UF permeate flux vs. time for first preliminary field demonstration experiment (Test P1).

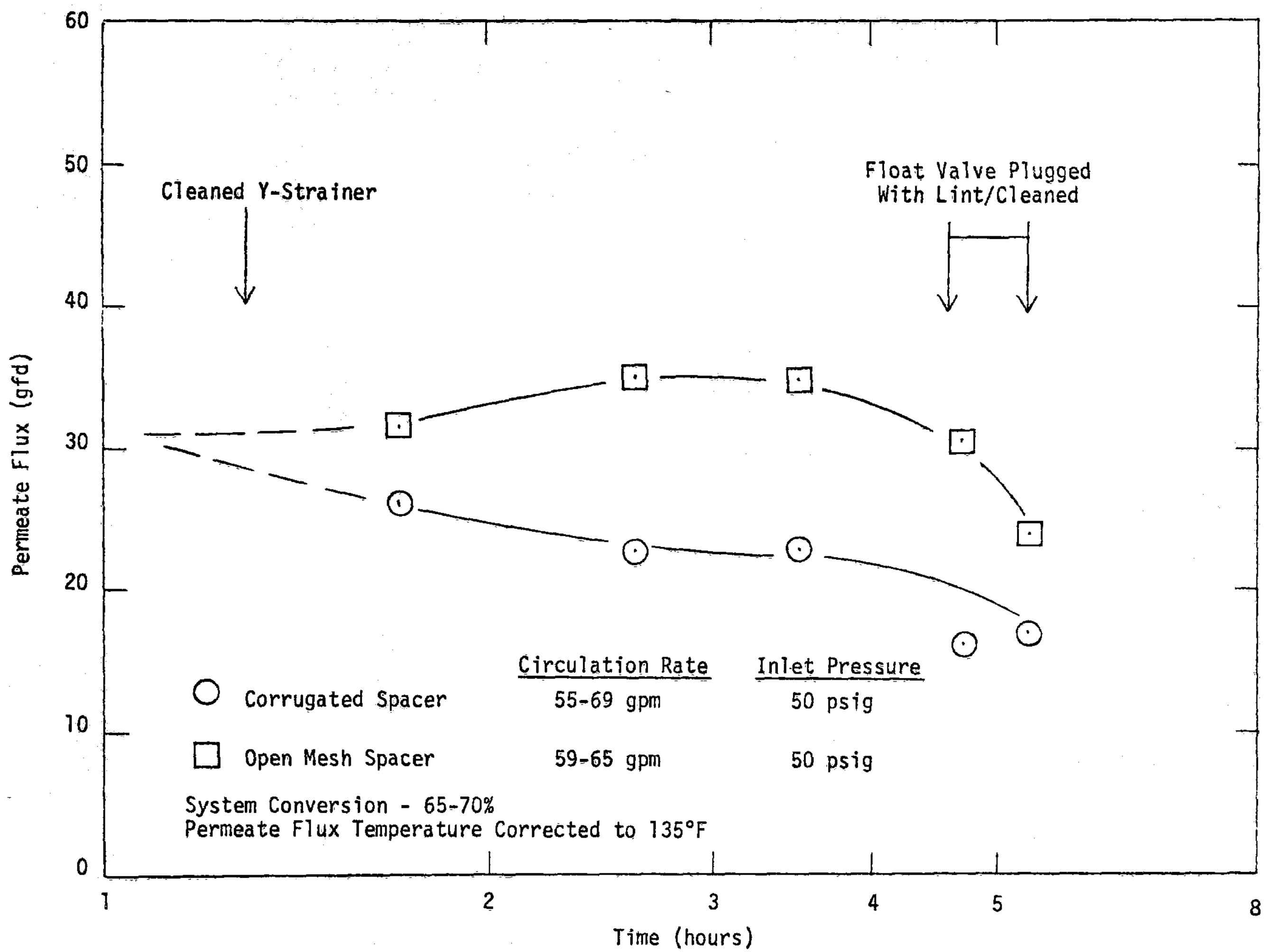


Figure B2. UF permeate flux vs. time for second preliminary field demonstration experiment (Test P2) .

