



Porous cylindrical media as supports for reverse osmosis desalination membranes
by Darrel Eugene Coverdell

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY in Chemical Engineering
Montana State University
© Copyright by Darrel Eugene Coverdell (1969)

Abstract:

With the development of high flux, high salt rejection cellulose acetate membranes, reverse osmosis has become one of the important methods being considered for desalination. It combines flexibility and simplicity with thermodynamic efficiency. Good membrane performance at a high membrane density is important if reverse osmosis is to be successful. Using small diameter cylindrical porous media as supports for cellulose acetate membranes offers a solution to this problem.

Two membrane casting techniques and five different types of cylindrical porous media were investigated. The effects of support type, casting technique, casting solution, and various casting variables on membrane performance were studied. Membrane life investigations were also made.

Fluxes of 10-11 GSFD at 95% salt rejection were obtained when dip casting on ceramic supports using a casting solution containing 14.9% Eastman 400-25 cellulose acetate, 21.3% formamide, and 63.8% acetone. A 5-second solvent evaporating time and an 86°C heat treatment were used. For dip casting, acetone concentration ranges were established: for E398-3 cellulose acetate, 54-59% acetone; for e400-25, 60-65% acetone; and for E394-60, 63-68% acetone. A cellulose acetate-formamide ratio of 7:10 was used in all cases. Viscosities in the dip casting range vary from ~900 centipoise to ~3500 centipoise.

Fluxes of 16-18 GSFD at 93% salt rejection were obtained for extruded membranes on ceramic supports using a casting solution containing 14.9% Eastman 394-60 cellulose acetate, 21.3% formamide, and 63.8% acetone. A 5-second solvent evaporating time and an 86°C heat treatment were used. Extruded membranes always gave fluxes of 1.4 to 2.2 times those of similar dip cast membranes.

Porous ceramic, porous polyethylene, and porous polyvinylidene fluoride supports were the most promising. A membrane performance of 17 GSFD at 93% salt rejection was obtained on the ceramic; 11 GSFD at 92% salt rejection on the polyethylene, and 7.7 GSFD at 93% salt rejection on the polyvinylidene fluoride.

Support length and support diameter did not appear to affect membrane performance; however, support permeability does limit the length of porous rod that can be used. Use of tubular porous media is suggested.

Water flux declined about 15% during the first hours of operation, but remained constant thereafter provided the membrane surface remained clean. Salt rejection declined slightly during long runs.

POROUS CYLINDRICAL MEDIA AS SUPPORTS
FOR
REVERSE OSMOSIS DESALINATION MEMBRANES

by

DARREL EUGENE COVERDELL

A thesis submitted to the Graduate Faculty in partial
fulfillment of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

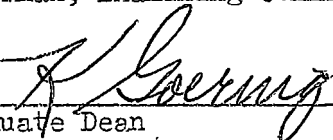
in

Chemical Engineering

Approved:


Head, Major Department


Chairman, Examining Committee


Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

August, 1969

ACKNOWLEDGMENT

The author wishes to thank the entire staff of the Chemical Engineering Department of Montana State University, and in particular, Dr. Robert Nickelson who directed the research, for their suggestions which led to the completion of the project. Thanks are also due to other faculty members at Montana State University who have served on his graduate committee.

Financial support from the Office of Saline Water and from a National Defense Education Act (NDEA) Fellowship has been very useful and is greatly appreciated.

The help and encouragement of his parents, Mr. and Mrs. Floyd Coverdell, and his wife, Loretta, are also gratefully acknowledged.

TABLE OF CONTENTS

	Page
Abstract	x
I. Introduction	1
II. Equipment and Procedure	12
A. Membrane Fabrication Techniques	12
B. Membrane Test System.	15
C. Test Procedure.	16
III. Casting Membranes on Porous Rods and Tubes	19
A. Dilute Solutions on Flat Supports	20
B. Studies on Dip Casting	24
Effect of Casting Solution Composition	24
Effect of Solvent Evaporating Time	27
Effect of Heat Treatment Temperature	29
Effect of Cellulose Acetate Type	31
Use of Warm Casting Solutions	34
C. Studies of Extrusion Casting	35
Effect of Casting Solution Composition.	35
Effect of Cellulose Acetate Type	37
D. Comparison of Dip and Extrusion Casting	37
IV. Evaluation of Support Materials	43
A. Initial Screening of Supports	43
B. Membrane Performance on Various Supports	45
Effect of Support Type on the Perform-	
ance of Dip Cast Membranes	45
Effect of Cellulose Acetate Type When	
Dip Casting on Various Supports	49
Effect of Support Type on the Perform-	
ance of Extruded Membranes	51
Re-use of Supports	53
V. Consideration of Support Properties	55
A. Support Permeability.	55
B. Support Diameter	57
C. Support Length	60
VI. Studies of Membrane Life	61

TABLE OF CONTENTS (continued)

	Page
VII. Economic Considerations	65
VIII. Conclusions	68
IX. Recommendations	70
X. Appendix	71
XI. Literature Cited	126

LIST OF TABLES

Table		Page
I	Effect of Cellulose Acetate Type on the Performance of Extruded Membranes.	38
II	Effect of Polyvinylidene Fluoride Support Condition on Membrane Performance.	48
III	Performance of Membrane Dip Cast on Various Supports Using Various Cellulose Acetate Types . . .	50
IV	Performance of Extruded and Dip Cast Membranes on Various Supports	52
V	Economic Estimations	67
VI	Summary of Casting Solutions	76
VII	Summary of Support Properties	77
VIII	Performance of Membranes Cast on Versapor Using Dilute Solutions	78
IX	Effect of Casting Solution Composition and Solvent Evaporating Time on Dip Cast Membranes.	79
X	Effect of Heat Treatment Temperature on the Performance of Dip Cast Membranes.	81
XI	Effect of Cellulose Acetate Type and Acetone Concentration on the Performance of Dip Cast Membranes.	83
XII	Comparison of Casting Solutions for Extrusion Casting	85
XIII	Comparison of the Performance of Extruded and Dip Cast Membranes	86
XIV	Effect of Solvent Evaporating Time on Dip Cast and Extruded Membranes	88

LIST OF TABLES (continued)

Table		Page
XV	Effect of Cellulose Acetate Type on the Performance of Extruded Membranes.	89
XVI	Comparison of Performance of Membranes Dip on Various Supports	91
XVII	Comparison of Membrane Performance for Membranes Dip Cast on Various Supports Using Various Types of Cellulose Acetate	93
XVIII	Comparison of Extruded and Dip Cast Membranes for Various Supports and Various Cellulose Acetate Types	95
XIX	Permeability Data for Porous Supports	97
XX	Pressure Drop as a Function of Length for Various Supports	100
XXI	Effect of Rod Diameter on Membrane Performance	101
XXII	Effect of Support Length on Membrane Performance	102
XXIII	Summary of Results for Membranes Cast on 0.9 micron Versapor Supports	103
XXIV	Results for Membranes Cast on 0.5 micron Porous Tubular Stainless Steel Supports.	106
XXV	Summary of Results for Membranes Cast on Norton RA-5021 Ceramic Tubes	107
XXVI	Summary of Results for Membranes Cast on Norton RA-4021 Ceramic Rods.	108
XXVII	Summary of Results for Membranes Cast on Porous Polyethylene Rods.	119
XXVIII	Summary of Results for Membranes Cast on Porous Polyvinylidene Fluoride Supports.	122

LIST OF FIGURES

Figure		Page
1.	Osmosis Phenomena	3
2.	Casting Techniques.	13
3.	Performance of Membranes Cast on Versapor Using Dilute Casting Solutions.	23
4.	Effect of Casting Solution Composition on the Performance of Dip Cast Membranes	26
5.	Effect of Solvent Evaporating Time on the Performance of Dip Cast Membranes When Using Different Casting Solutions.	28
6.	Effect of Heat Treatment Temperature on the Performance of Dip Cast Membranes	30
7.	Effect of Cellulose Acetate on the Perform- ance of Dip Cast Membranes	32
8.	Effect of Casting Solution Composition on the Performance of Extruded Membranes	36
9.	Comparison of Dip Cast and Extruded Mem- branes for Various Heat Treatment Tem- peratures.	40
10.	Comparison of Dip Cast and Extruded Mem- branes for Various Solvent Evaporating Times	41
11.	Effect of Support Type on the Performance of Dip Cast Membranes.	46
12.	Pressure Drop as a Function of Length for Various Supports	56
13.	Effect of Support Diameter on the Perform- ance of Dip Cast Membranes	59
14.	Lifetime Studies of Dip Cast Membranes	62

LIST OF FIGURES (continued)

Figure	Page
15. Lifetime Studies of Extruded Membranes	63
16. Flow Diagram of Test Equipment.	72
17. Flat Test Cell	73
18. Tubular Test Cell	74
19. Conductivity Cell Calibration	75
20. Permeability Data for Various Supports	98

ABSTRACT

With the development of high flux, high salt rejection cellulose acetate membranes, reverse osmosis has become one of the important methods being considered for desalination. It combines flexibility and simplicity with thermodynamic efficiency. Good membrane performance at a high membrane density is important if reverse osmosis is to be successful. Using small diameter cylindrical porous media as supports for cellulose acetate membranes offers a solution to this problem.

Two membrane casting techniques and five different types of cylindrical porous media were investigated. The effects of support type, casting technique, casting solution, and various casting variables on membrane performance were studied. Membrane life investigations were also made.

Fluxes of 10-11 GSFD at 95% salt rejection were obtained when dip casting on ceramic supports using a casting solution containing 14.9% Eastman 400-25 cellulose acetate, 21.3% formamide, and 63.8% acetone. A 5-second solvent evaporating time and an 86°C heat treatment were used. For dip casting, acetone concentration ranges were established: for E398-3 cellulose acetate, 54-59% acetone; for E400-25, 60-65% acetone; and for E394-60, 63-68% acetone. A cellulose acetate-formamide ratio of 7:10 was used in all cases. Viscosities in the dip casting range vary from ~900 centipoise to ~3500 centipoise.

Fluxes of 16-18 GSFD at 93% salt rejection were obtained for extruded membranes on ceramic supports using a casting solution containing 14.9% Eastman 394-60 cellulose acetate, 21.3% formamide, and 63.8% acetone. A 5-second solvent evaporating time and an 86°C heat treatment were used. Extruded membranes always gave fluxes of 1.4 to 2.2 times those of similar dip cast membranes.

Porous ceramic, porous polyethylene, and porous polyvinylidene fluoride supports were the most promising. A membrane performance of 17 GSFD at 93% salt rejection was obtained on the ceramic; 11 GSFD at 92% salt rejection on the polyethylene, and 7.7 GSFD at 93% salt rejection on the polyvinylidene fluoride.

Support length and support diameter did not appear to affect membrane performance; however, support permeability does limit the length of porous rod that can be used. Use of tubular porous media is suggested.

Water flux declined about 15% during the first hours of operation, but remained constant thereafter provided the membrane surface remained clean. Salt rejection declined slightly during long runs.

I. INTRODUCTION

The world's need for fresh water is increasing at a very rapid rate -- a rate which will soon outstrip new supplies of fresh water in many areas. Finding new sources of good quality water at a reasonable cost is becoming a major problem.

Natural sources of water (wells, rivers, etc.) may currently be tapped at a cost of between 13 and 70¢ per thousand gallons (8). It is doubtful that new technology or equipment will be able to lower this cost or increase the natural supplies. On the basis of the high cost and unavailability of new natural fresh water supplies, it seems likely that soon it will be necessary to tap the world's vast quantities of brackish and sea water. This is especially true in the more arid areas such as the Middle East or the highly populated areas such as Southern California.

Until recently, thermal distillation was the only technique that had been developed for desalting water; however, because of the increased interest in desalted water, a number of new techniques are being developed. Commercial possibilities and research under the direction of the United States Office of Saline Water have enhanced the rapid development of these techniques. The more important processes for desalination now include: multistage flash distillation, falling film distillation, vapor compression distillation, electrodialysis (brackish water only), direct freezing, and reverse osmosis.

Distillation techniques are the most advanced. Using present day technology, costs of 80¢ to \$1.10 per thousand gallons of fresh water for small multistage flash evaporation plants have been reported. For large plants (50 million gallons per day or more), this cost would be lowered to 20 to 40¢ per thousand gallons (8). Electrodialysis and reverse osmosis are also becoming important processes and costs are approaching those of distillation; especially in the area of brackish water desalting. Costs of 75.5¢ per thousand gallons have been estimated for a one million gallons per day reverse osmosis plant (2).

The principle of reverse osmosis is quite simple. Figure 1 illustrates osmosis processes. In ordinary osmosis, the pure water will pass through the membrane into the brine so as to dilute the brine solution (Figure 1-a). No flow occurs at osmotic equilibrium (Figure 1-b); however, the flow of pure water may be reversed (Figure 1-c) by applying a pressure greater than the osmotic pressure (osmotic pressure 1.15 psi for each 100 ppm NaCl) on the brine. This is called reverse osmosis.

Several inherent advantages exist for the reverse osmosis process. First, large energy requirements are not required as in the distillation techniques. Reid (17) reported that the minimum theoretical energy required for desalting sea water is 2.63 Kw-Hr per thousand gallons. Distillation techniques require up to 6 times this amount (23) while reverse osmosis approaches this minimum energy requirement.

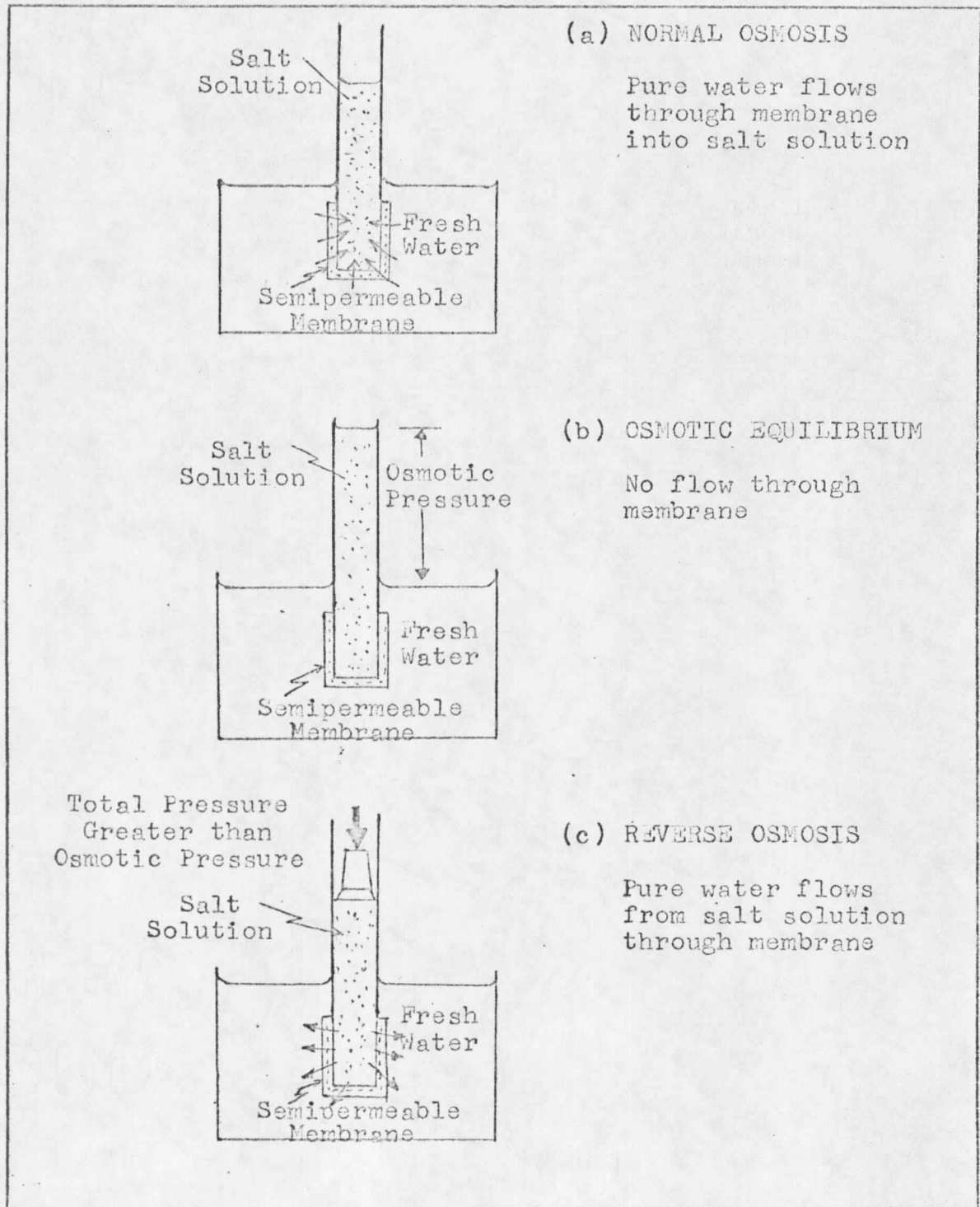


Figure 1. Osmosis Phenomena

Secondly, reverse osmosis operates at ambient temperatures which tends to lessen corrosion. Scaling problems are also virtually non-existent when compared to distillation techniques.

Another advantage is the simplicity of the reverse osmosis process and its equipment. The process is essentially an ultra-filtration of salt from the brine. The equipment consists of only two major items: a pump capable of pumping the brine to high pressures (600-800 psi for brackish water and 1200-1500 psi for sea water) and a membrane module in which the reverse osmosis process operates. The most important part is, of course, the membrane and the module in which it is mounted.

Membranes have improved considerably since Breton (3) first reported in 1957 that cellulose acetates act as semi-permeable membranes for sodium chloride solutions. Almost all other polymers have been tested as reverse osmosis membranes. Other reverse osmosis systems have also been fabricated from materials such as graphitic oxide (9), porous glass (11), and clay-like compounds. Many of these other polymers and systems do possess the ability to act as semipermeable membranes, but none possess the better desalination qualities of the cellulose acetate membranes.

The performance of cellulose acetate membranes has improved considerably. In 1958, Reid and Breton (18) obtained membranes 6 microns thick which produced a water flux of .945 GSFD (gallons per square foot

per day) and a salt rejection of 95%. Loeb and Sourirajan (14) obtained fluxes of 1.265 GSFD and 99% salt rejection in 1961 by shrinking commercially available cellulose acetate filters which were 100 microns thick. As a result of their experience and an article by Mlle Dobry (7) which suggested the use of magnesium perchlorate as a solvent in the preparation of ultrafiltration membranes, Loeb and Sourirajan developed a membrane with a flux of 5.4 GSFD and 99.8% salt rejection. A casting solution containing acetone, magnesium perchlorate, water, and acetone in the ratio 22.2-1.1-10.0-66.7 wt. percent was typical for preparing these membranes. They also found that it was necessary to strictly control the fabrication steps in order to obtain good results.

More recently, in 1964, Manjikian, Loeb, and McCutchan (15) prepared casting solutions which contained non-electrolytes. A ternary casting solution of cellulose acetate, formamide, and acetone was found to produce good membranes. Membranes from this casting solution gave fluxes of 20 GSFD and salt rejections of 95%. Today this type of cellulose acetate membrane is the most widely used.

Electron microscopy studies of the high flux cellulose acetate membranes have shown that they consist of two definite layers. The top layer is a dense, very thin layer often referred to as the "active" layer. It comprises between 1 and 10% of the total membrane thickness and is on the order of .1 to .25 microns in thickness. This layer (on

the air-dried side of the membrane) is that portion of the membrane which acts as the semipermeable barrier. The remainder of the membrane is an amorphous porous substructure estimated to have a pore size of between .1 and .4 microns (19).

Many theories have been proposed for the mechanism of water transport through the membrane. Breton (3) proposed that water was transported through the membrane via alignment-type diffusion while some salt and additional water was transported via hole-type diffusion with no desalting. Sourirajan (22) proposed that a thin film of pure water exists at the liquid-membrane interface. For pores with diameters of greater than twice the film thickness, both pure water and saline water will flow. Through the smaller pores, only pure water will pass. Using these criteria, Blunk (1) postulated the following mechanism: "Water is retained in the osmotic skin part of the membrane in such a way that it still possesses the solubilizing properties attributable to its hydrogen bonding capacity, but has largely lost the solubilizing properties attributable to its high dielectric constant. Therefore, small species whose solubilities in water are due partially (hydrogen-bonding univalent ions) or wholly (nonelectrolytes) to their hydrogen-bonding capacities, tend to pass through the membrane. On the other hand, small species whose water solubilities are due primarily to the high dielectric constant of water tend to be rejected. Those species include non-hydrogen-bonding univalent ions, and all ions of valence greater than unity re-

ardless of hydrogen-bonding characteristics." (1)

The development of high flux membranes has presented an additional problem. For high flux membranes, a polarization effect due to a salt concentration buildup at the brine membrane interface becomes an important factor. This concentration buildup lowers the water flux (the effective driving pressure is lowered because of a higher osmotic pressure at the membrane surface) and increases the salt flux (the salt gradient increases). Brian (17), using a thin film model for turbulent flow, gave the following equation to describe the polarization effect:

$$\frac{C'}{C^b} = \frac{\exp \left[\left(\frac{v'}{j_D \bar{U}} \right)^{N_{Sc} \frac{2}{3}} \right]}{r + (1-r) \exp \left[\left(\frac{v'}{j_D \bar{U}} \right)^{N_{Sc} \frac{2}{3}} \right]}$$

where

C' = salt concentration at the membrane interface, g/cm³

C^b = salt concentration in bulk solution, g/cm³

v' = product water flow velocity through the membrane, cm/sec

j_D = Chilton-Coburn mass transfer j-factor

$\bar{U}$ = average velocity over the cell, cm/sec

N_{Sc} = Schmidt number for salt diffusion; kinematic viscosity of solution, (cm²/sec)/molecular-diffusion coefficient in salt, (cm²/sec)

r = salt rejection

This equation shows that the polarization effect is a strong function of desalinized water flux and feed velocity. Therefore, in the case of high flux, high salt rejection membranes, it is necessary to maintain a high brine flow rate past the membrane (turbulent flow) to prevent the polarization effect, thus keeping C'/C^b near unity.

Two other basic problems also exist with reverse osmosis systems. First, the pressures exerted on the membrane are quite high (600-800 psi for brackish water and even higher for sea water). The membranes described thus far are not capable of handling such pressures without additional support. Secondly, even though membrane performance has improved considerably, the desalinized water fluxes are still relatively low. This necessitates a reverse osmosis system to be designed so that a high membrane area per unit volume exists.

Several approaches have been used to solve these problems. An additional approach is being proposed by the author.

One of the first methods used was to mount the membranes in a porous tube (6). The porous tube would act as a support for the membrane. The brine would flow within the tube and the product would exit through the porous walls. Such membranes possess sufficient strength; but because larger diameter porous tubes are used, the membrane density is somewhat low. Also, the cost of mounting the membranes is relatively high. Recent advances in dynamically casting the membranes have given

more promise to this approach. Pilot plants of up to 5000 gallons per day have been successfully tested using the tubular design (6).

A second method is that of spirally winding the membranes to form a tubular module (5). Brine and a porous matrix alternate between membrane layers. The product water exits through the matrix material. Sealing problems, a telescoping effect, and finding a suitable matrix material are major problems. Despite these problems, pilot plants of up to 10,000 gallons per day have been successfully tested (5).

Another technique is that of mounting flat membranes in a "filter press type" arrangement (5). Again, spacers for brine and product flow alternate between membranes. Good membrane densities are obtained, but flow distributions, mounting of the membranes, and the large number of seals required are major disadvantages. Pilot plants of up to 50,000 gallons per day have been tested using this approach.

A fourth technique is that of using hollow fiber membranes (16). These are mounted in a shell and tube design with the brine flowing on the shell side and the product exiting through the hollow fibers. A system of this type produces a very high membrane density; however, because no membrane support exists, the fibers are thick-walled, resulting in low fluxes (< 1 GSF/D and generally on the order of .1 to .2 GSF/D). This system is one of the more promising as the equipment is simple and easily assembled and low brine flow rates may be used (low

fluxes, therefore no polarization problem); however, clogging is often a problem on the brine side because of the very small interstitial spaces between fibers. Up till now, fibers have not been successfully constructed of cellulose acetate. The polymers currently used for the fibers do act as barriers for many ions, but they are only imperfect barriers for Na^+ and Cl^- ions. This is the major disadvantage of this design. The development of membrane fibers which would act as Na^+ and Cl^- barriers would certainly make this approach more appealing.

The alternative approach being proposed by the author is one in which high flux cellulose acetate membranes are cast on the outer surface of small diameter porous rods or tubes. A shell and tube design would be used to mount the membranes. Such a system would be simple and would provide a high density of high flux cellulose acetate membranes. Also, the clogging problems encountered with the hollow fiber system would be substantially reduced due to a larger diameter tube and the resulting larger interstitial spaces.

