SRI International

Final Report

RESEARCH AND DEVELOPMENT TO OVERCOME FOULING OF MEMBRANES

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SUMMARY

Fouling is a serious problem in the recovery and recycle of electrocoat paint, and the membrane industry is actively seeking methods to reduce it. We have shown that piezoelectrically assisted ultrafiltration (PZ UF) produces significant flux enhancements during ultrafiltration of electrocoat paint; however, the high power consumption of the piezodriver offsets any pump power savings. On the other hand, high flux enhancements and a ten-fold lower energy consumption were realized by transmitting vibration directly to a UF membrane with a mechanical transducer. According to our initial experiments, these high flux enhancements may be achieved with even less energy. Mechanically-assisted UF therefore promises to be a valuable process to lower the permeate and electricity cost of electrocoat paint operations.

We conducted experiments of ultrafiltration of dextran solutions on flat sheet membranes to evaluate the dependance of PZ flux enhancement on parameters including the membrane-piezodriver configuration, the nature of the driver, and the use of the polymer insulating coating on the driver. We found that the highest flux enhancements are obtained when the driver is in close contact to the membrane, without any intermediate separator, and a thin hard polymer coating is applied to the piezodriver for insulating purposes. Under the best experimental conditions, we achieved a flux enhancement of 4.2 for the filtration of dextran.

Additional ultrafiltration experiments on flat sheet membranes were conducted for electrocoat paint under various conditions of pressure, feed flow, and paint composition. Piezo-enhancements typically resulted in flux increases of about 50%, but flux increases as high as a factor of 3.3 were obtained under some conditions. A 700-hour electrocoat paint ultrafiltration experiment was performed on a flat sheet membrane in a test cell simulating commercial operating conditions. Flux enhancement was consistently observed throughout the experiment upon applying power to the driver. However the flux declined slowly for both piezo-cell and control cell at the same rate, indicating that piezo-enhancement has no significant effect on the long-term performance of the membrane.

On the basis of our 700-hour experiment, we performed an economic evaluation of piezoelectrically enhanced ultrafiltration for electrocoat applications. Our economic results show that substantial savings in pumping energy (over four-fifths) can be achieved. However, the increase in energy consumption of the piezoelectric system more than offsets this savings (we assumed that the piezodriver needs to be on continuously to produce a consistent flux enhancement). Because of the high energy consumption of the piezoelectric system, piezo-

enhanced UF is not currently viable for the electrocoat paint application. If power consumption can be reduced, however, piezo-enhanced UF could become economically attractive, and savings in pumping energy could be realized.

Indeed, we have shown that power consumption can be significantly reduced if the flux is enhanced by means of a mechanical transducer instead of a piezoelectric transducer. During ultrafiltration on dextran solutions, the flux through a tubular membrane (identical to those used for electrocoat applications) was increased by more than a factor of 2, when the membrane was vibrated with a mechanical driver working at the frequency of 60 Hz with a power consumption of only 0.63 kW/m^2 (instead of 7.1 kW/m^2, as found for the piezodriver). Very importantly, a further reduction of energy is likely to be achieved, since the same power source produced the same flux enhancement on tubular membranes at different lengths (2-inch and 14-inch long). Even with a power consumption of 0.63 kW/m^2, the permeate cost is lower than with conventional ultrafiltration (13.91 $/kgal versus 14.54 $/kgal). Moreover, if the power consumption can be further lowered (likely indicated in our initial experiments), a significant energy saving can be achieved.

CONTENTS

INTRODUCTION

Ultrafiltration (UF) is increasingly being applied as a separation process in the treatment of liquid industrial waste, in food processing, and in the pharmaceutical and medical industries. One of the oldest and most important commercial applications for ultrafiltration is the recovery of electrocoat paint used as priming coat for automobile parts. Ultrafiltration applied to industrial processes, such as whey protein filtration and solvent recovery in deasphalting of oil, would be energy-saving, effective, and economically competitive with traditional separation processes if the membrane performances could be improved. Indeed, commercial acceptance of ultrafiltration has been severely limited because membranes do not perform consistently for extended periods. Fouling of UF membranes results in a serious flux decline of the permeate and increases the cost of using a membrane separation process as a unit operation.

UF membranes are vulnerable to fouling by pore blockage because they have low surface porosity and uneven pore sizes. Fouling generally proceeds as follows:

- The flux declines rapidly because of the buildup of solutes near the membrane surface.
- Macromolecules such as proteins are adsorbed on the hydrophobic membrane material and plug the pores.
- Particles deposited by convection and cake solids are compressed.

The rate of decline in permeate flux through the membrane depends significantly on the particular composition of the liquid treated and on the interaction between the solute and the membrane.

Several approaches have been tried to reduce fouling of membranes. Pretreatment of the membrane with hydrophilic surfactants and polymers to increase the initial flux and reduce the flux decline gives only a marginal and short-term improvement. Prefiltration of the feed solution with membranes of larger pore size adds the cost of another unit operation. Backwashing unplugs the blocked pores and dislodges the cake; however, it implies interruption of operation and can decrease membrane life.

To overcome fouling of membranes, SRI International is developing a unique piezoelectric backing for ultrafiltration membranes. This backing is capable of producing local turbulence next to the membrane to minimize concentration polarization and the rate of buildup of solutes and particulate matter on the membrane surface.

During the first year of this program, SRI demonstrated the feasibility of piezoelectrically assisted ultrafiltration in reducing membrane fouling and enhancing the flux through ultrafiltration membranes. Piezoelectric transducers, such as piezoelectric lead zirconate titanate (PZT) discs, driven by moderate power, were found to significantly enhance the permeate flux on fouled membranes. Under the best circumstances, flux enhancements as high as a factor of 8 were recorded during the filtration of dextran solutions.

During this second year of the program, we have studied piezoelectrically assisted ultrafiltration in more detail, with the objective to apply this process to industrial ultrafiltrations. We conducted several ultrafiltration experiments on flat sheet membranes with model dextran solutions and with electrocoat paint to study flux enhancement as a function of parameters such as feed flow rate, feed pressure, as well as the piezodriver-membrane system. The most critical variable to define was the piezodriver itself. We found that flux enhancement, and therefore the effectiveness of the driver in transmitting vibration to the membrane, depended on

- The driver configuration with respect to the membrane
- The nature of the polymer insulating the driver and its thickness.

The critical role of each of these parameters is clearly shown by the variability of flux enhancements obtained this year.

OPTIMIZATION OF PIEZOELECTRICALLY ENHANCED ULTRAFILTRATION

Aqueous solutions of dextran with molecular weight of 162,000 were initially used to study piezoelectrically enhanced ultrafiltration. Experiments using several UF membrane/ piezoelectric driver configurations were conducted to identify the conditions resulting in the greatest flux enhancement.

EXPERIMENTAL PROCEDURE

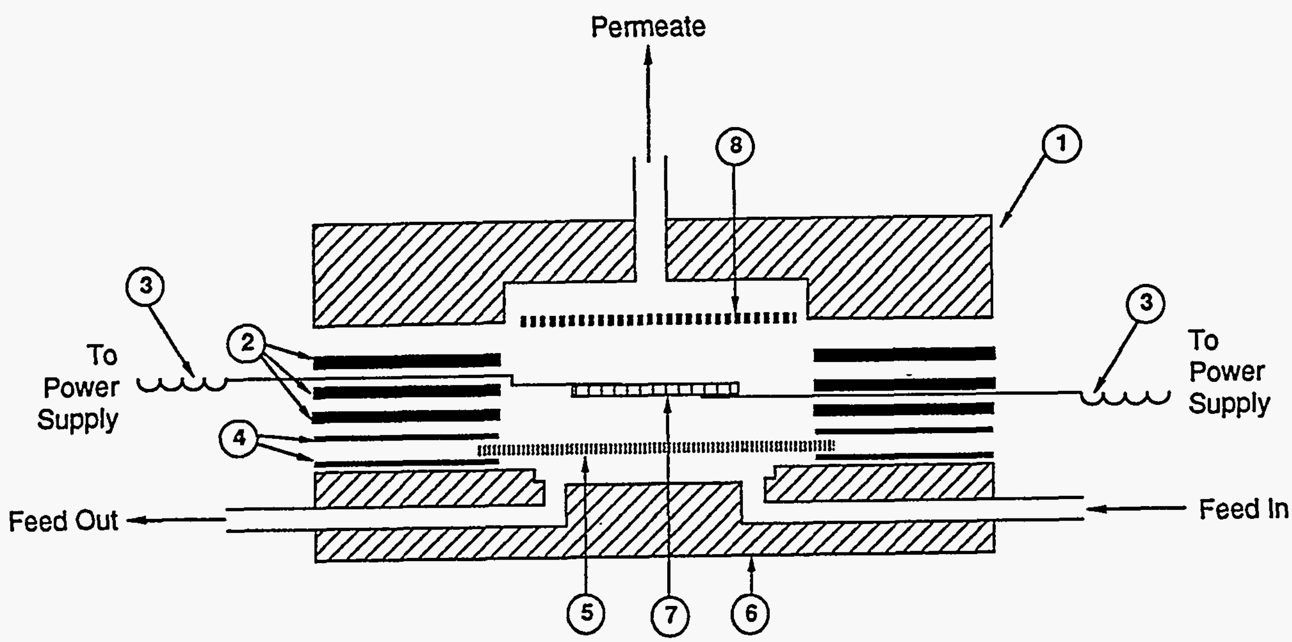
Initial ultrafiltration experiments were conducted on a stainless-steel test cell (Figure 1) holding a flat polysulfone membrane sheet —100,000 or 10,000 molecular weight cut-off (MWCO)— with an active area of 28.3 cm^2. Dextran solutions with concentration varying from 0.5% to 1.5% were tested. A PZT ceramic disc 37.5-mm in diameter and 2.5-mm thick was placed on the permeate side of the cell. Electrical leads were attached to each of the metalized surfaces of the PZT disc by soldering. The PZT disc was coated with a suitable insulating polymer. Some ultrafiltration tests of electrocoat paint were also performed to study the experimental conditions leading to the highest flux enhancement. The details of these tests are described in the next chapter.

A second set of ultrafiltration experiments of dextran solutions was conducted on a single, flat-membrane sheet test cell (Millipore Minitan® test cell) (Figure 2), analogous to a plate-and-frame module. Polysulfone membranes — 100,000 or 10,000 MWCO — with an active area of 30 cm^2 were used. A PZT disc 37.5-mm in diameter and 2.5-mm thick, having electrical leads attached and coated with an insulating polymer, was used. Additionally, the performance of a flexible composite piezodriver was tested.

Control Experiments

Control experiments to validate the experimental procedure were conducted by using two stainless steel test cells in parallel. One of the cell contained the piezodriver (the PZ cell), while the other did not contain any piezodriver (the control cell).

To show the effectiveness of piezoelectric drivers in enhancing the flux, two possible mechanisms leading only to artificial flux enhancements must be ruled out. First, if piezoelectric action enhances UF by changing the structure of the membrane pores, enlarged pores would lead to increased flux, but also to unacceptable solute content in the permeate. Second, artificial flux



1. Top half
2. Thick rubber gaskets
3. Electrical leads
4. Thin rubber gaskets
5. Ultrafiltration membrane
6. Bottom half
7. PZT disc transducer
8. Stainless Steel Microfilter

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Figure 1. PZT disc-driven ultrafiltration test cell.

The cell is round when viewed from the top.

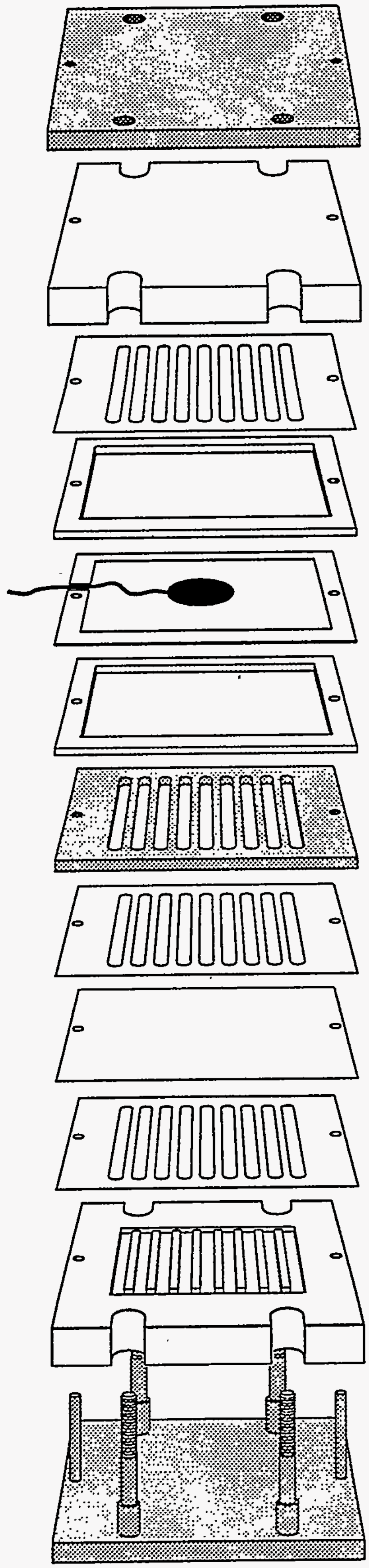

Figure 2. Exploded-view diagram of Millipore® test cell.

enhancements would also take place if the piezoelectric disc, that is in close contact with the membrane, blocks a portion of the active membrane area when it is not powered. In this case, when power is applied to the disc, the vibration would create a space between the disc and the membrane through which permeate can flow, effectively unblocking the membrane. Flux enhancement by these mechanisms would not be an improvement over current membranes.

To test whether the pore structure is altered by piezoelectric action, we performed flux enhancement experiments with pure water. If the piezoelectric enhancement is a result of enlarged pores, the flux of water should be enhanced; if the flux enhancement is due to reduced fouling, then the flux should be unchanged with piezo-enhancement since there are no solids in pure water to cause fouling. The pure water fluxes with and without piezo-enhancement were within 2%: (232 gal/ft^2/day (GFD) with piezo-enhancement and 235 GFD without), demonstrating that piezoelectric action does not change the pore structure. Further evidence that the pore structure does not enlarge is that, during ultrafiltration of electrocoat paint as described in the next chapter, any paint solids entrained in the permeate stream would color the stream and be easily visible. Indeed, the permeate did not show any coloration upon piezo-enhancement during filtration of electrocoat paint.

To determine whether the piezoelectric disc blocks some of the membrane area, we compared the flux in the PZ cell (without power) to that in the control cell containing no disc. If the disc does block the membrane, the PZ cell should have a lower flux than the control cell. Upon applying power to the PZ cell the flux should increase, possibly reaching a maximum flux equal to the flux in the control cell. As will be seen from the electrocoat paint experiment data included in the following sections, the flux in the PZ cell (without piezo-enhancement) was consistently slightly lower than in the control cell. However, upon piezo-enhancement the flux increased to a value significantly greater than that in the control cell. Therefore the enhancement we observed cannot be due only to the disc blocking a portion of the membrane area.

PIEZO-ENHANCED ULTRAFILTRATION OF DEXTRAN SOLUTIONS

We performed several experiments to evaluate the dependance of the flux enhancement on membrane-piezodriver configuration, nature of the driver, and insulating coating on the driver is discussed. Under the best conditions, a flux enhancement by factor of 4.2 was achieved for the ultrafiltration of dextran.

Membrane-Piezodriver Configuration

Several experiments of ultrafiltration of dextran were performed to study how the membrane-driver configuration affects the flux enhancement. We found that the highest fluxes are obtained when the driver is in close contact to the membrane, without any intermediate separator, and when the driver electrical leads are attached on opposite sides to hold it firmly in place on top of the membrane.

