The fluidized bed as a turbulence promoter in the reverse osmosis desalination process
by Juin-yih Lai

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

Abstract:
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At this time, total cost for desalinated water by the reverse osmosis process is still high, mainly due to the low flux obtained and the short membrane life. The purpose of this research was to determine the feasibility of using a fluidized bed to improve the performance and hence to decrease the product cost of reverse osmosis desalination. Five different sizes of glass beads and six different kinds of membranes' have been tested under a variety of conditions in l4l runs. A brief economic study was also made.

A glass bead size of approximately 0.018,5-inch diameter appears best for this fluidized bed in the brine flow velocity range between 0.57 and 0.97 cm/sec. The significance of using the fluidized bed with these glass beads was to increase the salt rejection and to increase the water flux by 21.7 to 35.8% for nylon supported membranes. The most significant effects were on membranes where concentration polarization was the greatest.

It was determined that different membrane positions and cell geometry affected the performance of the membranes.. The flux decline with time for cellulose acetate membranes on nylon supports was greatly decreased.

A study conducted on scale formation shows that by employing a fluidized bed system with a scale-forming feed, both the water flux and membrane life are significantly improved. In view of the economics, the most significant effect of using the fluidized bed is to decrease the considerable cost of membrane replacement.

THE FLUIDIZED BED AS A TURBULENCE PROMOTER IN THE REVERSE OSMOSIS DESALINATION PROCESS

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of

DOCTOR OF PHILOSOPHY

in

Chemical Engineering

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Bozeman, Montana

June, 1971

ACKNOWLEDGMENT

The author wishes to thank the staff of the Chemical Engineering Department of Montana State University for their advice and assistance during the course of his research project. Special thanks go to Professor Robert L. Nickelson, with whose direction, assistance and encouragement this research program was carried out. Thanks are also due to professors Lloyd Berg, Michael J. Schaer, F. P. McCandless, B. L. McAllister, and Thomas Hanson, who have served on his graduate committee. The assistance given by John Sikonia in the preparation of the first draft of this thesis is gratefully acknowledged.

For her cheerful encouragement and continuous support throughout this endeavor, much credit is due to my wife, Ching-chih.

Financial support from Montana State University has been very useful and is greatly appreciated.

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ABSTRACT

The reverse osmosis process is characterized by the use of pressure in excess of osmotic pressure to force fresh water at ambient temperature through a selective membrane capable of rejecting dissolved salts. It is a technically feasible process with good thermodynamic efficiency, flexibility, and simplicity.

At this time, total cost for desalinated water by the reverse osmosis process is still high, mainly due to the low flux obtained and the short membrane life. The purpose of this research was to determine the feasibility of using a fluidized bed to improve the performance and hence to decrease the product cost of reverse osmosis desalination. Five different sizes of glass beads and six different kinds of membranes have been tested under a variety of conditions in 141 runs. A brief economic study was also made.

A glass bead size of approximately 0.0185-inch diameter appears best for this fluidized bed in the brine flow velocity range between 0.57 and 0.97 cm/sec. The significance of using the fluidized bed with these glass beads was to increase the salt rejection and to increase the water flux by 21.7 to 35.8% for nylon supported membranes. The most significant effects were on membranes where concentration polarization was the greatest.

It was determined that different membrane positions and cell geometry affected the performance of the membranes. The flux decline with time for cellulose acetate membranes on nylon supports was greatly decreased.

A study conducted on scale formation shows that by employing a fluidized bed system with a scale-forming feed, both the water flux and membrane life are significantly improved. In view of the economics, the most significant effect of using the fluidized bed is to decrease the considerable cost of membrane replacement.

I. INTRODUCTION

The water problem--the problem of how to have water in adequate quantity and of adequate quality, available at a reasonable cost, when and where needed--is one of worldwide importance.

A new conventional source of water may be developed today for a cost of 13 cents to 70 cents per thousand gallons. It is estimated that by 1980 this cost will have risen to 20 cents to 90 cents per thousand gallons (7). In terms of improvements in technology and/or equipment for conventional sources of water, there is little potential for cost reduction. Clearly, desalination will be a part of the solution of the total water problem.

Many processes have been tried for desalination. Some of them have been used in actual large desalination plants in many countries. Those are: multistage flash distillation, electrodialysis (brackish water only), vapor compression distillation, direct freezing, and reverse osmosis.

Saline water conversion is still in its infancy; therefore the cost of desalination is still relatively high. However, in some areas where the conventional water supplies are very meager, desalination is even now competitive with other means of obtaining usable water.

It was reported that the cost of fresh water obtained by a small desalination plant (multistage flash evaporation) was \$0.80 to \$1.10 per thousand gallons, and for a large plant the cost was \$0.20 to \$0.40 per thousand gallons (50 million gallons per day product or more) with present technology (7).

Recently, reverse osmosis has become one of the most interesting processes. Possibly the most important reason is the development of membranes which combine good salt rejection with moderately high water flux. Second, is the appealing conceptual simplicity of the method, which essentially consists of removal of salt by filtering it away from water under pressure.

Third, this process tends to avoid scaling problems and to minimize corrosion since it always operates at ambient temperature. Fourth, the theoretical work for desalting sea water by reverse osmosis at 25°C is 2.65 kilowatt-hours per thousand gallons. The energy consumption of multistage flash distillation and long-tube vertical evaporator distillation, for example, is six times that of the reverse osmosis process (26).

The reverse osmosis process is characterized by the use of pressure in excess of the osmotic pressure to force fresh water at ambient temperature through a selective membrane capable of rejecting dissolved salts. The process name is derived from the phenomenon whereby water under an applied pressure driving force flows in a reverse direction to the flow in an osmotic experiment where the driving force is the concentration gradient.

Many theories have been proposed for the mechanism of water transport through the membrane. According to Reid and Breton (18), the semipermeability of cellulose acetate is caused by regions of bound water within the membrane, and the transfer of water and ions through the membrane is governed by two different mechanisms. Those ions and molecules which can associate with the membrane through hydrogen bonding actually combine with the membrane and are transported through it by alignment-type diffusion; those which can not enter into hydrogen bonding with the membrane are transported by hole-type diffusion with no desalting.

A solution-diffusion mechanism is favored by Riley et al. (19), whose transport equations are apparently limited to their concept of perfect membranes, which are presumably those which have a completely nonporous surface structure. Banks and Sharples (3) also consider that the mechanism of reverse osmosis is one of diffusive flow through the pore-free layer on the membrane surface. Sherwood et al. (22) proposed that water and solute cross the membrane by parallel processes of diffusion and pore flow.