Therefore, the object of the author's thesis is to determine the feasibility of casting reverse osmosis desalination membranes on small diameter porous tubular media as an alternative design for reverse osmosis systems. This includes the determination of casting conditions for casting membranes on porous tubular media, making performance tests on various porous media, studying important design factors, and briefly considering economic aspects.

Prior research considering the casting of membranes directly on porous substrates has been performed at Montana State University by Donald Wang (24). He cast cellulose acetate membranes upon a number of porous substrates, but found that an epoxy filled fiber glass material (Gelman Versapor filter material) proved most useful. Fluxes of 21 GSFD and 95% salt rejection were obtained for membranes cast on this material. These membranes were cast from a cellulose acetate - formamide - acetone (21.9, 31.2, and 46.9 weight percent, respectively) casting solution using a 5-second solvent evaporating time and a heat treatment at 85°C. Later work by Lai (10) showed that other porous materials also have promise as supports. Polyvinyl chloride was most promising. A flux of 21.3 GSFD and 97.3% salt rejection was obtained for membranes cast on this support. Casting conditions were the same as those used by Wang. The work of Wang and Lai has been used as a basis for this author's work.

II. EQUIPMENT AND PROCEDURE

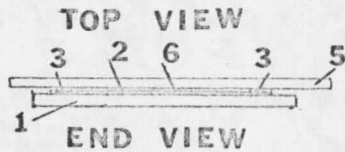
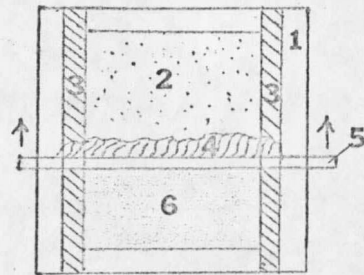
A. Membrane Fabrication Techniques

Three different techniques were used for preparing membranes. The first of these was spreading the casting solution on flat porous media using a doctor blade. The other two techniques, used on porous cylindrical rods and tubes, were dip casting and extrusion. Figure 2, page 13, illustrates these techniques.

Membranes cast on the flat porous media were prepared in a constant temperature (70°F) and constant humidity (50% relative humidity) chamber. Casting was done on small glass plates using masking tape for clearance (about .005" clearance per layer of masking tape) and a smooth glass rod as a doctor blade. After spreading the cellulose acetate - formamide - acetone casting solution on the porous support, a measured solvent evaporating time was allowed. The membranes were then placed in cold (<10°C) water for at least one hour for gelation. The membranes were annealed (heat treated) in hot water for four minutes at a desired temperature (usually between 75 and 90°C). Circular sections 2-1/2 inches in diameter were cut from the membrane for testing.

In dip and extrusion casting, 4-inch lengths of porous tubes or rods were used. Epoxy cement was used to seal one end of the tubes with the other end being left open for product flow. About one inch of the porous rods and tubes at the product end was sealed prior to casting,

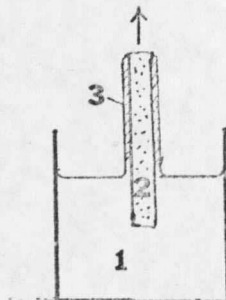
1. SPREAD CASTING ON FLAT SUPPORT



- 1. GLASS PLATE
- 2. POROUS SUPPORT
- 3. MASKING TAPE
- 4. CASTING SOLUTION
- 5. GLASS ROD
- 6. MEMBRANE

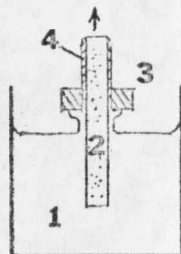


2. DIP CASTING



- 1. CASTING SOLUTION
- 2. POROUS ROD OR TUBE
- 3. MEMBRANE

3. EXTRUSION



- 1. CASTING SOLUTION
- 2. POROUS ROD OR TUBE
- 3. EXTRUSION DIE
- 4. MEMBRANE

Figure 2. Casting Techniques

using a silastic sealant. This was done for mounting purposes and to insure uniform flow past the tube length being tested. The porous rods and tubes were saturated with water to prevent air bubbles from escaping from the pores of the support during casting. Such bubbles often caused leaks when complete saturation was not obtained.

Dip casting was performed by dipping the rods and tubes into the casting solution, withdrawing the rod from the casting solution at a nearly constant, relatively rapid rate ($\cong 2$ inches per second), allowing a measured solvent evaporating time, and then placing the membrane in cold water for gelation. Casting was done at room conditions (approximately 75°F and variable humidity). All membranes with rods or tubes as supports were annealed by immersing the membrane-coated rod in water at 60°C, heating the water at 5-6° per minute to a desired temperature, and leaving it at that temperature for four minutes.

Extrusion casting on the porous rods and tubes differed from dip casting only in that a die was dropped over the rod as the rod was withdrawn from the casting solution. A clearance of .010 inches was allowed between the rod and the die.

All membranes were stored in water when not being tested.

B. Membrane Test System

A flow diagram of the test equipment is shown on Figure 16, page 72. The system consisted of a 10-liter brine tank, a pump (Jaeco Model 753 S-8), and two parallel test lines, each containing one or more test cells and a back pressure regulator. The test lines could be operated both at the same time or independently, as needed. All equipment was of plastic or stainless steel material to eliminate corrosion. A high pressure filter was used in some runs to maintain a clean system; however, it was found that frequent changing of the brine was more expedient.

High pressure nitrogen was used as back pressure against the circulating brine. The pump and brine circulation caused an increase in brine temperature. A cooling coil using cold tap water was used to maintain the brine temperature in the tank at $24 \pm .5^{\circ}\text{C}$. Brine temperature at the membrane was $25 \pm .5^{\circ}\text{C}$.

Two types of test cells were used; one for flat membranes, another for membranes cast on cylindrical porous media. The flat test cell (See Figure 17, page 73) consisted of two 304 stainless steel flanges, 4-1/2 inches in diameter, which were machined to desired dimensions. The upper flange contained a 2-inch diameter space for brine flow. This space tapered from 1/8-inch deep at the outer edge to 1/16-inch deep at the center to obtain an even flow distribution across the test cell.

The lower flange contained a 1/8-inch thick, 2-1/2-inch diameter porous (5-micron pore size) stainless steel plate upon which the membrane was supported. Product water passed through the porous support and exited through a 1/4-inch male Swagelok connector fitting. Eight 1/4-inch bolts and a neoprene gasket were used to seal the test cell.

The second type of test cell (Figure 18, page 74) consisted of a 1/2-inch diameter stainless steel tube with a Swagelok heat exchanger tee and a reducing union at the ends. In this case, the membranes were sealed into the heat exchanger fitting using General Electric RTV silastic sealant, a Swagelok front ferrule, and a fabricated reducing nut. See Figure 18 for details of the method used to seal membranes into the test cell. A 12-hour curing time was allowed for the silastic sealant. During this time it was necessary to keep the silastic area dry while maintaining the membrane section wet. Cell assembly consisted only of attaching the heat exchanger fitting containing the membrane to the test tube. The brine flowed on the outside of the membrane-coated porous rod and the product water exited by flowing lengthwise through the porous rod.

C. Test Procedure

After a membrane had been mounted in a test cell, the test cell was attached to a test loop. The brine was then circulated past the membrane at a gradually increasing pressure until the desired operating

pressure was reached. This was 800 psi for most runs. A 10,000 ppm (1%) NaCl brine solution prepared from deionized water and reagent grade NaCl was used in all runs.

Flow past the membrane was 8.7 cm/sec for the flat membrane and varied between 13.6 cm/sec and 43.8 cm/sec for the cylindrical membranes. The variation in the cylindrical membranes was due to the use of various diameter porous rods as supports. Performance was not affected by the variation in brine flow for the above velocity range. Also, membrane performance was not noticeably affected by pressure and flow surges from the reciprocating pump. Using a surge tank (50 feet of 1/4-inch diameter tube), the pressure surge could be lowered to 20 psi from 100 psi.

Product water rates and product water conductivity (resistance) were measured at 1/2, 2, 4, and 6 hours. During the first hours of operation, a flux decline occurs and the salt rejection increases slightly. By 6 hours, product flux and salt rejection are nearly constant. Except where noted, the data reported is that at the end of 6 hours.

Salt concentrations were measured using a conductivity bridge and two conductivity cells. These cells were calibrated and checked periodically using known brine samples. Conductivity cell #1 was used for determining product water NaCl concentration and conductivity cell #2 was used for determining brine concentrations. The calibration curve for

cell #1 showing a temperature dependence is shown in Figure 19, page 75.

Casting solution viscosities were determined using a falling ball viscometer, which was calibrated using glycerin at 0°C and 25°C. The viscometer could be used for only the more dilute casting solutions such as those used for dip casting. The accuracy of the viscometer was somewhat limited when using any of the casting solutions, but it did provide a good approximation for the viscosities of the various casting solutions.

III. CASTING MEMBRANES ON POROUS TUBES AND RODS

The use of porous tubes or rods as direct supports for reverse osmosis desalination membranes necessitates careful consideration of the membrane casting processes involved. Because the life of cellulose acetate membranes is relatively short (approximately 6 months to 1 year (17)), it is necessary that membranes be replaced periodically. Where direct membrane supports are used, two alternatives are open at the time of membrane replacement. Either the support may be discarded or the support may be reused. Expensive supports must be reused if they are to be justified economically. Cheap supports could possibly be discarded after use.

In consideration of the above alternatives, two casting techniques have been proposed by the author. Where supports must be reused, dip casting (at least for casting membranes on used supports) is suggested. A two-step process would be necessary for reusing supports. First, the old membrane must be removed by dissolution and then a new membrane would be dip cast upon the support. In the case where the porous media may be discarded or as a first membrane upon the porous media, extrusion is perhaps the best casting technique.

The more important casting variables for both dip casting and extrusion have been studied. These variables included casting solution composition, solvent evaporating time, and heat treatment temperature.

Other factors such as support type, support diameter, support permeability, support length, and membrane life have also been considered.

A. Dilute Solutions on Flat Supports

The casting solutions used by Wang (24) and Lai (10) for casting on flat supports are much too viscous for dip casting. Only a thick "glob" occurs when a support is dipped into this solution. This necessitated the development of a more dilute, less viscous casting solution.

For a number of membranes, Wang (24) used more dilute casting solutions. He obtained less viscous casting solutions by reducing the cellulose acetate content while maintaining the same formamide:acetone ratio. Membranes cast on Gelman 0.9 micron Versapor porous media using these dilute solutions gave poorer results. Lai (10) found similar results when using other porous media. In both cases, the dilute, lower viscosity casting solutions had a high formamide:cellulose acetate ratio. This perhaps caused the poorer membrane performance. By maintaining a constant cellulose acetate:formamide ratio and lowering the solution's viscosity by increasing the acetone concentration, one may possibly obtain membranes of good performance from dilute casting solutions. A series of membranes cast on flat 0.9 micron Versapor porous material were prepared from a dilute solution to check this approach.

First, the casting technique of Wang (24) was checked and his results using a viscous casting solution reproduced (see Runs V-5 to V-11,

Table XXIII, page 103). This casting solution (Casting Solution A)* contained 21.9% Eastman 400-25 cellulose acetate, 31.2% formamide, and 46.9% acetone. Spread Casting (see Figure 2, page 13) using a 5-second solvent evaporating time and an 85°C heat treatment temperature was used. A less viscous (thin enough to be dip cast) casting solution (Casting Solution B) was then prepared using 14.9% Eastman 400-25 cellulose acetate, 21.3% formamide, and 63.8% acetone. This casting solution's viscosity was approximately 3150 centipoise.

Preliminary membranes indicated that an increased clearance was needed when using Casting Solution B. Increasing the casting clearance to .010 inches from .005 inches eliminated imperfections in the membranes and thus improved salt rejection. The imperfections were due to flow of the casting solution into the pores of the support and to the slight roughness of the support.

Because of the increased acetone (solvent) concentration, the solvent evaporating time was thought to be a most important variable when using dilute solutions. A series of membranes were prepared from Casting Solution B on 0.9 micron Versapor supports using several different solvent evaporating times: 5, 10, 20, 30, and 60 seconds. A heat treatment temperature of 86°C was used in annealing the membranes.

* All casting solutions used are designated by an alphabetic letter. See Table VI, page 76, for a complete list of the compositions and the viscosities of all casting solutions.

Figure 3 on the following page shows the performance* of these membranes as a function of the solvent evaporating time. Water flux decreased and salt rejection increased as the solvent evaporating time increased. A solvent evaporating time of 20 to 30 seconds produced membranes with fluxes of between 20 and 24 GSFD at salt rejections of 91 to 93%.

Using a 20-second solvent evaporating time, membranes were prepared at a higher heat treatment temperature of 88°C. This higher heat treatment temperature improved the salt rejection to 95.9% with the water flux declining slightly, but still remaining at 20.3 GSFD. This compares favorably with the flux of 19.5 GSFD and 95% salt rejection obtained for the best membranes cast on the Versapor support using the more viscous Casting Solution A.

Results indicate that using a more dilute casting solution as required for dip casting is practical; however, an increased casting thickness, a slightly longer solvent evaporating time, and a slightly higher heat treatment temperature were required to obtain good membrane performance on flat supports. Also, a less viscous casting solution which produces membranes of good quality can be obtained by increasing the acetone concentration while maintaining the cellulose acetate:formamide ratio constant at 7:10.

* Each data point reported on the figures is an average for two or more membranes. Tables in the appendix provide details for each data point.

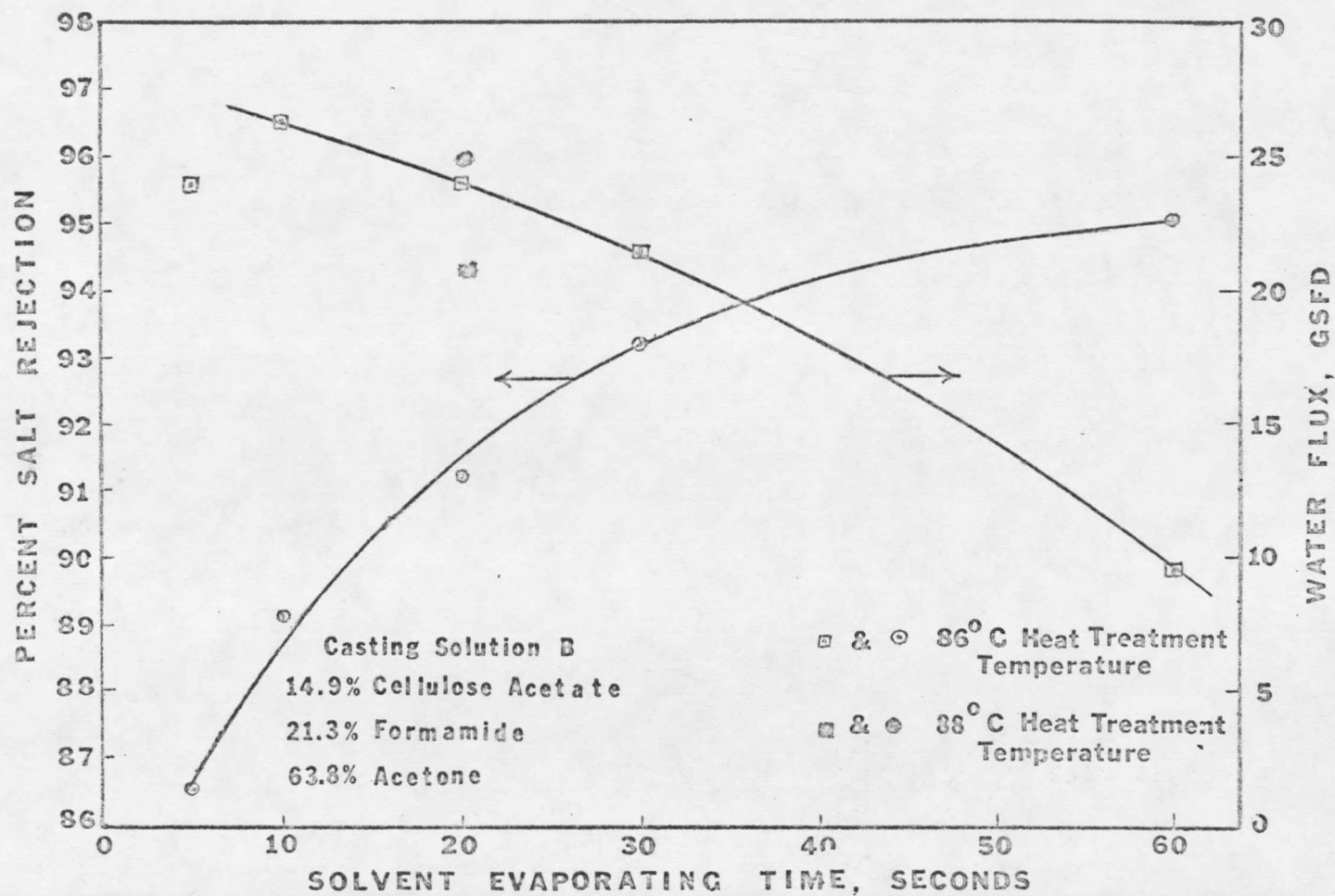


Figure 3. Performance of Membranes Cast on Versapor Using Dilute Casting Solutions. (See Table VIII, page for data details.

B. Studies on Dip Casting

Porous ceramic rods (Norton RA-4021 alundum rods) 5/16" in diameter were used to study the more important casting variables for dip casting. The ceramic support was chosen because it is relatively strong, is dimensionally stable, is easy to work with, and it can be reused without adverse effect.

Effect of Casting Solution Composition

Of particular importance in dip casting are the casting solution viscosity and the solvent evaporating time. Several casting solutions were prepared using Eastman 400-25 cellulose acetate and three different acetone concentrations (thus different viscosities). These casting solutions, designated B, C, and D, had acetone concentrations ranging from 63.8% to 70.2% and viscosities ranging from 3150 to 995 centipoise.

Preliminary membranes on ceramic supports indicated that when dip casting on porous rods, solvent evaporating times of 5 to 15 seconds were sufficient to produce good quality membranes. Better air circulation and possible convection effects around the vertical cylindrical rod perhaps enhanced the solvent evaporation rate and made possible smaller solvent evaporating times when compared to flat supports.

A number of membranes were dip cast using casting solutions B, C, and D. A heat treatment temperature of 86°C and solvent evaporating

times of 5, 10, and 15 seconds were used. Figure 4 shows in detail the effect of the casting solutions composition (viscosity) on membrane performance for various solvent evaporating times. As the acetone concentration increases, the water flux increases while the salt rejection decreases. For longer solvent evaporating times, one may use slightly less viscous casting solutions to obtain the same or slightly better performance.

Those membranes prepared using the lower acetone concentrations (Casting Solution B, for example) were relatively thick; $1/64''$ to $1/32''$ as cast. Those of high acetone concentration were quite thin. When using dilute casting solutions, there is a point of maximum dilution at which the membrane surface begins flowing and cracking during the solvent evaporating time. New membrane of zero solvent evaporating time is thus always present. These areas have essentially a porous surface with no actual membrane present. The rapid deterioration of salt rejection (as in Figure 4) defines the beginning of the flow structure.

The point of maximum dilution is $65 \pm .5\%$ acetone when using E400-25 cellulose acetate, a cellulose acetate:formamide ratio of 7:10, and a solvent evaporating time of 5 seconds. This may be increased slightly to 67-68% acetone by increasing the solvent evaporating time to 10-15 seconds.

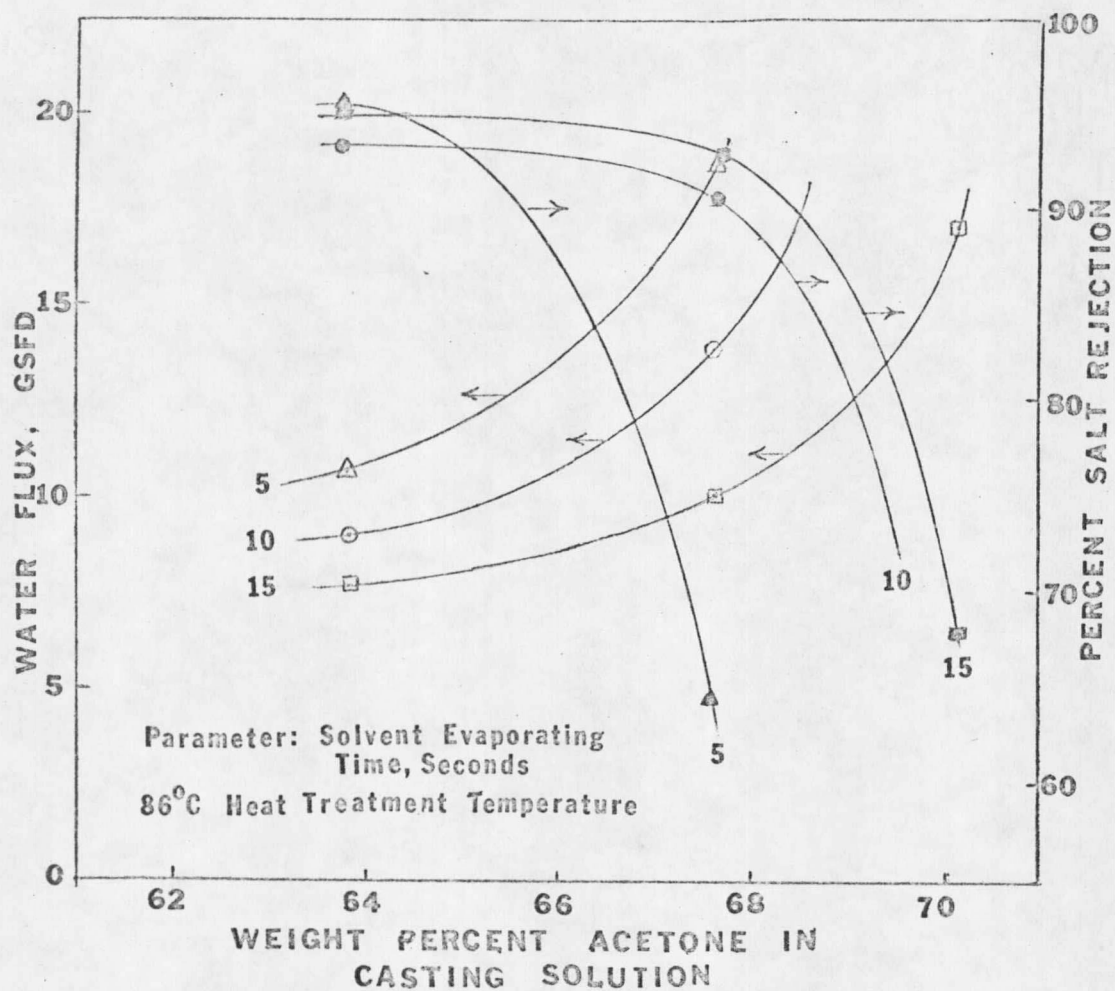


Figure 4. Effect of Casting Solution Composition on the Performance of Dip Cast Membranes. (See Table IX, page 79 for data details.)

Effect of Solvent Evaporating Time

The importance of the solvent evaporating time when using dilute solutions is shown by plotting membrane performance (water flux and salt rejection) as a function of the solvent evaporating time for two different casting solution compositions. This has been done in Figure 5. For Casting Solution B, the more viscous of the casting solutions, good performance (10.5 GSFD and 95.4% salt rejection) is obtained using a 5-second solvent evaporating time; however, for Casting Solution C, a 5-second solvent evaporating time produced membranes having poor salt rejection (< 65%). Increasing the solvent evaporating time to 10 seconds improved the salt rejection of these membranes to 90.5%.

For all solvent evaporating times, the membranes prepared from the more dilute solutions gave better water fluxes, but lower salt rejection. For example, at a 10-second solvent evaporating time and 86°C heat treatment temperature, Casting Solution C gave membranes having performance of 13.7 GSFD at 90.5% salt rejection while Casting Solution B produced membranes with 8.6 GSFD and 92.7% salt rejection. A similar comparison could be made at other solvent evaporating times. All membrane performances given (here and throughout the thesis) are an average performance for two or more membranes similarly prepared.