A first set of experiments was conducted on the stainless-steel test cell holding a flat polysulfone membrane sheet with a molecular weight cut-off (MWCO) of 100,000 and an active area of 28.3 cm^2. A 0.5% dextran solution, at the feed flow rate of about 1.5 L/min and pressure of 50 psig, was tested. In these experiments the leads were attached on the same side of the driver, therefore allowing some freedom of movement to the disc. The disc was coated with an insulating layer of neoprene, required to prevent electrical shorting in water when voltage is applied across the disc.

Figure 3 shows the UF membrane/piezoelectric driver configurations tested. These configurations vary in the way the piezoelectric driver is supported (free floating or mechanically forced into contact with the membrane) and in the way in which the membrane and the driver are separated from each other. (The membrane and the driver may be in direct contact, or a steel mesh support and/or a tricot spacer may separate them.)

Our results in Table 1 show that the configuration with direct contact between membrane and piezodriver provides the best performance, with a factor of 2 flux increase. The similarity of the pre-sonication flux both for the direct and indirect configurations indicates that the direct contact between the membrane and the piezodriver does not inhibit permeate flow, confirming that the driver does not block the membrane. The effectiveness of the direct contact configuration suggests that the vibration generated by the the piezodriver is efficiently transmitted when membrane and piezodriver are mechanically coupled. On the other hand, the transmission of the vibration through the liquid phase is significantly less effective.

A better contact of piezodriver and membrane is obtained when the piezodriver electrical leads are attached on opposite directions. This configuration provides mechanical support and allows the driver to lie flat on the membrane. Accordingly, the highest flux enhancement, a factor of 4.2, was obtained with the piezodriver-membrane configuration illustrated in Figure 4. The UF membrane was glued to the thin bottom gasket with epoxy, and nickel strips, about 3 mm. wide, were attached to the driver on opposite directions. A 1.5 % dextran solution was filtered through a polysulfone membrane with MWCO of 100,000 at a feed-side pressure of 50 psig and feed flow

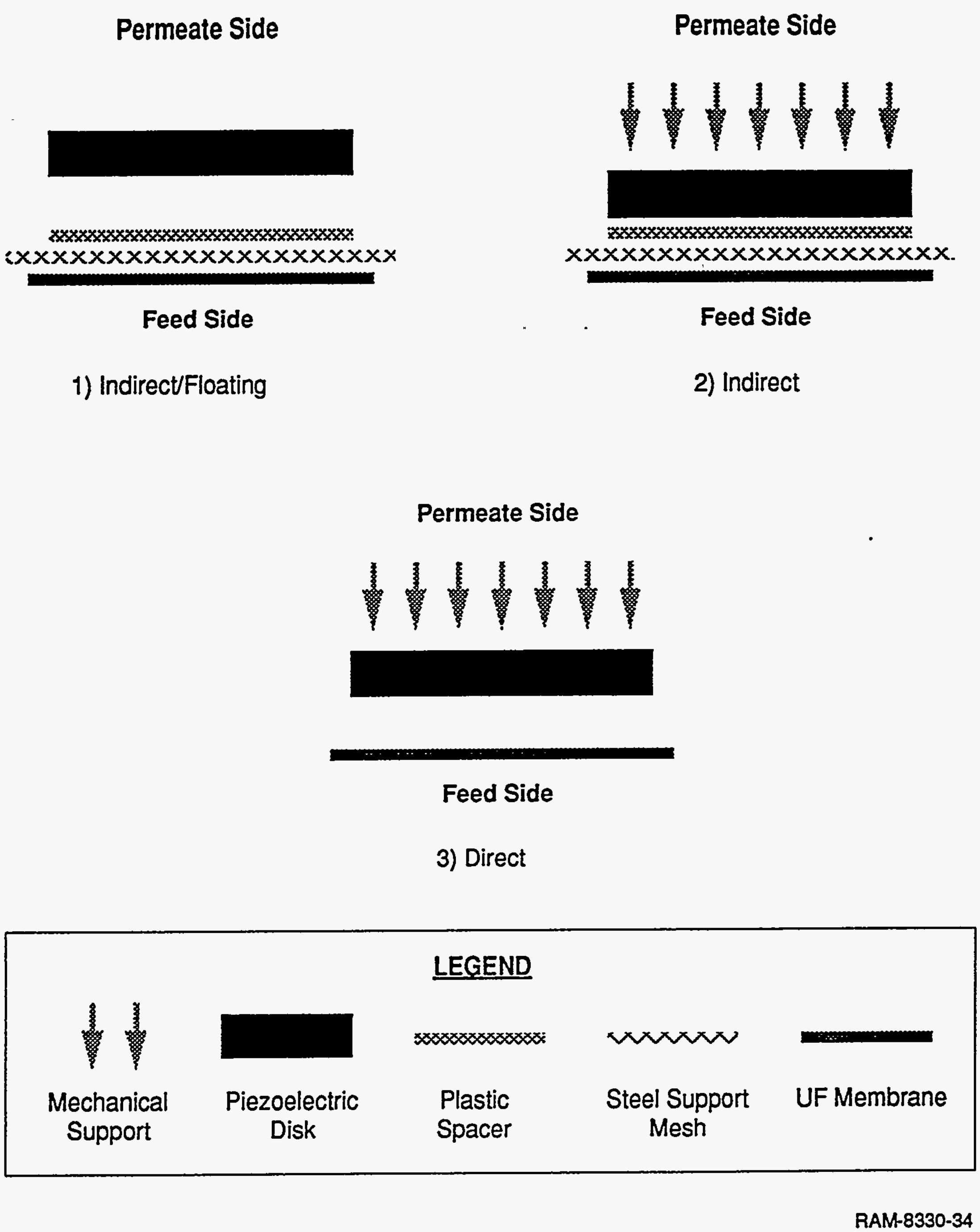

Figure 3. System configurations being evaluated for piezoeletric ultrafiltration.

Table 1
DEPENDENCE OF FLUX ENHANCEMENT[1] ON RELATIVE UF MEMBRANE-PIEZODRIVER CONFIGURATION

Experiment Number	Configuration	Feed Flow Rate (L/min)	Flux with PZ Off (L/hr/m^2/atm)	Flux with PZ On (L/hr/m^2/atm)	Relative Flux Enhancement (%)
1a	Indirect/Floating	1.5	8.20	10.05	23
2a	Indirect/Floating	1.4	7.76	9.97	28
2b	Indirect	1.3	9.97	16.67	67
3a	Indirect/Floating	1.5	12.88	17.11	33
3b	Direct	1.4	13.41	27.17	103

[1]Membrane: polysulfone, 100,000 MWCO.
Piezoelectric driver: PZT ceramic disc coated by a neoprene insulating film (~3 mil thick).
Feed: 0.5% aqueous solution of dextran, MW 162,000.

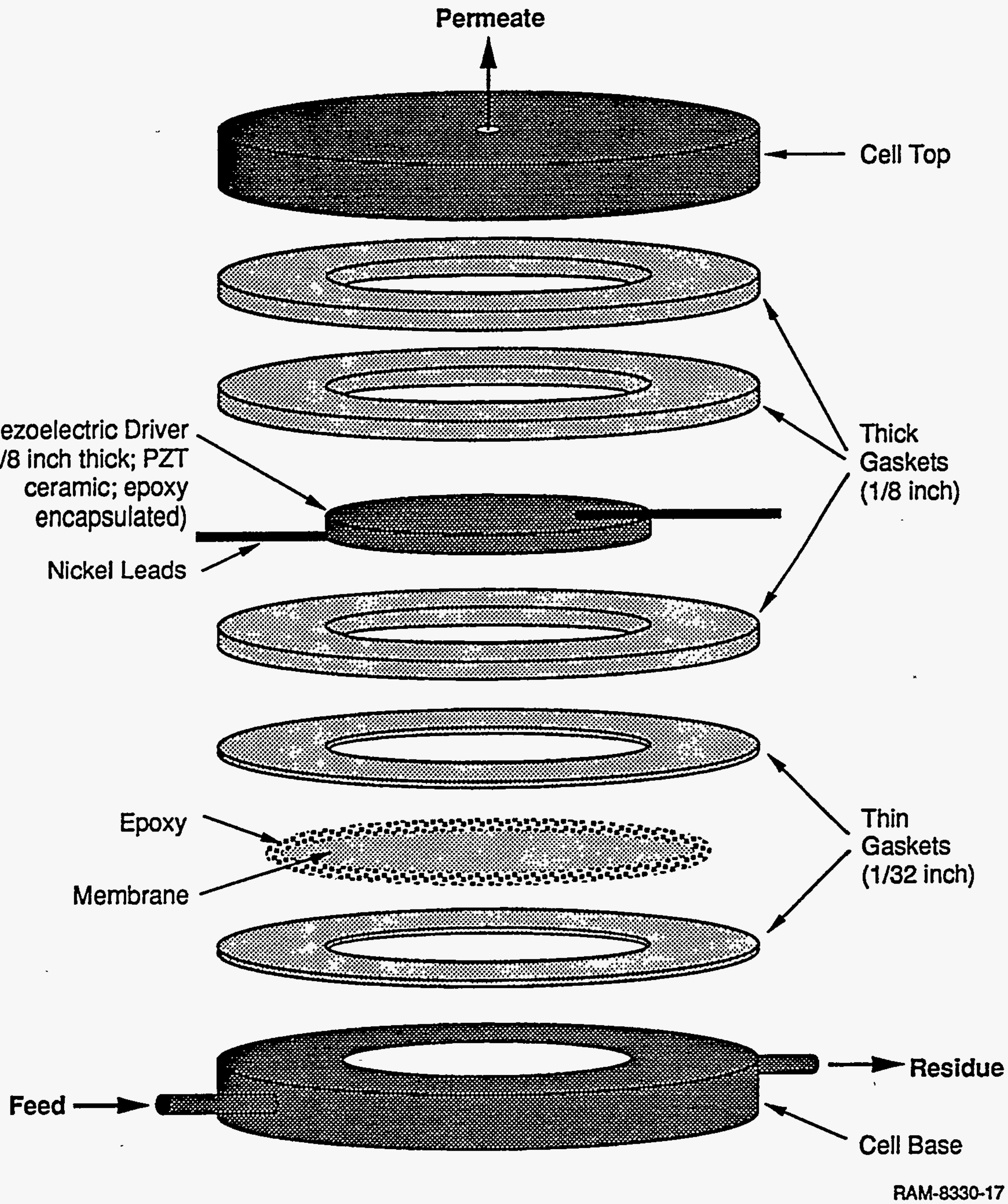

Figure 4. Ultrafiltration test cell configuration used to produce high enhancement factors.

rate of 1.7 L/min. The membrane fouled quickly during the first three hours, after which the flux remained relatively constant at 14.0 L/hr/m^2/atm. When we applied power to the driver, the flux increased to 58.9 L/hr/m^2/atm, a factor of 4.2 increase.

Ultrafiltration experiments were also conducted on the single, flat-membrane sheet test cell analogous to a plate-and-frame module (Millipore Minitan® test cell). We tested PZT drivers coated with neoprene as well as with a heat shrinkable tubing (Thermofit® ATUM, Raychem Corporation, Menlo Park, California). Electrical leads were attached on the same side of the driver. A stainless-steel separator or a tricot separator were used to provide the space necessary to insert the piezodriver, while holding the UF membrane in place. Without the separator the membrane was found to deform under pressure, eventually breaking the ceramic piezo-transducer.

Table 2 summarizes the experiments that were conducted on the Millipore test cell. In some experiments the flux with the PZ driver on and the relative flux enhancement increased with the filtration time, possibly due to the formation of a thicker foulant layer on the membrane. In general, experimental conditions leading to greater fouling (e.g., low feed flow rates, lower MWCO membrane) give the highest flux enhancements. On the whole, however, the relative flux enhancement was quite modest. We believe that the rigid separator between the UF membrane and the piezodriver does not allow the efficient transmission of vibration. The separator was however found to be necessary to hold in place the membrane during operation.

Figures 5 through 7 illustrate the variation of the membrane flux as a function of the feed-side flow rate both with and without power applied to the disc at the dextran concentrations of 3.5%, 3.75%, and 4%. Polysulfone membranes with 10,000 MWCO were used in these experiments. Figure 8 summarizes the relative flux enhancement for each set of experiments. As expected, the highest flux enhancement was found at the lowest feed flow rate for which the highest fouling is expected. The concentration change from 3.5 to 4% dextran in the feed solution was found to have little effect on flux.

Flexible Composite Driver

The feasibility of using a flexible piezoelectric composite driver (NTK Technical Ceramic Division, NGK Spark Plug Co., Ltd., Japan) was studied (run number 5 of Table 2). After attaching electrical leads, the 3.5-inch long and 1.5-inch wide piezorubber sheet was encapsulated with the heat-shrinkable tubing. During testing, a relative flux enhancement of 17% was obtained, about one sixth of the flux enhancement obtained under similar conditions with the piezoceramic driver. The piezorubber is therefore advantageous because of its flexibility, however the

Table 2

SUMMARY OF PIEZOELECTRICALLY ASSISTED ULTRAFILTRATION EXPERIMENTS ON MILLIPORE TEST CELL

Run	PZT Driver/ Coating	Coating Thickness (inch)	Membrane (MWCO)	Configuration	Dextran (%)	Feed Flow Rate (L/min)	Flux with PZ Off ($L/hr/m^2/atm$)	Flux with PZ On ($L/hr/m^2/atm$)	Relative Flux Enhancement (%)
1	Disc/neoprene	0.035	100K	Stainless-steel separator	2.00	0.3	7.50	8.91	19
					2.50	0.58	5.91	7.06	19
					2.50	0.18	6.09	10.14	67
					2.50	<0.18	2.47	3.97	61
					3.50	0.18	2.91	4.32	48
2	Disc/heat- shrink tubing	0.075	100K	Tricot separator	3.50	0.18	5.20	6.61	27
					3.50	0.18	4.94	6.79*	37.5*
3	Disc/heat- shrink tubing	0.075	100K	Stainless-steel separator	3.50	0.18	3.79	4.76	26
					3.50	0.18	3.97	5.38*	36*
					3.50	0.18	4.14	6.44*	55*
4	Disc/heat- shrink tubing	0.075	10K	Stainless-steel separator	3.50	0.58	4.94	7.67	55
					3.50	0.31	4.06	6.88	70
					3.50	1.43	7.06	8.73	24
					3.75	0.18	2.73	5.91	116
					3.75	0.31	3.53	6.26	77.5
					3.75	0.58	4.06	6.61	63
					4.00	0.18	2.56	5.38	110
					4.00	0.31	3.44	6.26	82
					4.00	0.58	4.32	6.88	59
5	0-3 Composite/ heat-shrink tubing	0.035	10K	Stainless-steel separator	4.00	0.18	4.76	5.56	17

*Flux PZ increased with the filtration time.