According to Sourirajan's (24) preferential sorption-capillary flow mechanism, reverse osmosis separation is the combined result of an interfacial phenomenon and fluid transport under pressure through capillary pores. He proposed that a thin film of pure water exists at the liquid-membrane interface. For pores with diameters greater than twice the film thickness, both pure water and saline water will flow. Through the smaller pores, only pure water will pass.

The most important part of reverse osmosis equipment is the membrane. The important membrane properties are water flux, salt rejection, and membrane life. Flux is usually given in gallons/ft^2-day (GSFD) and salt rejection is usually given as percent salt rejection or salt reduction factor = 100/(100-percent rejection). Many kinds of membranes have been tried for reverse osmosis, some of them with high rejection but very low flux, such as ethyl cellulose-polyacrylic acid membranes, and some of them with high flux but low rejection, such as poly-acrylonitrile membranes.

Cellulose acetate is the most promising membrane which provides high rejection and moderately low flux. The first recognition that salt rejection by membranes might be useful in desalination seems to have been by Reid at the University of Florida (26). Reid and Breton (18) obtained a maximum water flux of 0.945 GSFD and salt reduction factor of 25 (96% salt rejection) from their cellulose acetate membranes. Since then, cellulose acetate membranes have been improved quite rapidly. 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, salt rejections of 95% and membrane life of six months (1). Today this type of cellulose acetate membrane is the most widely used.

Total cost for products by the reverse osmosis process, using cellulose acetate membranes, is still high. It is mainly caused by the low flux and short membrane life.

General Atomic Division of General Dynamics has proposed a design for a one million gallon per day reverse osmosis pilot plant. The minimum cost of fresh water produced by this pilot plant was estimated to be 75.5 cents per thousand gallons from sea water. The water flux of their membranes is about 10 GSFD under 1440 psi pressure. If the flux can be increased to 20 GSFD keeping the other conditions the same, for example, the cost of fresh water obtained from this pilot plant could be reduced to about 50 cents per thousand gallons (26).

In this pilot plant the cost of membrane replacement is about one third of the total cost. It is reported that the labor cost of membrane replacement would be much higher than the cost of the membrane itself. It is believed that the membranes cast directly onto porous supports could reduce the high labor cost of membrane replacement, as a shorter time and more simple procedure would be required to replace the membrane.

Wang (28) has investigated a membrane formed by using direct casting on porous supports. His membrane, cast from cellulose acetate (E-400-25, 21.9%), formamide (31.2%), acetone (46.9%), ternary solution on rigid porous epoxy filled fiberglass supports (Gelman Versapor, 0.9 micron), can provide an average water flux of 21 GSFD and 95% salt rejection.

Lai (15) showed that other porous materials also have promise as supports. Polyvinyl chloride was most promising. The average water flux and salt rejection based on a 124-hour-long run were 23.5 GSFD and 95.7%, respectively. Casting conditions were the same as those used by Wang except heat treatment temperature was 84°C instead of 86°C.

Coverdell (6) used small diameter cylindrical porous media as supports to provide a high membrane area per unit volume of equipment. His was one of the approaches to decrease the total cost for products by the reverse osmosis process.

When brine is pumped through a salt-rejection membrane, the salt held back concentrates in the layer adjacent to the membrane surface. This salt build-up in the boundary layer is called 'concentration polarization'. The concentration polarization has been an important problem of high water flux membranes in reverse osmosis desalination. The salt concentration polarization has several effects which are detrimental to the desalination process. First of all, concentration polarization results in the effective osmotic pressure at the membrane surface exceeding the osmotic pressure of the bulk saline water and hence lowers the water flux. In addition, the concentration polarization has a detrimental effect by increasing the salinity of the product water. The useful life of the osmotic membrane is often shortened by increased salinity of the saline water and concentration polarization will aggravate this effect.

Several analytical studies of concentration polarization have been reported with particular reference to saline water conversion (5,8,23). These studies assume that the membrane exhibits either complete salt rejection or incomplete salt rejection at a constant level. A more desirable approach to the subject is given by Sherwood et al. (22), who have coupled the equations of solute and solvent transport through the membrane to the theory of concentration polarization. A similar approach is offered by the Kimura-Sourirajan (14) analysis, which is based on a generalized pore diffusion model applicable for the entire possible range of solute separation.

In view of the detrimental effects of concentration polarization, it is logical to consider ways by which the effect of salt build-up can be reduced. Tien (28) proposed a system consisting of impermeable relaxation sections placed alternately between semi-permeable membrane sections. The high concentration at the boundary of the impermeable section can be attenuated by molecular diffusion and convection which redistributes salt more uniformly across the flow channel. It is possible that by proper arrangement of the impermeable sections and membrane sections, one could obtain greater production capacity in a reverse osmosis system even though a fraction of the conduit is nonproductive.

Spiral turbulence promoters positioned away from the membrane surface by small wire runners were used by Thomas and Watson (27) to get reduction of concentration polarization.

The semi-empirical analyses of Brian (5) and Sherwood (22) show that the polarization effect is a function of desalinized water flux and axial velocity. Sheppard and Thomas (20) maintained a very high axial velocity (24 ft/sec) which provided a high turbulence to decrease the polarization problem.

In order to provide a combination of higher axial velocity and greater turbulence, Hamer (11) used movable glass spheres in a tubular membrane unit.

A cavitational method to increase turbulence was investigated by Harvey (12). He used ultrasonic transducers close to the membrane to generate a high frequency vibration. Huff (13) proposed an infrasonic activation to avoid the destructive effects that are associated with high frequency vibration and cavitation.

The reason for trying the glass-bead fluidized bed approach to reverse osmosis by the author was to establish high turbulence at low feed velocity. The high turbulence was expected to increase the water flux and salt rejection through the membrane by decreasing the concentration polarization effect. A longer membrane life would be expected due to the fact that the fluidized bed decreases the salinity of the product water.

The object of the author's thesis was to determine the feasibility of using a fluidized bed to improve the performance of reverse osmosis desalination. Five different sizes of glass beads and six different kinds of membranes have been tested under a variety of operating conditions in 141 runs. A brief economic study was also made.

II. EQUIPMENT AND PROCEDURE

A. Membrane Fabrication Equipment

A constant temperature and humidity chamber was used for membrane casting of all runs. The chamber was constructed with a fiber glass body, a safety glass window (10-1/2+ x 32") in front of the chamber, and two 6" diameter rubber plate covered working holes on the front chamber door (40" x 10"). The chamber contained lights, a heater, cooler, fan, two salt solution containers, and a thermo-probe connected to an electronic temperature controller. The temperature was kept at 70°F and humidity was kept at 50% by using saturated $Ca(NO_3)_2 \cdot 4H_2O$ salt solution. A level aluminum surface with the dimensions of 8 inches by 5 inches was used for membrane casting in order to produce even membrane thicknesses.