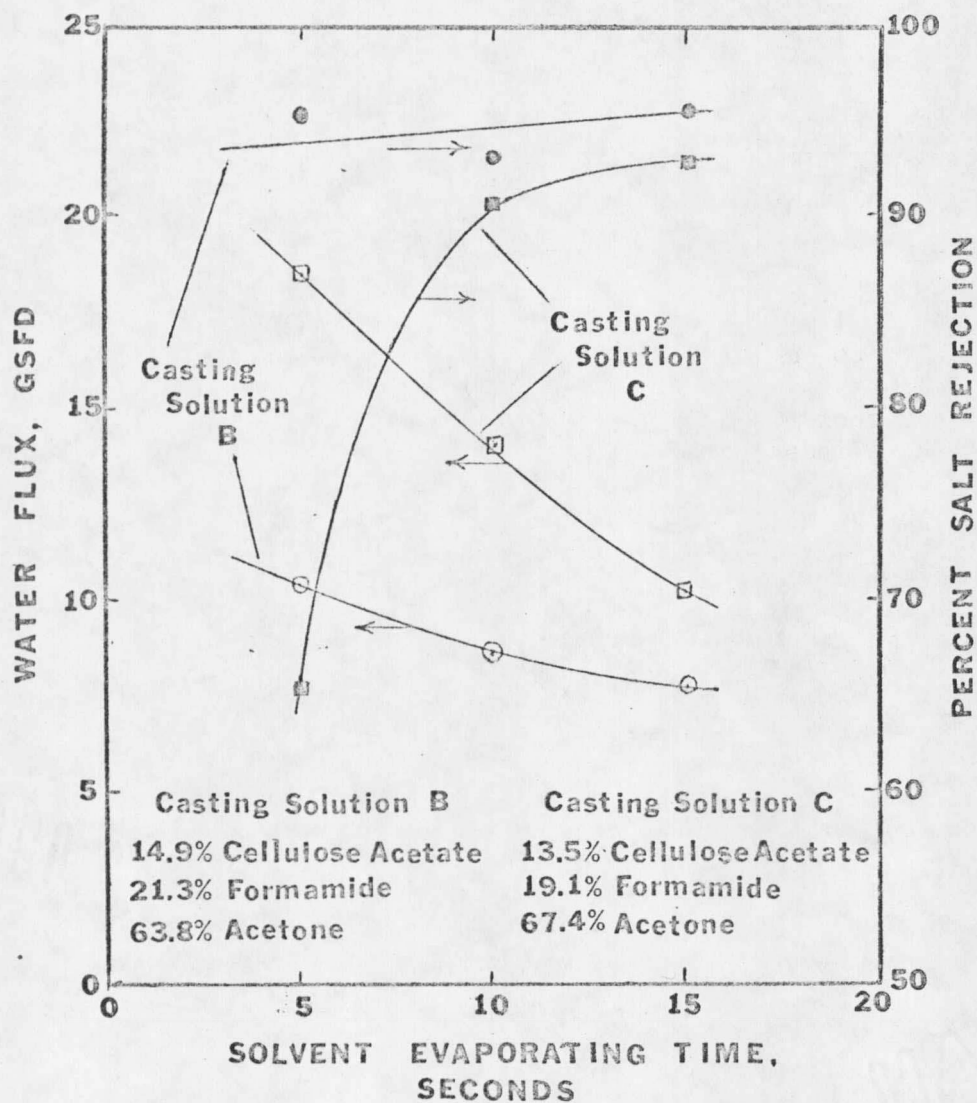


Figure 5. Effect of Solvent Evaporating Time on the Performance of Dip Cast Membranes When Using Different Casting Solutions. (See Table X, page 81 for data details.)

Effect of Heat Treatment Temperature

When using membranes cast directly on porous supports, it was necessary to alter the heat treatment procedure. If the membrane-coated support was dipped directly into the hot heat treatment bath, bubbles caused by trapped air and vaporized acetone would form between the membrane and the support. These often caused the membrane to rupture. A gradual increase in heat treatment temperature was necessary to allow gradual release of the pressures within the support.

The effect of heat treatment temperature on dip-cast membranes is shown in Figure 6, page 30. Water flux declines and salt rejection increases as the heat treatment temperature increases. The slight rise in water flux at 86°C heat treatment (noted in much of the data) may be due to imperfections which arise at higher heat treatment temperatures. It is thought that the membrane shrinkage during annealing may cause cracks or other similar imperfections.

Comparison of Casting Solutions B and C over the range of heat treatment temperatures again shows that Casting Solution C, the more dilute of the two, produces membranes of better flux but slightly lower salt rejection. Best salt rejection for both casting solutions resulted when heat treatment temperatures of greater than 82°C were used.

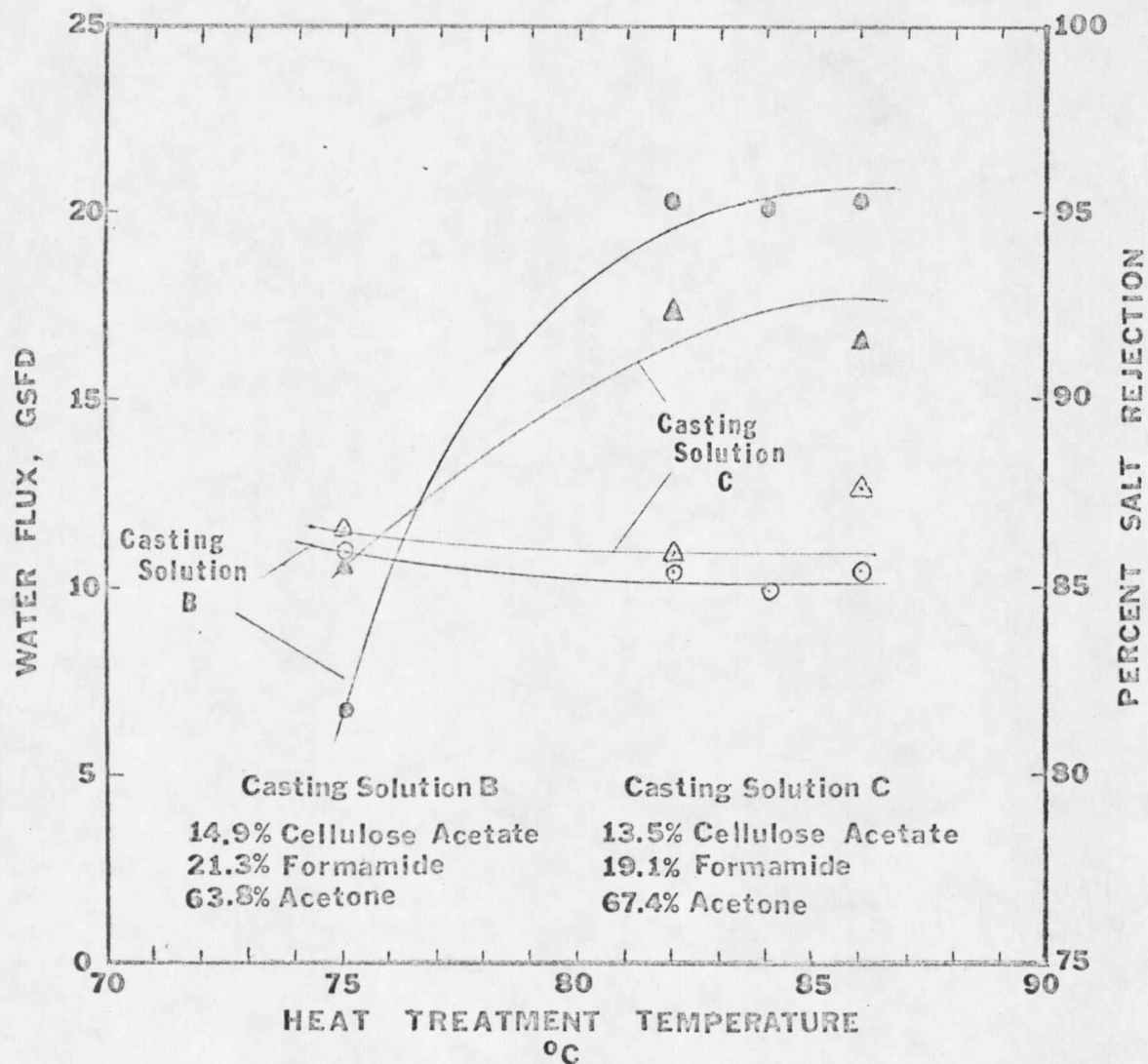


Figure 6. Effect of Heat Treatment Temperature on the Performance of Dip Cast Membranes. (See Table X, page 81 for data details.)

Effect of Cellulose Acetate Type

The viscosity of the casting solution can also be altered by using other cellulose acetate types. Several types of cellulose acetates are available. These differ only slightly in acetyl content, but they do vary widely in molecular weight, thus viscosity. Three types of cellulose acetate were chosen to check the effect of using other cellulose acetates. The three chosen were Eastman 398-3,* Eastman 400-25, and Eastman 394-60.

A number of casting solutions were prepared using these cellulose acetates. The lower the viscosity of the cellulose acetate, the less acetone it takes to achieve a desired casting solution viscosity. Table VI, page 76, shows the composition of the various casting solutions and their viscosities.

A number of membranes were prepared using three different casting solutions (viscosities) for each cellulose acetate type. Performance of these membranes is presented in Figure 7, page 32. For each type of cellulose acetate, there is a point of maximum dilution at which membrane performance begins to decline. The point of maximum dilution is $59 \pm .5\%$ acetone for 398-3 cellulose acetate, $65 \pm 5\%$ acetone for 400-25 cellulose acetate, and $68 \pm 5\%$ acetone for 394-60 cellulose acetate.

*Acetyl content 39.8%, mean viscosity 3 sec -- range of 1.8 to 3.9 sec.

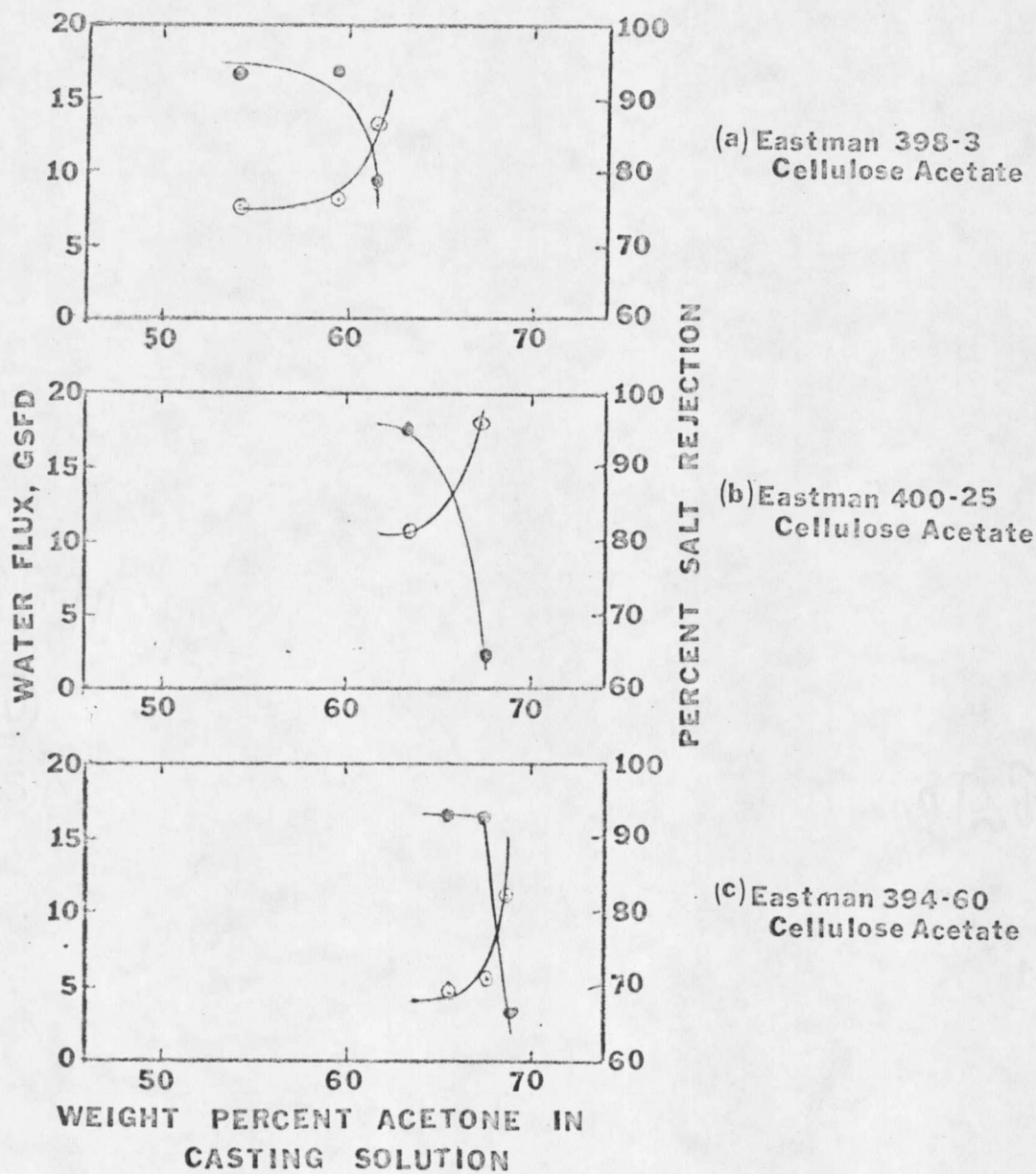


Figure 7. Effect of Cellulose Acetate on the Performance of Dip Cast Membranes.

In all cases, the remainder of the casting solution consisted of cellulose acetate and formamide in the ratio of 7 to 10. The viscosity at the point of maximum dilution was approximately 900 centipoise. In all cases a flow structure in the membrane was noted for solutions with acetone concentrations higher than that at the point of maximum dilution. The flow structure was noticeable as cracks and lengthwise, wavy streaks in the membrane surface.

From the curves in Figure 7, an acetone concentration range has been established for dip casting for each of the cellulose acetate types tested. The lowest acetone concentration (most viscous casting solution) is determined by the point at which the membranes become thick and start to "glob" during casting. The maximum acetone concentration (least viscous casting solution) is determined by the point of maximum dilution discussed above. Acetone concentrations of between 54% and 59% for E398-3, between 60% and 65% for E400-25, and between 63% and 68% for E394-60 are required for dip casting. In all cases, a cellulose acetate: formamide ratio of 7 to 10 was used. Viscosities in the dip casting range vary from 900 to 3500 centipoise. The acetone concentration ranges are for a 5-second solvent evaporating time. The percent acetone could be increased slightly when using longer solvent evaporating times.

Figure 7 also compares the performance of membranes prepared from the various cellulose acetate types. E400-25 cellulose acetate produced

membranes of better performance than did the other cellulose acetate types. For example, at the point of maximum dilution, E400-25 membranes gave fluxes of 10 GSFD at 95% salt rejection compared to fluxes of 7.5 GSFD and 6.0 GSFD for E398-3 and E394-60, respectively, at salt rejections of 93.5%.

Attempts to use very dilute casting solutions were made by using multiple dipping. In this approach, the porous ceramic rods were dipped twice (or more) into a very dilute casting solution (Casting Solution E). A long solvent evaporating time (> 1 minute) was allowed between dips with the final solvent evaporating time being 30 seconds. Membrane performance in all cases was poor with a flow structure being observed on the membrane surface.

Use of Warm Casting Solutions

Heating a casting solution also reduces its viscosity and may make possible the use of more concentrated casting solutions for dip casting. It was thought that thin membranes without the flow structure could possibly be obtained using this method. Several membranes were cast using warm (46°C) casting solutions. Performance of these membranes was poor (see Runs CR-27 to CR-30, page 109). Water fluxes were always relatively low (< 10 GSFD) and most membranes contained pinholes. These pinholes, when dyed and observed under a microscope, appeared to be minute bubbles. Such bubbles may have originated from gases trapped in the

surface pores of the support or from the vaporization of the acetone in the casting solution. Because of the low fluxes and the defects, the use of warm casting solutions was discontinued.

C. Studies on Extrusion Casting

A modified extrusion technique (see Figure 2, page 13) was used to study the possibilities of extruding membranes upon the porous tubes and rods. An extrusion clearance of .010" was used to produce all extruded membranes. This technique produced relatively thin uniform membranes. Again ceramic rods were used in studies of the casting variables.

Effect of Casting Solution Composition

For extrusion casting, two different casting solutions were used to check the effect of casting solution composition; especially acetone content and viscosity. Highly viscous Casting Solution A (used by Wang (24) to produce his best membranes by spread casting) and Casting Solution B were used. Membranes were prepared using a 5-second solvent evaporating time and various heat treatment temperatures. Figure 8 shows the performance of these membranes.

Water fluxes were quite similar at lower heat treatment temperatures; however, at a heat treatment temperature of 86°C, Casting Solution B gave a water flux of 14.3 GSFD compared to 8.3 GSFD for Casting Solution A. Salt rejections were similar for both casting solutions over the heat treatment range.

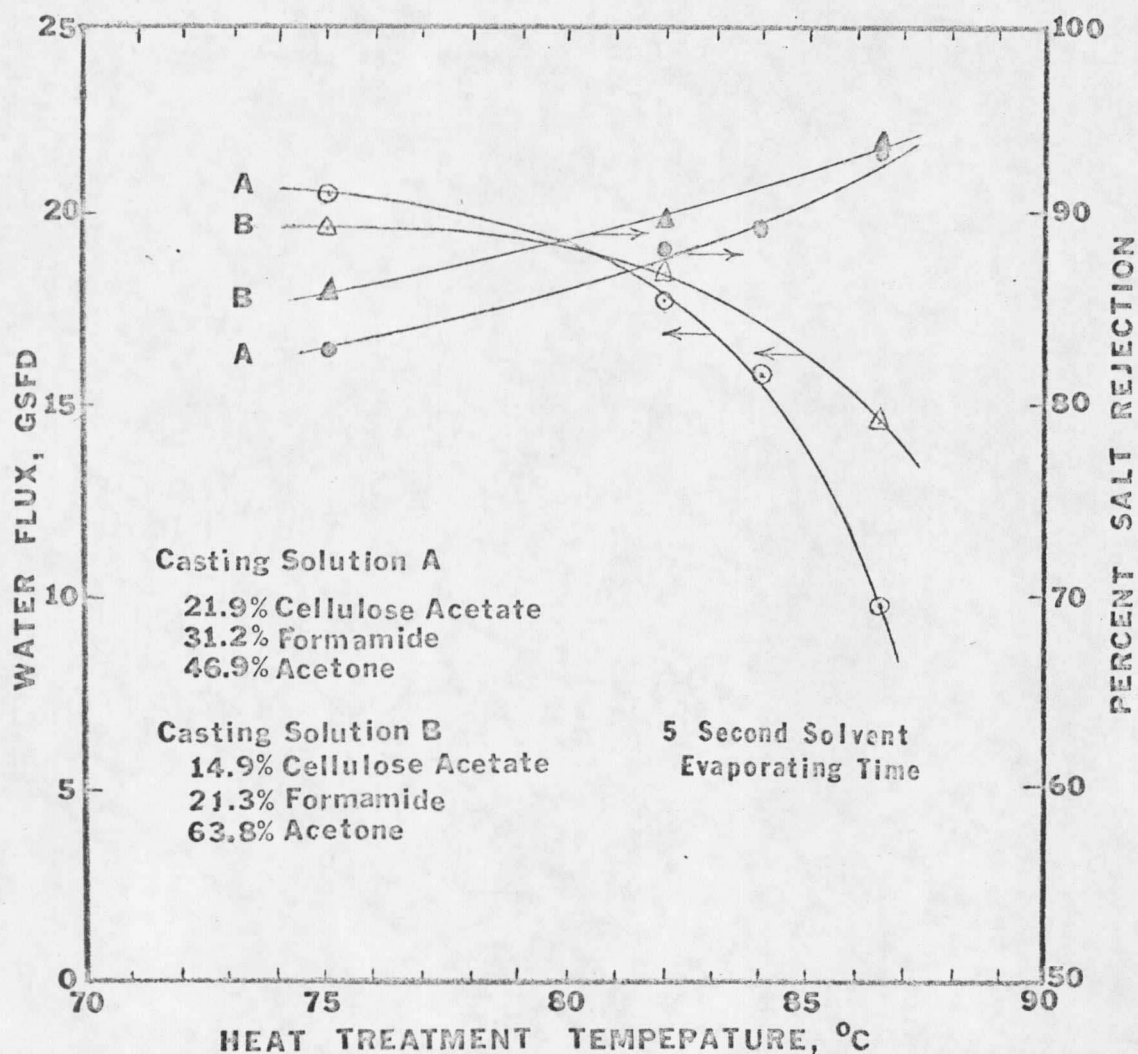


Figure 8. Effect of Casting Solution Composition on the Performance of Extruded Membranes.

Effect of Cellulose Acetate Type

The effect of cellulose acetate type on the performance of extruded membranes was studied using three different cellulose acetate types, each at three different levels of acetone concentration. A solvent evaporating time of five seconds and a heat treatment temperature of 86°C. was used for all runs. Performance of these membranes is shown in Table I, page 38.

Best membrane performance (17.1 GSFD, 93.7% salt rejection) for extruded membranes was obtained when using Casting Solution K (cellulose acetate type 394-60). This casting solution was slightly below the acetone concentration range for dip casting. Use of high or low viscosity casting solutions generally resulted in poorer membrane performance. Salt rejection was similar for all cellulose acetate types.

D. Comparison of Dip and Extrusion Casting

The performances of dip cast and extruded membranes have been compared as a function of both heat treatment temperature and solvent operating time. Dip cast and extruded membranes were prepared on ceramic supports using Casting Solution B, heat treatment temperatures of 75, 82, 84, and 86°C, and solvent evaporating times of 5, 10, and 15 seconds. Results of these studies are shown in Figures 9 and 10, pages 40 and 41.

Table I: Effect of Cellulose Acetate Type on the Performance of Extruded Membranes.

Cellulose Acetate Type		High ^a Viscosity	Moderate ^b Viscosity	Low ^c Viscosity
E398-3	Casting Solution	F	G	H
	Water Flux (GSFD)	7.3	11.0	11.7
	Salt Rejection (%)	92.7	94.2	93.5
E400-25	Casting Solution	A	B	C
	Water Flux (GSFD)	8.3	14.3	9.1
	Salt Rejection (%)	91.1	93.9	91.1
E394-60	Casting Solution	J	K	M
	Water Flux (GSFD)	12.8	17.1	17.2
	Salt Rejection (%)	89.3	93.7	87.9

^a Much above dip casting range -- >>> 3500 centipoise

^b Near upper end of dip casting range -- ~ 3500 centipoise

^c Near lower end of dip casting range -- ~ 1000 centipoise

Figure 9 indicates that extruded membranes have better performance than dip cast membranes for all heat treatment temperatures. At heat treatment temperatures of 82 to 86°C, fluxes of 15 to 18 GSFD and salt rejections of 90 to 94% were obtained for extruded membranes while fluxes of 10 to 11 GSFD and salt rejections of 95% were obtained for similar dip cast membranes. The lower flux of the dip cast membranes presumably results from the resistance to flow in the thick porous substructure of the membrane. Lack of imperfections results in a slightly higher salt rejection for the dip cast membranes. If a more dilute solution is used in preparing the dip cast membranes, their performance more closely approaches that of the extruded membranes. Water fluxes of 12 GSFD and salt rejections of 91.5% were obtained for dip cast membranes prepared from Casting Solution C.