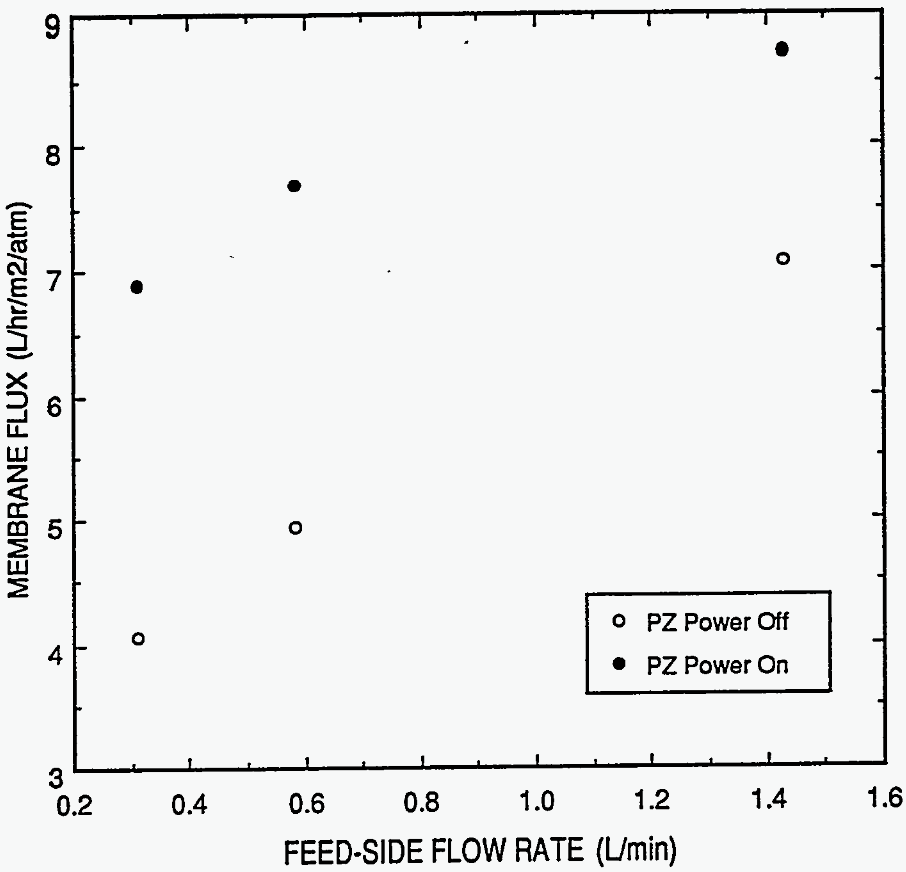

Figure 5. Effect of feed-side flow rate on ultrafiltration of 3.5% dextran solution.

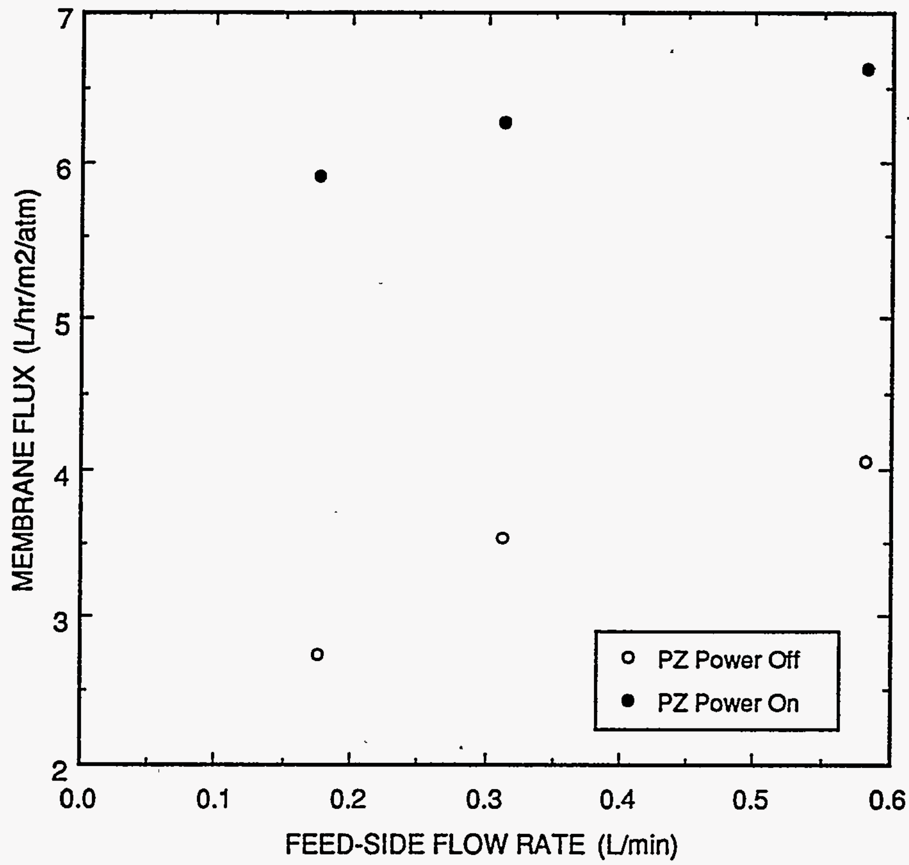

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Figure 6. Effect of feed-side flow rate on ultrafiltration of 3.75% dextran solution.

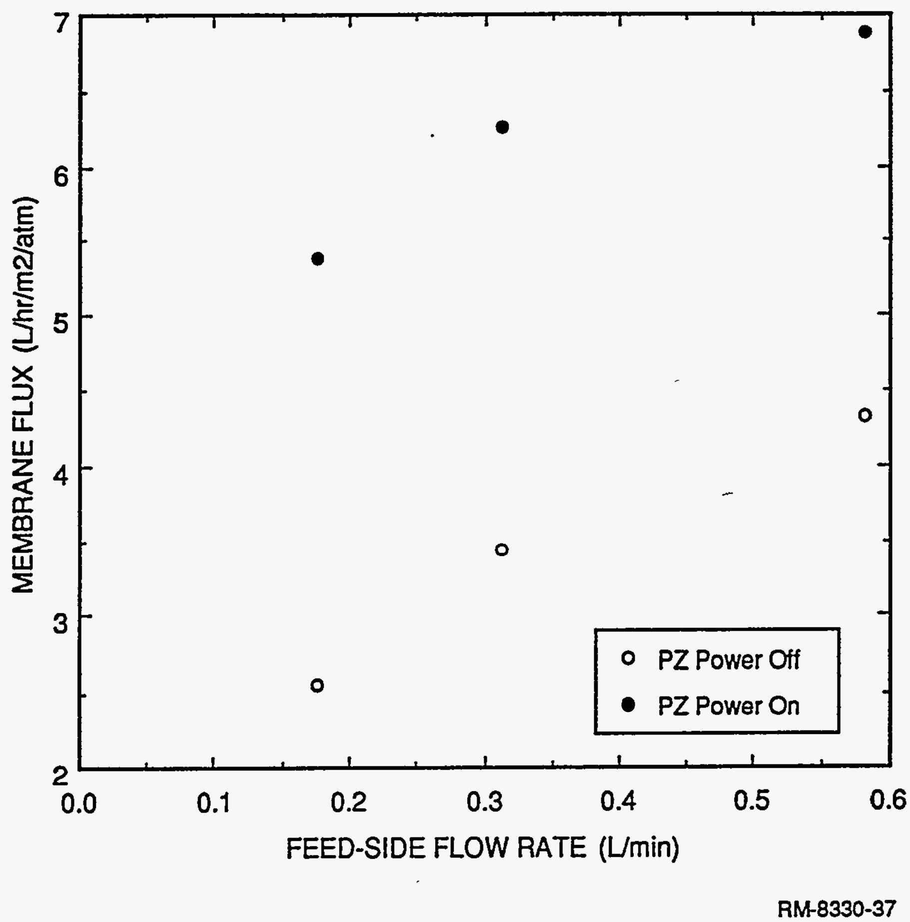

Figure 7. Effect of feed-side flow rate on ultrafiltration of 4.00% dextran solution.

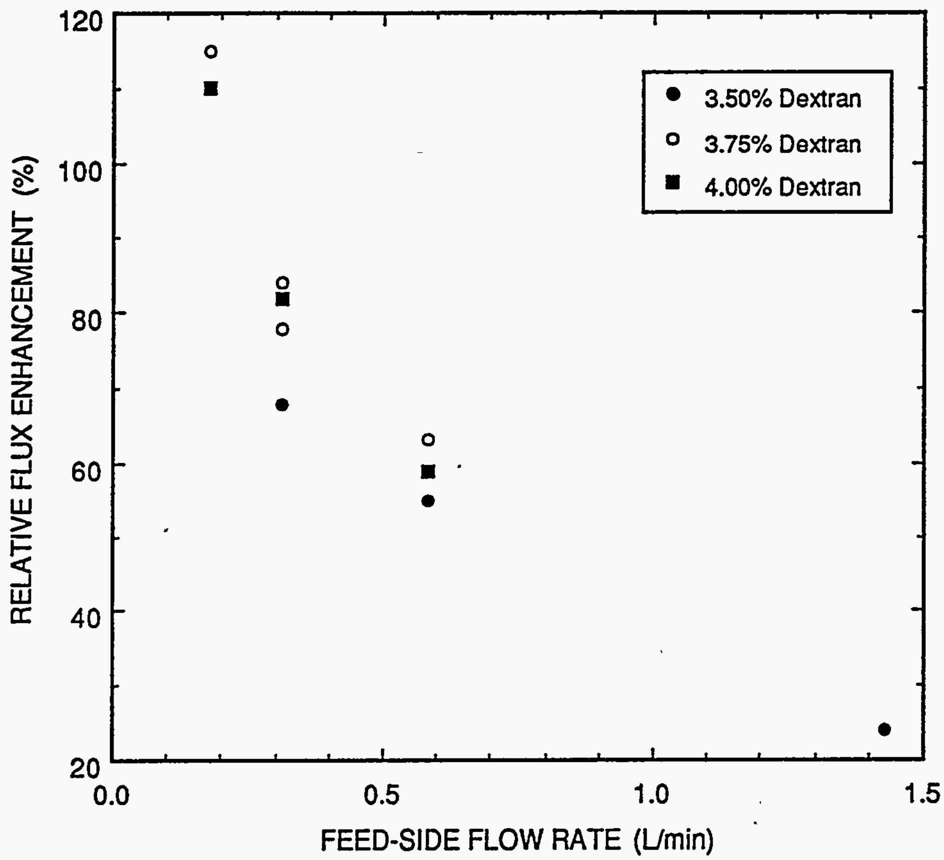

Figure 8. Relative flux enhancement over a range of feed-side flow rates.

electromechanical coupling of the piezorubber is lower than that of the piezoceramic,* thus resulting in poor flux enhancements .

Piezodriver Coating

The effect of the nature of the insulating coating on the performance of the driver was studied for ultrafiltration experiments of electrocoat paint. The coating needs to have high resistance to water penetration to ensure long-term operation, as well as high efficiency in transmitting sonic energy to the UF membrane. An epoxy, silicone (Sylgard 182), neoprene rubber, and a heat-shrinkable Thermofit ATUM tubing (Raychem Corporation) were tested. All the coatings, with the exception of neoprene, were tested during ultrafiltration of electrocoat paint. Although the coatings were not tested rigorously under the same experimental conditions, the available experimental data provide a good basis of comparison and indicate that epoxy is the best performing coating.

The epoxy coating was found to be durable, and indeed was used during our 700-hour ultrafiltration test of electrocoat paint. The coating is readily applied to the piezodriver because it can be cured on the driver. Epoxies are quite rigid, and therefore are expected to efficiently transmit mechanical vibration. The highest flux enhancement with electrocoat paint (by a factor of 3) was achieved when the piezodriver was coated with a 2-mm thick epoxy. The coating thickness is also critical, and it should be optimized to meet needs of durability and good vibration transmission. When a 5-mm thick epoxy was used, a flux enhancement lower than a factor of 1 was obtained, but the coated driver was successfully used for more than 700 hours.

Neoprene was applied to the driver by solvent casting. To properly encapsulate the driver, several coatings were required. Neoprene has excellent water resistance, and showed flux enhancement comparable with that of epoxy coatings. However, epoxies were preferred because of their ease of application.

A 5-mm thick silicone coating was applied to the driver by curing. This coating was quite flexible, and no appreciable flux enhancement was observed when power was applied to piezodriver. The "soft" silicone is probably dampening the mechanical energy transmitted by the transducer.

The piezodriver was also encapsulated with a heat-shrinkable polymer tubing from Raychem Corporation. This tubing is radiation-crosslinked, heat-shrinkable, and adhesive-lined to provide environmental sealing in a wide variety of electrical applications. When heated, the internal adhesive melts and flows to form a good environmental seal. The coating adheres to the

* The piezorubber has lower piezoelectric strain constants (d_{ij}) than the piezoceramic material.

outer tubing and the piezodriver, creating an excellent barrier to water penetration. The overall thickness of the tubing is about 2 mm. With this insulating coating, a flux enhancement of about 20% was obtained during filtration of electrocoat paint, in agreement with the partial flexibility of this coating.

Concluding Remarks on Variables Affecting Piezo-enhanced Ultrafiltration

The configuration piezodriver/membrane and the nature of the driver itself (including the insulating coating) are key parameters that affect the flux enhancement of piezoelectrically-assisted ultrafiltration. We have consistently observed that the mechanical vibration is more efficiently transmitted to the membrane when the driver is mechanically supported over the membrane. Moreover, piezoceramic drivers work better than piezoelectric polymer composites because of their higher electromechanical coupling. On the other hand to avoid dissipation of mechanical power, the piezodriver should be coated by a thin hard coating of insulating material (thick insulating coatings may however be preferred to assure insulation over prolonged use).

ULTRAFILTRATION OF ELECTROCOAT PAINT

Recovery and recycle of electrocoat paint is one of the oldest and most important applications for ultrafiltration. Because the membrane industry is actively seeking methods to reduce membrane fouling in electrocoat paint applications, and because large amounts of pumping energy are currently used to minimize fouling, we chose to study piezoelectrically enhanced ultrafiltration with electrocoat paint. We performed several experiments to evaluate the effectiveness of piezo-enhancement for electrocoat paint under various pressure, feed flow, and paint composition conditions. Piezo-enhancement typically resulted in flux increases of about 50%, but flux increases as high as a factor of 3.3 were obtained under some conditions.

APPLICATION OF ULTRAFILTRATION TO ELECTROCOAT PAINT

Electrocoat paint was one of the first industrial applications of ultrafiltration (UF) membranes used on a large scale. Since the mid-1960s, electrocoat paint has been used as the priming coat for a variety of products, particularly automobiles parts. In electrodeposition of paint, the object to be coated is immersed in an aqueous solution containing the paint suspension (a mixture of pigments and resins). Paint is deposited by direct electric current onto the object that can act as either the positively charged electrode (anodic deposition) or the negatively charged electrode (cathodic deposition, the preferred method for most applications). The advantage of electrocoat paint is that the entire object can be coated, including recessed areas that are difficult to coat by other methods. Detailed descriptions of the electrocoat paint process are available in the literature (Brewer, 1985; Cheryan, 1986).

When a coated object is removed from the paint bath, some undeposited paint adheres to the object and must be removed by rinsing. Disposal of the rinse water is economically unwise because valuable paint is lost, and because the rinse water must be treated before disposal into the sewer. The rinse water cannot simply be pumped back into the paint tank because the stability of the paint emulsion would be upset. Use of the ultrafiltration system allows the rinse water to be reused, eliminating disposal costs and recovering paint.