B. Test Cells

The test cell shown in Figure 8 was made of stainless steel 304 blank flanges with 4.5" outside diameter and a 2" diameter test area. The membrane was supported by a 1/8-inch porous stainless steel plate (Grade H, pore size 5 microns, Pall Corp.) which was mounted between the two halves of the cell. This cell was originally designed for use without a fluidized bed and was used only for the preliminary study.

The test cell shown in Figure 9 was used for testing all membranes after Run 6 with or without a fluidized bed. The body of the test cell, which was made of stainless steel 316, consisted of three parts: namely, front plate, frame, and back plate. These three parts were held together by twelve 5/16-inch stainless steel bolts, which were tightened stepwise to obtain a good seal. The space (3-3/4" x 1-3/4" x 7/8") inside the frame sandwiched between the front plate and the back plate was used as a fluidizing bed.

The porous stainless steel plates (pore size 40 microns, Mott Metallurgical Corp.) on the bottom entrance and the top exit were used to give uniform flow distribution and to prevent the glass beads from escaping, respectively. The membrane was supported by a porous stainless steel plate (pore size 5 microns, Pall Corp.) with the dimension 1-3/4 inches by 1-3/4 inches, which was glued in the back plate.

In order to increase the linear fluid velocities across the space without the fluidized bed, plexi-glass plates (3-3/4" x 1-3/4") of various thicknesses can be inserted inside the cell. These fillers were located against the front plate and served to reduce the volume of the cell.

As shown in Figure 10, glass beads were introduced into the fluidized bed through a hole on one side of the frame. The salt water under pressure was circulated through the entrance on the bottom of the frame, and left through the top. The product water flowed through the membrane and its supporting porous steel plate into the receiver.

C. Membrane Test System

As shown in Figure 11, the test system consisted of a pump (Jaeco Model 753 S-8), surge tank, filter, test line, test cell, and a plastic feed tank with stirrer and cooler. All equipment was of plastic or stainless steel construction to eliminate corrosion.

The surge tank was used to keep a stable brine feed rate and the filter was used to maintain a clean system. The brine feed rate was controlled by a needle valve which was connected to the exit stream of the filter. Two pressure gauges were connected to the test cell to detect the pressure drop across the cell.

The system pressure was controlled with two back pressure regulators located at the filter and after the test cell. A high-pressure nitrogen cylinder was used to load the regulators. The temperature of the feed solution (1% NaCl) was kept at 25°C. The heat added by the pump and brine circulation was removed by cooling water. The pressure used for all runs was 800 psi.

A conductivity bridge (Industrial Instruments Model RC-16 B-2) was used in conjunction with a conductivity cell to analyze the concentration of salt water and product water. The relationship between concentration and resistance can be approximately expressed as:

$$C_t = \frac{6.4 - (t-25) \times 0.1}{(R_t)^{1.0496}}$$

where C_t = salt water concentration, moles/liter

t = temperature of conductivity measurement, °C

R_t = resistance at temperature t, ohms

This equation was used to calculate concentration from different temperature and resistance to make a plot of concentration versus resistance at different temperatures. This plot, Figure 12, was used to convert the resistance of every sample to concentration. Periodically this curve was checked against standard NaCl solutions.

D. Chemicals and Materials

Five kinds of glass beads with a density of 156 lb/ft^3 have been used. Three spherical glass beads made by 3M Company were tried first. Those with 0.0185-inch diameter were called No. 1 for this study; those with 0.011-inch diameter were designated No. 2, and those with 0.008-inch diameter, No. 3. A bigger size of spherical glass beads with 0.0394-inch diameter (called No. 4) made by Van Water & Rogers Company was used later. The irregular shaped glass beads with diameters between 0.0232 and 0.0328-inch (called No. 5) which were obtained by washing and screening the developer for a Xerox machine were also considered.

The membranes used for all runs were cast on porous supports, nylon (#5055, Travis Mill Co.) or dacron (#601, Travis Mill Co.) materials.

The composition of the casting solution used in this study was cellulose acetate 21.9%, formamide 31.2%, and acetone 26.9% by weight. The E 398-10 cellulose acetate, containing 39.8% acetyl from lot No. AC-1466, was from Eastman Chemical Company. "Baker grade" formamide and "Baker analyzed" reagent grade acetone, both from Baker Chemical Company, were used.

E. Test Procedure

The following is the membrane fabrication procedure used for this study. The support was fixed on the aluminum plate with masking tape which was about 0.005 thick. A glass rod was used to spread the solution smoothly onto the support, with the tape as a thickness guide, in a constant temperature and humidity chamber. The cast solution was evaporated as long as needed. The aluminum plate was immersed with the membrane in ice water for one hour. Then the membrane was heat treated with the aluminum plate in hot water which had been heated to the required temperature. The heat treatment time used was four minutes. The membrane was immersed in cold water until it was tested. It was cut to the dimension to fit the test cell when it was tested.

The membranes were firmly mounted in the test cells with the cellulose acetate film facing the high pressure side. The pump was started and the pressure gradually increased until 800 psi was reached. Cold water to the cooler was adjusted to keep the temperature of the feed solution at 25°C. The feed concentration was checked every day. A product water sample was taken once every hour or two and most tests were run two to four hours.

III. RESULTS

One hundred and forty-one runs have been made to determine the feasibility of using a fluidized bed to improve the performance of reverse osmosis desalination. The results of all these tests are tabulated in Table XIII.

PRELIMINARY TESTS

Several runs were made for preliminary tests with the cell shown in Figure 8, which was designed for use without a fluidized bed. With the cell positioned vertically, the salt water entered through the lower entrance and left through the upper hole. Most of these runs showed that by using a fluidized bed both the water flux and salt rejection were improved. At the end of a 124-hour run with a fluidized bed, the salt rejection decreased only slightly from the original value. It appeared that there was no destruction caused by glass beads on the membrane surface after a long running time. The geometry of this cell was improper to achieve a uniform fluidized bed. When a plexi-glass plate was used instead of one stainless steel plate, the fluidization could be visually observed. Even at high brine flow velocities approximately 1/4 of the bed was not fluidized. To improve the flow distribution, a new experimental cell was deemed necessary.