Figure 10 compares the performance of dip cast and extruded membranes for various solvent evaporating times when using Casting Solution B. Salt rejections are nearly identical for membranes cast using either technique; however, water fluxes decrease rapidly when long solvent evaporating times are used for extrusion. It is thus quite important to use small (5 seconds or less) solvent evaporating times when casting membranes by extrusion. Longer solvent evaporating times (up to 15 seconds) may be used for dip casting without drastically affecting the water flux. The dependence on solvent evaporating time is primarily a result of the "as cast" membrane thickness. More sol-

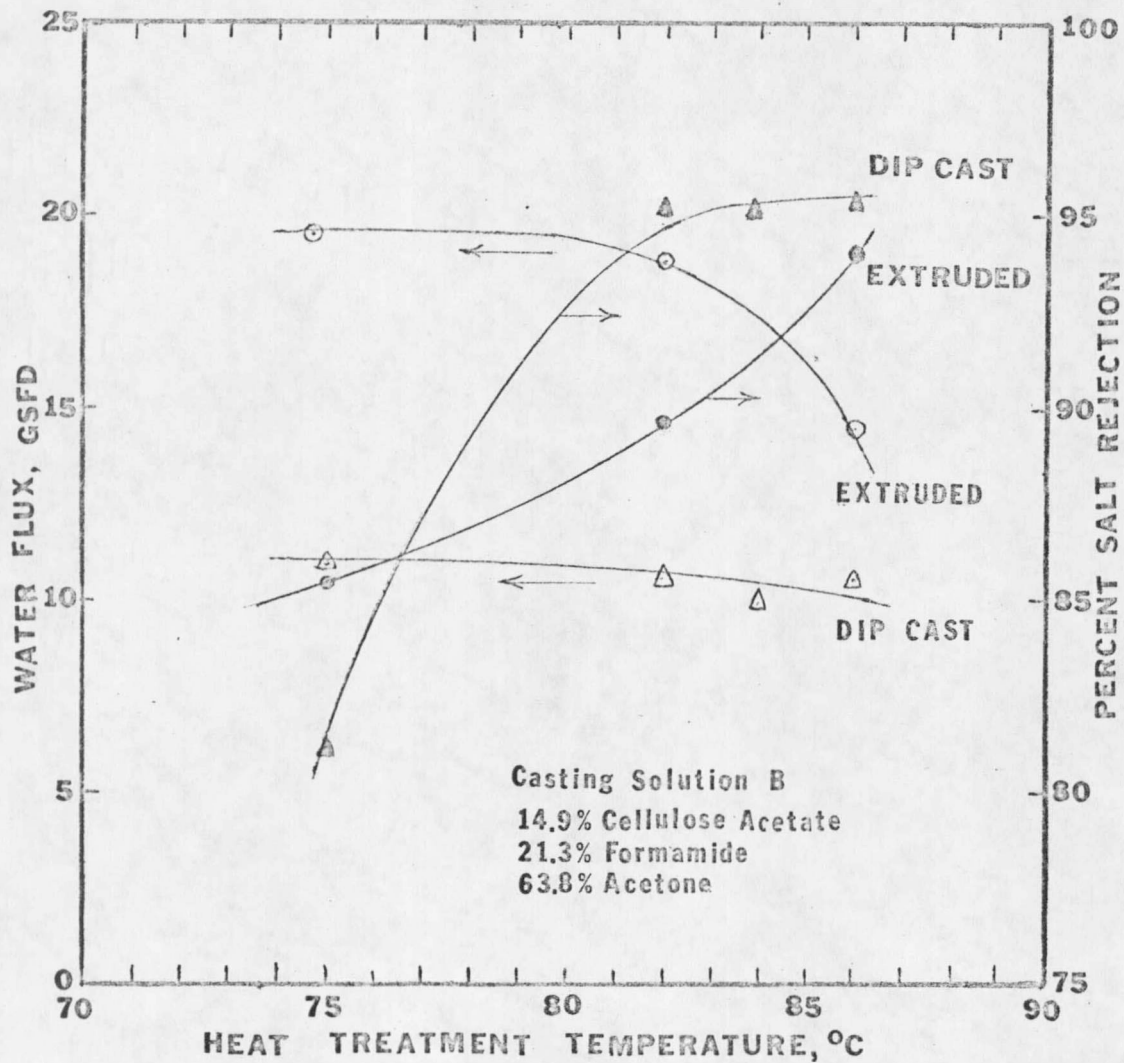


Figure 9. Comparison of Dip Cast and Extruded Membranes for Various Heat Treatment Temperatures.

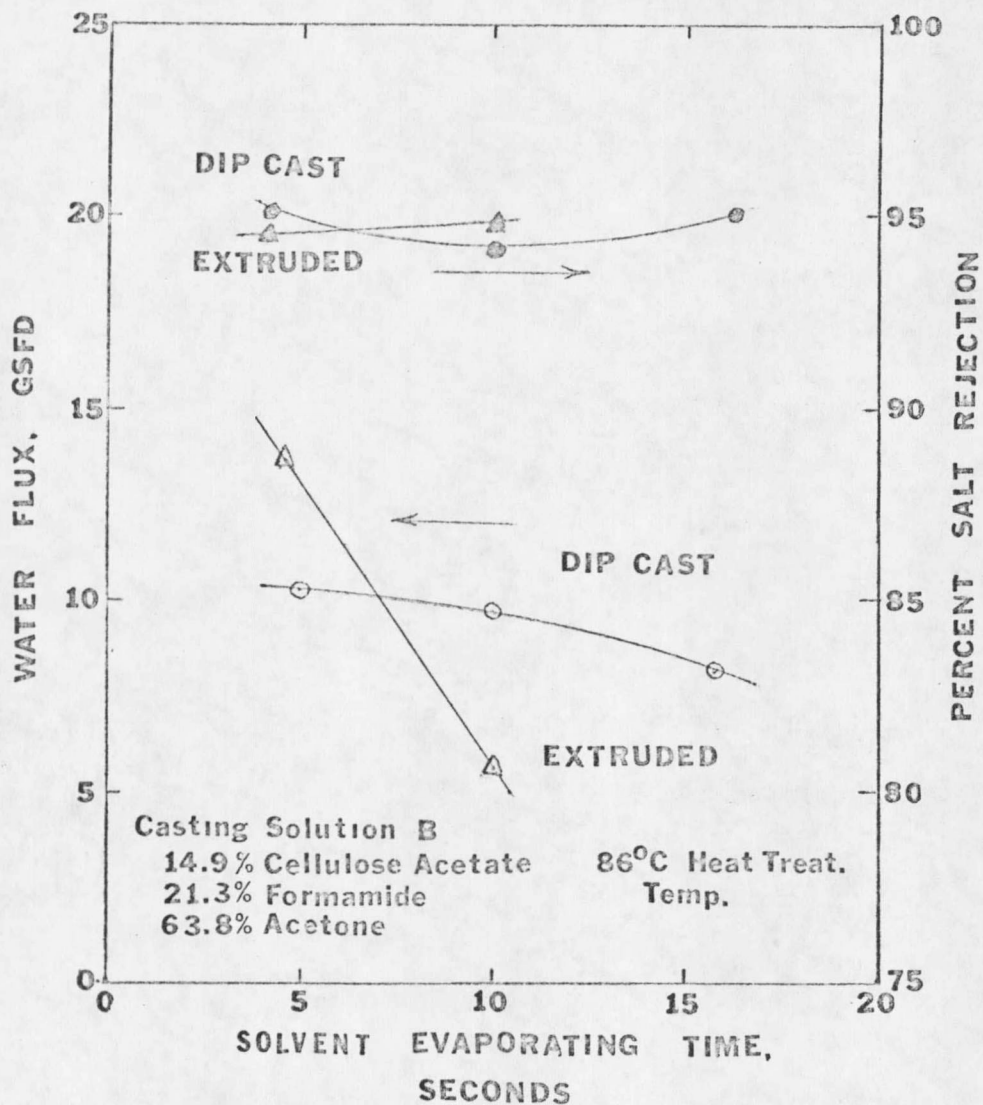


Figure 10. Comparison of Dip Cast and Extruded Membranes for Various Solvent Evaporating Times.

vent is available in the case of dip casting to prevent the membrane skin from becoming thick. Relatively thick surface films result when extruded membranes are given longer solvent evaporating times due to the small total amount of solvent present.

IV. EVALUATION OF SUPPORT MATERIALS

A. Initial Screening of Supports

A number of materials are available in the form of porous media. For use as a support for reverse osmosis desalination membranes, a porous media must be of small pore size (on the order of microns or less), must have good strength, and must be resistant to salt solutions. For the author's work, the additional requirement of being available as a small diameter rod or tube is necessary. Porous stainless steel, porous ceramics, porous fiberglass, and certain porous plastics are possibilities for membrane supports.

Five different porous support materials were obtained in the form of small diameter porous rods or tubes. These included porous tubular stainless steel (.5 microns pore size), two types of porous ceramic material (unknown, but small, pore size), and two types of porous plastic; polyethylene (10 micron pore size) and polyvinylidene fluoride (25 micron pore size). Small diameter porous fiberglass material, although of interest as supports, could not be obtained. Table VII, page 77, provides a qualitative analysis of the various support types used.

Ten membranes were prepared on stainless steel supports. The performance of these membranes is shown in Table XXIV, page 106. In all cases the product water flux was quite low. Microscopic inspection

of the support indicated that only a small portion of the support (perhaps 10-20%) actually possessed a porous surface. The remainder was shiny nonporous steel. This is the probable reason for the low water flux of membranes cast on the porous stainless steel. Because of the poor membrane performance and the high cost of the stainless steel, the use of this support was discontinued.

Two types of ceramic materials were used; Norton RA-5021 alundum tubes and Norton RA-4021 alundum rods. These materials were quite similar except that the RA-5021 material was fired to a higher temperature during fabrication and thus was somewhat denser (less void space). Both types of ceramic were brittle, necessitating care in handling. Performance of membranes prepared on both types of ceramic supports indicated that the RA-4021 material was at least as good as, or slightly better than the RA-5021 material. RA-5021 ceramic, being of smaller diameter and tubular in form, was more difficult to seal in the test cell. Because of their similarity and the sealing problems, the use of RA-5021 ceramic was discontinued. RA-4021 was evaluated further as a membrane support.

Both of the porous plastic materials appeared to be promising as supports for reverse osmosis membranes. The plastic materials are quite strong and relatively cheap. A more complete evaluation of the porous plastics as membrane supports was made.

B. Membrane Performance on Various Supports

Effect of Support Type on the Performance of
Dip Cast Membranes

After initial evaluation, the three most promising types of supports were compared. Using RA-5021 ceramic rods, polyethylene rods, and polyvinylidene fluoride rods, a number of dip cast membranes were prepared and performance evaluated to check the effect of support type. Casting Solution B, a 5-second solvent evaporating time, and various heat treatment temperatures were used. Results of this study are presented in Figure 11.

The ceramic rods produced membranes of better performance at all heat treatment temperatures. For example, at a heat treatment temperature of 86°C, membranes dip cast on ceramic supports gave fluxes of approximately 10.5 GSFD whereas similar membranes on polyethylene and polyvinylidene fluoride gave fluxes of 7.4 GSFD and 4.5 GSFD, respectively. Salt rejection was 94-95% for all support types at the above fluxes.

The major differences between the ceramic and the plastic supports are the pore size and the wettability of the support. The ceramic support is of unknown, but small pore size (on the order of 1 micron as estimated from permeability data), while the pore size of the plastic supports is 10 and 25 microns for the polyethylene and polyvinyl-

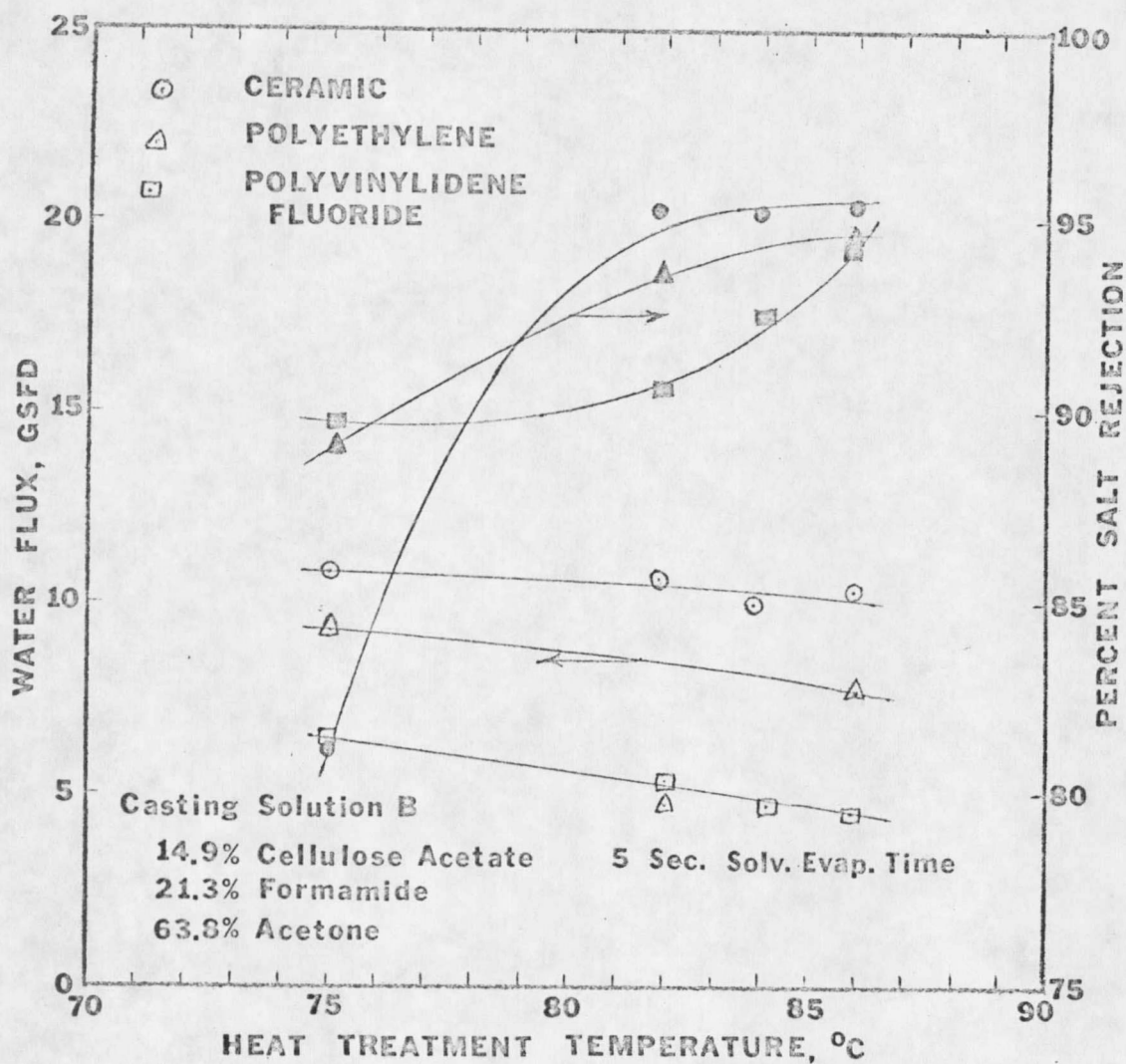


Figure 11. Effect of Support Type on the Performance of Dip Cast Membranes.

idene fluoride, respectively. The larger pore size perhaps allowed the casting solution to flow into the pores. This would have increased the resistance to flow and reduced the water flux. The plastic supports were also hydrophobic while the ceramic supports were hydrophillic. This also may have slightly reduced the water flux. The effect of pore size and wettability are thought to reduce the water flux when using the plastic supports. It was not possible to obtain plastic supports of a smaller pore size.

Several attempts were made to increase the performance of dip cast membranes on the plastic supports by pretreating the support prior to casting. Membranes were prepared using Casting Solution G, a 5-second solvent evaporating time, and an 86°C heat treatment temperature. Table II shows the results of pretreating the support by various methods.

The effect of dip casting on wet and dry polyvinylidene fluoride supports was studied. Results (Table II) indicate that the use of water in the pores does improve water flux (by approximately 10-15%) presumably by preventing the casting solution from entering the pores of the support.

A further attempt to retard the flow of casting solution into the pores was made by coating the support with Non-Aqua stopcock grease prior to dip casting. In this case, the membrane (as cast) would not be in contact with the support. Upon operation, the water soluble stopcock

Table II: Effect of Polyvinylidene Fluoride Support Condition on Membrane Performance.

<u>Condition of Polyvinylidene Fluoride Support</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Dry	PFR-29	4.60	94.9
	PFR-30	4.67	93.8
	PFR-37	4.82	95.5
	Avg.	4.70	94.7
Wet	PFR-31	5.08	94.9
	PFR-32	5.24	93.8
	PFR-33	5.94	97.6
	Avg.	5.42	95.4
Non-Aqua Coated	PFR-34	3.53	79.8
	PFR-35	3.14	78.9
	PFR-36	2.13	81.3
	Avg.	2.93	80.0
Detergent Washed - Wet	PFR-47	6.20	91.0
	PFR-48	5.35	97.5
	PFR-49	5.00	93.1
	Avg.	5.52	93.9

grease on the support would dissolve in the product water and be carried away. Performance of membranes prepared using this technique was poor both in respect to salt rejection (80%) and water flux (~ 3 GSFD).

A third technique was that of washing the support in detergent. This changed the support from hydrophobic to hydrophillic. This did not significantly improve results.

Effect of Cellulose Acetate Type When Dip Casting on Various Supports

The effect of using other cellulose acetate types when dip casting on each of the three support types was also studied. Casting solutions of approximately the same viscosity (upper end of the dip casting range) were used for all three cellulose acetate types. A 5-second solvent evaporating time and an 86°C heat treatment temperature were used in preparing the membranes. Table III shows the results of this study.

E400-25 cellulose acetate produced membranes of better flux on both the ceramic and the polyethylene supports. For example, on ceramic supports, E400-25 cellulose acetate gave an average flux of 10.5 GSFD compared to fluxes of 8.4 GSFD and 6.0 GSFD for E398-3 and E394-60 cellulose acetate, respectively. Similarly, on polyethylene, fluxes of 7.4, 5.4, and 6.5 GSFD were obtained for E400-25, E398-3, and E394-60 cellulose acetate, respectively. The cellulose acetate type had no

Table III: Performance of Membranes Dip Vast on Various Supports Using Various Cellulose Acetate Types

<u>Support Type</u>	<u>Cellulose Acetate Type</u>	<u>Casting Solution</u>	<u>Water Flux (GSFD)</u>	<u>Salt Rejection (%)</u>
Ceramic	398-3	G	8.4	93.6
	400-25	B	10.5	95.4
	394-60	K	6.0	93.9
Polyethylene	398-3	G	5.4	96.1
	400-25	B	7.4	94.4
	394-60	K	6.5	92.3
Polyvinylidene Fluoride	398-3	G	5.4	95.4
	400-25	B	4.6	94.7
	394-60	K	5.5	92.0

large effect on the water flux of membranes dip cast on polyvinylidene fluoride supports. Also, no effect on the salt rejection could be determined.

Effect of Support Type on the Performance of Extruded Membranes

The effect of support type on the performance of extruded membranes was also studied. A series of membranes were prepared by extrusion using three types of cellulose on ceramic supports and one type of cellulose acetate (E400-25) on both the polyethylene and polyvinylidene fluoride supports. A 5-second solvent evaporating time and an 86°C heat treatment temperature were used. Table IV shows the performance of these membranes. A comparison to dip casting is also made in each case.

Membranes extruded on ceramic supports gave best performance. Water fluxes of 14.3 GSFD at 93.9% salt rejection was obtained when using Casting Solution B (E400-25 cellulose acetate). Casting Solution M (394-60 cellulose acetate) produced membranes having a water flux of 17.2 GSFD and 88.9% salt rejection. Water fluxes of 11.0 GSFD and 7.7 GSFD at ~92-3% salt rejection were obtained for the polyethylene and polyvinylidene fluoride supports, respectively, when using Casting Solution B and extruded membranes.

Table IV: Performance of Extruded and Dip Cast Membranes on Various Supports

<u>Support Type</u>	<u>Cellulose Acetate Type</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Water Flux (GSFD)</u>	<u>Salt Reject. (%)</u>
Ceramic	398-3	G	Extruded	10.1	92.9
			Dip Cast	8.4	93.6
	400-25	B	Extruded	14.3	93.9
			Dip Cast	10.5	95.4
	394-60	M	Extruded	17.2	87.9
			Dip Cast	6.0	93.9
Polyethylene	400-25	B	Extruded	11.0	91.7
			Dip Cast	7.4	94.3
Polyvinylidene Fluoride	400-25	B	Extruded	7.7	92.9
			Dip Cast	4.6	94.7

Some difficulty was encountered when extruding membranes upon the large pore size plastic supports. Even with the pores saturated with water, minute bubbles would form in the membrane from air trapped in the surface pores of the support. These would cause leaks. It was found that dipping the porous plastic supports into a dilute solution (8% cellulose acetate in acetone) and allowing complete solvent evaporation prior to extruding would eliminate the bubbles and prevent the leaks. Membranes fabricated using this two-step process had good salt rejection. The membranes on plastic supports whose results are reported in Table IV were fabricated using this method.

The water flux of extruded membranes was always greater than that of dip cast membranes by a factor of 1.4 to 2.2. This was true for all support types and all cellulose acetate types when identical solvent evaporating times and heat treatment temperatures were used.

Reuse of Supports

Other than a few ceramic supports which broke during testing, none of the support types appeared damaged after testing. Removal of a used membrane was easily accomplished in all cases by dissolution of the membrane in acetone. During this step the polyvinylidene fluoride tended to swell and become more easily broken. It returned to its normal dimensions after having dried. None of the other support types were thus affected.

A number of supports were marked and reused a number of times.
Membrane performance on a used support was not noticeably affected.

V. CONSIDERATION OF SUPPORT PROPERTIES

A. Support Permeability

The permeability of the three support types (RA-4021 ceramic, polyethylene, and polyvinylidene fluoride) has been investigated. Three-inch sections of each of the support types were sealed along their entire length, but not at the ends. Flow of water through these sections was then measured as a function of pressure drop. This permeability data is presented in Figure 20, page 98. As expected, the larger pore size polyvinylidene fluoride was most permeable, followed by the polyethylene and the ceramic.

It would be desirable to know the effect of the support permeability on membrane performance. If a support has a low permeability, the pressure drop through the porous media would be large and may seriously lower the effective driving force through the membrane. To check the magnitude of the pressure drop for porous rods, a mass balance was used in association with Darcy's Law for flow through porous media and the defining equation for reverse osmosis to find the pressure drop as a function of length. These equations plus the resulting differential equation describing the system are given on page 99 in the Appendix.

The differential equation, Equation 4 given on page 99, was solved using the Runge-Kutta method for numerical integration. Results for various diameter rods of three different support types are shown in Figure 12.

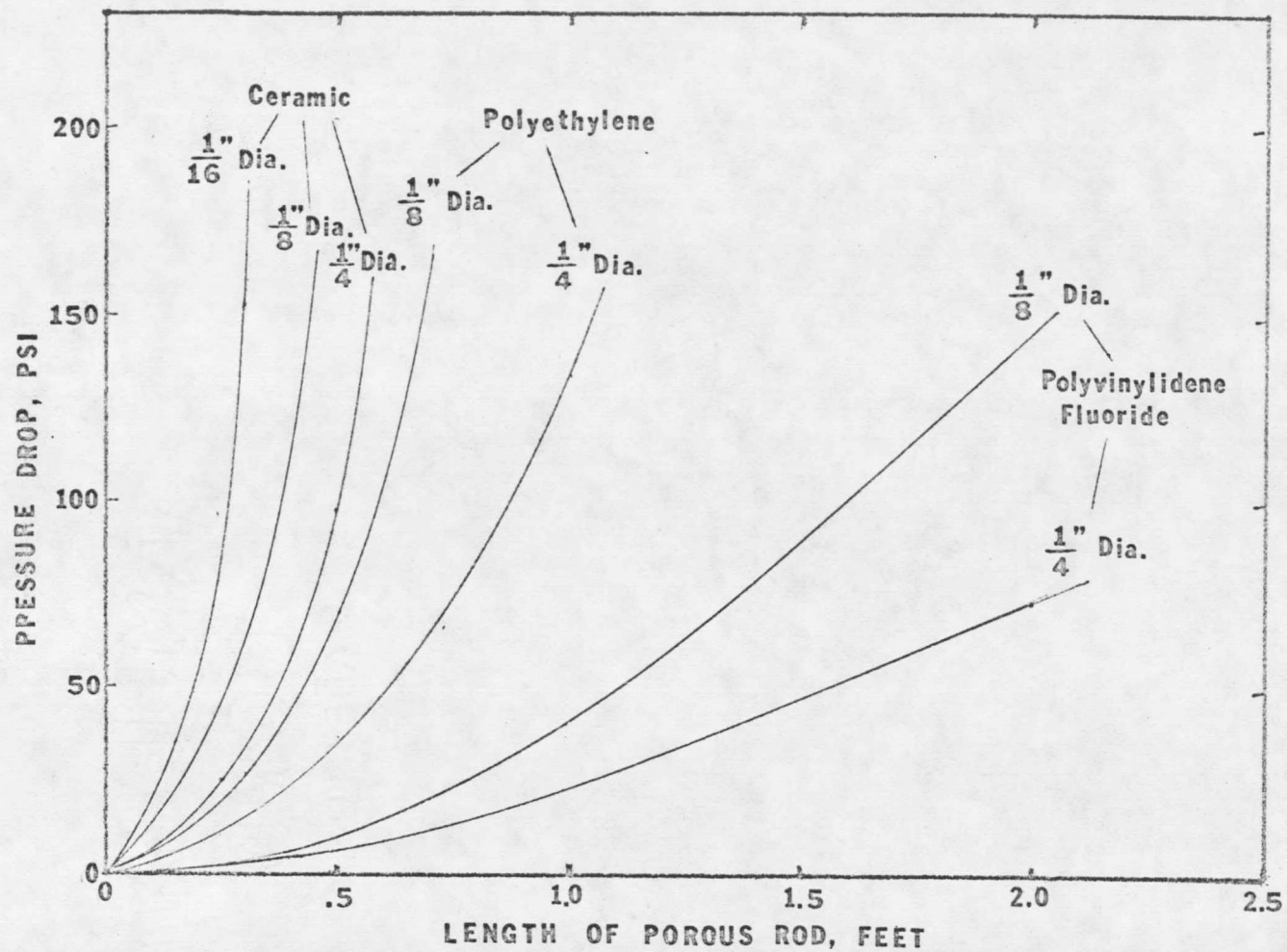


Figure 12. Pressure Drop as a Function of Length for Various Supports.