It is useful to understand how the UF system fits into the electrocoat paint operation. Paint is withdrawn from the paint bath and pumped through the UF membranes (Figure 9). Only a small fraction (~1%) of the feed permeates the membrane, allowing the nonpermeated paint to return to the paint bath at nearly the same composition at which it was withdrawn. The membrane retains all the pigments and resins from the paint, and the permeate is used for rinsing. The paint bath

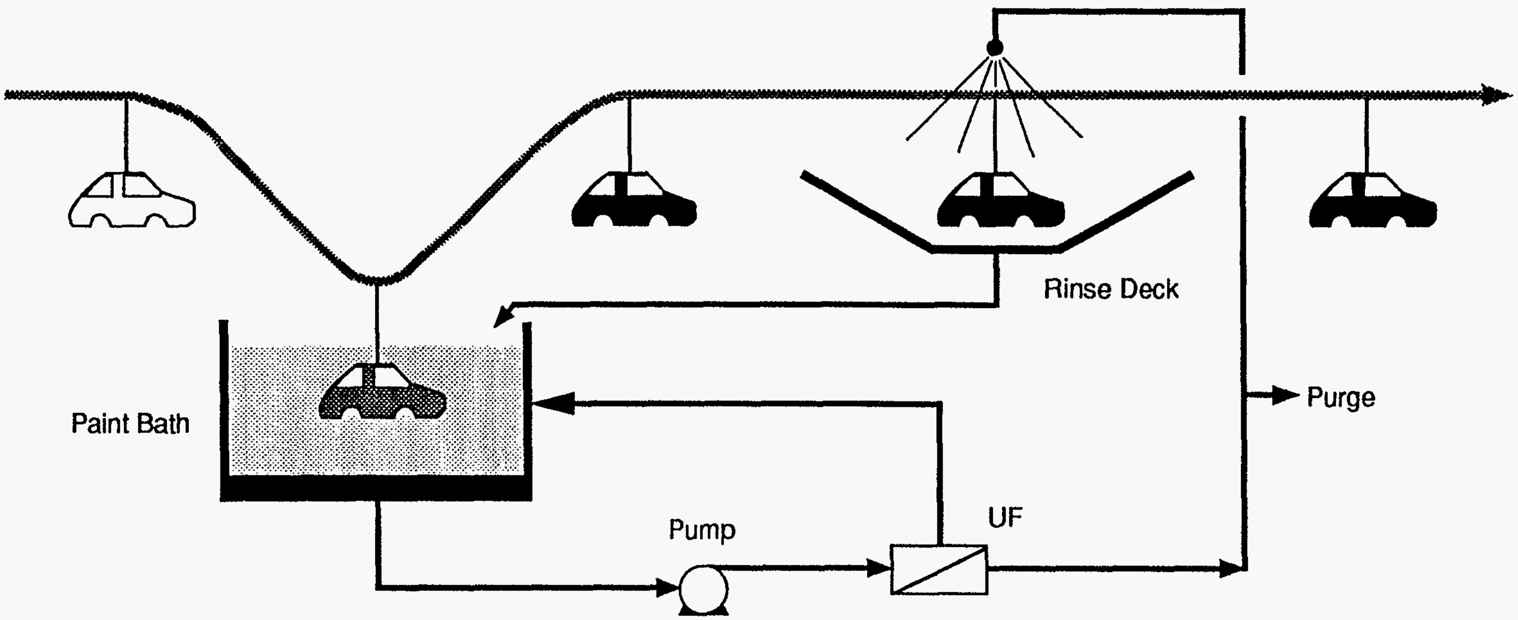

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Figure 9. Electrocoat paint system.

The UF system provides rinse water and allows recovery of retained paint without upsetting paint stability.

contains some dissolved salts from pretreatment steps which can upset the paint stability if allowed to build up. These salts permeate the membrane; hence, purging a small amount of the permeate maintains the paint stability.

The UF membranes used in electrocoat paint operations are typically charged polymer membranes with molecular weight cutoffs in the 10,000 to 50,000 range. The charge of the membrane is equal to that of the paint and helps to reduce fouling by preventing the pigment and resin particles from adhering to the membrane. Membranes can be configured as hollow-fiber, spiral-wound, or tubular modules; tubular modules are more resistant to fouling and plugging (some paints can only be run through tubular membranes) but typically have a higher cost per unit of membrane area than do spiral-wound and hollow-fiber modules.

Because of the high solids content of electrocoat paint, both short- and long-term membrane fouling can be a serious problem. Short-term fouling is due to anything that causes a reduction in flux but which occurs quickly (several hours) after starting up a clean membrane and which can be removed by operating the membrane with clean water or by backflushing. Concentration polarization is a typical mechanism causing short-term fouling. Long-term fouling occurs over a long period of time (weeks or months) and requires stronger cleaning procedures, such as chemical cleaning for removal. Plugging of membrane pores by solid particles or covalent bonding of solute molecules to the membrane surface are typical causes of long-term fouling. A reduction in either short- or long-term fouling would be of great benefit to electrocoat paint operators because the methods used to minimize fouling can be expensive.

To minimize long-term fouling membranes are chemically cleaned periodically. During this procedure the UF plant is shut down. The chemicals used in cleaning are hazardous and their disposal can be expensive. The length of time between cleanings varies from site to site but is typically between three and six months. If long-term fouling could be reduced, the length of time between cleanings could be extended, reducing downtime and hazardous waste disposal costs.

Short-term fouling is conventionally minimized by using a high feed velocity in the membrane. The high velocity prevents paint solids from concentrating near the membrane surface, and reducing membrane flux. To provide the high feed velocity to the membrane, a large recycle stream is used around the membrane. Figure 10 shows the stream flows and compositions in a typical automobile electrocoat paint line. If short-term fouling could be reduced by some means other than using a high feed velocity, substantial savings would be incurred by lowering the required pump size and thereby reducing capital and energy costs.

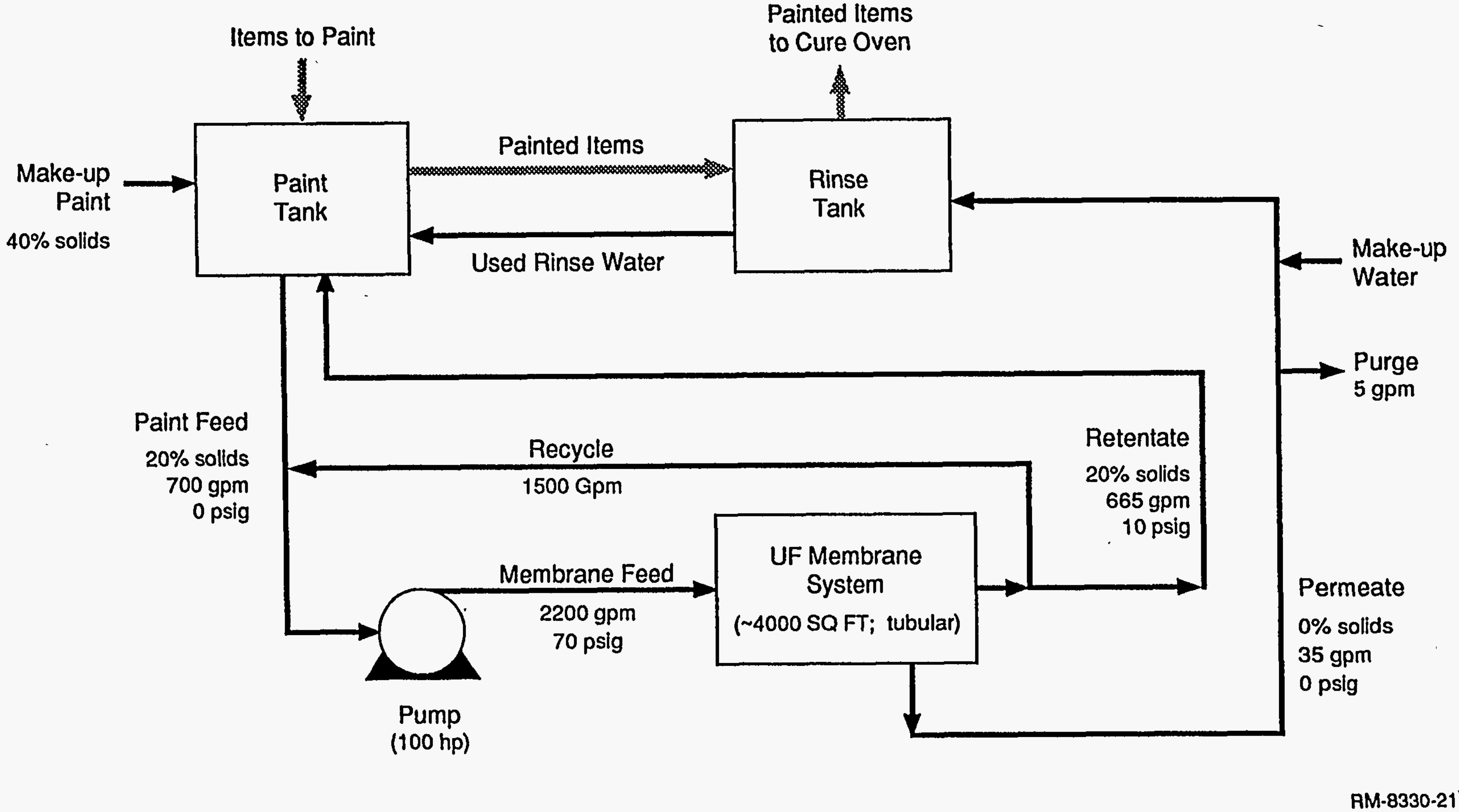

Figure 10. Typical Automobile Electrocoating Line.

A typical automobile plant will have four lines running in parallel.

EXPERIMENTAL PROCEDURE

Several experiments were performed to study the usefulness of piezoelectrically enhanced UF, including varying the paint concentration, feed pressure, and feed flow rate. A 700-hour test was also performed to evaluate the long-term performance of piezoelectrically enhanced UF. These tests were performed with commercial automobile paint (type ED-11, 20 wt% solids; PPG Industries, Pittsburgh, PA) and with membranes used commercially in electrocoat paint applications (type HFM-183, molecular weight cutoff ~20,000; Koch Membrane Systems, Wilmington, MA). Two stainless-steel test cells, as previously shown in Figure 1, were used, each holding a flat membrane sheet with an active area of 28.3 cm^2. A PZT ceramic disc 37.5-mm in diameter and 2.5-mm thick was placed in one cell (the PZ cell); the other cell contained no disc (the control cell). The disc was coated with epoxy to provide electrical insulation.

The paint was pumped to the test cells by a double diaphragm pump; a surge suppressor was used to reduce flow and pressure fluctuations. Although centrifugal pumps are typically used in commercial systems, we could not find a small-volume pump that would perform satisfactorily with the high-solids-content of electrocoat paint, so we used the double diaphragm pump. PPG personnel use a similar double diaphragm pump in their test apparatus and reported that the performance of the UF system with the double diaphragm pump does not differ significantly from that with a centrifugal pump.

The entire test apparatus is illustrated in Figure 11. After the apparatus was started up, or when any operating conditions were changed, the system was allowed to reach a steady permeate flux before any measurements were taken; from several hours to a full day was required to reach steady state.

The control cell was used in all experiments to check for any qualitative behavior changes due to the piezoelectric disc. The PZ cell without power and the control cell behaved identically in all of the experiments.

SIMULATION OF COMMERCIAL OPERATING CONDITIONS IN THE TEST CELL

Because our test cell has a different geometry than that of a commercial membrane module, the permeate flux in the two systems will be different even if the Reynolds numbers are the same. The flow in a commercial module consisting of tubes 10-ft long and 0.5-inch in diameter, is fully developed throughout most of the module, while flow in small test cells such as ours is typically dominated by entrance effects. Turbulence is greater in entrance regions than in regions where

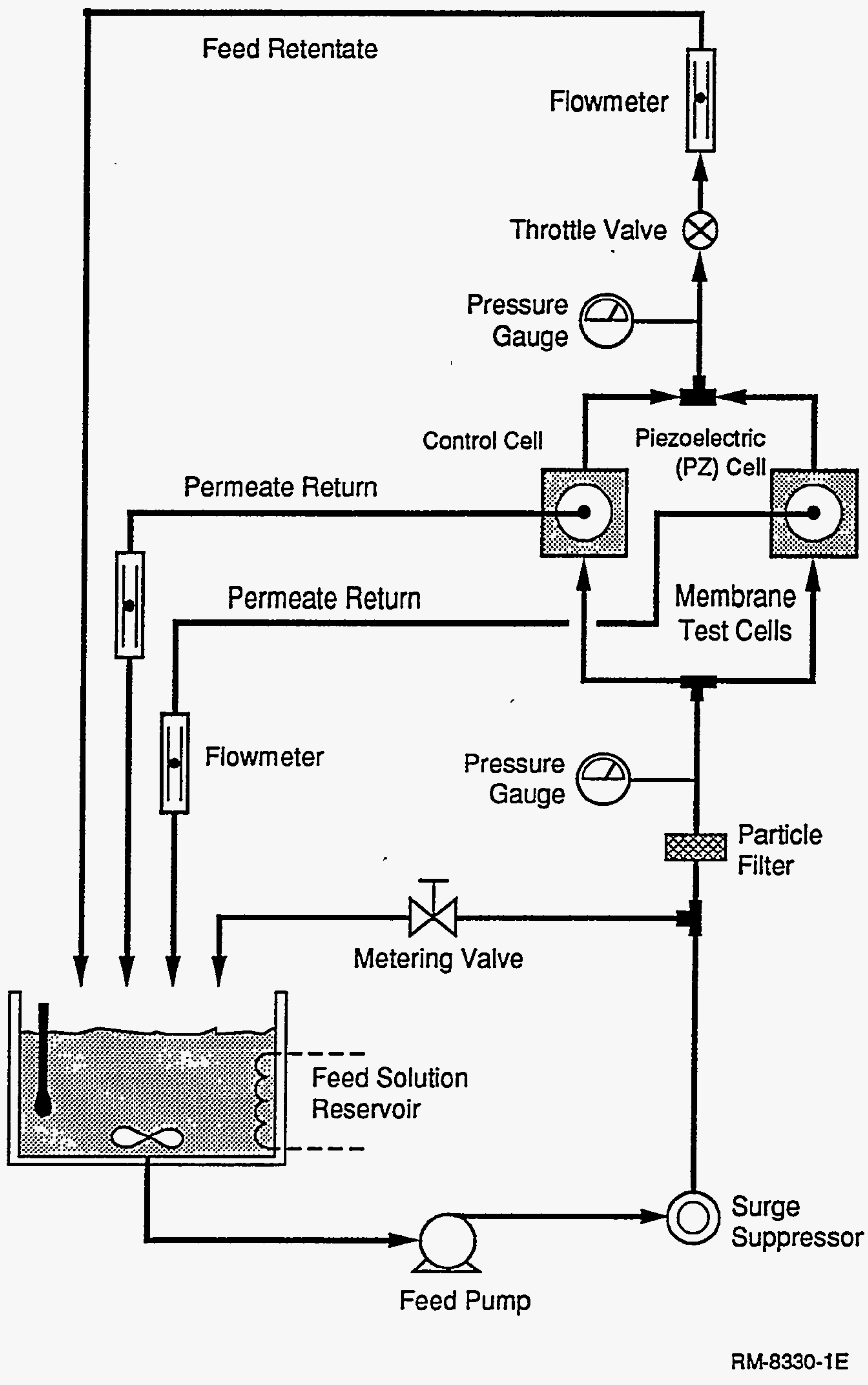

Figure 11. Cross-flow ultrafiltration test apparatus.

flow is fully developed, and the greater turbulence in a small cell typically results in higher membrane permeation rates than is obtained with large modules operating at the same Reynolds number. To simulate commercial operating conditions, we matched the membrane permeation rate in our cell to that reported for commercial membrane systems. The feed flow rate in the test cell was adjusted until the permeate flux was approximately 12 GFD; the required feed flow rate was approximately 1.4 gal/min (GPM). The feed pressure in a commercial membrane system drops from a feed value of about 70 psig to about 10 psig at the outlet. In our test cell there is very little pressure drop between the entrance and the exit, so we operated the cell at the average of the inlet and outlet pressures in a commercial system (40 psig).