MINIMUM FLUIDIZED BED VELOCITY

A plexi-glass plate was used instead of a front steel plate as shown in Figure 9 in order to visually observe the minimum fluidized bed velocity. The brine (1 wt.%) was pumped through the cell at atmospheric pressure. This velocity for glass bead No. 1 was 0.385 cm/sec; No. 2, 0.254; No. 3, 0.152; No. 4, 0.86; No. 5, 0.515.

THE BASIS FOR COMPARISON BETWEEN RESULTS WITH FLUIDIZED BED AND WITHOUT FLUIDIZED BED

Increasing brine flow velocity resulted in increased water flux and salt rejection without a fluidized bed although it increased only slightly for a brine flow rate above 6 cm/sec. This is also true for a fluidized bed in the brine flow velocity range between 0.57 and 2.0 cm/sec. Figure 1 shows the effect of brine flow velocity on water flux and salt rejection of a typical run for both cases. Because of this condition it is important to determine a suitable basis for comparing the results of these two situations.

The pure water permeability constant (A) was used to help determine a basis. This constant is a membrane permeability (GSFD/psi) determined with pure water in the cell. Constant A with fluidized bed and without fluidized bed at varied velocities with feed containing 150 ppm salt was determined in Runs 50, 53, 58, 59, 60,

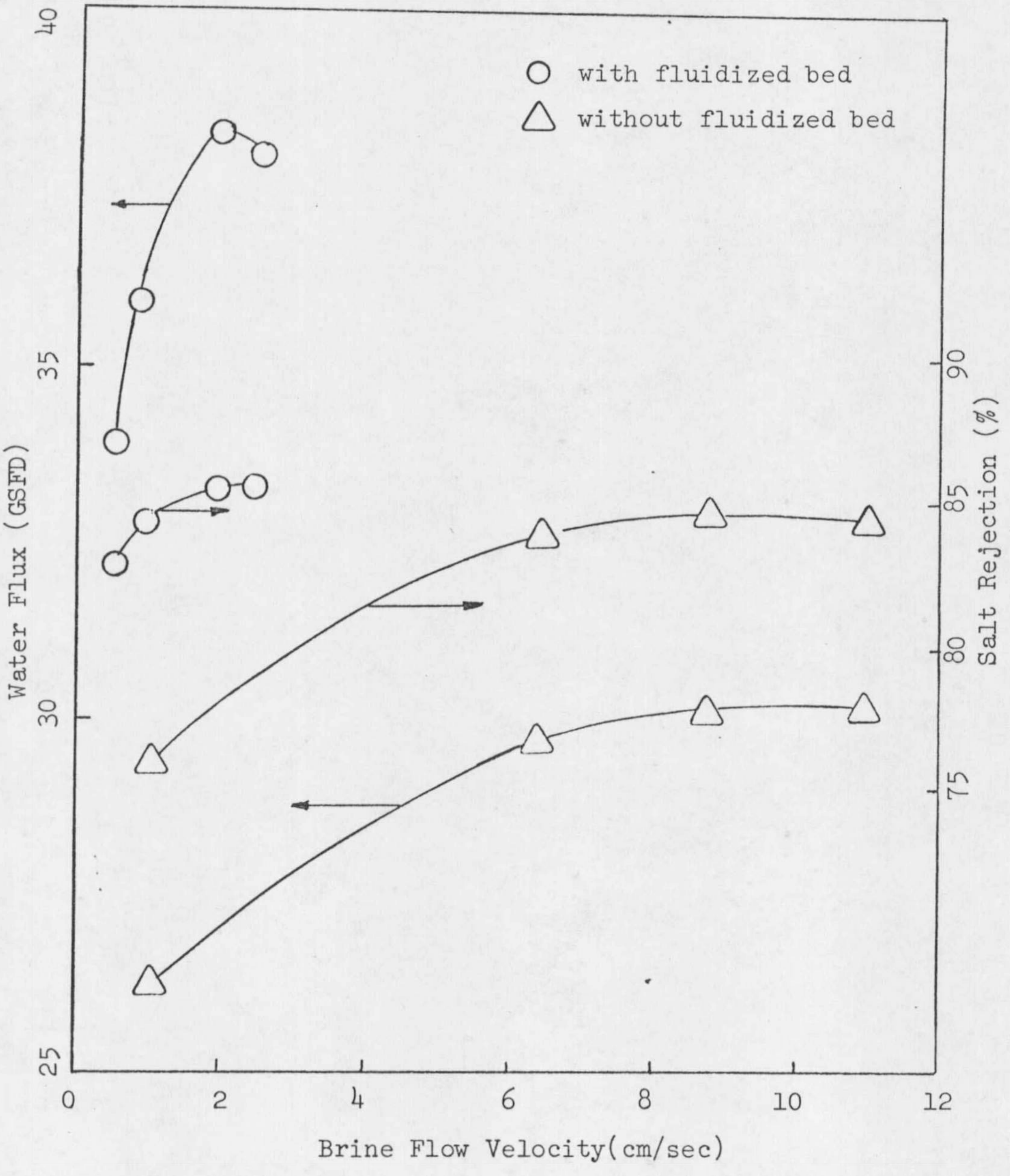

Figure 1 Effect of Brine Flow Velocity on Water Flux and Salt Rejection(398-10-82-nylon membrane)

and 61, all of which employed the 398-10-86 membranes. Figure 2 shows the selected brine flow velocity of 0.97 cm/sec for the fluidized bed was the maximum possible flow without inserting a plastic block to reduce the cell volume. In order to obtain the same value of A, a brine flow velocity of 11.0 cm/sec was needed without the fluidized bed. As also shown in Figure 2, constant A was determined with a feed solution of less salt content (8 ppm) and the same value was obtained at 11.0 cm/sec. The two values for salt content were those of salt residue in the system after washing with pure water. In the determination of another value for constant A using the 398-10-82 membrane at the selected brine flow velocity of 0.97 cm/sec for the fluidized bed, a value of 11.0 cm/sec was obtained without the fluidized bed. Therefore, as a result of these two determinations with the pure water permeability constant as a criterion, it appears that a valid basis for comparison is obtained when using results of a fluidized bed run at a brine flow velocity of 0.97 cm/sec and a run without the fluidized bed at a brine flow velocity of 11.0 cm/sec.