The pressure drops due to product water flow are quite large and limit the length of rod that may be used. If one considers the maximum allowable pressure drop to be 100 psi, maximum useable lengths would be $\sim .5$ feet for $1/4$ inch ceramic rod, $\sim .80$ feet for $1/4$ inch polyethylene rod, and ~ 2.5 for $1/4$ inch polyvinylidene fluoride rod. Even smaller useable lengths would be noted if smaller diameter rods were used. If product flow were allowed at both ends of the porous rod, the useable lengths would be doubled.

Because of these pressure drops through the porous media, it appears that it would be advantageous to use tubular porous media rather than porous rods. The center hole could be very small so as not to reduce the strength of the material. A $1/64$ -inch hole or possibly less would be sufficient to reduce the pressure drop to tolerable levels for longer tubes.

Because all data reported by the author is for casting on small lengths of porous media ($4-1/2$ inches or less), the pressure drop within the porous rod due to product water flow has not had significant effect on results.

B. Support Diameter

By utilizing smaller diameter support media, one can greatly increase the membrane density. The effect on membrane performance when smaller diameter rods are used was checked. To do this, $5/16$ -inch

porous ceramic rods were sanded down to smaller diameter; in particular to 1/8- and 1/16-inches. These, along with 5/16-inch rods and 5/16-inch rods with sanded surfaces, were dip cast and membrane performance checked. Casting Solution B, a 5-second solvent evaporating time, and an 86°C heat treatment temperature were used. Figure 13 shows the results of this investigation.

Sanding the surface of the rods did not noticeably alter membrane performance nor did reducing the diameter to 1/8-inch; however, for 1/16-inch diameter rods, the membrane performance was significantly lower.

Several possible causes for the poorer performance are thought to exist. First, and perhaps most important, is the pressure drop due to product water flow through the porous media. Four-inch sections of 1/16-inch rod were used. Note that in Figure 12, the maximum pressure drop for such a length would be ~100 psi. This would significantly lower the effective driving force and thus lower the product water flux. A second possibility is that the smaller diameter membranes are more susceptible to compaction of the porous membrane substructure because of the increased "as cast" membrane thickness to diameter ratio. This would be especially true for membranes that were dip cast using more viscous casting solutions. A final possibility is that of concentration polarization because of lower brine velocities through the test cell when small diameter porous supports are used. This possibility is

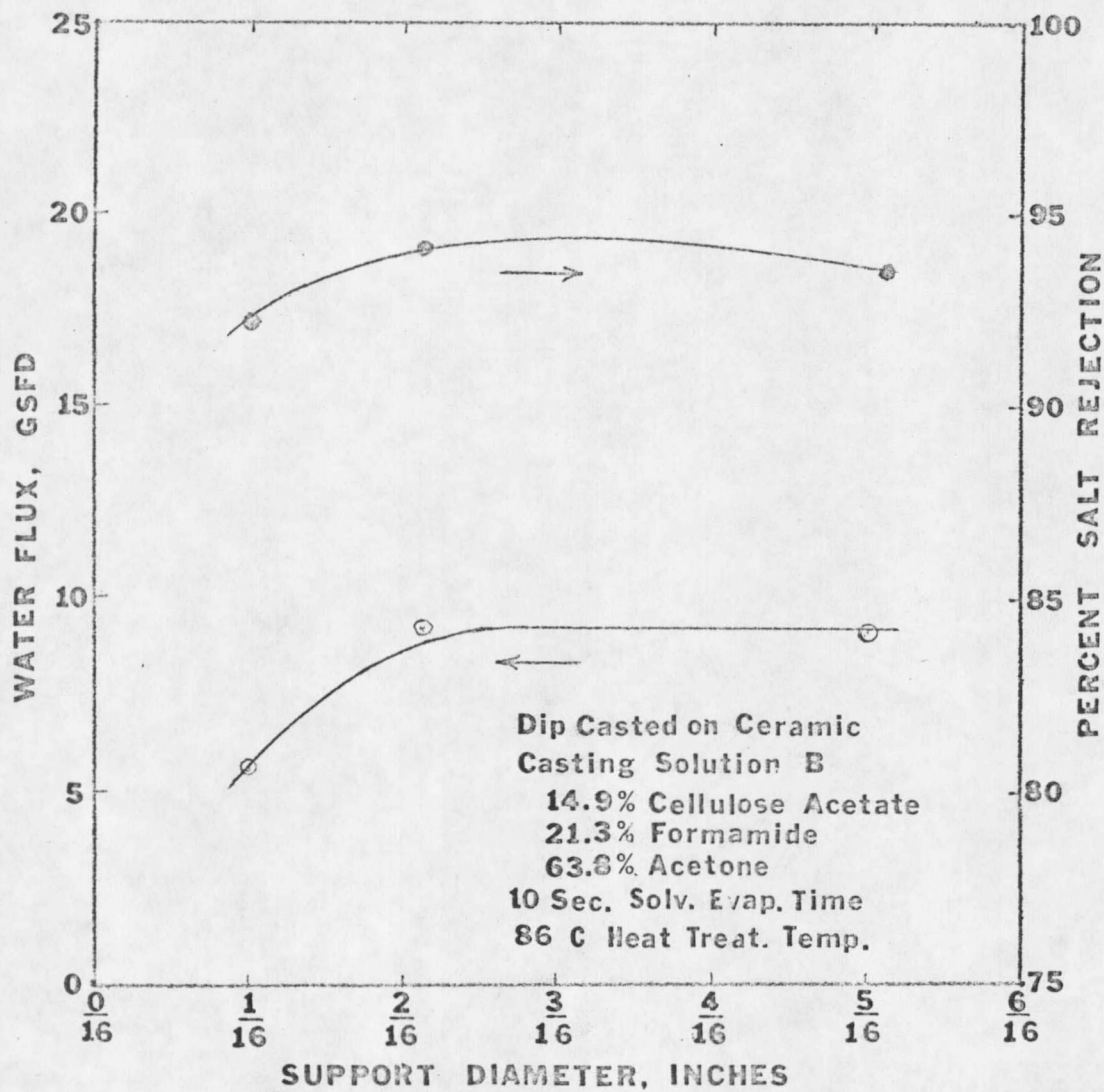


Figure 13. Effect of Support Diameter on the Performance of Dip Cast Membranes..

thought to be minimal as doubling the brine flow did not alter results when using 1/16-inch rods.

C. Support Length

Most of the data reported is that for using small lengths (4 inches or less) of porous rod. Dip casting on the small lengths would not be practical in a commercial system; therefore it is desirable to know if there are limitations when dip casting on longer lengths of rod. Membranes were dip cast on 8-inch sections of porous polyvinylidene fluoride using Casting Solution B. Casting Solution B is quite viscous, being near the maximum viscosity that can be used for dip casting, and would be most apt to present problems when dip casting on longer rods.

Membranes prepared on the longer rods were of nearly uniform thickness throughout their entire length, being only very slightly thicker near the lower end (last to exit from the casting solution). Average performance on the long rods was 4.4 GSFD and 98.7% salt rejection compared to 4.6 GSFD and 94.7% salt rejection on the short length. See Table XXII, page 102, for results on the different lengths of rods. Water flux was not appreciably affected by rod length. There is no apparent reason for the abnormally high salt rejection for membranes cast on the long rods.

VI. STUDIES OF MEMBRANE LIFE

All data reported thus far is that at the end of six hours of operation. It is important to know what the effect of time is on membrane performance.

Four membranes were prepared to check the long run membrane performance. Two dip cast and one extruded membrane were tested for a period of ten days. A second extruded membrane was tested for a period of thirty days. The performance of these membranes is shown in Figures 14 and 15.

A number of important aspects may be noted from Figures 14 and 15. First, in all cases, the flux declined approximately 10 to 15% during the first six hours. Secondly, in all cases, the salt rejection increased slightly (about 2 to 3%) during the first 24 hours of operation. From 24 hours to 10 days, the salt rejection was fairly constant.

A decline in the water flux was noted in most runs; however, in all cases where the flux decline occurred, the water flux could be restored to its original level by cleaning the membrane surface. The contamination of the membrane surface appeared to be a thin oil or grease film presumably originating from the packing of the pump. Each point at which major flux declines began corresponds to periods during which difficulties were encountered with the pump packing.

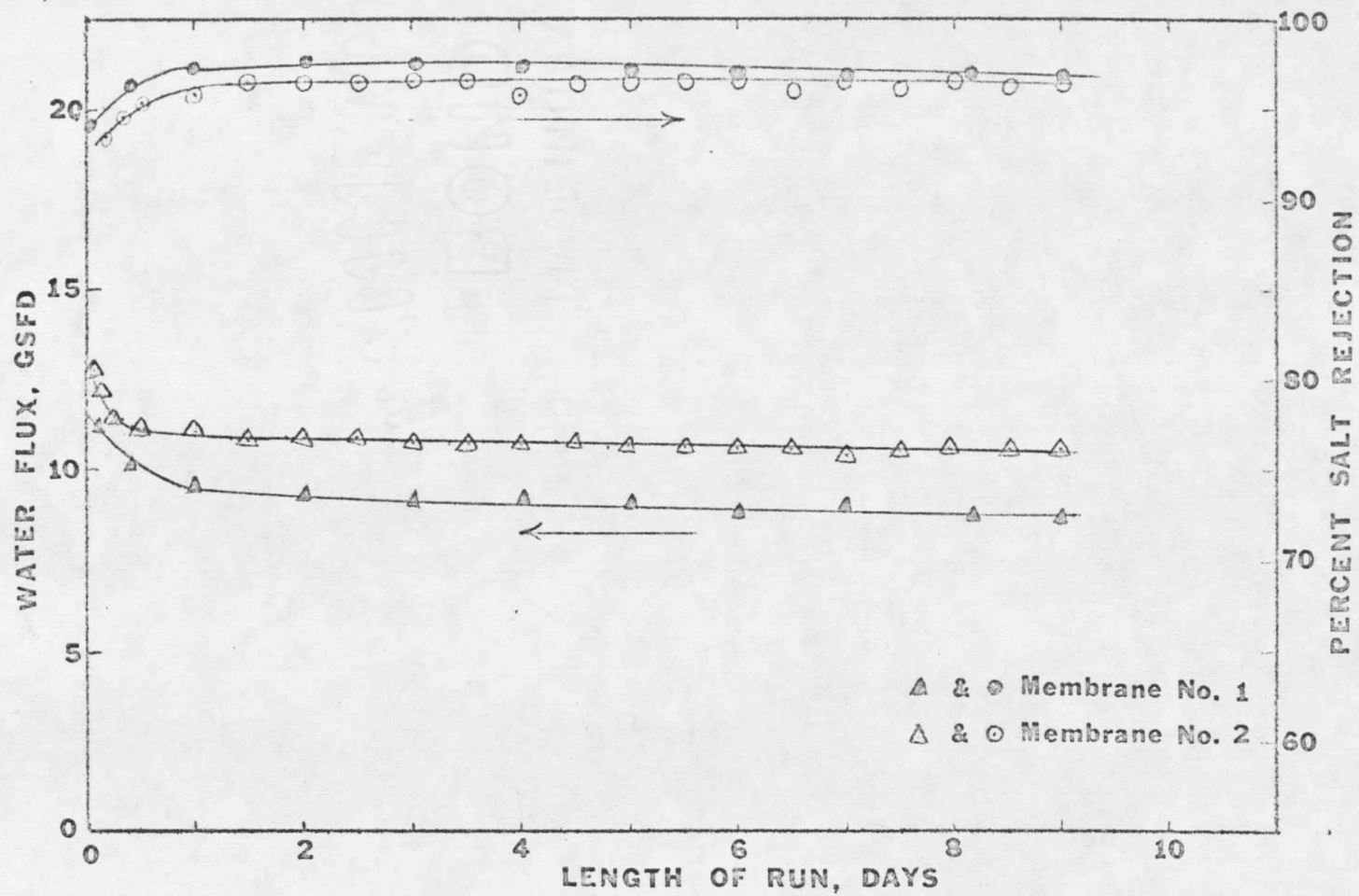


Figure 14. Lifetime Studies of Dip Cast Membranes.

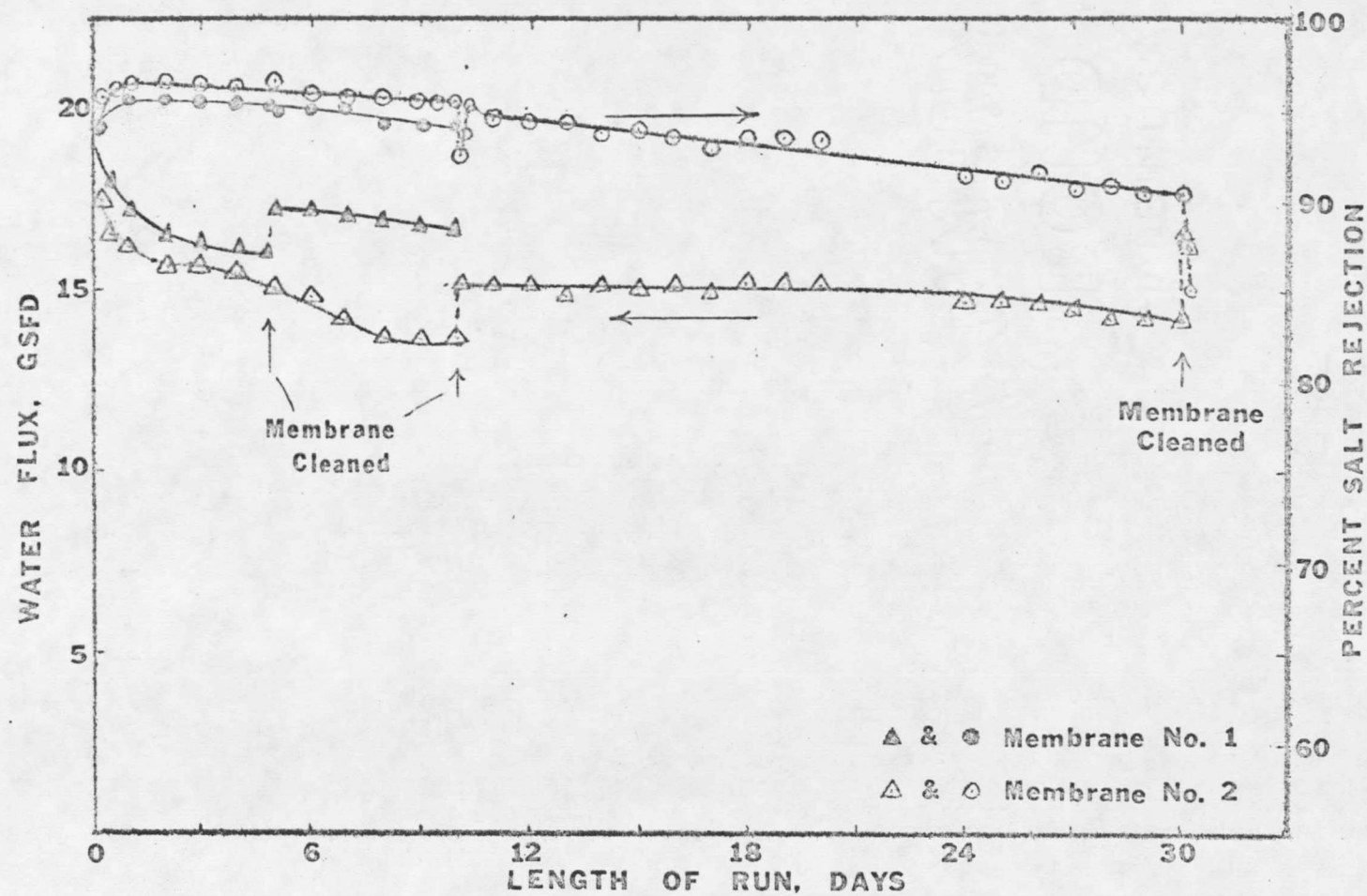


Figure 15. Lifetime Studies of Extruded Membranes.

A salt rejection decline was noted in the 30-day run. An initial salt rejection of 96% was reduced to 90% at the end of 30 days. Other researchers have reported two probable causes for such a decline in salt rejection. First is hydrolysis of the membrane reducing the acetyl content of the membrane (21). Cellulose acetates of lower acetyl content provide membranes of lower salt rejection (20). Proper control of pH would control the hydrolysis effect. No pH control was used by the author. Secondly, bacterial action (4) may have degraded the membrane resulting in poor salt rejection. Addition of 2 ppm chlorine would eliminate such bacteria (5).

An additional explanation for the salt rejection decline exists in the author's work. It is possible that the oil film that was found on the membrane may have had a slight solubilizing effect on the membrane surface. This could have lowered the salt rejection. Note that the salt rejection decline appears to correspond with the water flux decline, but that cleaning the membrane did not revitalize the salt rejection.

VII. ECONOMIC CONSIDERATIONS

The economics of the author's proposed reverse osmosis system are dependent upon the cost of the membrane support. In order to approximate the allowable cost per unit length of membrane-coated support, a brief economic study was made.

Hollow fiber reverse osmosis systems are analogous to the author's proposed system. Mattson and Tomsic (16) have made brief economic estimates for a hollow fiber system. For a plant of 100,000 gallons per day, they estimate a total operating cost of 75¢/1000 gallons. Of this, 35¢/1000 gallons was attributable to membrane module (permeator) amortization and replacement. For the author's system to be economically attractive, a maximum cost for membrane module amortization and replacement of 35¢/1000 gallons was chosen. Membrane modules of similar capacity (8600 gallons per day) were also chosen.

The 35¢/1000 gallons may be divided into three parts: module (shell) amortization; membrane amortization; and membrane replacement charges. The module would be amortized at the same rate as the remainder of the plant (7% as given by Mattson and Tomsic (16)). This would be 2¢/1000 gallons. Membrane replacement costs would be 10¢/1000 gallons based on a one-year membrane life, or five times that of Mattson and Tomsic who based replacement costs on a five-year membrane life. This allows 23¢/1000 gallons for membrane amortization.

Based on modules of 8600 gallons per day (26,320 feet of 1/8-inch diameter tubes, water flux of 10 GSFD), a cost of \$725 may be allowed for membrane replacement. Allowing \$225 to assemble the membranes, a maximum allowance for membrane cost would be \$500 per year per module or 1.9¢/foot of membrane-coated support. A summary of the economic estimate is given in Table V. It should be noted that the cost data is meant only to give an approximate allowable support cost. The above cost (1.9¢/ft of 1/8" membrane-coated porous tube) was not actually obtained, but is a cost value that must be obtained if the system is to be economically competitive.

The cost of the porous supports used by the author is somewhat higher than the cost figure above. The cheapest support used were the plastic supports which were obtained in small, custom-made quantities at 33¢/foot for 1/4" diameter porous rods. Mass production would lower this cost considerably -- possibly to below the maximum allowable cost of 1.88¢/foot calculated above. Reuse of the supports, possibly by dip casting, would possibly increase the maximum allowable cost for supports.

Table V: Economic Estimations

Plant Capacity, gal/day	100,000*
Membrane Module, gal/day	8,600*
No. of Modules	12
Feed Pressure, psig	800*
Conversion, %	70*

Capital Costs

Module Investment	\$ 14,700
Plant Investment	100,000*
Total Investment	114,700

Operating Costs, \$/1000 gal.

Power @ \$.01/KWH	0.14*
Plant Amortization @ 7%/yr.	0.09*
Maintenance and Insurance @ 1.75%/yr.	0.07*
Module Shell Amortization @ 7%/yr.	0.02
Membrane Unit Amortization @ 100%/yr.	0.23
Membrane Replacement	0.10
Total Operating Cost	0.75*

Module Data

Support Diameter, inches	.125
No. of Tubes/Module	3,760
Water Flux, GSFD	10
Module Length, feet	7
Module Diameter, inches	6
Cost of Shell, \$	500
Cost of Membrane Unit, \$	725
Cost of Membrane Assembly, \$	225
Cost of Membrane-Coated Supports, ¢/ft.	1.9
Cost of Membrane-Coated Supports/ Module	500
Total Cost per Module, \$	1,275

*Estimates reported by Mattson and Tomsic (16).

VIII. CONCLUSIONS

The experimental work of the author has shown that reverse osmosis desalination membranes of good quality can be cast upon porous tubular media by either dip casting or extrusion.

For dip casting, average water fluxes of 10.5 GSFD at 95% salt rejection were obtained when using ceramic supports, Casting Solution B, a 5-second solvent evaporating time, and a heat treatment temperature of 86°C. Low viscosity casting solutions were best obtained by increasing the acetone concentration while maintaining the cellulose acetate:formamide ratio constant at 7 to 10. For each cellulose acetate type there is a particular range of acetone concentration that may be used when dip casting. For E400-25 cellulose acetate this was 60% to 65% acetone.

For extrusion casting, average water fluxes of 17.2 GSFD at 93.7% salt rejection were obtained when using ceramic supports, Casting Solution K, 5-second solvent evaporating time, and an 86°C heat treatment temperature. Casting solutions of moderate viscosity (near the more viscous end of the dip casting range) generally produced better results.

In all cases, membranes fabricated by extrusion produced better average fluxes, but slightly lower average salt rejections than dip cast membranes. Water fluxes of extruded membranes were between 1.4 to 2.2 times those of dip cast membranes.

Among the support types, ceramic supports gave better membrane performance; however, they are limited because of their brittleness. Among the plastic supports, performance of membranes cast on porous polyethylene was the best. A flux of 11 GSF/D at 92% salt rejection was obtained on this support when using extrusion Casting Solution B, a 5-second solvent evaporating time, and an 86°C heat treatment temperature. It was necessary to predip the plastic supports in a very dilute (8% cellulose acetate) casting solution prior to casting in order to obtain good membrane performance. Predipping presumably filled large surface pores. The polyethylene support is strong, is cheaper than the other support types tested, and could possibly be produced in long lengths, in a small diameter, and tubular in form. Such would be an excellent support.

Length of rod did not affect membrane performance; however, the permeability of the support is limiting. Tubular porous media must be used if long lengths of support are used. This is especially true in the case of small diameter supports.

Long run investigations indicated that a 15% decline in flux occurs during the first hours of operation, but that the flux will remain nearly constant thereafter provided the membrane surface is kept clean. Salt rejection increased slightly during the first hours of operation, but declined gradually thereafter.

IX. RECOMMENDATIONS

The use of porous tubular media as supports for reverse osmosis desalination appears to have considerable promise. Such media enable high flux membranes to be incorporated into a high membrane density reverse osmosis design.

Much future work will be necessary for the process to be commercially realized. First, it is important to have the ability to produce long lengths of the support in a small diameter tubular form. Continuous production of the support while simultaneously extruding membrane upon the support would be a big step forward.

Additional work in the development of the support is also recommended. Porous fiberglass may offer an attractive alternative as a support. Plastics, such as the polyethylene, of smaller pore size may also be attractive.

A final area of additional work is in the development of a module using the membrane-coated porous tubes. This would involve studying the mounting of the membranes in the module and studying ways of preventing concentration polarization effects due to flow maldistribution in a large module.

APPENDIX

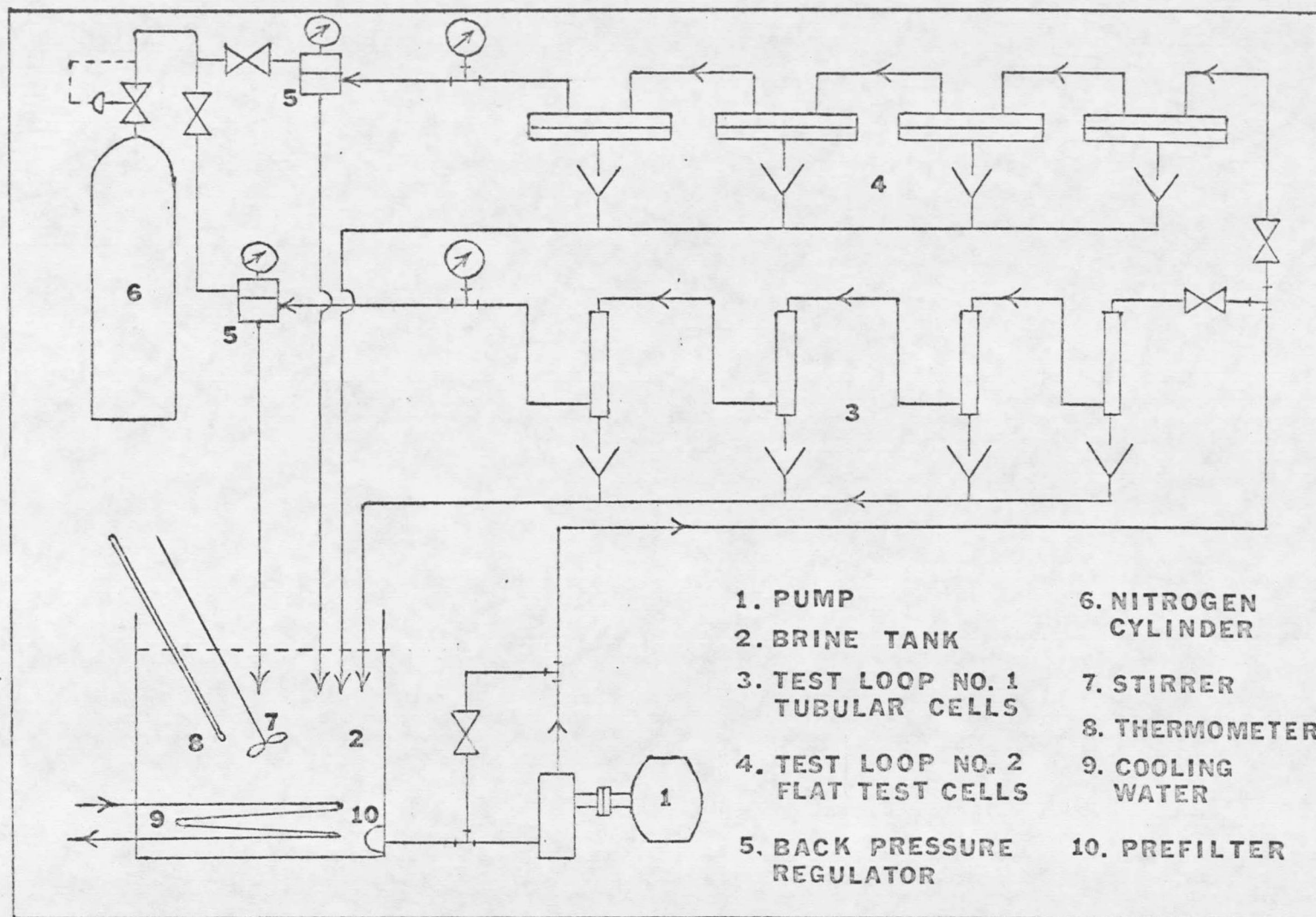


Figure 16. Flow Diagram of Test Equipment.