When an experiment was started with paint, the membrane flux decreased as the membrane fouled until a steady state value was reached, usually within 12 hours. (This steady state flux value was steady only relative to the initial flux decline period; over the next weeks or months the flux decreased further because of long-term fouling).

PIEZO-ENHANCEMENT RESULTS

Figure 12 shows the effect of piezo-enhancement for several disc/membrane combinations at simulated commercial conditions. Although the data in this figure includes different discs and membranes, the membrane flux and the piezo-enhanced flux increase do not vary greatly. The flux is increased by about 5 GFD, or 40 to 50% of the conventional flux.

During our enhancement experiments the increased flux lasted only as long as the power was applied to the piezoelectric disc. This differs from the results obtained previously with polyethylene glycol and dextran (Narang, et al; 1990), wherein the enhancement continued long after the power was off. We believe that the different flux response in the electrocoat paint experiments and the polyethylene glycol/dextran experiments is due to different fouling mechanisms. During ultrafiltration of electrocoat paint, short-term fouling mechanisms predominate and the foulant layer quickly reforms after the piezodriver power is turned off. On the other hand, during filtration of polyethylene glycol and dextran, long-term fouling mechanisms likely predominate, so the foulant layer reforms over a longer period of time. Figure 13 illustrates a typical flux response to piezo-enhancement during ultrafiltration of electrocoat paint. Because the power source overheated after 1 or 2 minutes, all the data points included in this chapter represent the steady flux achieved during a 1- to 2-minute period during which power was applied to the disc. If piezo-enhancement is to be used in a commercial system, the power will have to be applied continuously to achieve the increased flux consistently.

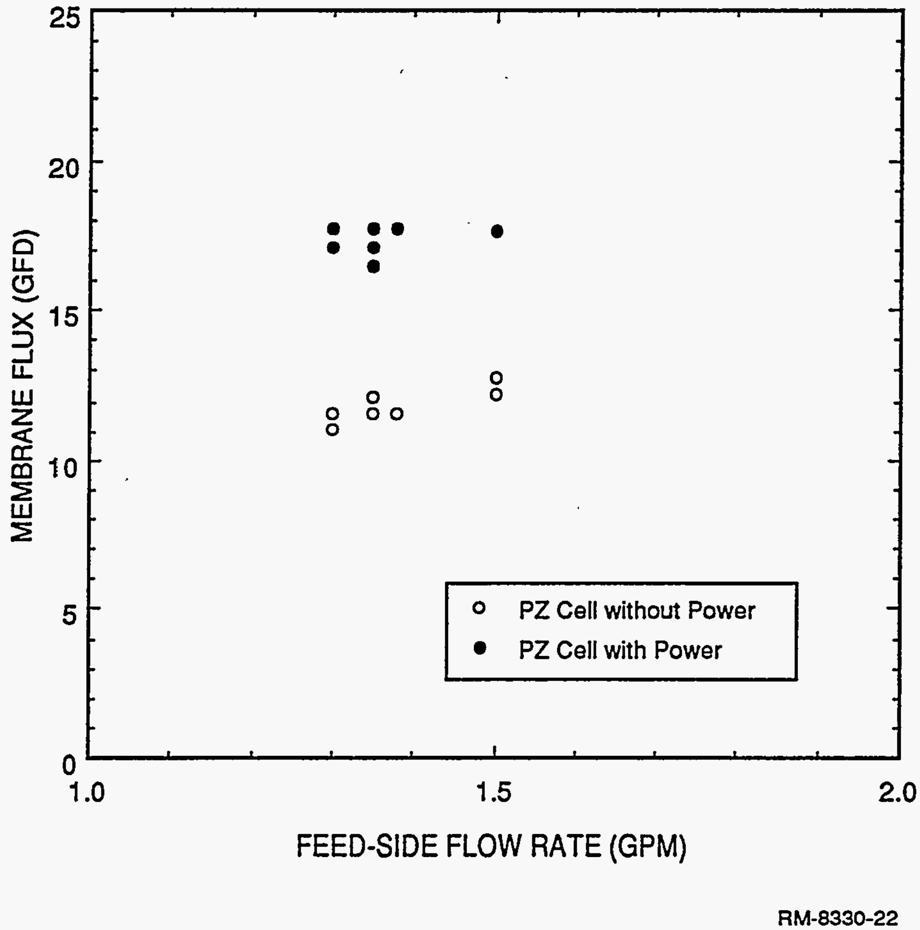

Figure 12. Electrocoat paint UF results for simulated commercial conditions.

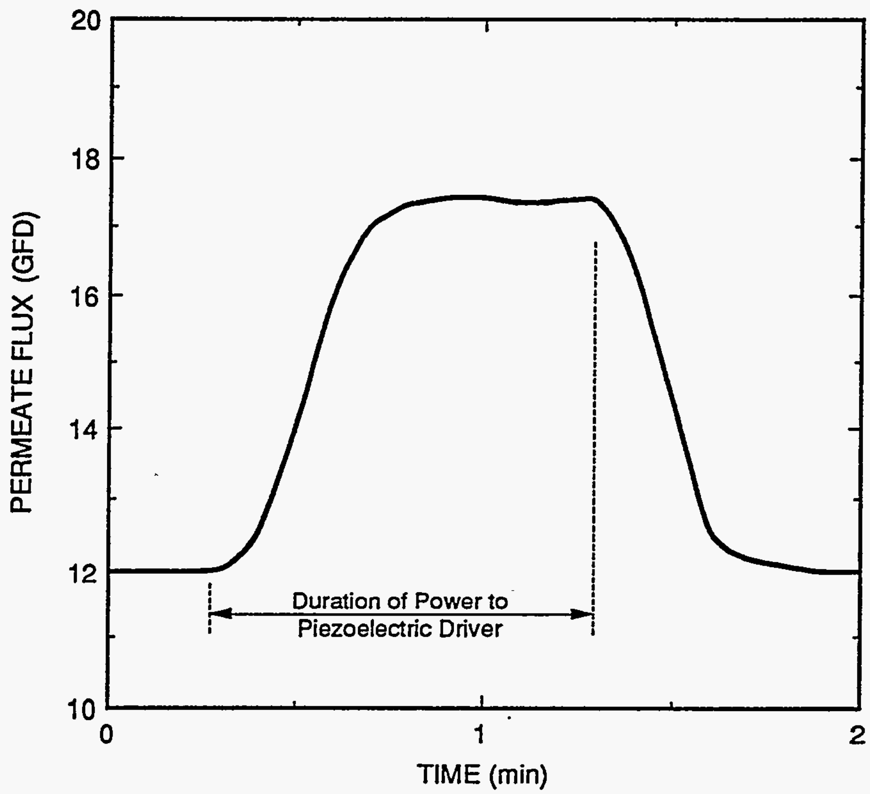

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Figure 13. Qualitative response of permeate flux to piezo-enhancement.

The flux is enhanced only when power is applied to the piezoelectric driver.

The feed velocity adjacent to the membrane has a strong effect on permeate flux under both laminar and turbulent conditions (Porter, 1972). As we described earlier, this effect is used to attain high fluxes. Therefore it is important to determine the effect of piezo-enhancement over a range of feed flow rates. We measured the permeate flux at three different feed flow rates — 0.8, 1.4, and 2.0 GPM — using the same membrane/disc combination in each case. Since fouling is greatest at the low feed rates (when the sweeping action of the feed is least), we expect the piezo-enhancement to also be greatest at low feed rates. Figure 14 shows the resulting membrane fluxes for the PZ cell (both with and without power to the disc). In relative terms, as shown in Figure 15, the piezo-enhancement behaves as expected, being greatest at low feed flow rates (66%) and highest at high feed flow rates (30%). In absolute terms, however, as shown in Figure 16, the difference in flux between the membrane with and without piezo-enhancement is about the same for all flow rates (~5 GFD).

While the relative flux enhancement is small compared to the several-fold enhancements previously achieved with polyethylene glycol and dextran (Narang et al.; 1990), Figure 14 shows that the feed flow rate necessary to achieve commercial fluxes with piezo-enhancement is about one half that required without piezo-enhancement. The economic implications of this result will be discussed in the next chapter.

Membrane flux and piezoelectric enhancement are shown as a function of feed pressure (at a constant feed flow rate of 1.4 GPM) in Figure 17. As we expected, flux increases with pressure. The absolute flux enhancement also increases with pressure, although the difference between fluxes at 40 psig and 70 psig is not significant.

Although commercial operations typically use paint containing 20% solids, we also tested piezo-enhanced UF with paint containing 13% solids. The flux increased from 6.7 GFD without piezo-enhancement to 22.2 GFD with piezo-enhancement, more than a three-fold increase (at a feed flow rate of 0.5 GPM and a feed pressure of 40 psig). According to our previous discussion, this favorable performance is likely due to the thin epoxy coating (2-mm thick) used in this experiment. An attempt to repeat this result, however, resulted in only a 50% enhancement; we suspect that the power supply began to fail during the second experiment, leading to the lower enhancement.

A long-term test was performed over a 700-hour period to determine if the piezoelectric driver had an effect on the long-term fouling, or whether the vibration causes harm to the membrane over longer periods of time. This test was performed under commercial conditions using a 5-mm thick epoxy-coated disc. Because the power supply could not be on for longer than about one minute, we applied power to the disc only periodically. During the first 400 hours, we applied

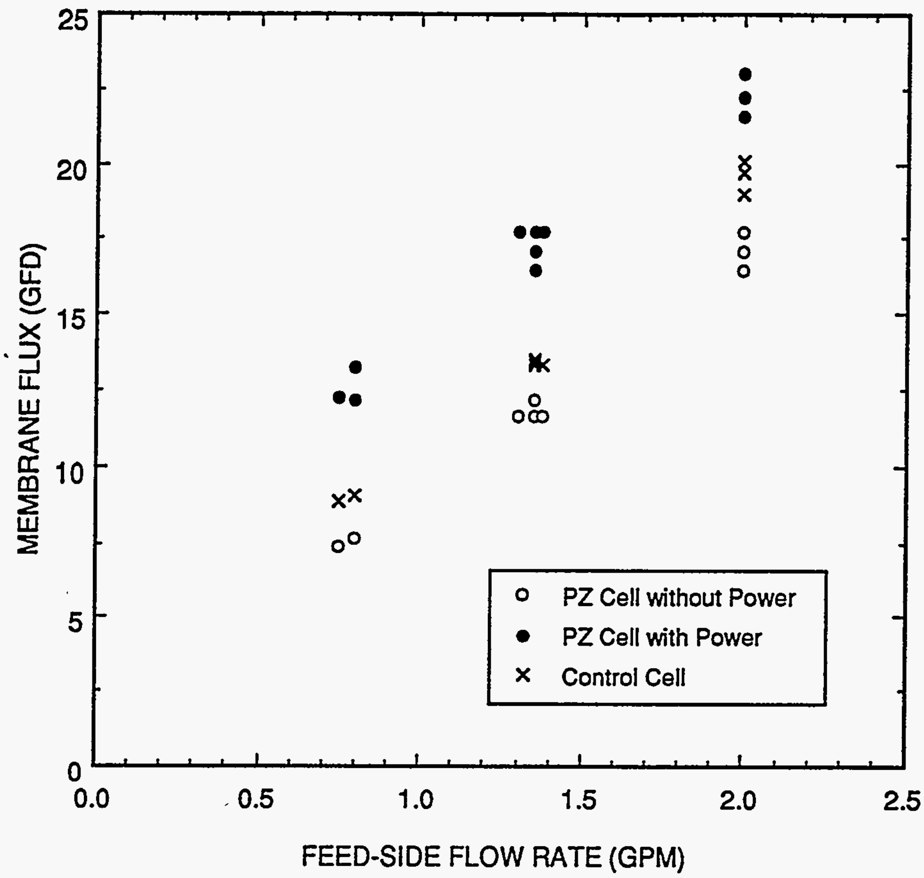

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Figure 14. Effect of feed-side flow rate on membrane flux with electrocoat paint.

The flux varies linearly with flow rate.

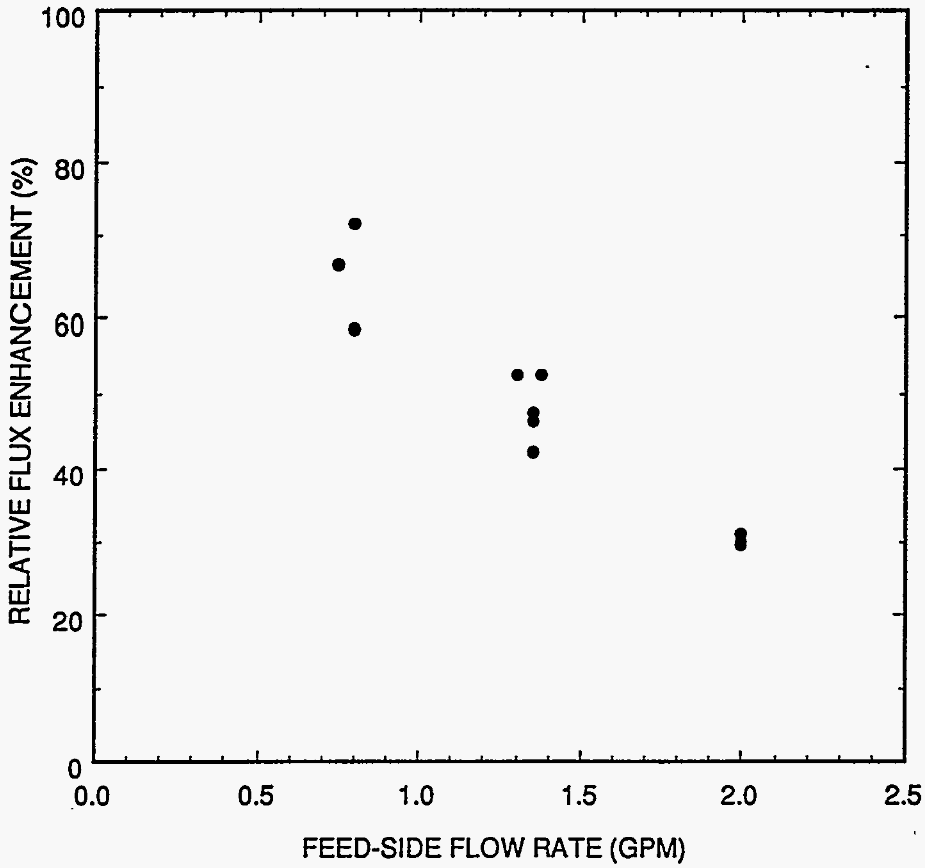

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Figure 15. Relative flux enhancement over a range of feed-side flow rates.

At higher flow rates the degree of fouling is less, therefore piezo-enhancement has less effect.