RESULTS FOR DACRON MEMBRANE

Three different kinds of dacron-supported membranes were tested: 398-10-86, 398-10-84, and 398-10-82, which were made of cellulose acetate type 398-10 casting solution with heat treatment

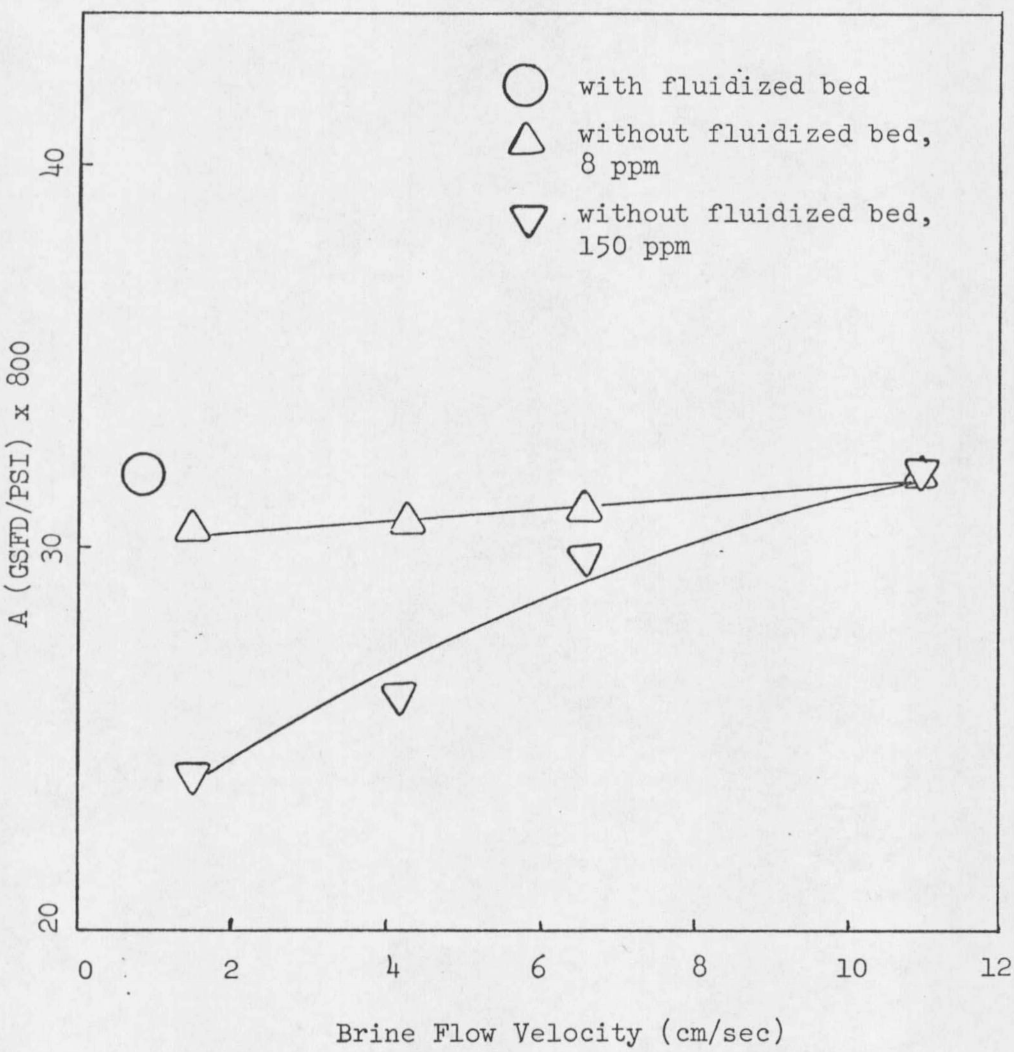

Figure 2. Pure Water Permeability Constants for Different Brine Flow Velocity (398-10-86-nylon membrane)

temperatures of 86, 84, and 82°C, respectively. The different heat treatment temperatures were used to control the water flux and salt rejection. A higher heat treatment temperature gives a lower water flux and a higher salt rejection.

By using the fluidized bed, the average water flux increased about 20% with an accompanying increase in salt rejection. Since the water fluxes and salt rejections of the dacron-supported membranes were not as consistent as with the nylon-supported membranes, dacron membranes were not tested extensively.

RESULTS USING A FLUIDIZED BED FOR 398-10-86 NYLON MEMBRANES

Three kinds of nylon-supported membranes have been used: 398-10-86, 398-10-82, and 398-10-78, which were made of cellulose acetate type 398-10 casting solution with heat treatment temperatures of 86, 82, and 78°C, respectively.

The average results using 398-10-86-nylon membranes without the fluidized bed but at high fluid velocity (11.0 cm/sec) were 22.1 GSFD and 92.0% salt rejection.

The significance of using the fluidized bed with No. 1 glass beads at 0.97 cm/sec brine flow velocity on these membranes was to increase the water flux 21.7% and to slightly increase the salt rejection. Results at 0.97 cm/sec brine flow velocity with the fluidized bed are compared with the results for the case without the fluidized bed. See Table II.

Three other sizes of spherical glass beads, No. 2, No. 3, and No. 4, have also been studied. Table III shows at 0.97 cm/sec brine flow velocity, average results of 26.0 GSFD and 94.2% salt rejection for No. 2 beads; 20.0 GSFD and 93.8% salt rejection for No. 3 beads; and 26.9 GSFD and 92.6% salt rejection for No. 4 beads. Glass beads No. 1, No. 2, and No. 4 gave about the same increase in salt rejection and water flux. The decrease in water flux noted with the No. 3 beads may be caused by their very small size. This agrees with observations of Baerns (2) that as the particle size was reduced the heat transfer coefficient increased, passed through a maximum, and then decreased. The decreasing heat transfer rates with the smallest particles corresponded with the region where the interparticle adhesive forces affected the quality of fluidization.

By using a lower brine flow velocity (0.57 cm/sec), the water flux and salt rejection were decreased slightly for glass beads No. 1, No. 2, and No. 3. No. 1 glass beads showed the best results and No. 3 the worst. Table IV shows the results for these kinds of glass beads at 0.57 cm/sec brine flow velocity.

RESULTS USING A FLUIDIZED BED FOR 398-10-82-NYLON MEMBRANES

The average results using this membrane without the fluidized bed but at high fluid velocity (11.0 cm/sec) were 28.0 GSFD and 85.5% salt rejection.

The fluidized bed with No. 1 glass beads at 0.97 cm/sec brine flow velocity increased the water flux by 29.6% and increased the salt rejection slightly for the 398-10-82-nylon membrane. Table V shows the results with and without the fluidized bed.

Using glass beads No. 2 and No. 4, the performance of the 398-10-82-nylon membrane showed about the same improvement as with the No. 1 glass beads. The smallest size beads again gave a poor result. Table VI shows the effect of bead sizes on performance of this membrane at 0.97 cm/sec brine flow velocity.