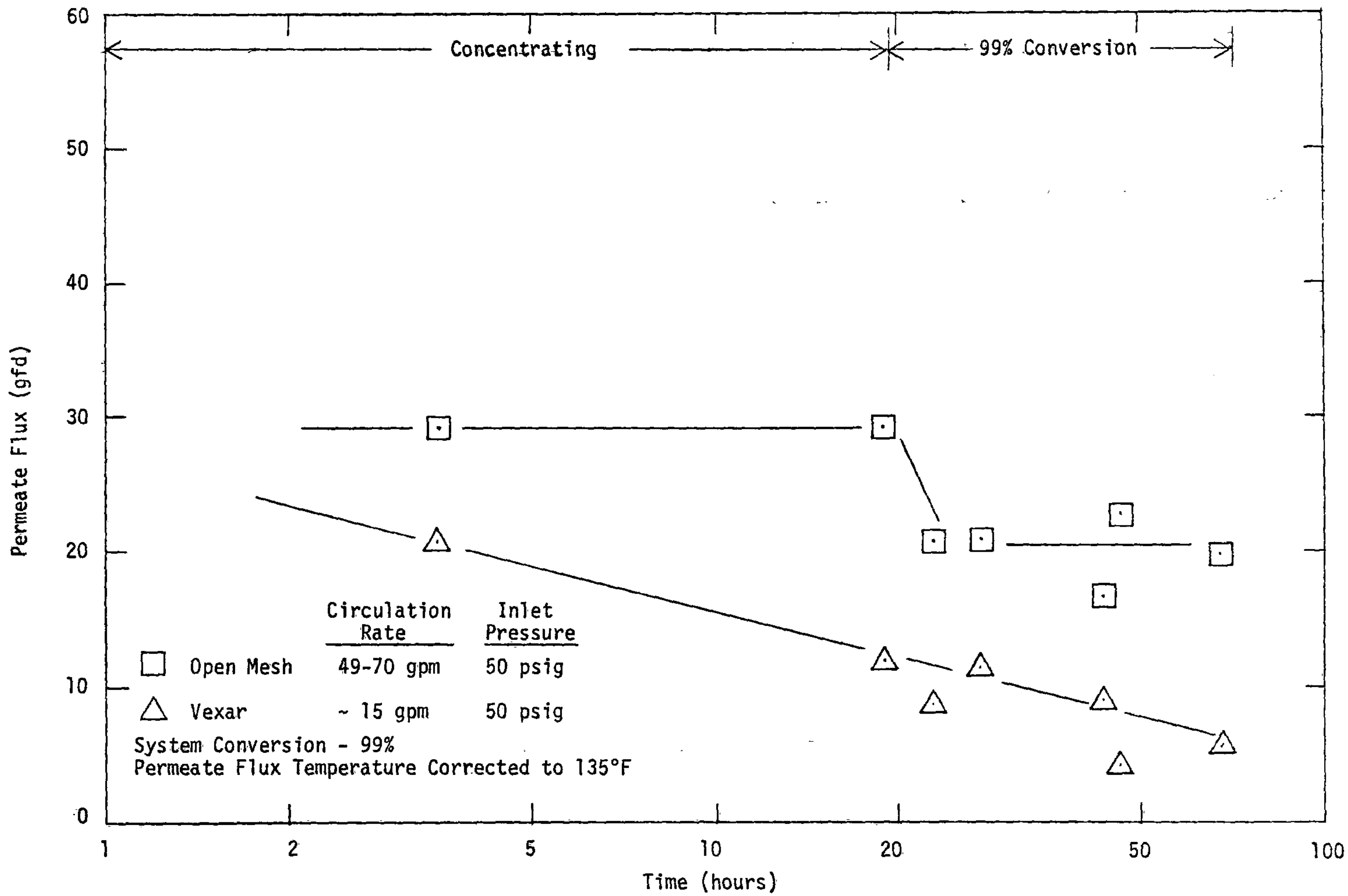


Figure B3. UF permeate flux vs. time for fourth preliminary field demonstration experiment (Test P4).

TABLE C1. DESIGN BASES USED FOR COSTING TUBULAR UF SYSTEMS

Design Option	Assumed Membrane Flux gal/ft^2-day	Membrane Area Requirements, ft^2 @ Each System Capacity gpd 25,000	75,000	100,000	Membrane Life, yrs	Membrane System Costs, \$/ft^2	Membrane Replacement Costs \$/ft^2
1. Tubular Modules (today's technology)	40	625	1875	2500	2	65	15
2. Tubular Modules (future technology)	50	500	1500	2000	3	45	10

TABLE C2. ESTIMATED PURCHASED EQUIPMENT COSTS FOR WASTEWATER TREATMENT SYSTEMS EMPLOYING TUBULAR ULTRAFILTRATION MODULES (Thousands of Dollars)

ITEM	UF SYSTEM CAPACITY (gpd)					
	TODAY'S COSTS			FUTURE COSTS		
	25,000	75,000	100,000	25,000	75,000	100,000
PRETREATMENT						
1. Holding tank and controls with a capacity of 75% system capacity	10	20	25	12	24	30
2. Prefiltration, see Note 4	3	4	5	3.6	4.8	6
3. Oil skimmer for free oil removal	2	3	4	2.4	3.6	4.8
	15	27	34	18.0	32.4	40.8
ULTRAFILTRATION SYSTEM						
1. UF System including controls, monitors and engineering design costs	40.6	121.9	162.5	22.5	67.5	90
	40.6	121.9	162.5	22.5	67.5	90
TOTAL ESTIMATED PURCHASED EQUIPMENT COSTS	55.6	148.9	196.5	40.5	99.9	130.8
PURCHASED EQUIPMENT COST PER GALLON OF WASTE TREATED PER DAY	$2.22	$1.99	$1.97	$1.62	$1.33	$1.31

NOTES:
1. This cost analysis does not include installation costs which will vary considerably from site to site depending on availability of utility connections, space, etc.
2. This analysis assumes discharge of UF permeate to the sewer and therefore carbon adsorption and product water storage costs are omitted.
3. Future costs include 20% inflation factor for pretreatment items.
4. Does not require the same level of sophistication as for the pretreatment to spiral-wound modules.