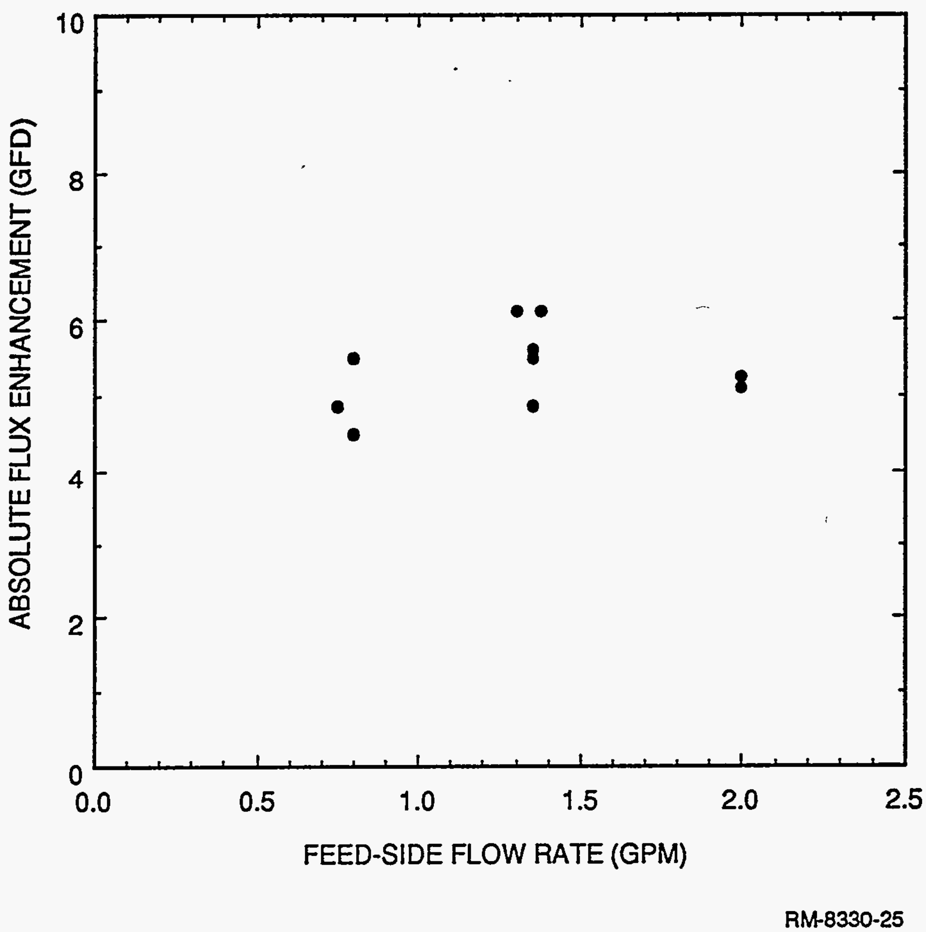

Figure 16. Absolute flux enhancement over a range of feed-side flow rates.

The absolute enhancement does not vary greatly.

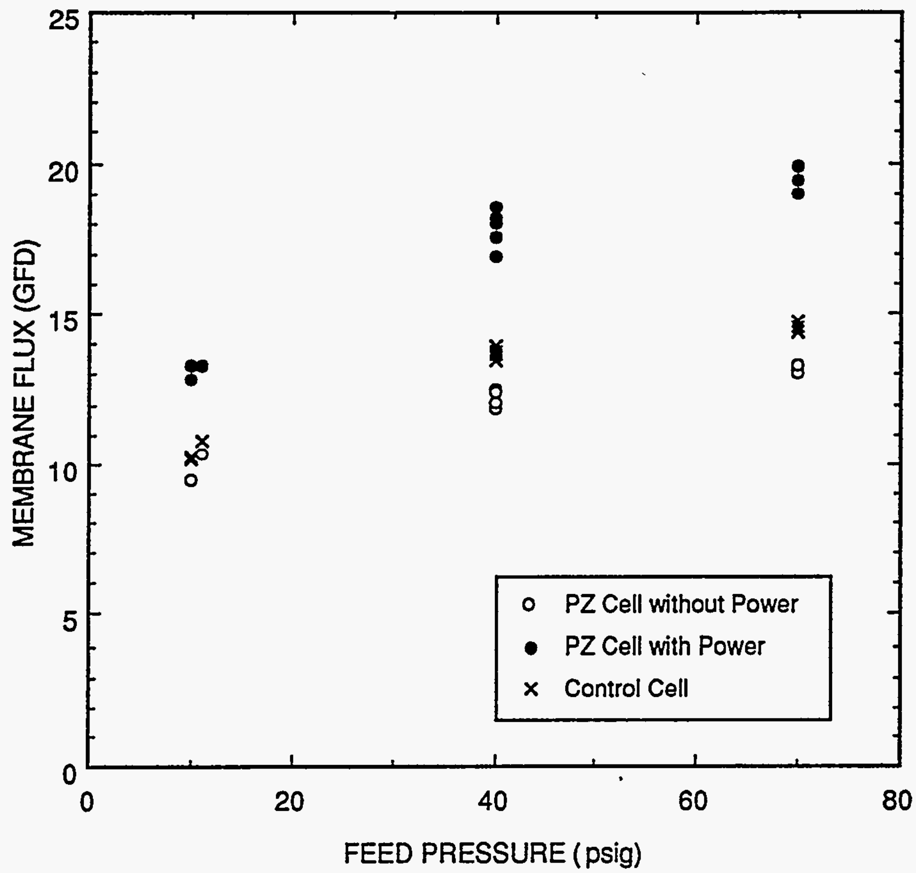

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Figure 17. Effect of pressure on membrane flux with electrocoat paint.

Pressure has the greatest effect on flux below 40 psig.

power to the disc once per day, during the last 300 hours, we applied power 5 times per day (except weekends). The results are shown in Figure 18; the enhancements displayed lasted only as long as power was applied to the disc.

The results in Figure 18 show that the flux in the control cell and in the PZ cell without power were very similar; both declined slowly during the 700 hours from about 13 GFD to about 11 GFD. The fact that the flux declines in both cells at the same rate indicates that piezo-enhancement has no significant effect on the long-term performance of the membrane. Increasing the number of times per day that power was applied had no effect on enhancement. The absolute flux enhancement declined over time from an increase of about 7 GFD initially to about 3 or 4 GFD at the end of the test.

A possible reason is that long-term fouling is responsible for the flux enhancement decline, and long-term fouling is unaffected by piezo-enhancement. As the significance of long-term fouling increases over time, the effectiveness of piezo-enhancement correspondingly decreases. A test for this hypothesis would be to see whether the flux enhancement returned to its initial value after a thorough cleaning of the membrane. (Unfortunately, our experiment sustained a leak, and the paint was lost after 700 hours, preventing us from performing this test.) The long term test did show that piezo-enhancement is effective over long periods of time.

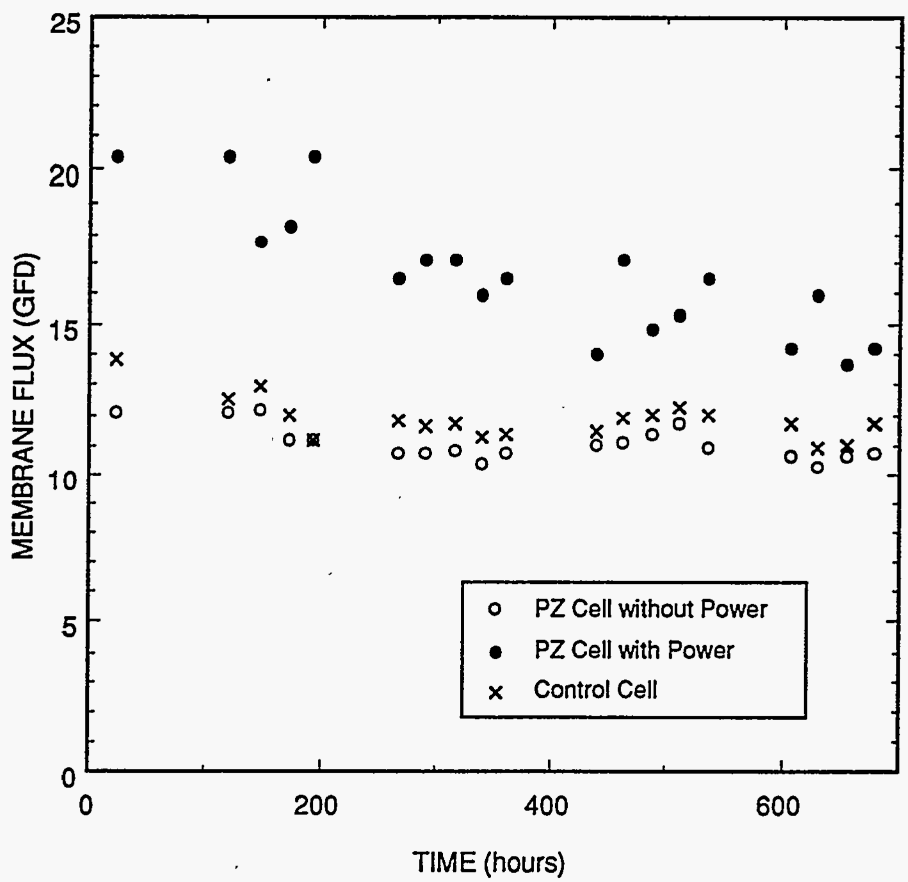

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Figure 18. Long term test of piezo-enhancement with electrocoat paint.

During the first 400 hours power was applied to the disk once per day, and five times per day after that.

ECONOMIC EVALUATION OF PIEZOELECTRICALLY ENHANCED ULTRAFILTRATION FOR ELECTROCOAT PAINT OPERATIONS

In this chapter we present an evaluation of the economic and energy benefits achieved with piezo-enhancement for ultrafiltration of electrocoat paint. The parameters used in this evaluation are based on the data obtained in our test cell. Our economic results show that substantial savings in pumping energy (over four-fifths) can be achieved; however, the increase in energy consumption of the piezoelectric system more than offsets this savings. Because of the high energy consumption of the piezoelectric system, piezo-enhanced UF is not currently feasible for the electrocoat paint application. If power consumption can be reduced, however, piezo-enhanced UF could become economically attractive, and savings in pumping energy could be realized.

The parameters used in this analysis include a piezoelectric power requirement based on the nominal power rating of the power supply (20 watts per disc), continuous application of power (necessary if the flux enhancement is moderate and is not prolonged after the power is turned off), and a membrane to disc ratio equal to that in our test cell (28.cm^2 membrane area per disc). This yields to a total power requirement of 7.1 KW/m^2. The flux enhancement we used in this analysis is the difference between the flux in the PZ cell with and without piezo-enhancement (Figure 19). The decline in enhancement observed during the long-term test was ignored. Because improvements in power consumption and enhancement promise to be achieved with further development efforts (we achieved a three-fold increase in one experiment), we believe this is a conservative analysis. We have performed a sensitivity analysis to show how the economic outlook for this application might change if further development was successful.

The differences between our current analysis and the one performed for the previous annual report (Narang et al.; 1990) are significant. The previous analysis was based on a different application, deasphalting of oil (DAO), which is currently performed by evaporation. The values for piezoelectric power consumption and flux enhancement used in the DAO analysis were more favorable than the values used in this analysis. (These favorable values were used because previous experiments resulted in greater enhancements that lasted over significant period of time, and lower power consumption than was achieved with electrocoat paint.). The piezoelectric power consumption used in the experiments reported here is over 1000 times greater than that used in the DAO analysis, and the relative flux enhancement is significantly lower than that used in the DAO analysis.

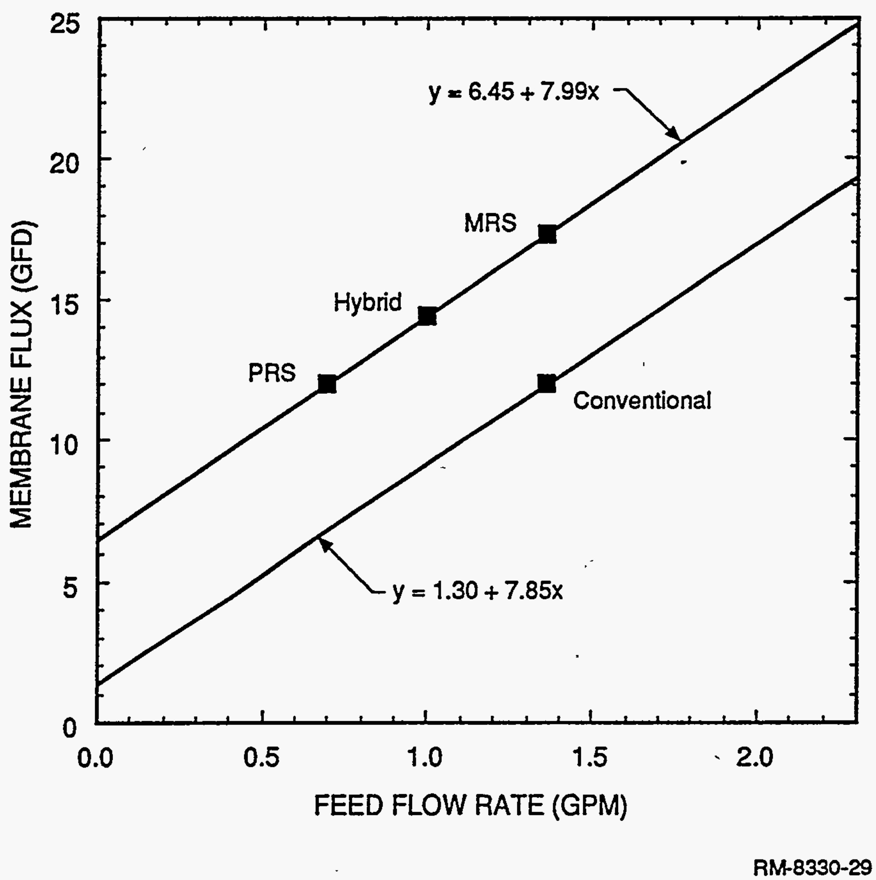

Figure 19. Conditions for operation of conventional and piezo-enhanced UF.

The conventional and piezo-enhanced flux lines were generated by linear regression of data shown in Figure 6 for the PZ cell with and without power.

PROCESS DESCRIPTIONS

With piezo-enhancement we have a choice of conditions under which we can operate the UF system. Figure 19 shows the relationship between membrane flux (with and without enhancement) and feed flow rate; the two lines can be thought of as the operating lines for the piezo-enhanced and conventional UF systems.

With piezo-enhanced UF we can operate the system with either of two goals in mind: to minimize membrane area requirements or to minimize pump requirements. With the system configured to minimize membrane requirements (the membrane reduction system, MRS), the feed flow rate is the same as in conventional UF. Piezo-enhancement results in a higher membrane flux (17.3 GFD) than with conventional UF (12 GFD), and therefore less membrane area is required to supply the same quantity of permeate. With the system configured to minimize pump requirements (pump reduction system, PRS), a low feed flow rate is used, such that the enhanced membrane flux is the same as that with conventional UF; the low feed flow rate results in reduced pump requirements. It is also possible to operate a hybrid system (HYB) as a mixture of MRS and PRS. The hybrid system in this economic analysis has a feed flow rate about halfway between the flow rates used in MRS and PRS.

Conventional UF

Figure 20 shows details of the conventional UF system described in the previous chapter. Many tubular membrane modules are needed to provide the necessary surface area. Eight modules are used in series; 68 of these series are needed to supply the required membrane area. A feed flow rate of 32.4 GPM is used in each series of modules, for a total feed rate of 2200 GPM, requiring a 100 HP pump. When piezo-enhancement is used, both the number of modules and the way they are arranged can change.