Table VII shows the comparison of results for using glass beads No. 1, No. 2, and No. 3 at the lower brine flow velocity (0.57 cm/sec). No. 1 glass beads gave the best results.

MEMBRANE PERFORMANCE WITH VARIED HISTORIES WITHOUT THE FLUIDIZED BED

Runs 26 and 27 were tested with the fluidized bed first and then without the fluidized bed on the same membrane. In order to see if previous use of the membrane with glass beads affects its performance, some runs were made using no glass beads. Table VIII shows that there is no difference in membrane performance between those previously used with beads and ones used with no glass beads.

Four different brine flow velocities (11.0, 8.7, 6.4, and 1.0 cm/sec) have been tried for each run, but only the first two cases have been listed in Table VIII.

This comparison shows that the test procedure used for the 398-10-86 and 398-10-82 membranes with and without the fluidized bed which were listed in Table II and Table V should be acceptable.

RESULTS USING A FLUIDIZED BED FOR 398-10-78-NYLON MEMBRANES

The water flux and salt rejection results for this loose membrane were not consistent when tested without the fluidized bed. This can be seen in Tables IX and XIV. Because of these inconsistencies, it was necessary to alter the experimental procedure in order to more fairly compare the results of the cases with and without the fluidized bed. Using the same membrane, runs were made first with the glass beads and then without. In the other case, for comparison, the runs were started without glass beads and then glass beads were added. This procedure tended to cancel the effects of membrane aging. Table IX shows the results of these four runs. The average water flux increase with glass beads No. 1 was 35.8%. The salt rejection was also considerably increased when using a fluidized bed.

As shown in Table X, the average water fluxes for glass beads No. 2, No. 3, and No. 4 were approximately the same. The salt rejection of No. 1 glass beads was the highest and that of No. 3 was the lowest.

EFFECT OF GLASS BEAD SIZE ON PERFORMANCE

The smallest glass beads gave the worst results among the four sizes of spherical beads for all membranes. Beads No. 2 and No. 4 gave results quite close to those of the No. 1 beads. However, the No. 1 size is the best for the fluidized bed in the brine flow velocity range between 0.57 and 0.97 cm/sec. It would be necessary to determine a new optimum glass bead size when the brine flow rate is beyond this range.

RESULTS USING IRREGULAR SHAPED GLASS BEADS

Irregular shaped glass beads with diameters between 0.0232 and 0.328 inch were tried to determine the effect of using non-spherical beads. Because the residue on the beads discolored the membrane and probably affected the property, no significant results were obtained.

EFFECT OF MEMBRANE ORIENTATION ON PERFORMANCE

All runs previously mentioned were operated with the membrane surface positioned vertically. Two other positions, one +30° from the vertical with the membrane facing upward, and one -30° with the membrane facing downward were studied in Run 30. By using the same membrane, this second position gave better results than for either the vertical or the other inclined position. The worst results were obtained with the membrane inclined 30° and facing upward. For these tests the brine flow velocity was 0.57 cm/sec and No. 1 glass beads were used. These results of Run 30 are shown in Table XIII. It appears that the position of the membrane surface does affect the performance of the membrane with the fluidized bed desalination process.

EFFECT OF CELL GEOMETRY ON PERFORMANCE

As shown in Figure 9, the fluidized bed used was 3-3/4 inches high by 1-3/4 inches wide by 7/8 inch thick. To determine the effect of bed thickness, a thinner space (3/8") was also used in Run 141. It was accomplished by inserting a plexi-glass plate inside the cell. By using the same brine flow velocity, the water fluxes of membrane using the smaller and regular space were 35.8 and 33.7 GSFD, respectively. The salt rejections were the same in both cases. Although it appears that there may be an optimum cell thickness to improve the water flux, this study indicates that the thinner space is superior.

EFFECT OF FLUIDIZED BED ON MEMBRANE INTERFACE AND PRODUCT CONCENTRATION

The following relation has been used (13) and is also assumed here to evaluate the interface salt concentration on the brine side of the membrane:

$$N_w = A\left[P - \pi(X_{A2}) - \pi(X_{A3})\right] \qquad [1]$$

where

N_w = water flux

A = pure water permeability constant

X_{A2} = mole fraction of salt in membrane interface solution

X_{A3} = mole fraction of salt in product solution

$\pi(X_{A2})$ = osmotic pressure of interface solution

$\pi(X_{A3})$ = osmotic pressure of product

The pure water permeability constant A was determined by measuring the product rate with pure water as a feed solution. Once N_w and X_{A3} are measured, (X_{A3}) can be calculated and then (X_{A2}) can be determined. The value of X_{A2} can be found from a plot of osmotic pressure versus concentration (14).

As shown in Figure 3, the ratio of interface to feed mole fraction (X_{A0}) is decreased when brine flow velocity is increased although there is no appreciable decrease after 8.4 cm/sec. On the