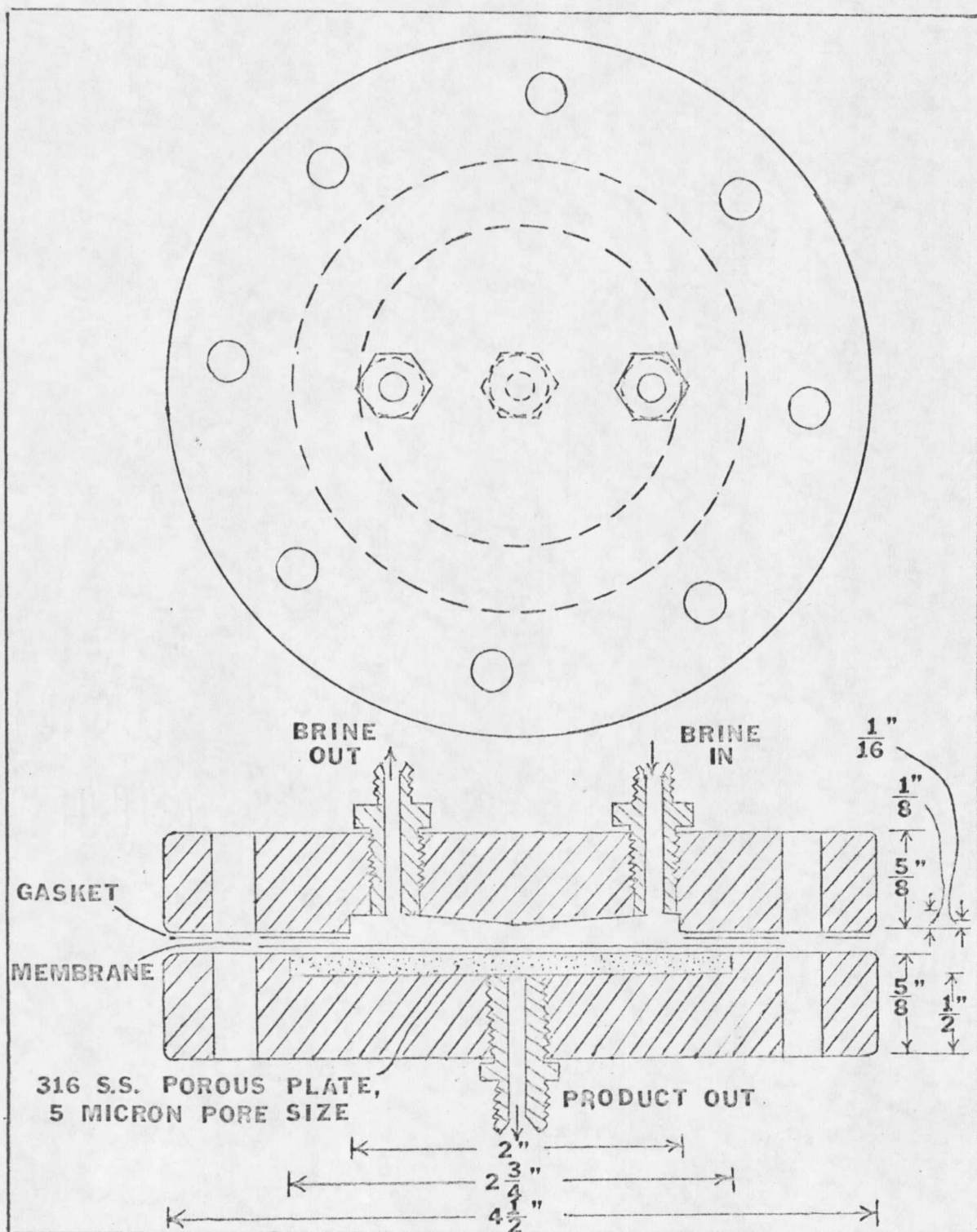


Figure 17. Flat Test Cell.

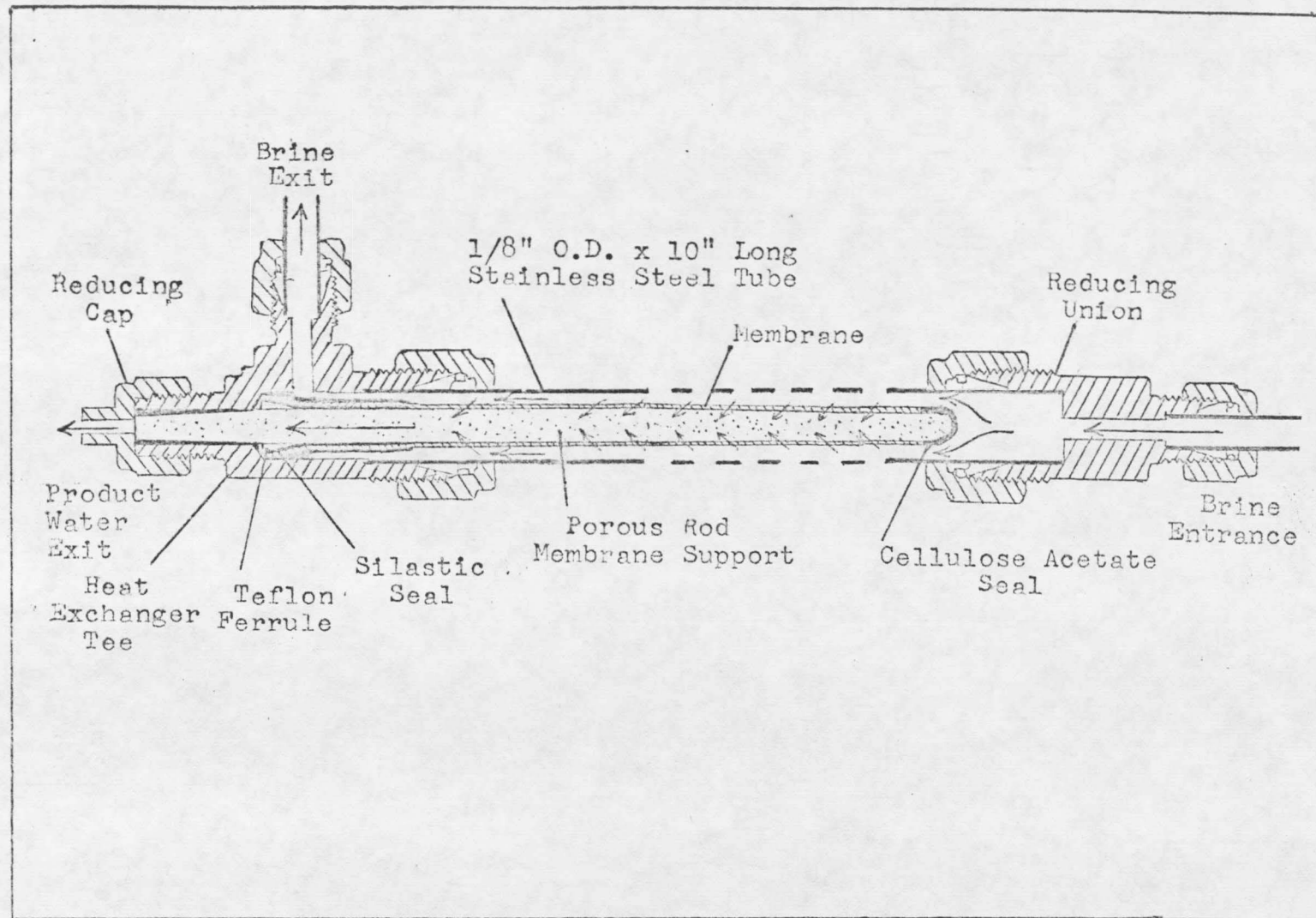


Figure 18. Tubular Test Cell.

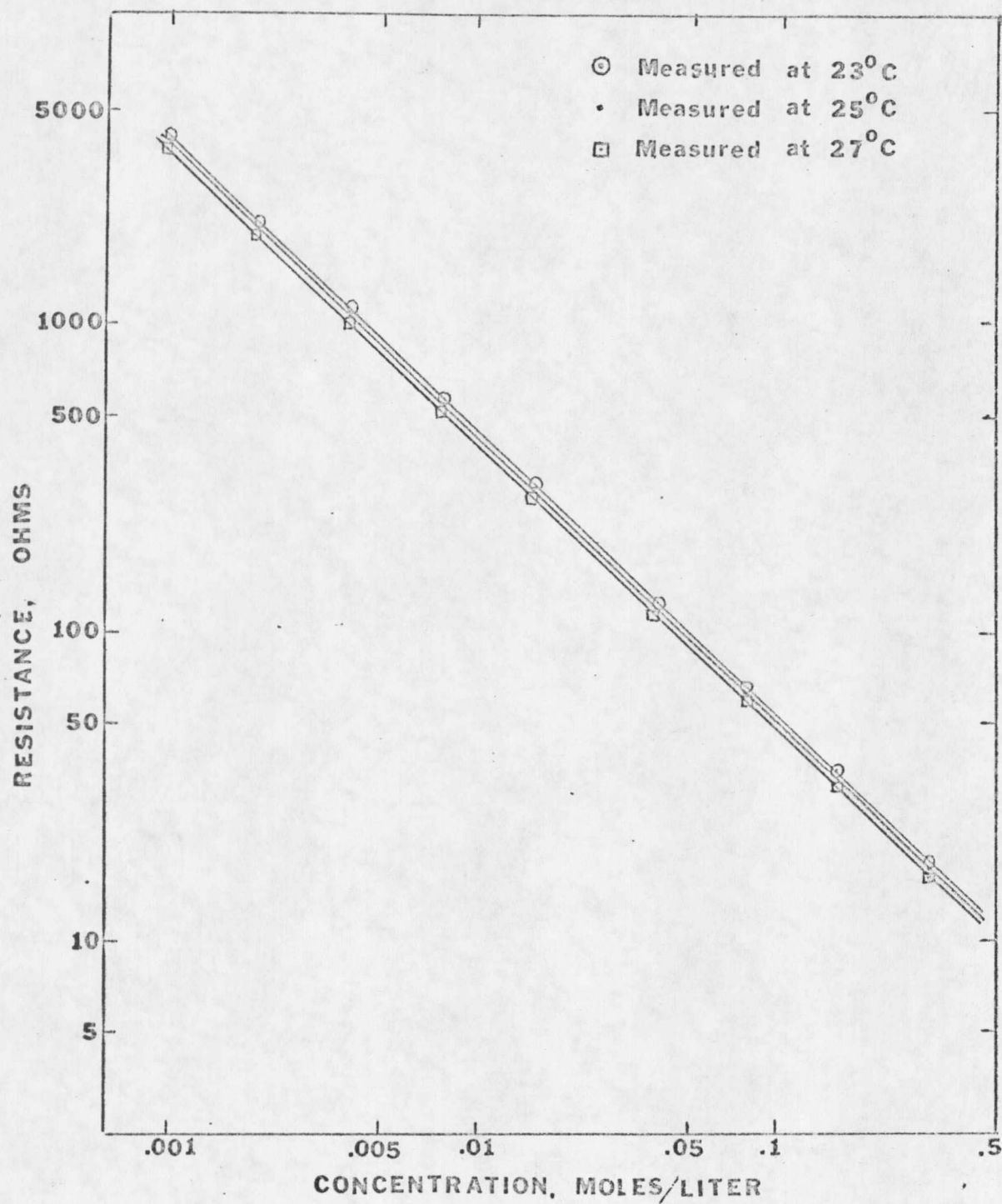


Figure 19. Conductivity Cell Calibration.

Table VI: Summary of Casting Solutions

Casting Solution	Cellulose Acetate Type	Cellulose Acetate (wt.%)	Formamide (wt.%)	Acetone (wt.%)	Viscosity (centipoise)
A	E400-25	21.9	31.2	46.9	*
B	E400-25	14.9	21.3	63.8	3150
C	E400-25	13.5	19.1	67.4	1560
D	E400-25	12.3	17.5	70.2	995
E	E400-25	10.5	14.9	74.6	
F	E398-3	21.9	31.2	46.9	*
G	E398-3	18.9	27.0	54.1	3260
H	E398-3	16.7	23.8	59.5	800
I	E398-3	15.7	22.5	61.8	550
J	E394-60	18.9	27.0	54.1	*
K	E394-60	14.9	21.3	63.8	
L	E394-60	14.1	20.2	65.7	
M	E394-60	13.5	19.1	67.4	2400
N	E394-60	12.8	18.4	68.8	976

*Viscosity not determined, but considered to be quite high.

Table VII: Summary of Support Properties

<u>Support Type</u>	<u>Pore Size</u>	<u>Diameter (inches)</u>	<u>Form</u>	<u>Strength</u>	<u>Other</u>
316 Stainless	0.5 μ	.25	tube	excellent	
Norton RA-4021 Ceramic	unknown; est. 1-5 μ	.3125	rod	excellent	brittle
Norton RA-5021 Ceramic	unknown; est. 1-5 μ	.25	tube	excellent	brittle
Polyethylene	10 μ	.25	rod	excellent	
Polyvinyl- idene Fluoride	25 μ	.25	rod	excellent	swells in acetone

Data for Figure 3

Table VIII: Performance of Membranes Cast on Versapor
Using Dilute Solutions

Solvent Evaporating Time (sec)	Run No.	Water Flux (GSFD)	Percent Salt Rejection
5	V-19	22.0	86.0
	V-20	25.7	87.1
	Avg.	23.9	86.6
10	V-21	23.5	92.5
	V-22	28.2	86.6
	V-23	27.2	88.1
	Avg.	26.3	89.1
20	V-24	21.9	90.5
	V-25	22.9	94.2
	V-26	27.2	88.8
	Avg.	24.0	91.2
30	V-27	24.8	90.8
	V-29	18.6	95.6
	Avg.	21.7	93.2
60	V-31	9.5	95.0
^a 20	V-35	22.8	95.6
	V-38	20.0	96.6
	V-42	20.3	94.5
	V-45	19.3	96.8
	Avg.	20.6	95.9

All membranes prepared using Casting Solution B and a heat treatment temperature of 86°C except as noted.

^aHeat treatment temperature of 88°C.

Data for Figures 4 and 5

Table IX: Effect of Casting Solution Composition and Solvent Evaporation Time on Dip Cast Membranes

<u>Casting Solution</u>	<u>Solvent Evaporating Time (sec)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
B - 14.9:21.3: 63.8*	5	CR-31	11.2	95.6
		CR-32	8.3	96.4
		CR-34	10.1	94.2
		CR-39	10.3	95.7
		CR-40	12.6	95.2
		Avg.	10.5	95.4
	10	CR-190	8.7	96.1
		CR-116	9.2	93.2
		CR-120	8.2	92.1
		Avg.	8.7	93.8
	15	CR-108	7.3	95.4
		CR-125	8.1	94.8
		Avg.	7.7	95.1
	5	CR-66	24.4	63.6
		CR-67	16.4	53.7
		CR-74	14.7	64.4
		CR-75	17.9	76.7
		Avg.	18.3	64.6
C - 13.5:19.2: 67.4	10	CR-186	8.8	93.6
		CR-69	16.9	89.6
		CR-71	10.6	91.4
		Avg.	12.1	91.5
	15	CR-70	11.7	89.6
		CR-72	8.5	95.4
		Avg.	10.1	92.5

* Cellulose acetate:formamide:acetone ratio (wt. percents).

Heat treatment temperature was 86°C for all data.

Table IX (continued)

<u>Casting Solution</u>	<u>Solvent Evaporating Time (sec)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
D - 12.3:17.5: 70.2	15	CR-62	13.0	73.1
		CR-63	17.7	67.0
		CR-64	18.6	62.8
		Avg.	16.8	67.6

Heat treatment temperature was 86°C for all data.

Data for Figure 6

Table X: Effect of Heat Treatment Temperature on the Performance of Dip Cast Membranes

<u>Casting Solution</u>	<u>Heat Treatment Temperature (°C)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
B - 14.9:21.3: 63.8*	75	CR-68	10.3	78.0
		CR-99	10.8	83.9
		CR-100	11.5	83.9
		Avg.	10.9	81.9
	82	CR-52	10.0	95.3
		CR-54	11.1	95.8
		CR-55	10.5	94.5
		Avg.	10.5	95.2
	84	CR-43	9.2	92.0
		CR-44	10.0	95.7
		CR-45	12.2	95.1
		CR-48	11.1	96.9
		CR-49	8.0	96.4
		CR-50	11.5	93.5
		CR-51	7.6	95.5
		Avg.	99.9	95.0
	86	CR-31	11.2	95.6
		CR-32	8.3	96.4
		CR-34	10.1	94.2
		CR-39	10.3	95.7
		CR-40	12.6	95.2
		Avg.	10.5	95.4

* Cellulose acetate:formamide:acetone ratio (wt. percents).
 5-second solvent evaporating time for Casting Solution B
 10-second solvent evaporating time for Casting Solution C

Table X (continued)

<u>Casting Solution</u>	<u>Heat Treatment Temperature (°C)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
C - 13.5:19.2: 67.3	75	CR-83	10.8	86.6
		CR-101	10.6	87.0
		CR-102	12.9	82.5
		Avg.	11.4	85.4
	82	CR-79	11.0	90.1
		CR-80	13.2	91.5
		CR-81	8.1	95.5
		CR-82	10.8	92.3
		Avg.	10.7	92.3
	86	CR-69	16.9	89.6
		CR-71	10.6	91.4
		CR-186	8.8	93.6
		Avg.	12.1	91.5

10-second solvent evaporating time for Casting Solution C.

Data for Figure 7

Table XI: Effect of Cellulose Acetate Type and Acetone Concentration on the Performance of Dip Cast Membranes

<u>Cellulose Acetate Type</u>	<u>Acetone Concentration (wt. percent)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
398-3	54.1	CR-136	7.1	91.5
		CR-139	6.6	92.8
		CR-140	9.4	91.5
		CR-147	7.4	95.9
		Avg.	7.6	92.9
	59.5	CR-137	5.7	96.5
		CR-138	6.5	92.8
		CR-143	9.7	92.3
		CR-144	8.7	94.0
		CR-148	9.0	94.0
		Avg.	7.9	93.9
	61.8	CR-141	10.8	85.0
		CR-142	7.8	86.2
		CR-145	9.8	91.0
		CR-146	8.4	92.3
		Avg.	9.2	88.6
400-25	63.8	CR-31	11.2	95.6
		CR-32	8.3	96.4
		CR-34	10.1	94.2
		CR-39	10.3	95.7
		CR-40	12.6	95.2
		Avg.	10.5	95.4
	67.4	CR-66	24.4	63.6
		CR-67	16.4	53.7
		CR-74	14.7	64.4
		CR-75	17.9	76.7
		Avg.	18.3	64.6

Table XI (continued)

<u>Cellulose Acetate Type</u>	<u>Acetone Concentration (wt. percent)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
394-60	65.7	CR-158	5.0	92.3
		CR-160	3.9	93.3
		CR-161	4.9	93.3
		Avg.	4.6	93.0
	67.4	CR-151	4.9	92.9
		CR-152	6.3	94.1
		CR-153	6.1	94.1
		CR-154	6.7	92.9
		CR-155	6.1	95.4
		Avg.	6.0	93.9
	68.8	CR-156	12.0	64.5
		CR-157	11.3	73.5
		CR-158	10.4	59.0
		Avg.	11.2	65.7

Data for Figure 8

Table XIII: Comparison of Casting Solutions for Extrusion Casting

<u>Casting Solution</u>	<u>Heat Treatment Temperature (°C)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
A - 21.9:31.2: 46.9	75	CR-84	19.4	84.9
		CR-85	22.0	82.5
		CR-86	21.8	80.6
		Avg.	20.7	82.7
	82	CR-8	17.5	85.4
		CR-9	17.3	89.6
		CR-10	16.7	90.9
		CR-11	19.2	85.4
		Avg.	17.7	87.8
	84	CR-13	17.2	91.0
		CR-14	14.5	90.5
		CR-16	16.7	85.0
		CR-18	14.9	89.1
		Avg.	15.8	88.9
	86	CR-20	9.3	89.9
		CR-105	9.3	96.5
		CR-189	10.7	93.6
		Avg.	9.8	93.3
B - 14.9:21.3: 63.8	75	CR-94	20.4	87.4
		CR-95	20.1	90.4
		CR-98	19.5	81.5
		CR-103	17.1	84.5
		Avg.	19.3	86.0
	82	CR-89	11.9	87.6
		CR-90	20.2	88.4
		CR-96	15.4	92.0
		CR-97	27.7	89.1
		Avg.	18.8	89.3
	86	CR-47	17.6	92.6
		CR-91	12.9	92.0
		CR-92	14.4	95.4
		CR-93	12.5	95.4
		Avg.	14.4	93.9

Data for Figure 9

Table XIII: Comparison of the Performance of Extruded and Dip Cast Membranes

<u>Casting Technique</u>	<u>Heat Treatment Temperature (°C)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Extruded	75	CR-94	20.4	87.4
		CR-95	20.1	90.4
		CR-98	19.5	81.5
		CR-103	17.1	84.5
		Avg.	19.3	85.8
	82	CR-89	11.9	87.6
		CR-90	20.2	88.4
		CR-96	15.4	92.0
		CR-97	27.7	89.1
		Avg.	18.8	89.3
	86	CR-47	17.6	92.6
		CR-91	12.9	92.0
		CR-92	14.4	95.4
		CR-93	12.5	95.4
		Avg.	14.4	93.9
Dip Cast	75	CR-68	10.3	78.0
		CR-99	10.8	83.9
		CR-100	11.5	83.9
		Avg.	10.9	81.9
	82	CR-52	10.0	95.3
		CR-54	11.1	95.8
		CR-55	10.5	94.5
		Avg.	10.5	95.2
	84	CR-43	9.2	92.0
		CR-44	10.0	95.7
		CR-45	12.2	95.1
		CR-48	11.1	96.9
		CR-49	8.0	96.4
		CR-50	11.5	93.5
		CR-51	7.6	95.5
		Avg.	9.9	95.0

Table XIII (continued)

<u>Casting Technique</u>	<u>Heat Treatment Temperature (°C)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Dip Cast	86	CR-31	11.2	95.6
		CR-32	8.3	96.4
		CR-34	10.1	94.2
		CR-39	10.3	95.7
		<u>CR-40</u>	<u>12.6</u>	<u>95.2</u>
		Avg.	10.5	95.4

All data is for Casting Solution B, and a 5-second solvent evaporating time; RA-5021 Ceramic Support.

Data for Figure 10

Table XIV: Effect of Solvent Evaporating Time on Dip Cast and Extruded Membranes

<u>Casting Technique</u>	<u>Solvent Evaporating Time</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Dip Cast	5	CR-31	11.2	95.6
		CR-32	8.3	96.4
		CR-34	10.2	94.2
		CR-39	10.3	95.7
		CR-40	12.6	95.2
		Avg.	10.5	95.4
	10	CR-190	8.7	96.1
		CR-116	9.2	93.2
		CR-120	8.2	92.1
		Avg.	8.7	93.8
	15	CR-108	7.3	93.2
		CR-125	8.1	94.8
		Avg.	7.7	95.1
Extruded	5	CR-91	12.9	92.0
		CR-92	14.4	95.4
		CR-93	12.5	95.4
		Avg.	13.3	94.3
	10	CR-22	4.1	96.4
		CR-23	6.5	95.6
		CR-24	5.2	93.7
		Avg.	5.3	95.2

Norton RA-4021 Ceramic Rod, Casting Solution B, and an 86°C heat treatment used for all data.