Membrane Reduction System (MRS)

When MRS is used with piezo-enhancement, the permeate flux from each module is greater (44% greater based on Figure 19), so fewer modules are required. Figure 21 shows how this system could be arranged. Since the flow rate through each module is the same as with conventional UF, the number of modules in series will also be the same. (The number of modules used in a series is determined by the overall pressure drop allowed.) Since fewer modules are needed, only 47 series are required — a 31% reduction in the total number of modules. Although the aim of this system is to reduce membrane area, a reduction in pumping requirements also results. Because the

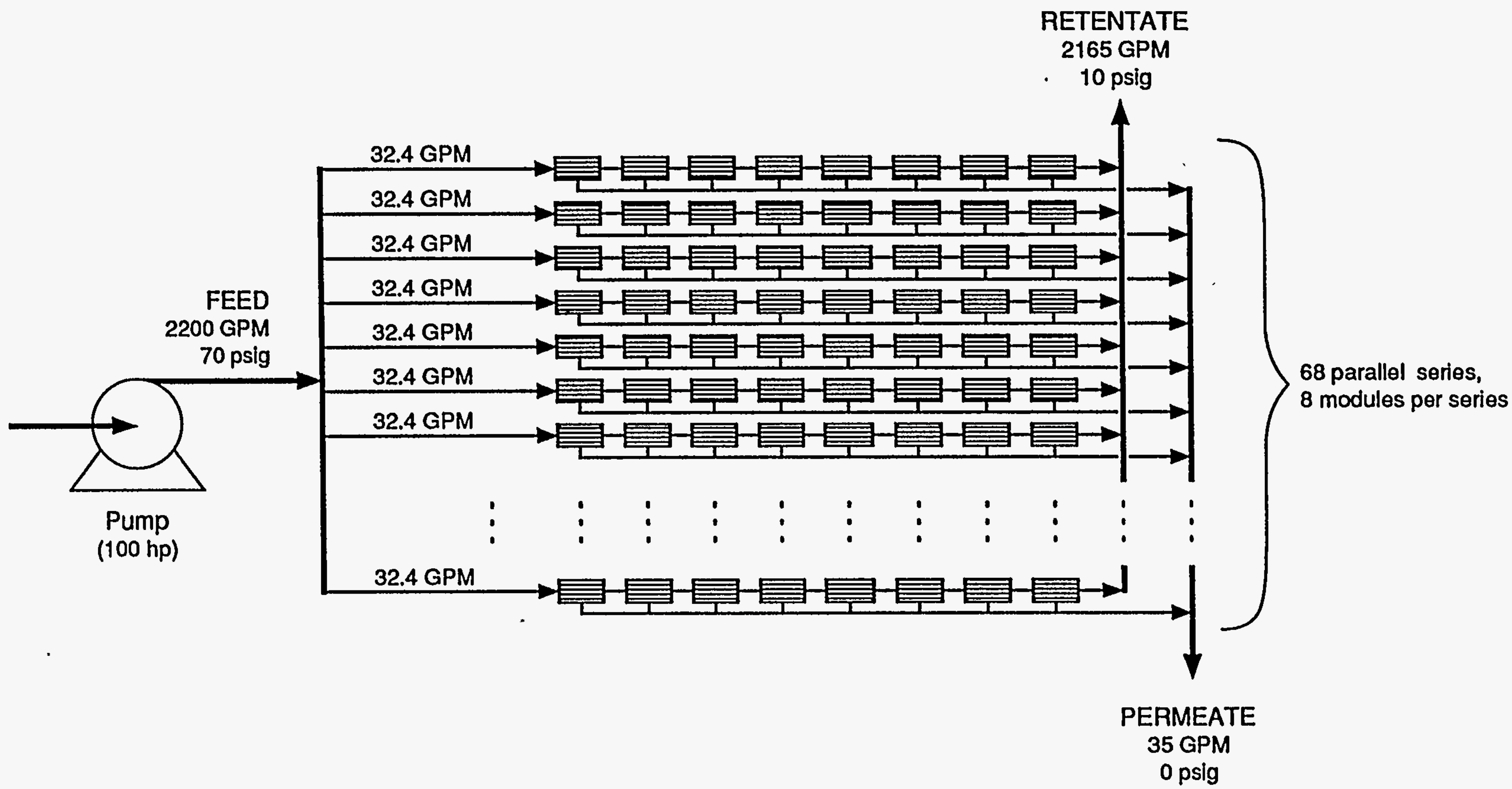

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Figure 20. Conventional UF system for a single automobile electocoat line.

A total 544 membrane modules and a 100 hp pump are required.

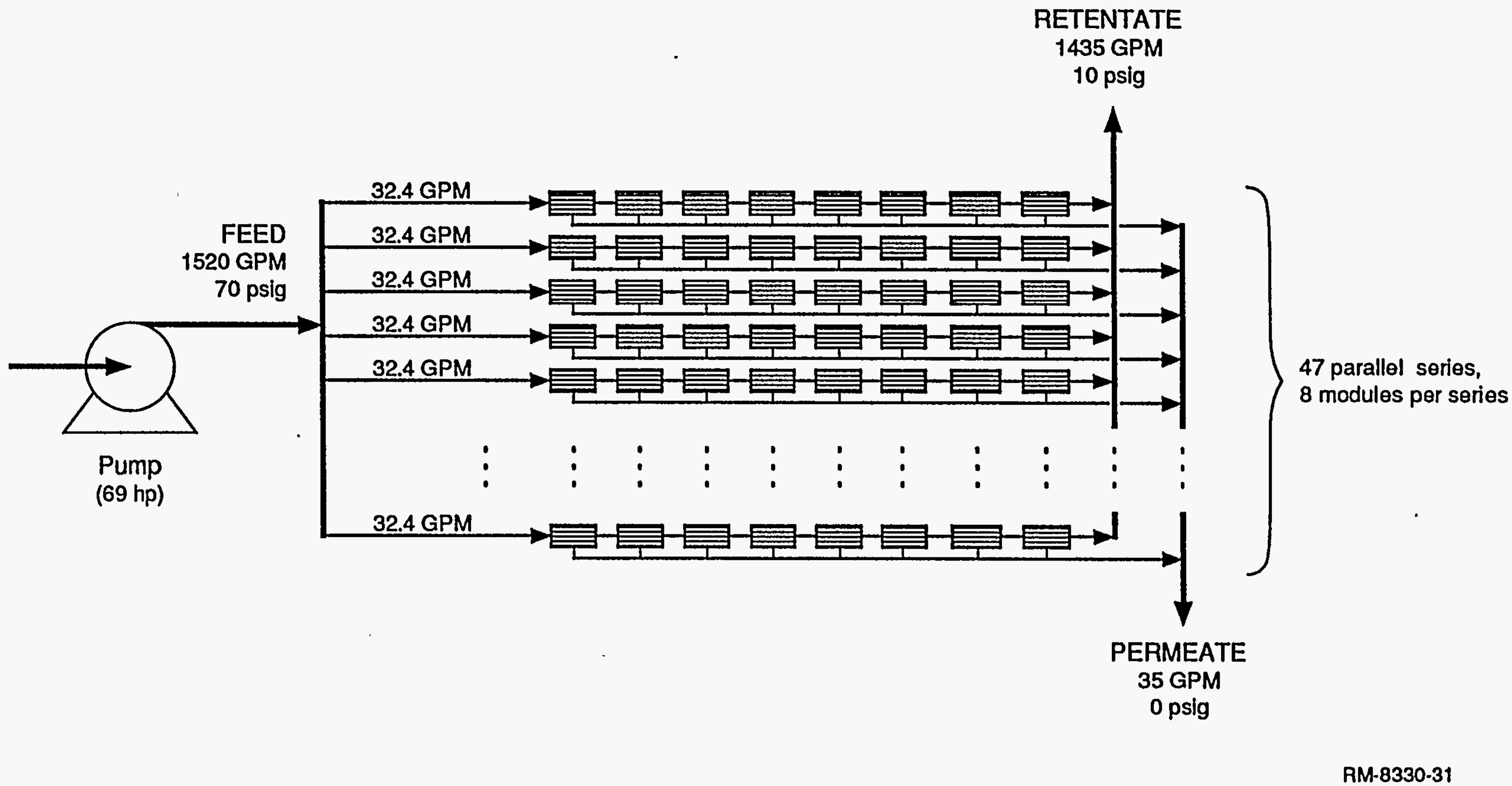

Figure 21. Piezo-enhanced UF operating as MRS.

A total 376 membrane modules and a 69 hp pump are required.

flow rate into each series is the same as with conventional UF, the total flow into the system is less than that with conventional UF; pumping requirements are correspondingly reduced.

Pressure Reduction System (PRS)

When PRS is used with piezo-enhancement, the permeate flux from each module is the same as with conventional UF, but the feed flow rate is only about half (from Figure 19). The configuration at the top of Figure 22 shows how this system could look. With a reduced flow rate through each series of modules, however, the pressure drop across each series is much less (18 psi instead of 60 psi)*. This pressure drop reduction can be used to our advantage in one of two ways: the higher average pressure on the feed side of the membrane could be used to provide a higher membrane flux and fewer total membrane modules could be used (based on Figure 17, the flux increase would be about 10%), or the number of series could be reduced by placing more modules into each series such that the final exit pressure would be the same as in conventional UF (reducing the number of series reduces the pump requirements proportionately). We chose the second approach (illustrated at the bottom of Figure 22) for our PRS analysis. At the reduced flow rate (16.5 GPM through each series of modules) a total of 27 modules can be used in each series. Since the total number of modules is the same for PRS as with conventional UF, only 20 series are needed, with 27 modules included in each series. With 16.5 GPM fed to each series, the total feed rate is only 330 GPM (15% of that with conventional UF), and a correspondingly sized pump is required (15 HP).

Hybrid System (HYB)

The hybrid system (HYB) is half way between MRS and PRS (Figure 19). The total feed flow rate is 783 GPM, and the pump size is 73 HP. A total of 452 membrane modules are used in 33 series containing 14 modules each.

PROCESS ECONOMICS

The three principal costs for the UF system are the membranes (conventional or piezoelectric), the pump, and electricity (for pumps and/or piezoelectric drivers). The purchase cost of the membrane modules used in the above designs (ULTRA-COR tubular module, Koch Membrane Systems, Wilmington, MA) is $250 each. The purchase cost of a piezoelectric module is difficult to estimate; however, since most of a module cost is labor, and piezoelectric materials are not particularly expensive, we will use $500 as a conservative purchase cost for a piezoelectric

* Pressure drop is proportional to flow rate raised to the 1.75 power. See Appendix A for details.

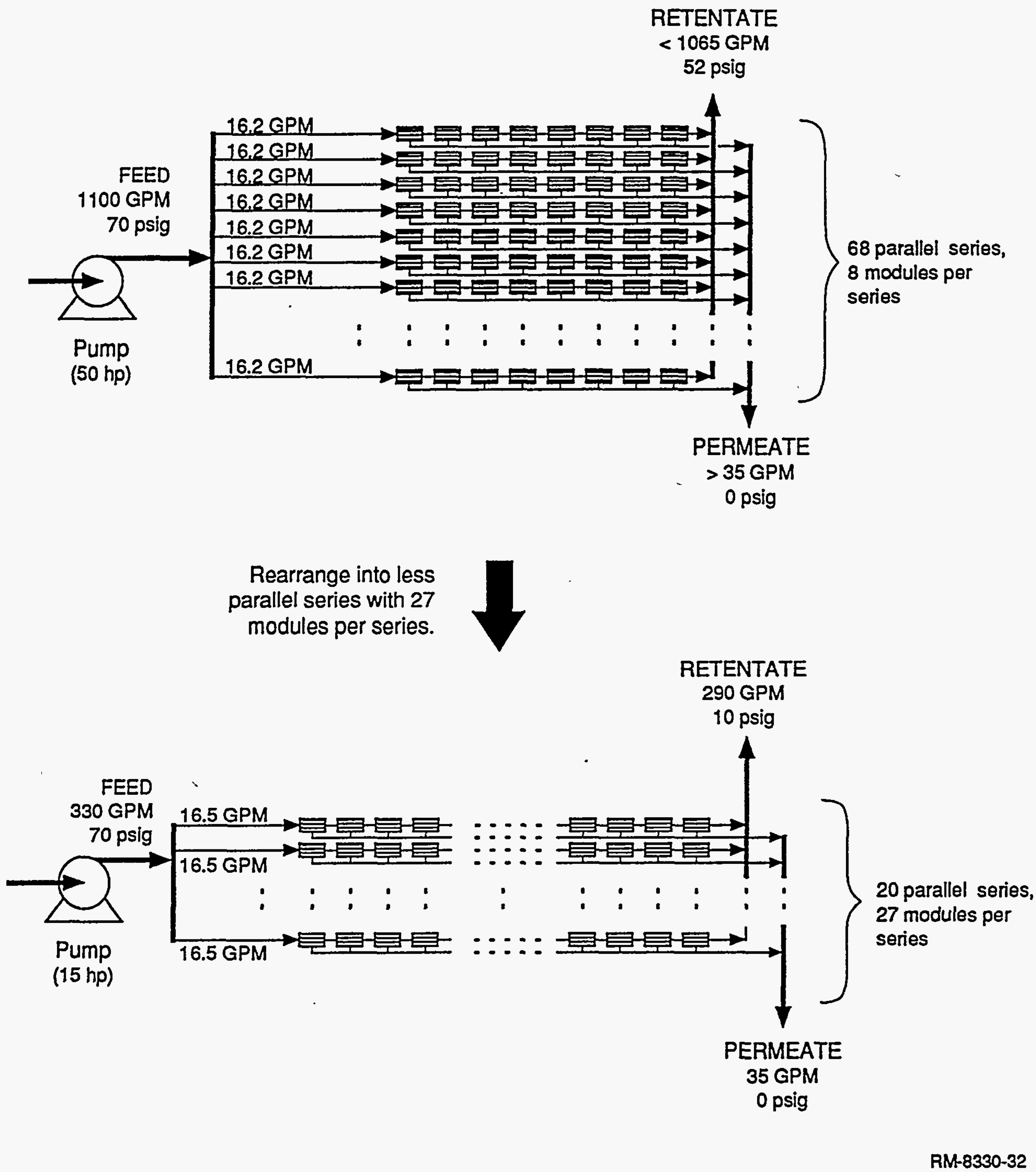

Figure 22. Piezo-enhanced UF operating as PRS.

Since reducing the feed flow rate lowers the pressure drop across each set of modules, more modules can be put in each series while still ending up with an exit pressure of 10 psig. Increasing the number of modules in each series reduces the number of parallel series required; a total of 544 membrane modules and a 15 hp pump are required.

module. Membrane installation costs are calculated by multiplying the purchase cost by 1.4. The cost of the electrical equipment needed to transform purchased electricity into the required voltage and frequency for the piezoelectric system is included in the membrane installation cost. Because membranes typically do not have a significant economy of scale, we use these costs no matter what the size of the installation. Pump costs are estimated using the algorithms of a commercial process simulator, ASPEN/SP (Simulation Sciences, Fullerton, CA). Operating costs include electricity, maintenance (labor and supplies), and miscellaneous fixed costs. A discounted cash flow analysis is performed on each configuration resulting in a permeate cost, PC ($/1000 gal permeate). Other key economic parameters are summarized in Table 3.

Table 4 shows the electricity requirements and capital costs for conventional UF, MRS, PRS, and the hybrid system. The conventional system has a total installed cost of $408,000 of which only 7% is due to the pump. Table 5 shows that the PC (which includes both capital and operating costs) is $14.54/1000 gal, of which 73% is due to capital charges and 12% is due to electricity used by the pump. Thus costs due to the pump account for less than 20% of the total costs, and reductions in the membrane costs will have the major effect on PC.

Of the three piezoelectric UF systems, MRS has the lowest PC, but it is still almost five times the PC of conventional UF ($66.57/1000 gal). This high cost is due in part to an increase in membrane capital cost since, although fewer modules are used, the cost per module is higher. The main cost, however — accounting for 65% of total costs — is for the electricity used to drive the piezoelectric elements. Since the pump costs are small in all the piezoelectric systems (<5% of total), PRS, which reduces pump size at the expense of membrane area, is most expensive of all the piezoelectric systems. The hybrid system, HYB, results in PC between those of MRS and PRS.