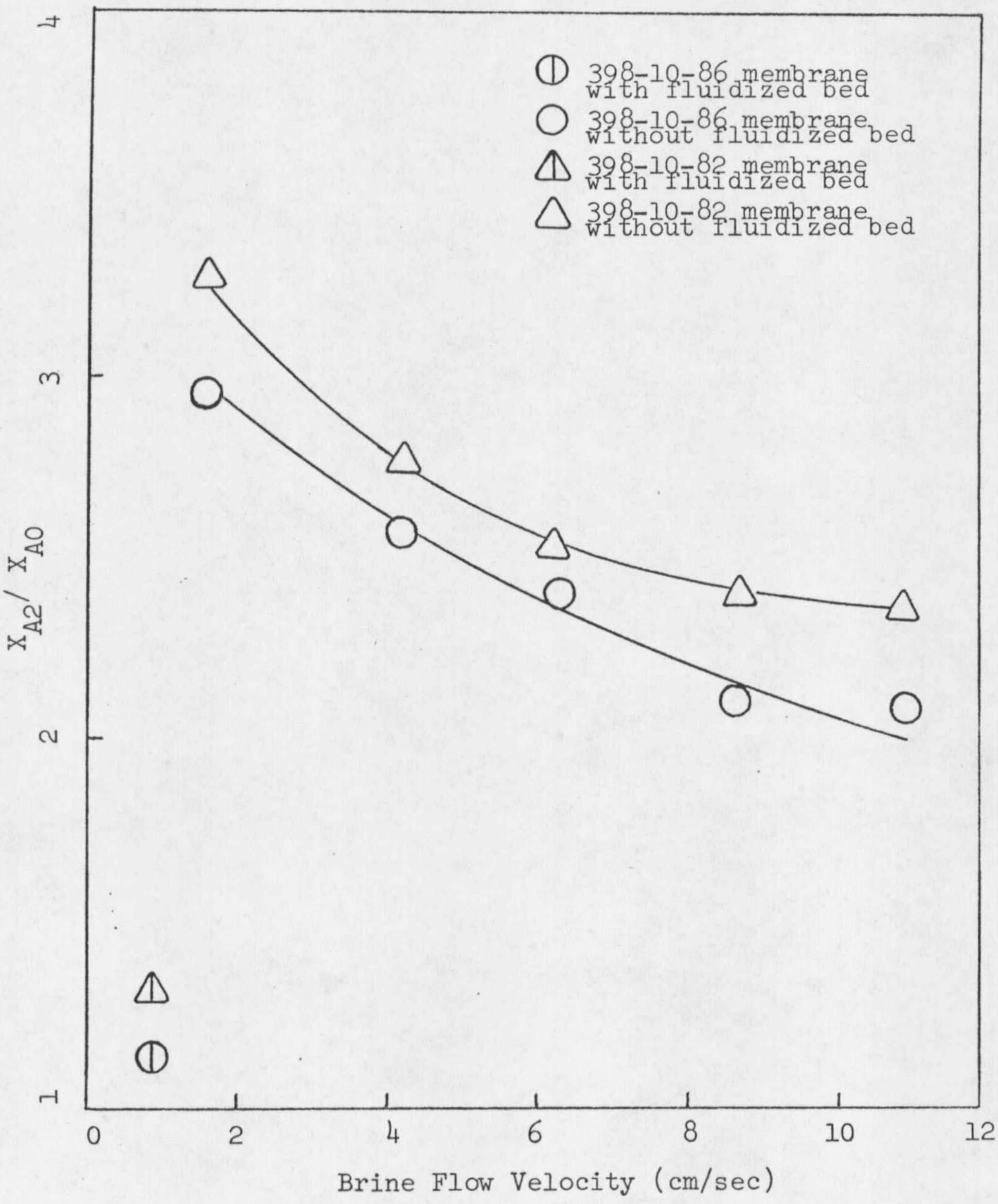

Figure 3. Effect of Brine Flow Velocity on Interface concentration

basis of the same pure water permeability A, the values of X_{A2}/X_{A0} were 2.13 and 1.12 without fluidized bed and with fluidized bed, respectively, using 398-10-86 membrane. For 398-10-82 membrane the values were 2.37 and 1.31, respectively. These values are a measure of the effectiveness of the fluidized bed in reducing concentration polarization. The fact that water flux is increased by applying a fluidized bed seems mainly due to the fact that the membrane interface concentration is decreased by the glass beads.

Sourirajan (24) has reported that the values of X_{A2} and X_{A3} must be uniquely related to each other for a given membrane and this relationship must be independent of feed concentration and brine flow velocity. He shows plots of X_{A2} versus X_{A3} for a wide variety of flow rates and feed concentrations which give a single line for each membrane. The results of plotting X_{A2}/X_{A1} versus X_{A3}/X_{A1} for the 398-10-82 membrane are shown in Figure 4. Since the effect of the fluidized bed was to decrease both interface and product concentration, the effect of the fluidized bed was to shift the points on the plot downward and to the left. However, the shift was in such a way that a different line is obtained when a change is made in the mode of operation.

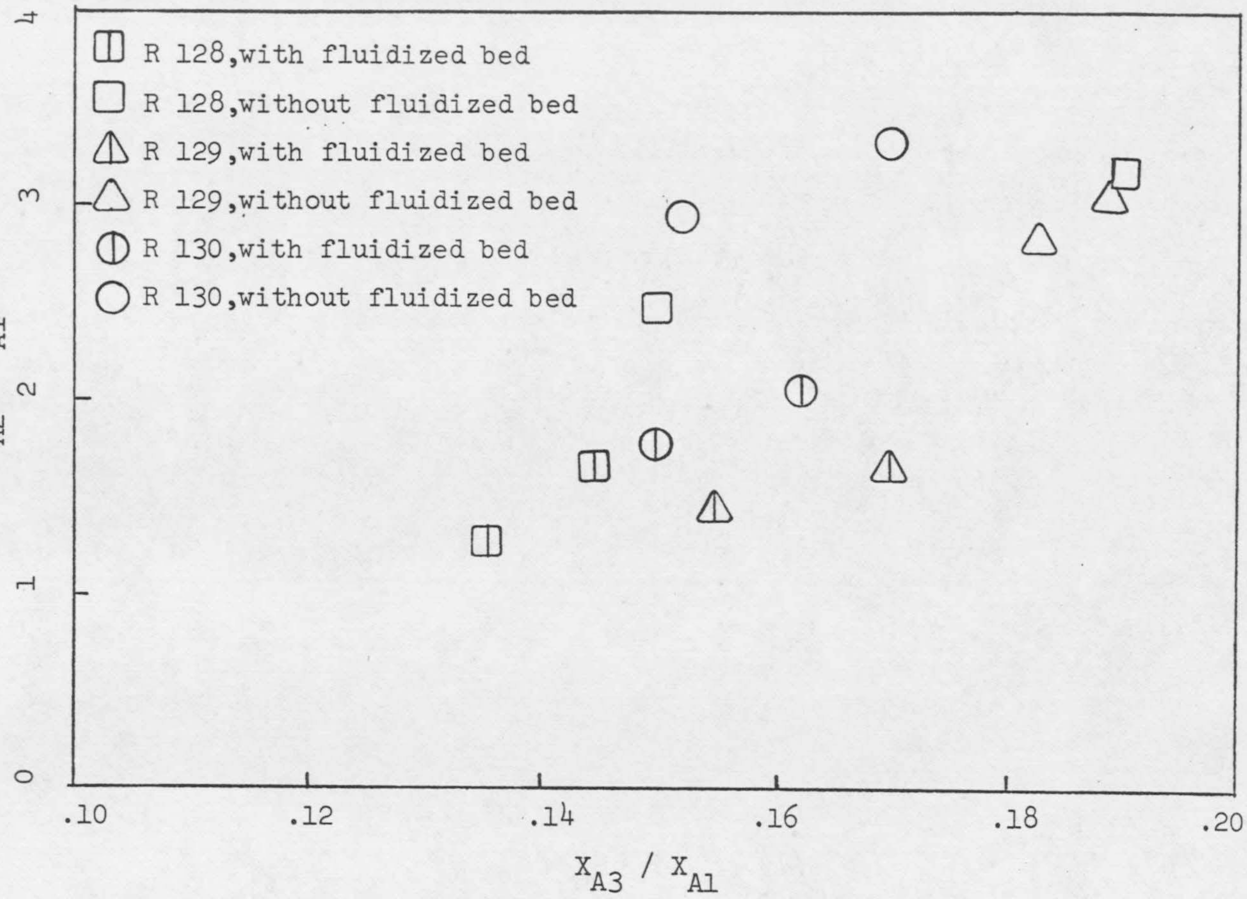

Figure 4. Concentration of Solute in the Boundary Solution versus that in the Product (398-10-82 Membrane)

SALT FLUX

Usually, when the concentration polarization is decreased by high brine flow velocity, the water flux is increased and the salt flux is decreased (20). In this study it was found that the salt flux of a tight membrane (398-10-86) was decreased when a fluidized bed was applied. However, this was not true for the looser membranes (398-10-82 and 398-10-78) with the fluidized bed. The salt fluxes with and without the fluidized bed for these three membranes are shown in Table XI.