Detailed Data for Table I

Table XV: Effect of Cellulose Acetate Type on the Performance of Extruded Membranes

<u>Cellulose Acetate Type</u>	<u>Casting Solution</u>	<u>Viscosity (centipoise)</u>	<u>Run No.</u>	<u>Water Flux (GSPD)</u>	<u>Percent Salt Rejection</u>
398-3	F	*	CR-178	7.0	94.6
			CR-182	7.0	91.8
			CR-183	7.8	91.8
			Avg.	7.3	92.7
	G	3260	CR-162	8.0	95.4
			CR-164	9.0	92.5
			CR-187	12.2	91.9
			CR-188	11.2	91.9
			Avg.	10.1	92.9
	H	800	CR-175	10.8	92.4
			CR-176	12.0	94.8
			CR-177	12.2	93.3
			Avg.	11.7	93.5
400-25	A	*	CR-20	9.3	89.9
			CR-105	9.3	96.5
			CR-189	10.7	93.6
			Avg.	9.8	93.3
	B	3150	CR-47	17.6	92.6
			CR-91	12.9	92.0
			CR-92	14.4	95.4
			CR-93	12.5	95.4
			Avg.	14.4	93.9
	C	1560	CR-179	11.0	91.6
			CR-180	8.6	90.5
			CR-181	7.7	91.3
			Avg.	9.1	91.1

* Viscosity not determined but considered to be quite high.

Table XV (continued)

<u>Cellulose Acetate Type</u>	<u>Casting Solution</u>	<u>Viscosity (centipoise)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
394-60	J	*	CR-184	12.6	87.4
			CR-185	13.0	91.2
			Avg.	12.8	89.3
	K	*	CR-169	18.8	94.8
			CR-170	17.7	93.5
			CR-171	14.9	92.8
			Avg.	17.1	93.7
	M	2400	CR-165	17.8	86.9
			CR-166	15.3	87.7
			CR-167	14.9	89.0
			CR-168	21.0	87.9
			Avg.	17.2	87.9

* Viscosity not determined but considered to be quite high.

Data for Figure 11

Table XVI: Comparison of Performance of Membranes Dip Cast on Various Supports

<u>Support Type</u>	<u>Heat Treatment Temperature (°C)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Ceramic	75	CR-68	10.3	78.0
		CR-99	10.8	83.9
		CR-100	11.5	83.9
		Avg.	10.9	81.9
	82	CR-52	10.0	95.3
		CR-54	11.1	95.8
		CR-55	10.5	94.5
		Avg.	10.5	95.2
	84	CR-43	9.2	92.0
		CR-44	10.0	95.7
		CR-45	12.2	95.1
		CR-48	11.1	96.9
		CR-49	8.0	96.4
		CR-50	11.5	93.5
		CR-51	7.6	95.5
		Avg.	9.9	95.0
	86	CR-31	11.2	95.6
		CR-32	8.3	96.4
		CR-34	10.1	94.2
		CR-39	10.3	95.7
		CR-40	12.6	95.2
		Avg.	10.5	95.4
Polyethylene	75	PR-18	11.8	91.3
		PR-19	8.0	86.7
		PR-20	7.2	88.0
		Avg.	9.0	88.7
	82	PR-16	4.7	93.4
		PR-17	4.6	97.3
		PR-29	4.3	91.6
		Avg.	4.5	93.7

Table XVI (continued)

<u>Support Type</u>	<u>Heat Treatment Temperature (°C)</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Polyethylene	86	PR-10	6.0	91.5
		PR-11	6.9	95.4
		PR-12	7.3	96.9
		PR-13	8.0	96.9
		<u>PR-15</u>	<u>8.9</u>	<u>91.2</u>
		Avg.	7.4	94.4
Polyvinylidene Fluoride	75	PFR-22	6.3	89.2
		PFR-23	5.3	89.8
		<u>PFR-24</u>	<u>7.0</u>	<u>89.9</u>
		Avg.	6.2	89.6
	82	PFR-13	5.6	91.7
		<u>PFR-15</u>	<u>5.2</u>	<u>89.9</u>
		Avg.	5.4	90.8
	84			
		PFR-19	4.7	91.1
		PFR-20	4.6	93.4
		<u>PFR-21</u>	<u>5.2</u>	<u>93.4</u>
		Avg.	4.8	92.6
	86			
		PFR-17	4.4	93.6
		PFR-18	4.5	97.5
		<u>PFR-53</u>	<u>5.0</u>	<u>93.0</u>
		Avg.	4.6	94.7

Data for Figure 11

Table XVII: Comparison of Membrane Performance for Membranes Dip Cast on Various Supports Using Various Types of Cellulose Acetate

<u>Support Type</u>	<u>Casting Solution</u>	<u>Run No.</u>	<u>Water Flux (GSTD)</u>	<u>Percent Salt Rejection</u>
Ceramic	B 400-25	CR-31	11.2	95.6
		CR-32	8.3	96.4
		CR-34	10.1	94.2
		CR-39	10.3	95.7
		CR-40	12.6	95.2
		Avg.	10.5	95.4
	G 398-3	CR-133	10.1	93.0
		CR-134	11.0	94.1
		CR-136	7.1	94.5
		CR-139	6.6	92.8
		CR-140	9.4	91.5
		CR-147	7.4	95.9
		Avg.	8.4	93.6
	M 394-60	CR-151	4.9	92.9
		CR-152	6.3	94.1
		CR-153	6.1	94.1
		CR-154	6.7	92.9
		CR-155	6.1	95.4
		Avg.	6.0	93.9
Polyethylene	G 398-3	PR-31	5.7	96.9
		PR-32	5.1	95.1
		PR-33	5.3	96.4
		Avg.	5.4	96.1
	B 400-25	PR-10	6.0	91.5
		PR-11	6.9	95.4
		PR-12	7.3	96.9
		PR-13	8.0	96.9
		PR-15	8.9	91.2
		Avg.	7.4	94.4

Table XVII (continued)

<u>Support Type</u>	<u>Casting Solution</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Polyethylene	M 394-60	PR-34	6.1	92.2
		PR-35	6.9	92.4
		<u>Avg.</u>	<u>6.5</u>	<u>92.3</u>
Polyvinylidene Fluoride	G 398-3	PFR-31	5.1	94.9
		PFR-32	5.2	93.8
		<u>PFR-33</u>	<u>6.0</u>	<u>97.6</u>
		<u>Avg.</u>	<u>5.4</u>	<u>95.4</u>
	B 400-25	PFR-17	4.4	93.6
		PFR-18	4.5	97.5
		<u>PFR-53</u>	<u>5.0</u>	<u>93.0</u>
		<u>Avg.</u>	<u>4.6</u>	<u>94.7</u>
	M 394-60	PFR-39	5.5	94.8
		PFR-40	6.0	91.7
		<u>PFR-41</u>	<u>5.3</u>	<u>89.6</u>
		<u>Avg.</u>	<u>5.6</u>	<u>92.0</u>

Detailed Data for Table IV

Table XVIII: Comparison of Extruded and Dip Cast Membranes for Various Supports and Various Cellulose Acetate Types

<u>Support Type</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Ceramic	G 398-3	Dip Cast	CR-133	10.1	93.0
			CR-134	11.0	94.1
			CR-136	7.1	94.5
			CR-139	6.6	92.8
			CR-140	9.4	91.5
			CR-147	7.4	95.9
			Avg.	8.4	93.6
	G 398-3	Extruded	CR-162	8.0	95.4
			CR-164	9.0	92.5
			CR-187	12.2	91.9
			CR-188	11.2	91.9
			Avg.	10.1	92.9
	B 400-25	Dip Cast	CR-31	11.2	95.6
			CR-32	8.3	96.4
			CR-34	10.1	94.2
			CR-39	10.3	95.7
			CR-40	12.6	95.2
			Avg.	10.5	95.4
	B 400-25	Extruded	CR-47	17.6	92.6
			CR-91	12.9	92.0
			CR-92	14.4	95.4
			CR-93	12.5	95.4
			Avg.	14.4	93.9
	M 394-60	Dip Cast	CR-151	4.9	92.9
			CR-152	6.3	94.1
			CR-153	6.1	94.1
			CR-154	6.7	92.9
			CR-155	6.1	95.4
			Avg.	6.0	93.9

Table XVIII (continued)

<u>Support Type</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
Ceramic	M 394-60	Extruded	CR-165	17.8	86.9
			CR-166	15.3	87.7
			CR-167	14.9	89.0
			<u>CR-168</u>	<u>21.0</u>	<u>87.9</u>
			Avg.	17.2	87.9
Polyethylene	B 400-25	Dip Cast	PR-10	6.0	91.5
			PR-11	6.9	95.4
			PR-12	7.3	96.9
			PR-13	8.0	96.9
			<u>PR-15</u>	<u>8.9</u>	<u>91.2</u>
			Avg.	7.4	94.3
	B 400-25	Extruded	PR-43	9.9	90.8
			PR-44	12.7	91.4
			<u>PR-46</u>	<u>10.5</u>	<u>93.0</u>
			Avg.	11.0	91.7
Polyvinylidene Fluoride	B 400-25	Dip Cast	PFR-17	4.4	93.6
			PFR-18	4.5	97.5
			<u>PFR-53</u>	<u>5.0</u>	<u>93.0</u>
			Avg.	4.6	94.7
	B 400-25	Extruded	PFR-42	9.0	92.0
			PFR-43	7.0	96.0
			<u>PFR-45</u>	<u>7.0</u>	<u>90.7</u>
			Avg.	7.7	92.9

Data for Figure 20

Table XIX: Permeability Data for Porous Supports

<u>Support</u>	<u>Length</u>	<u>Pressure Drop</u>	<u>Flow (ml/sec in²)</u>
Ceramic	3 inches	800 psi	5.45
		600 psi	3.81
		400 psi	2.28
		200 psi	1.00
		100 psi	.44
Polyethylene	3 inches	800 psi	13.50
		600 psi	9.75
		400 psi	6.23
		200 psi	3.20
Polyvinylidene Fluoride	3 inches	800 psi	101.0
		600 psi	74.1
		400 psi	46.0
		200 psi	13.42
		100 psi	4.28

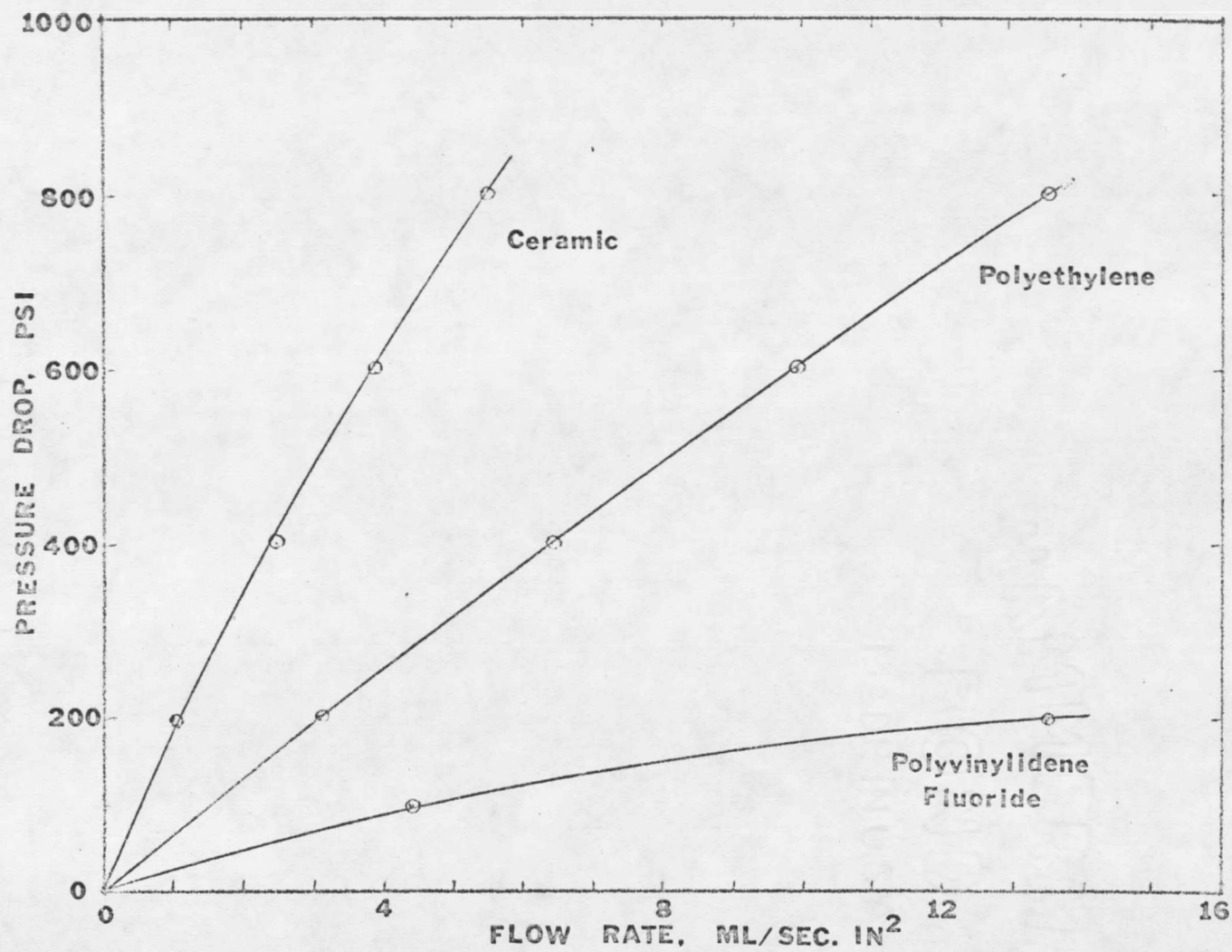
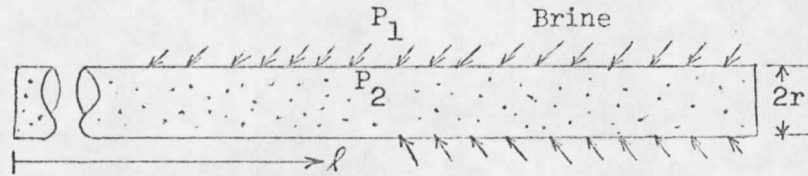


Figure 20. Permeability Data for Various Supports.

Equations Describing Flow, Pressure and Dimension Relationships



Mass Balance $\pi r^2 v = \pi 2r l v'$ (1)

Darcy's Equation for flow through porous media $dp/dl = \frac{\alpha \mu v}{g_c}$ (2)

Reverse Osmosis Equation $v' = A(P_1 - P_2 - \Delta \pi)$ (3)

Differential Equation $\frac{dP_2}{dl} = K_1 l - K_2 P_2$ (4)

$$K_1 = \frac{\alpha \mu 2A (P_1 - \Delta \pi)}{r g_c}$$

$$K_2 = \frac{\alpha \mu 2A}{r g_c}$$

- r = rod diameter (ft)
- v' = water flow through membrane (ft/sec)
- v = water flow through rod (ft/sec)
- l = rod length (ft)
- $1/\alpha$ = permeability coefficient of porous media (ft²)
- μ = viscosity of water (#/ft sec)
- $\Delta \pi$ = osmotic pressure of brine (psi)
- P_1 = brine pressure (psi)
- P_2 = pressure at given point in the rod (psi)
- A = membrane constant (ft³/#sec)
- g_c = constant

Data for Figure 12

Table XX: Pressure Drop as a Function of Length for Various Supports

<u>Support</u>	<u>Rod Diameter</u>	<u>Length</u>	<u>Pressure Drop</u>
Ceramic	1/4 inch	.25 ft.	25 psi
		.50 ft.	95 psi
		1.00 ft.	308 psi
		2.00 ft.	627 psi
	1/8 inch	.25 ft.	49 psi
		.50 ft.	93 psi
		1.00 ft.	480 psi
	1/16 inch	.15 ft.	35 psi
		.25 ft.	95 psi
		.50 ft.	308 psi
Polyethylene	1/4 inch	.25 ft.	9 psi
		.50 ft.	36 psi
		1.00 ft.	134 psi
		2.00 ft.	400 psi
	1/8 inch	.30 ft.	26 psi
		.50 ft.	71 psi
		1.00 ft.	243 psi
		2.00 ft.	569 psi
Polyvinylidene Fluoride	1/4 inch	1.00 ft.	20 psi
		2.00 ft.	77 psi
		4.00 ft.	261 psi
	1/8 inch	1.00 ft.	40 psi
		2.00 ft.	146 psi
		4.00 ft.	424 psi

Data for Figure 13

Table XXI: Effect of Rod Diameter on Membrane Performance

<u>Rod Diameter</u>	<u>Run No.</u>	<u>Water Flux (GSED)</u>	<u>Percent Salt Rejection</u>
5/16 inch	CR-116	9.2	93.2
	CR-120	8.2	92.1
	CR-190	8.7	96.1
	Avg.	8.7	93.8
5/16 inch Sanded Sur- face	CR-121	6.1	91.8
	CR-122	6.5	94.0
	CR-126	12.0	92.9
	CR-191	9.4	93.1
	CR-192	9.0	94.5
	Avg.	8.6	93.3
1/8 inch	CR-107	9.2	95.9
	CR-112	10.9	94.9
	CR-114	7.5	91.6
	Avg.	9.2	94.1
1/16 inch	CR-115	7.3	89.2
	CR-119	4.5	93.9
	CR-123	4.2	94.5
	CR-124	6.7	91.1
	Avg.	5.5	92.2

Casting Solution B, 10-second solvent evaporating time,
and an 86°C heat treatment used for all data.

Table XXII: Effect of Support Length on Membrane Performance

<u>Rod Length</u>	<u>Run No.</u>	<u>Water Flux (GSFD)</u>	<u>Percent Salt Rejection</u>
4 inches	PFR-17	4.4	93.6
	PFR-18	4.5	97.5
	<u>PFR-53</u>	<u>5.0</u>	<u>93.0</u>
	Avg.	<u>4.6</u>	<u>94.7</u>
8 inches	PFR-50	4.8	98.1
	PFR-51	4.2	98.8
	<u>PFR-52</u>	<u>4.1</u>	<u>99.4</u>
	Avg.	<u>4.4</u>	<u>98.7</u>

Table XXIII: Summary of Results for Membranes Cast on 0.9 Micron Versapor Supports

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp., °C</u>	<u>Water^a Flux (GSFD)</u>	<u>%^a Salt Reject.</u>	<u>Comments</u>
V-1	A	Spread	10	86	34.8	74.5	b
V-2	A	Spread	10	86	36.2	73.1	b
V-3	A	Spread	10	86	6.3	96.7	c
V-4	A	Spread	10	86	25.9	88.0	Leak
V-5	A	Spread	10	86	19.9	95.4	
V-6	A	Spread	10	86	18.3	94.8	
V-7	A	Spread	10	86	17.4	95.9	
V-8	A	Spread	10	86	20.9	93.8	
V-9	A	Spread	10	86	20.3	95.9	
V-10	A	Spread	10	86	17.0	97.4	
V-11	A	Spread	10	86	22.6	91.6	
V-12	A	Spread	10	86	23.4	86.4	Leak
V-13	A	Spread	5	86	14.3	98.3	c
V-14	A	Spread	5	86	18.0	97.2	c
V-15	A	Spread	5	86	12.6	97.8	c
V-16	A	Spread	5	86	19.6	96.7	c
V-17	B	Spread	10	86	38.2	77.5	Leak, d
V-18	B	Spread	20	86	26.0	74.3	Leak, d
V-19	B	Spread	5	86	22.0	86.0	

Table XXIII (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp., °C</u>	<u>Water^a Flux (GSFD)</u>	<u>%^a Salt Reject.</u>	<u>Comments</u>
V-20	B	Spread	5	86	25.7	87.1	
V-21	B	Spread	10	86	23.5	92.5	
V-22	B	Spread	10	86	28.2	86.6	
V-23	B	Spread	10	86	27.2	88.1	
V-24	B	Spread	20	86	21.9	90.5	
V-25	B	Spread	20	86	22.9	94.2	
V-26	B	Spread	20	86	27.2	88.8	
V-27	B	Spread	30	86	24.8	90.8	
V-28	B	Spread	30	86	17.8	85.3	Leak
V-29	B	Spread	30	86	18.6	95.6	
V-30	B	Spread	60	86	11.1	76.0	Leak
V-31	B	Spread	60	86	9.5	95.0	
V-32	B	Spread	5	88	23.1	90.5	
V-33	B	Spread	10	88	20.1	92.4	
V-34	B	Spread	10	90	22.5	93.4	
V-35	B	Spread	20	88	22.8	95.6	
V-36	B	Spread	5	88	20.5	93.8	
V-37	B	Spread	10	88	25.1	90.9	
V-38	B	Spread	20	88	20.0	96.6	
V-39	B	Spread	10	90	20.2	93.3	

Table XXIII (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp., °C</u>	<u>Water^a Flux (GSFD)</u>	<u>%^a Salt Reject.</u>	<u>Comments</u>
V-40	B	Spread	5	88	24.2	87.6	
V-41	B	Spread	10	88	25.4	88.7	
V-42	B	Spread	20	88	20.3	94.5	
V-43	B	Spread	10	90	26.2	91.0	
V-44	B	Spread	10	88	24.9	92.4	
V-45	B	Spread	20	88	19.3	96.8	

^aWater Flux and Salt Rejection at 24 hours of operation

^bMembrane cast on wrong side of support

^cImproper heat treatment

^dRuns V-1 to V-18 used .005-inch clearance, Runs V-19 to V-45 used .010-inch clearance.