TABLE C3. ESTIMATED ANNUAL OPERATING COSTS FOR WASTEWATER TREATMENT SYSTEMS EMPLOYING TUBULAR ULTRAFILTRATION MODULES (thousands of dollars/yr)

ITEM	UF SYSTEM CAPACITY (gpd)					
	TODAY'S COSTS			FUTURE COSTS		
	25,000	75,000	100,000	25,000	75,000	100,000
PRETREATMENT						
1. Labor, Operating & Maintenance, 1 hr/day @ $5.00/hr plus 75% fringe benefits and overhead	2.7	2.7	2.7	3.3	3.3	3.3
2. Supervisory Labor, 0.5 hr/day @ $10/hr plus 75% fringe benefits and overhead	2.7	2.7	2.7	3.3	3.3	3.3
3. Power, 5 hp (27,900 kw-hr @ 3¢/kw-hr)	0.8	0.8	0.8	1.0	1.0	1.0
	6.2	6.2	6.2	7.6	7.6	7.6
ULTRAFILTRATION SYSTEM						
1. Labor, Operating & Maintenance, 3 hr/day @ $5.00/hr plus 75% fringe benefits and overhead	9.6	9.6	9.6	11.5	11.5	11.5
2. Supervisory Labor, 1 hr/day @ $10/hr plus 75% fringe benefits and overhead	6.4	6.4	6.4	7.7	7.7	7.7
3. Membrane Replacement, see Table C1	4.7	14.1	18.8	1.7	5.0	6.7
4. Power, see Table C4	6.8	20.3	27.1	6.6	19.9	26.5
5. Cleaning Chemicals, 1 cleaning per week, 25, 35 or 45 lbs @ $1.85/lb	2.4	3.4	4.3	2.9	4.1	5.2
6. UF Concentrate Disposal, assumes 99.5% conversion; 125, 375 or 500 gpd, 312 days/yr (contract hauling @ 5¢/gal)	2.0	5.9	7.8	2.4	7.1	9.4
	31.9	59.7	74.0	32.8	55.3	67.0
TOTAL ANNUAL OPERATING COSTS	38.1	65.9	80.2	40.4	62.9	74.6
TREATMENT COSTS, $/1000 gal	$4.88	$2.82	$2.57	$5.18	$2.69	$2.39

NOTES: 1. Annual operating cost analysis does not include capital related costs such as amortization, interest and taxes.

2. Future costs include 20% inflation over today's costs for labor, power, chemicals and concentrate disposal.

TABLE C4. ESTIMATED POWER REQUIREMENTS FOR WASTEWATER TREATMENT SYSTEMS EMPLOYING TUBULAR ULTRAFILTRATION MODULES

System Capacity	No. of Tubular Assemblies	No. of Parallel Passes	Total Flow, gpm	ΔP per pass, psig	Actual Horsepower, hp	kw-hr per 1000 gal	Cost per year, $
TODAY'S TECHNOLOGY							
25,000	284	36	1080	30	26.6	18.5	6,800
75,000	852	106	3180	30	76.0	18.5	20,300
100,000	1136	142	4260	30	102	18.5	27,100
FUTURE TECHNOLOGY							
25,000	227	28	840	30	20.1	14.5	6,600
75,000	682	85	2550	30	60.6	14.5	19,900
100,000	909	114	3420	30	81.6	14.5	26,500

NOTES:
1. Tubular assembly is 1 inch diameter X 10 foot long; membrane area is 2.2 ft^2.
2. 8 tubes in series per pass.
3. Flow rate per pass is 30 gpm.
4. Horsepower requirement assumes 70% pump efficiency.
5. Current power costs based on 4¢/kw-hr, future power costs based on 5¢/kw-hr.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-78-177	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Demonstration of Ultrafiltration and Carbon Adsorption for Treatment of Industrial Laundering Wastewater		5. REPORT DATE August 1978 issuing date 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) M.H. Kleper, R.L. Goldsmith, A.Z. Gollan		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Walden Division of Abcor, Inc. 850 Main Street Wilmington, Massachusetts 01887		10. PROGRAM ELEMENT NO. IBB610 11. ~~CONTRACT~~/GRANT NO. S-804367-01
12. SPONSORING AGENCY NAME AND ADDRESS Industrial Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Task Final, 3/76-4/77 14. SPONSORING AGENCY CODE EPA/600/12

15. SUPPLEMENTARY NOTES

IERL-Ci project leader for this report is R.J. Turner 513-684-4481

16. ABSTRACT

This study of industrial laundry wastewater treatment by ultrafiltration and activated carbon adsorption has indicated that a consistently high quality product water, potentially reusable within the laundry, can be produced. The operation of the spiral-wound ultrafiltration modules was, however, hindered by the fouling tendency of the feed stream. Average module permeate flux was therefore low. This factor, in turn, resulted in high capital and operating cost estimates for full-scale treatment systems.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
	Wastewater Treatment Carbon Adsorption Industrial Laundries Ultrafiltration	13B
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 121
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1978—757-140/1455