If the piezoelectric membranes could be made to use less power than the 7.1 kW/m^2 assumed in this analysis without sacrificing performance, the costs of the piezoelectric systems would go down significantly. Piezoelectric power consumption could be reduced by applying power to the disc periodically instead of continuously, by optimizing the power supply to be more energy efficient, or by using fewer piezoelectric drivers per unit of membrane area. To show the effect of piezoelectric power requirement, we calculated the PC with the piezoelectric power requirement ranging from our estimated value, 7.1 kW/m^2, to one-thousandth of that value. We are also interested in the sensitivity of permeate cost to membrane capital cost; we calculated permeate cost at our predicted piezoelectric module cost of $500/module (twice that of a conventional module), at $250/module (the cost of a piezoelectric module no higher than a conventional module), and at an intermediate cost ($375/module). Figure 16 shows the results of these calculations; to get the PC of piezoelectric UF below that of conventional UF, the power

Table 3
KEY ECONOMIC PARAMETERS
(Basis: 35 GPM Total Permeate Flow)

Capital Costs	
Conventional UF purchase cost	$250/module
Piezoelectric UF purchase cost	$500/module
Membrane installation cost	1.4 times purchase cost
Pump type	Centrifugal (170 rpm, cast steel)
General facilities services	15% of installed equipment cost
Operating Costs	
Membrane electricity requirement	4.9 kw per module
Electricity cost	$0.05/kwh
Maintenance costs:	
Supplies	2.0% of total installed cost
Labor	2.5% of total installed cost
Supervision	15% of labor
Benefits	35% of labor and supervision
General and administrative costs	20% of labor and supervision costs
Property taxes and insurance	2.5% total installed costs
Plant life	5 years
Depreciation schedule	Straight line over 5 years
Effective tax rate	40%
Return on capital investment	15%

Table 4
ELECTRICITY AND CAPITAL COSTS FOR THE UF SYSTEM USED FOR ELECTROCOAT PAINT
(Basis: 35 GPM Permeate Flow)

	Conventional UF	MRS	PRS	HYB
Conditions				
Feed flow (GPM)	2,200	1,520	330	783
Permeate flow (GPM)	35.4	35.4	35.4	35.4
Number of modules	544	376	544	452
Electricty Requirements (kw)				
Membrane electricity	0.0	1829.0	2645	2198
Pump electricity	71	51	14	28
Capital Costs ($1000)				
Membrane purchase cost	136	188	272	226
Membrane installed cost	326	451	653	542
Pump purchase cost	11	8	3	5
Pump installed cost	28	22	9	14
General services	53	71	99	83
Total Installed Cost	408	544	761	640

requirement must be at least a factor of 10 less than our estimated power requirement, and even then only if the piezoelectric membrane purchase cost is the same as that for a conventional membrane.

Because of the high energy requirements of the piezoelectric driver, this analysis shows little promise for the commercial use of piezo-enhanced ultrafiltration for electrocoat paint. Considering the small cost due to the pump in this application, any reductions in pumping requirements at the expense of membrane area are not advised. With lower power consumption or higher flux enhancements, or if piezo-enhancement proved to increase the length of time between cleanings, the system would be more attractive.

POTENTIAL FOR ENERGY SAVINGS

With the high power requirement of the piezoelectric system, there is no energy benefit to be gained by using piezo-enhanced UF. However, it is still interesting to estimate the pumping energy that can be saved if the piezoelectric power requirements could be reduced. Table 5 shows that the pumping electricity requirement can be reduced by over four-fifths (the PRS system compared with the conventional system) by using a piezo-enhanced membrane.

In terms of national energy savings, we estimate that more than 500 million BTUs (thermal energy equivalents) can be saved annually if an enhanced flux membrane could be developed which uses negligible power.* Further savings could be achieved by applying this technology to other UF applications, and the greatest potential savings are in applications where a fouling-resistant UF membrane could replace another process which utilizes a high-energy-consuming technology (such as evaporation).

* This estimate is based on the assumption that a typical automobile plant uses four UF trains of the size that have been discussed in this chapter, and that there are 100 such plants in the United States. Electrocoat paint manufacturers have stated that there are hundreds of electrocoat paint systems operating in various applications, from large automotive and other transport facilities, to appliance manufacturing, food and beverage containers.

Table 5
OPERATING AND PERMEATE COSTS FOR THE UF SYSTEM USED FOR ELECTROCOAT PAINT
(Basis: 35 GPM Permeate Flow)

	Conventional UF			MRS			PRS			HYB		
	($1000/yr)	($/kgal)	%	($1000/yr)	($/kgal)	%	($1000/yr)	($/kgal)	%	($1000/yr)	($/kgal)	%
Operating Costs:												
Pump electricity	28	1.70	12	20	1.21	2	5	0.32	0	11	0.67	1
Membrane electricity	0	0.00	0	722	43.54	65	1,044	62.99	67	868	52.33	67
Total maintenance labor	16	0.95	7	21	1.27	2	30	1.78	2	25	1.50	2
Maintenance supplies	8	0.49	3	11	0.66	1	15	0.92	1	13	0.77	1
General & administrative	2	0.14	1	3	0.19	0	4	0.26	0	4	0.22	0
Property tax	8	0.49	3	11	0.66	1	15	0.92	1	13	0.77	1
Property insurance	2	0.12	1	3	0.16	0	4	0.23	0	3	0.19	0
Total operating	65	3.90	27	791	47.69	72	1,118	67.42	72	936	56.46	72
Total capital (including tax)	176	10.64	73	313	18.89	28	438	26.44	28	368	22.20	28
Permeate cost	241	14.54	100	1,104	66.57	100	1,556	93.86	100	1,304	78.66	100

PIEZOELECTRICALLY AND MECHANICALLY ENHANCED ULTRAFILTRATION THROUGH TUBULAR MEMBRANES

Ultrafiltration experiments on dextran solutions were conducted through tubular membranes (identical to those used for electrocoat paint applications) by applying vibration to the membrane both by means of a piezoelectric and mechanical transducer. We used a ceramic PZT transducer that generates vibration at the frequency of 20 KHz, and a mechanical vibrator that works at the frequency of 60 Hz.

A 1.5% dextran solution was tested at the feed pressure of 50 psig and feed flow rate of 1.1 L/min. A tubular membrane (HFM-183, MWCO 20,000, Koch Membrane Systems, Inc.) 2.5-inch long and 0.5-inch in diameter was used for our initial experiments. The initial flux was 9.97 L/hr/m^2/atm. To assure complete fouling the filtration was run for several hours before trying to enhance the flux. A steady state flux of 2.03 L//hr/m^2/atm was reached. Two PZT transducers were then pressed on the wall of the tubular membrane to assure good transmission of vibration. When power was applied to the transducers, a moderate flux enhancement by a factor of 1.6 was observed. The flux increased from 2.03 L//hr/m^2/atm to 3.26 L//hr/m^2/atm. A similar flux enhancement was obtained when only one transducer was used. This modest flux enhancement can be explained by poor mechanical coupling between the transducer and the tubular membrane. Indeed, by applying less contact pressure the flux enhancement factor was lowered.

In a separate set of experiments we tested a mechanical vibrator instead of the piezodriver to enhance flux. We used a mechanical vibrator operating at the frequency 60 Hz and power of 9 W. A metal L-shaped tip was attached to the vibrator and connected to the tubular membrane via a stainless steel rod.

Initial experiments were conducted on a tube 2.5-inch long and 0.5-inch in diameter, as previously described. After reaching steady-state fouling conditions, the mechanical vibrator was turned on. The flux increased from 1.68 L/hr/m^2/atm to 4.03 L/hr/m^2/atm, or by a factor of 2.4. Reproducible flux enhancements were obtained, when the experiment was repeated. An additional experiment was conducted on a 14-inch long tube under similar conditions and using the same mechanical driver again the flux was enhanced by a factor of 2.3.

These preliminary data clearly indicate that the mechanical driver is a far more effective than the PZ driver in transmitting vibration to the tubular membrane. Because the two methods of applying vibration to the tubular membrane are quite different, we can not make any conclusive analysis of the effect of the frequency on the flux enhancement. However, we have shown that a frequency of 60 Hz is sufficient to generate a significant flux enhancement. Moreover, not only the flux enhancement is higher, but also the power consumption is significantly lower with the mechanical driver than with the piezodriver. According to our present data 0.63 kW/m^2 are effective in producing a flux enhancement higher than a factor of two for the ultrafiltration of dextran. The effect of the mechanical driver to enhance flux has not been optimized yet. Since a 9W driver produced the same flux enhancement on a 2.5-inch long tube as well as a 14-inch long tube, we might expect that even longer tubes can be operated with the 9W driver. Nonetheless using the present data, the power consumption of the mechanical driver is more than 10 times lower than that of the piezodriver. The possibility that the mechanically driven tubular ultrafiltration modules can use even lower power promises to make this process competitive on an economic basis in comparison with conventional processes.

A comparative economic analysis for electrocoat paint ultrafiltration and solvent recovery in deasphalting of oil is discussed in the next section. This analysis is preliminary and assumes that flux enhancements similar to those above can be obtained in both the electrocoat paint and deasphalted oil applications.

ECONOMIC EVALUATION OF MECHANICALLY-ENHANCED ULTRAFILTRATION

Table 6 shows the results of an evaluation of the economics and energy consumption for several cases of a mechanically vibrated UF system, in comparison with conventional technology and piezo-enhanced UF. The electrocoat paint application discussed previously and the deasphalting of oil (DAO) process described in the previous annual report (Narang, et al; 1991) are analyzed. For the mechanically vibrated UF systems the following parameter assumptions were used:

- The permeate flux is enhanced by a factor of two, as shown in the dextran experiment. (In one case, an hypothetical flux enhancement by a factor of four is analyzed.)
- The UF system is configured like the membrane reduction system (MRS) described in the previous chapter.
- The purchase cost for the mechanically vibrated membrane is 50% greater than for conventional UF membrane. This cost is less than that assumed for the piezoelectric UF membrane. We expect that mechanically vibrated membranes will require only minor changes in the module design, since the mechanical driver will be external to the membrane module.
- The power consumption is equal to that in our experiments with the 14 inch long tube, 0.63 kW/m^2. (In one case a lower power consumption, 0.063 kW/m2, is analyzed.)

Table 6
ECONOMIC AND ENERGY RESULTS FOR ULTRAFILTRATION WITH MECHANICAL VIBRATION

Electrocoat Paint

	Conventional UF	PZ (MRS)	Mechanical Vibration		
Flux enhancement factor		1.44	2.00	2.00	4.00
Membrane purchase multiplier*	1	2.00	1.50	1.50	1.50
Membrane power consumption (kw/m^2)	0	7.1	0.63	0.063	0.63
Thermal energy equivalent** (kwh/kgal)	101	2655	227	73	116
Capital cost ($1000)	408	544	311	311	159
Permeate cost ($/kgal)	14.54	66.57	13.91	11.02	7.11

Deasphalted Oil

	Evaporation	PZ UF	Mechanical Vibration		
Flux enhancement factor		8.00	2.00	2.00	4.00
Membrane purchase multiplier*		2.00	1.50	1.50	1.50
Membrane power consumption (kw/m^2)		0.0056	0.63	0.063	0.63
Thermal energy equivalent** (kwh/kgal)	1373	463	1936	598	1193
Capital cost ($1000)	4332	5078	7300	7300	5634
Permeate cost ($/kgal)	1.004	0.593	0.887	0.754	0.701

* The purchase cost for an enhanced membrane is the conventional membrane cost multiplied by the membrane purchase cost multiplier.

** Thermal energy equivalent is based on an electric power generation efficiency of 33% and a steam generation efficiency of 85%.

The results for the conventional technology and the piezoelectric UF cases with electrocoat paint are taken from Tables 4 and 5, and from the previous annual report (Narang, et al; 1991) for DAO.

For electrocoat paint, the mechanically vibrated UF system resulted in a lower cost than conventional UF ($13.91/kgal versus $14.54/kgal) when the conservative values of flux enhancement and power consumption are used. When the hypothetical flux enhancement by a factor of 4 and the lower power consumption are used, the economics are even more favorable for the mechanically vibrated UF system. In terms of energy consumption, however, only the low energy consumption case resulted in energy savings over conventional UF.

For the DAO application all the mechanically vibrated UF cases were economically favored over evaporation, the conventional technology. (The piezoelectric UF case had the lowest cost of all because of the high flux enhancement and low power consumption assumed in last year analysis.) However, as with electrocoat paint, only the case assuming a low power consumption resulted in significant energy savings over the conventional technology.

According to this analysis, a flux enhancement by a factor of two may be adequate for favorable economics with mechanically vibrated UF, however only with a power consumption less than that obtained in our initial experiments there will be an opportunity for energy savings. Considering that the same power source (9W) was used for both a 2-inch and 14-inch long tubes with the same enhancement factor, it is likely that further reductions in energy can be achieved.

REFERENCES

Brewer, G. E. F., "Electrodeposition of Paint," *Applied Polymer Science*, American Chemical Society, pp. 227-238 (1985).

Cheryan, M., *Ultrafiltration Handbook*, Technomic Publishing Company, Lancaster, PA (1986).

Narang, S. C., S. K. Sharma, S. Ventura, D. L. Roberts, N. Ahner, "Research and Development to Overcome Fouling of Membranes," First Annual Report, November 1990.

Porter, M. C., "Concentration Polarization with Membrane Ultrafiltration," *Ind. Eng. Chem. Prod. Res. Develop.*, Vol. 11, No. 3, pp. 234-247 (1972).

APPENDIX A

The pressure drop due to friction of an incompressible fluid is given by Bernoulli's Theorem (Equation 5-41; Perry, et al., 1984) which can be reduced to:

$$\Delta P = \rho \cdot F \qquad \text{(A-1)}$$

where,

ΔP = Pressure difference (Pa)

ρ = Fluid density (kg/cm^3)

F = Friction loss (N•m/kg)

The total pressure drop in the membrane system is a result of friction losses due to membrane tubes, pipes, bends, valves, and other fittings. The friction losses due to straight tubes (including membranes) and to fittings are given by the following equations (Equations 5-57 and 5-133; Perry, et al., 1984).

$$F_{tube} = \frac{4\,f\,L}{D}\frac{V^2}{2g_c} \qquad \text{(A-2)}$$

$$F_{fitting} = K \cdot \frac{V^2}{2g_c} \qquad \text{(A-3)}$$

where,

D = Tube diameter (m)

f = Friction factor (dimensionless)

g_c = Dimensional constant

K = Constant defined for every fitting type (dimensionless)

L = Tube length (m)

V = Fluid velocity (m/s)

The friction factor, f, for Reynolds Number between 3000 and 100,000 (including the electrocoat paint application) can be approximated (see Figures 6.2-2; Bird, et al., 1960) as follows:

$$f = 0.0791 \cdot Re^{-0.25} \qquad \text{(A-4)}$$

where,

Re = Reynolds Number (=DVρ/μ)

μ = Fluid viscosity (Pa•s)

Combining Equations A-1 through A-4 gives an expression for total ΔP:

$$\Delta P = \left(\frac{0.0791 \cdot \mu^{.25}}{D^{.25} \rho^{.25}}\right)\left(\frac{4L\rho}{D\,2g_c}\right)V^{1.75} + \left(\frac{\rho K}{2g_c}\right)V^2 \quad \text{(A-5)}$$

For a specific UF system the only variable in Equation A-5 is the fluid velocity, V, thus ΔP is proportional to the velocity raised to a power between 1.75 and 2.0. In our pressure drop calculations we used 1.75.