Table XXIV: Summary of Results for Membranes Cast on 0.5 Micron Porous Tubular Stainless Steel Supports

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp., °C</u>	<u>Water^a Flux (GSFD)</u>	<u>%^a Salt Reject.</u>	<u>Comments</u>
SS-1	D	Dip Cast	10	90	11.5	62.8	Leak ^b
SS-2	D	Dip Cast	20	90	6.8	77.7	Leak ^b
SS-3	B	Dip Cast	60	86	1.2	97.5	
SS-4	B	Dip Cast	30	84	3.7	88.4	
SS-5	B	Dip Cast	20	84	2.9	74.4	Leak
SS-6	B	Dip Cast	20	84	1.2	95.8	
SS-7	B	Dip Cast	10	85	5.0	78.7	Leak
SS-8	B	Dip Cast	10	85	2.3	91.9	
SS-9	D	Dip Cast	20	85	7.5	70.0	Leak ^b
SS-10	D	Dip Cast	20	85	2.0	83.4	^b

^aWater Flux and Salt Rejections at six hours of operation

^bFlow structure observed -- probable cause of leaks

Table XXV: Summary of Results for Membranes Cast on Norton RA-5021 Ceramic Tubes

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water^a Flux (GSFD)</u>	<u>%^a Salt Reject.</u>	<u>Comments</u>
CT-1	D	Dip Cast	15	88	10.1	88.9	
CT-2	E	Dip Cast	20	86	9.4	82.1	
CT-3	E	Dip Cast	15	85	12.6	73.9	
CT-4	E	Dip Cast	30	85	6.2	83.0	
CT-5	D	Dip Cast	30	88	15.6	87.6	
CT-6	D	Dip Cast	30	88	15.5	87.6	
CT-7	D	Dip Cast	30	88	13.7	85.0	
CT-8	B	Dip Cast	30	88	5.2	94.3	
CT-9	B	Dip Cast	30	88	3.0	95.0	
CT-10	B	Dip Cast	15	88	3.5	96.7	
CT-11	B	Dip Cast	15	85	2.6	91.0	
CT-12	B	Dip Cast	15	85	2.5	90.4	
CT-13	B	Dip Cast	15	85	1.4	91.5	
CT-14	D	Dip Cast	15	90	3.5	94.4	
CT-15	D	Dip Cast	15	90	6.0	97.8	
CT-16	E	Dip Cast	10	88	8.8	78.0	
CT-17	E	Dip Cast	10	88	5.0	90.5	
CT-18	E	Dip Cast	10	88	13.8	64.6	

^aWater Flux and Salt Rejections at six hours of operation

Table XXVI: Summary of Results for Membranes Cast on Norton RA-4021 Ceramic Rods

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Solution</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water^a Flux (GSFD)</u>	<u>%^a Salt Reject.</u>	<u>Comments</u>
CR-1	A	Extruded	20	85	9.0	93.2	
CR-2	A	Extruded	20	85	7.2	95.0	
CR-3	B	Extruded	15	82	5.6	75.7	Leak
CR-4	B	Extruded	15	82	6.9	84.1	
CR-5	B	Extruded	15	82	7.3	84.1	
CR-6	A	Extruded	10	84	8.9	90.5	
CR-7	A	Extruded	5	85	16.4	94.7	
CR-8	A	Extruded	5	82	17.5	85.4	
CR-9	A	Extruded	5	82	17.3	89.6	
CR-10	A	Extruded	5	82	16.7	90.9	
CR-11	A	Extruded	5	82	19.2	85.4	
CR-12	A	Extruded	5	82	23.0	89.6	
CR-13	A	Extruded	5	84	17.2	91.0	
CR-14	A	Extruded	5	84	14.5	90.5	
CR-15	A	Extruded	5	84	21.2	87.9	
CR-16	A	Extruded	5	84	16.7	85.0	
CR-17	A	Extruded	5	84	10.2	87.1	

^aWater Flux and Salt Rejections at six hours of operation

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-18	A	Extruded	5	84	14.9	89.1	
CR-19	A	Extruded	5	86	5.9	86.8	
CR-20	A	Extruded	5	86	9.3	89.9	
CR-21	B	Extruded	10	86	8.2	90.9	Extruded Warm
CR-22	B	Extruded	10	86	4.1	96.4	
CR-23	B	Extruded	10	86	6.5	95.6	
CR-24	B	Extruded	10	86	5.2	93.7	
CR-25	B	Extruded	10	86	4.5	96.5	a
CR-26	B	Extruded	10	86	4.7	89.4	a
CR-27	B	Dip Cast	5	86	3.6	89.3	a
CR-28	B	Dip Cast	5	86	7.6	93.4	a
CR-29	B	Dip Cast	5	86	3.9	76.5	a
CR-30	B	Dip Cast	5	86	---	30.0	a
CR-31	B	Dip Cast	5	86	11.2	95.6	
CR-32	B	Dip Cast	5	86	8.3	96.4	
CR-33	B	Extruded	5	86	5.7	92.9	
CR-34	B	Dip Cast	5	86	10.1	94.2	

^a Warm 45°C Casting Solution Used

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-35	B	Dip Cast	5	86	8.1	85.1	a
CR-36	B	Extruded	5	86	6.4	94.6	
CR-37	B	Extruded	5	86	7.6	95.4	
CR-38	B	Extruded	5	86	5.3	96.9	a
CR-39	B	Dip Cast	5	86	10.3	95.7	
CR-40	B	Dip Cast	5	86	12.6	95.2	
CR-41	B	Extruded	5	86	4.0	87.3	a
CR-42	B	Extruded	5	86	9.6	93.1	a
CR-43	B	Dip Cast	5	84	9.2	92.0	
CR-44	B	Dip Cast	5	84	10.0	95.7	
CR-45	B	Dip Cast	5	84	12.2	95.1	
CR-46	B	Extruded	5	86	25.2	88.4	
CR-47	B	Extruded	5	86	17.6	92.6	
CR-48	B	Dip Cast	5	84	11.1	96.9	
CR-49	B	Dip Cast	5	84	8.0	96.4	
CR-50	B	Dip Cast	5	84	11.5	93.1	
CR-51	B	Dip Cast	5	84	7.6	95.5	

^a Warm 45°C Casting Solution used

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-52	B	Dip Cast	5	82	10.0	95.3	
CR-53	B	Dip Cast	5	82	4.5	95.9	
CR-54	B	Dip Cast	5	82	11.1	95.8	
CR-55	B	Dip Cast	5	82	10.5	94.5	
CR-56	B	Dip Cast	5	82	9.4	83.8	Leak
CR-57	B	Dip Cast	5	82	5.3	92.1	a
CR-58	B	Dip Cast	5	82	5.3	94.0	a
CR-59	B	Dip Cast	5	75	16.2	85.5	
CR-60	B	Dip Cast	5	None	42.2	38.8	2-hr data
CR-61	B	Dip Cast	5	None	52.5	33.0	2-hr data
CR-62	D	Dip Cast	15	86	13.0	73.1	
CR-63	D	Dip Cast	15	86	17.7	67.0	
CR-64	D	Dip Cast	15	86	18.6	62.8	
CR-65	C	Dip Cast	5	86	21.9	63.6	
CR-66	C	Dip Cast	5	86	24.4	63.6	
CR-67	C	Dip Cast	5	86	16.4	53.7	
CR-68	B	Dip Cast	5	75	10.3	78.0	
CR-69	C	Dip Cast	10	86	16.9	89.6	

^aDry Support Used

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-70	C	Dip Cast	15	86	11.7	89.6	
CR-71	C	Dip Cast	10	86	10.6	91.4	
CR-72	C	Dip Cast	15	86	8.5	95.4	
CR-73	C	Dip Cast	15	86	2.2	81.5	Leak
CR-74	C	Dip Cast	5	86	14.7	64.4	
CR-75	C	Dip Cast	5	86	17.9	76.7	
CR-76	C	Dip Cast	10	82	6.6	95.2	
CR-77	C	Dip Cast	10	82	6.1	84.4	Slight Leak
CR-78	C	Dip Cast	10	75	20.0	87.8	
CR-79	C	Dip Cast	10	82	11.0	90.1	
CR-80	C	Dip Cast	10	82	13.2	91.5	
CR-81	C	Dip Cast	10	82	8.1	95.5	
CR-82	C	Dip Cast	10	82	10.8	92.3	
CR-83	C	Dip Cast	10	75	10.8	86.6	
CR-84	A	Extruded	5	75	19.4	84.9	
CR-85	A	Extruded	5	75	22.0	82.5	
CR-86	A	Extruded	5	75	21.8	80.6	
CR-87	A	Extruded	2	75	27.1	75.2	

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-88	A	Extruded	2	75	22.2	77.6	
CR-89	B	Extruded	5	82	11.9	87.6	
CR-90	B	Extruded	5	82	20.2	88.4	
CR-91	B	Extruded	5	86	12.9	92.0	
CR-92	B	Extruded	5	86	14.4	95.4	
CR-93	B	Extruded	5	86	12.5	95.4	
CR-94	B	Extruded	5	75	20.4	87.4	
CR-95	B	Extruded	5	75	20.1	90.4	
CR-96	B	Extruded	5	82	15.4	92.0	
CR-97	B	Extruded	5	82	27.7	89.1	
CR-98	B	Extruded	5	75	19.5	81.5	
CR-99	B	Dip Cast	5	75	10.8	83.9	
CR-100	B	Dip Cast	5	75	11.5	83.9	
CR-101	C	Dip Cast	10	75	10.6	87.0	
CR-102	C	Dip Cast	10	75	12.9	82.5	
CR-103	B	Extruded	5	75	17.1	84.5	
CR-104	C	Dip Cast	10	86	18.1	95.0	1/8" Rod
CR-105	A	Extruded	5	86	9.3	96.5	

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-106	B	Dip Cast	10	86	6.3	94.1	
CR-107	B	Dip Cast	10	86	9.2	95.9	
CR-108	B	Dip Cast	15	86	7.3	95.4	
CR-109	B	Dip Cast	10	86	11.2	90.6	1/8" Rod
CR-110	B	Dip Cast	10	86	13.8	95.9	
CR-111	B	Dip Cast	10	86	14.1	88.6	2-hr data
CR-112	B	Dip Cast	10	86	10.9	94.9	1/8" Rod
CR-113	B	Dip Cast	10	86	13.1	88.6	Leak
CR-114	B	Dip Cast	10	86	7.5	91.6	1/8" Rod
CR-115	B	Dip Cast	10	86	7.3	89.2	1/16" Rod
CR-116	B	Dip Cast	10	86	9.2	93.2	
CR-117	B	Dip Cast	10	86	13.0	95.6	Sanded
CR-118	B	Dip Cast	10	86	7.4	90.1	Sanded Pinholes
CR-119	B	Dip Cast	10	86	4.5	93.9	1/16" Rod
CR-120	B	Dip Cast	10	86	8.2	92.1	
CR-121	B	Dip Cast	10	86	6.1	91.8	Sanded
CR-122	B	Dip Cast	10	86	6.5	94.0	Sanded
CR-123	B	Dip Cast	10	86	4.2	94.5	1/16" Rod
CR-124	B	Dip Cast	10	86	6.7	91.1	1/16" Rod

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-125	B	Dip Cast	15	86	8.1	94.8	
CR-126	B	Dip Cast	10	86	12.0	92.9	Sanded
CR-127	B	Dip Cast	5	84	11.4	95.2	10 Day Run
CR-128	B	Dip Cast	15	86	7.3	94.0	
CR-129		Dip Cast	10	86	5.4	33.4	Flow Structure
CR-130		Dip Cast	10	86	3.5	43.1	"
CR-131	F	Dip Cast	5	86	6.9	93.0	Glob
CR-132	F	Dip Cast	5	86	4.0	93.0	Glob
CR-133	G	Dip Cast	10	86	10.1	93.0	
CR-134	G	Dip Cast	10	86	11.0	94.1	
CR-135	G	Dip Cast	5	86	5.6	91.5	1/16" Rod
CR-136	G	Dip Cast	5	86	7.1	94.5	
CR-137	H	Dip Cast	5	86	5.7	96.5	
CR-138	H	Dip Cast	5	86	6.5	92.8	
CR-139	G	Dip Cast	5	86	6.6	92.8	
CR-140	G	Dip Cast	5	86	9.4	91.5	
CR-141	I	Dip Cast	5	86	10.8	85.0	
CR-142	I	Dip Cast	5	86	6.8	86.2	

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-143	H	Dip Cast	10	86	9.7	92.3	
CR-144	H	Dip Cast	5	86	8.7	94.0	
CR-145	I	Dip Cast	5	86	9.8	91.0	
CR-146	I	Dip Cast	5	86	8.4	92.3	
CR-147	G	Dip Cast	5	86	7.4	95.9	
CR-148	H	Dip Cast	5	86	9.0	94.0	
CR-149	H	Dip Cast	10	86	6.6	92.5	
CR-150	H	Dip Cast	10	86	6.4	92.5	
CR-151	M	Dip Cast	5	86	4.9	92.9	
CR-152	M	Dip Cast	5	86	6.3	94.1	
CR-153	M	Dip Cast	5	86	6.1	94.1	
CR-154	M	Dip Cast	5	86	6.7	92.9	
CR-155	M	Dip Cast	5	86	6.1	95.4	
CR-156	N	Dip Cast	5	86	12.0	64.5	
CR-157	N	Dip Cast	5	86	11.3	74.3	
CR-158	N	Dip Cast	5	86	10.4	59.0	
CR-159	L	Dip Cast	5	86	5.0	92.3	
CR-160	L	Dip Cast	5	86	3.9	93.3	

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-161	L	Dip Cast	5	86	4.9	93.9	
CR-162	G	Extruded	5	86	8.0	95.4	
CR-163	G	Extruded	5	86	16.0	94.8	
CR-164	G	Extruded	5	86	9.0	92.5	
CR-165	M	Extruded	5	86	17.8	86.9	
CR-166	M	Extruded	5	86	15.3	87.7	
CR-167	M	Extruded	5	86	14.9	89.0	
CR-168	M	Extruded	5	86	21.0	87.9	
CR-169	K	Extruded	5	86	18.8	94.8	
CR-170	K	Extruded	5	86	17.7	93.5	
CR-171	K	Extruded	5	86	14.9	92.8	
CR-172	B	Extruded	5	84	16.3	95.8	30 Day Run
CR-173	E	Dip Cast	15	86	10.2	42.5	2 Dips
CR-174	E	Dip Cast	15	86	10.1	53.1	4 Dips
CR-175	H	Extruded	5	86	10.8	92.4	
CR-176	H	Extruded	5	86	12.0	94.8	
CR-177	H	Extruded	5	86	12.2	93.3	
CR-178	F	Extruded	5	86	7.0	94.6	
CR-179	C	Extruded	5	86	11.1	91.6	

Table XXVI (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
CR-180	C	Extruded	5	86	8.6	90.5	
CR-181	C	Extruded	5	86	7.7	91.3	
CR-182	F	Extruded	5	86	7.0	91.8	
CR-183	F	Extruded	5	86	7.8	91.8	
CR-184	J	Extruded	5	86	12.6	87.4	
CR-185	J	Extruded	5	86	13.0	91.2	
CR-186	C	Dip Cast	10	86	8.8	93.6	
CR-187	G	Extruded	5	86	12.2	91.9	
CR-188	G	Extruded	5	86	11.2	91.9	
CR-189	A	Extruded	5	86	10.7	93.6	
CR-190	B	Dip Cast	10	86	8.7	96.1	
CR-191	B	Dip Cast	10	86	9.4	93.1	
CR-192	B	Dip Cast	10	86	9.0	94.5	
CR-193	B	Extruded	5	84	17.4	94.3	10 Day Run
CR-194	B	Dip Cast	5	84	10.1	96.2	10 Day Run

Table XXVII: Summary of Results for Membranes Cast on Porous Polyethylene Rods

Run No.	Casting Solution	Casting Technique	Solv. Evap. Time, sec.	Heat Treat. Temp, °C	Water ^a Flux (GSFD)	% ^a Salt Reject.	Comments
PR-1	A	Extruded	20	86	3.5	97.5	
PR-2	A	Extruded	5	82	6.2	91.5	
PR-3	A	Extruded	5	82	3.2	94.3	
PR-4	A	Extruded	5	82	2.7	81.6	Leak Probable
PR-5	A	Extruded	5	82	6.5	67.9	Leak
PR-6	B	Dip Cast	10	86	2.5	63.5	Warm Dip
PR-7	B	Extruded	10	86	2.0	94.4	45°C
PR-8	B	Extruded	10	86	3.7	94.0	
PR-9	B	Dip Cast	5	86	2.2	95.1	
PR-10	B	Dip Cast	5	86	6.0	91.5	
PR-11	B	Dip Cast	5	86	6.9	95.4	
PR-12	B	Dip Cast	5	86	7.3	96.9	
PR-13	B	Dip Cast	5	86	8.0	96.9	
PR-14	B	Dip Cast	5	86	4.0	87.4	
PR-15	B	Dip Cast	5	86	8.9	91.2	

^aWater Flux and Salt Rejection at six hours of operation

Table XXVII (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
PR-16	B	Dip Cast	5	82	4.7	93.4	
PR-17	B	Dip Cast	5	82	4.6	97.3	
PR-18	B	Dip Cast	5	75	11.8	91.3	
PR-19	B	Dip Cast	5	75	8.0	86.7	
PR-20	B	Dip Cast	5	75	7.2	88.0	
PR-21	C	Dip Cast	15	86	4.3	94.5	
PR-22	C	Dip Cast	15	86	3.1	92.5	
PR-23	C	Dip Cast	5	86	11.6	88.9	
PR-24	C	Dip Cast	10	86	5.6	90.2	
PR-25	C	Dip Cast	5	86	6.3	82.6	Leak
PR-26	C	Dip Cast	10	86	5.4	96.5	
PR-27	C	Dip Cast	5	86	23.2	62.9	Leak
PR-28	B	Dip Cast	5	82	10.4	92.3	
PR-29	B	Dip Cast	5	82	4.3	91.6	
PR-30	B	Dip Cast	5	82	7.3	90.5	
PR-31	G	Dip Cast	5	86	5.7	96.9	Dry
PR-32	G	Dip Cast	5	86	5.1	95.1	Dry
PR-33	G	Dip Cast	5	86	5.3	96.4	Dry

Table XXVII (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
PR-34	M	Dip Cast	5	86	6.1	92.2	
PR-35	M	Dip Cast	5	86	7.0	92.4	
PR-36	G	Dip Cast	5	86	5.0	91.5	Wet
PR-37	M	Dip Cast	5	86	6.9	92.1	
PR-38	G	Dip Cast	5	86	6.1	93.4	Wet
PR-39	G	Dip Cast	5	86	6.1	97.0	Wet
PR-40	B	Extruded	5	86	6.0	91.5	Small Pinholes
PR-41	B	Extruded	5	86	5.7	92.0	
PR-42	B	Extruded	5	86	8.8	92.1	
PR-43	B	Extruded	5	86	9.9	90.8	Predipped
PR-44	B	Extruded	5	86	12.7	91.4	Predipped
PR-45	B	Extruded	5	86	10.5	93.0	Predipped

Table XXVIII: Summary of Results for Membranes Cast on Porous Polyvinylidene Fluoride Supports.

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water^a Flux (GSFD)</u>	<u>%^a Salt Reject.</u>	<u>Comments</u>
PFR-1	A	Extruded	5	82	7.0	91.2	
PFR-2	A	Extruded	5	82	7.3	86.0	
PFR-3	A	Extruded	5	82	7.8	87.1	
PFR-4	A	Extruded	5	82	12.6	62.4	Leak Probable
PFR-5	A	Extruded	5	82	8.4	84.1	
PFR-6	A	Extruded	5	82	7.4	89.4	
PFR-7	B	Extruded	10	86	4.8	89.9	
PFR-8	B	Dip Cast	5	86	4.2	94.3	Warm Dip 45°C
PFR-9	D	Dip Cast	30	86	4.6	85.5	
PFR-10	D	Dip Cast	30	86	12.6	61.9	Leak
PFR-11	C	Dip Cast	10	86	9.3	93.9	
PFR-12	C	Dip Cast	15	86	7.0	92.6	
PFR-13	B	Dip Cast	5	82	5.6	91.7	

^aWater Flux and Salt Rejection at six hours of operation

Table XXVIII (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
PFR-14	B	Dip Cast	5	82	3.2	91.6	2-hr data Leak started
PFR-15	B	Dip Cast	5	82	5.2	89.9	
PFR-16	B	Dip Cast	5	86	7.2	90.6	
PFR-17	B	Dip Cast	5	86	4.4	93.6	
PFR-18	B	Dip Cast	5	86	4.5	97.5	
PFR-19	B	Dip Cast	5	84	4.7	91.1	
PFR-20	B	Dip Cast	5	84	4.6	93.4	
PFR-21	B	Dip Cast	5	84	5.2	93.4	
PFR-22	B	Dip Cast	5	75	6.3	89.2	
PFR-23	B	Dip Cast	5	75	5.3	89.8	
PFR-24	B	Dip Cast	5	75	7.0	89.9	
PFR-25	B	Dip Cast	5	a	11.9	83.5	
PFR-26	B	Dip Cast	5	a	9.3	81.6	

^aNo heat treatment.

Table XXVIII (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
PFR-27	B	Dip Cast	5	86	5.4	94.2	
PFR-28	B	Dip Cast	5	86	5.8	92.9	
PFR-29	G	Dip Cast	5	86	4.6	94.9	Dry
PFR-30	G	Dip Cast	5	86	4.7	93.8	Dry
PFR-31	G	Dip Cast	5	86	5.1	94.9	Wet
PFR-32	G	Dip Cast	5	86	5.2	93.8	Wet
PFR-33	G	Dip Cast	5	86	5.9	97.6	Wet
PFR-34	G	Dip Cast	5	86	3.5	79.5	Non-Aqua Coated
PFR-35	G	Dip Cast	5	86	3.1	79.8	Non-Aqua Coated
PFR-36	G	Dip Cast	5	86	2.3	81.3	
PFR-37	G	Dip Cast	5	86	4.8	95.5	Dry
PFR-38	G	Dip Cast	5	86	8.9	92.6	Detergent Washed
PFR-39	M	Dip Cast	5	86	5.5	94.8	
PFR-40	M	Dip Cast	5	86	6.0	91.7	

Table XXVIII (continued)

<u>Run No.</u>	<u>Casting Solution</u>	<u>Casting Technique</u>	<u>Solv. Evap. Time, sec.</u>	<u>Heat Treat. Temp, °C</u>	<u>Water Flux (GSFD)</u>	<u>% Salt Reject.</u>	<u>Comments</u>
PFR-41	M	Dip Cast	5	86	5.3	89.6	
PFR-42	B	Extruded	5	86	9.0	92.0	Predipped
PFR-43	B	Extruded	5	86	7.0	96.0	Predipped
PFR-44	B	Extruded	5	86	7.0	82.9	Untreated
PFR-45	B	Extruded	5	86	7.0	90.7	Predipped
PFR-46	B	Extruded	5	86	9.7	85.6	Untreated
PFR-47	G	Dip Cast	5	86	6.2	91.0	Detergent Washed
PFR-48	G	Dip Cast	5	86	5.4	97.5	Detergent Washed
PFR-49	G	Dip Cast	5	86	5.0	93.1	Detergent Washed
PFR-50	B	Dip Cast	5	86	4.9	98.1	Long Rod
PFR-51	B	Dip Cast	5	86	4.2	98.8	Long Rod
PFR-52	B	Dip Cast	5	86	4.1	99.4	Long Rod
PFR-53	B	Dip Cast	5	86	5.0	93.0	

LITERATURE CITED

1. Blunk, R. W., "A Study of Criteria for the Semipermeability of Cellulose Acetate Membranes to Aqueous Solution", UCLA Department of Engineering Report: 64-28 (1964).
2. Bray, Donald T., et al, "Design Study of a Reverse Osmosis Plant for Sea Water Conversion", Research and Development Progress Report No. 176, Interior Department, Office of Saline Water, (1967).
3. Breton, E. J., "Water and Ion Flow Through Imperfect Osmosis Membranes", Ph.D. Thesis, University of Florida, 1957.
4. Cantor, P. A., et al, "Biological Degradation of Cellulose Acetate Reverse Osmosis Membranes", Quarterly Report to the Office of Saline Water No. 1144-01-1, (1967).
5. Channabasappa, K. C., et al, 1967 Saline Water Conversion Report, Membrane Division, U. S. Office of Saline Water, (1968).
6. Channabasappa, K. C., et al, 1968 Saline Water Conversion Report, Membrane Division, U. S. Office of Saline Water, (1969).
7. Dobry, A., Bull. Soc. Chem. France, 5e S'erie, III, 312 (1936).
8. Ennis, Charles E., "Desalted Water as a Competitive Commodity", Chemical Engineering Progress, Vol. 63, No. 1, p. 54, (1967).
9. Flowers, L. C., et al, "Reverse Osmosis Membranes Containing Graphitic Oxide", Final Report to the Office of Saline Water, Contract No. 14-01-0001-550, (1969).
10. Lai, J. Y., "Development of Reverse Osmosis Membranes Cast Directly on Various Support Materials", M.S. Thesis, Montana State University, Bozeman, Montana, 1969.
11. Littman, F. E., and G. A. Guter, "Research on Porous Glass Membranes for Reverse Osmosis", Missile and Space Systems Division Astropower Laboratory, Douglas Aircraft Company, Quarterly Report to OSW under Contract 14-01-0001-1282, January, 1968.
12. Loeb, S., "Sea Water Demineralization by Means of a Semipermeable Membrane", UCLA Department of Engineering Report: 62-26 (1962).

13. Loeb, S., and S. Sourirajan, UCLA Department of Engineering Report No. 60-60, Los Angeles, California, 1960.
14. Loeb, S., and S. Sourirajan, Advan. Chem. Ser. 38, 117 (1962).
15. Manjikian, S., S. Loeb, and J. W. McCutchan, Proc. First Intn'l Desalination Symp., Paper SWD/12, Washington, D. C., Oct. 3-9, 1965.
16. Mattson, R. J., and V. J. Tomsic, "Improved Water Quality", Chemical Engineering Progress, Vol. 65, No. 1, p. 62, (1969).
17. Mertin, U., Editor, (Reid, C. E., 1.4 12; Brian, P.L.T., 5.2 178) Desalination by Reverse Osmosis, The MIT Press, Cambridge, Mass., 1966.
18. Reid, C. E., and E. J. Breton, J. Appl. Polymer Sci. L, 133 (1959).
19. Riley, R. L., and H. K. Lonsdale, "Development of Ultrathin Membranes", Gulf Feneral Atomic Incorporated, Quarterly Report to OSW under Contract No. 14-01-0001-1242, Jan. 31, 1968.
20. Saltonstall, C. W., et al, "Research and Development of New and Improved Cellulose Ester Membranes", Report No. 3343-01-1 to the Office of Saline Water, (1968).
21. Sharples, A., and G. Thomson, "New Synthetic Membranes for Reverse Osmosis Desalination", Arthur D. Little Research Institute, Final Report to OSW under Contract No. 14-01-0001-741, October, 1967.
22. Sourirajan, S., IEC Fundamentals 2, 51 (1963).
23. Spiegler, K. S., "Principles of Desalination", Academic Press, New York, (1966).
24. Wang, D. G., "Membranes for Reverse Osmosis Desalination by Direct Casting on Porous Supports", Ph.D. Thesis, Montana State University, Bozeman, Montana, 1968.

MONTANA STATE UNIVERSITY LIBRARIES



3 1762 10010733 1

D378

C836 Coverdell, Darrel Eugene
cop.2 Porous cylindrical
media as supports for
reverse osmosis desalin-
ation membranes

NAME AND ADDRESS

2 WEEKS USE

INTERLIBRARY LOAN

12/1/58

1621 W College, #29 G-4213
LORI MARTINSON

D378

C836

cop. 2