The salt flux (N_S) through the membrane is usually expressed by the following equation (13):

$$N_S = k(X_{A2} - X_{A3}) \qquad [2]$$

where k is the diffusion constant. The fluidized bed operation reduced the interface composition so that the driving force, (X_{A2} - X_{A3}), became less but the salt flux increased. This indicates a coupled flow of salt and water through the loose membranes. Equation [2] is inadequate to describe such a situation.

Results similar to those with the loose membranes were obtained by Goldsmith et al., (10), who directly measured the interface concentration in their concentration polarization study. They observed the greatest salt flux when the concentration polarization was least.

STUDY OF MEMBRANE LIFE

Sourirajan and Govindan (25) were among the first to describe flux decline with time, observing a 60% decline in flux in the first 20 hours of a run with sea water feed at 1500 psi and a further 20% decline in the next 150 hours of the run. Merton et al., (16), found their data followed a straight-line relation when plotted as log flux versus log time. The slopes were between -0.13 and -0.19 in a series of 34 experiments. The data of Sourirajan and Govindan (25) yield a value of -0.14. The straight line of Shepard's (31) long run showed almost zero slope. Under some circumstances the plot of flux versus log time resulted in a linear relationship (9).

Several long runs by the author investigated the membrane life using the fluidized bed. The data were fitted by an almost horizontal straight line on a log flux versus log time plot. Figure 5 shows that the slopes of all runs are the same, -0.012. At the end of five days the sater flux decrease was 6.6 percent with negligible decrease in salt rejection.

The water flux measured when using the fluidized bed did not decrease as fast as when using just the membrane. Figure 6 shows the comparison of both systems. The run with polyvinyl chloride support membrane was one of the previous life study runs by the author (15). It shows that at the end of five days the water flux decrease

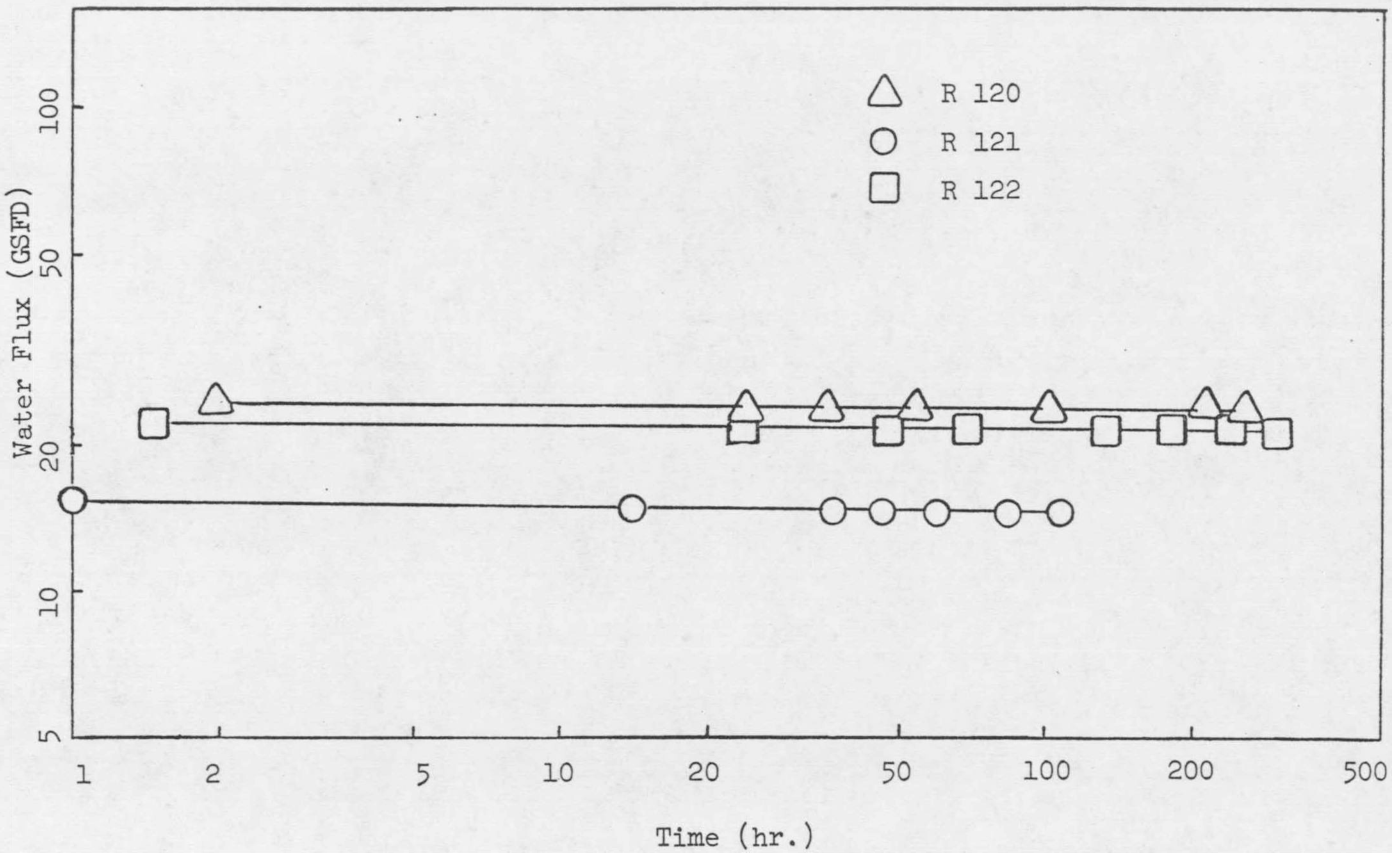

Figure 5. Effect of Time on Water Flux for 398-10-86-nylon Membrane with Fluidized Bed

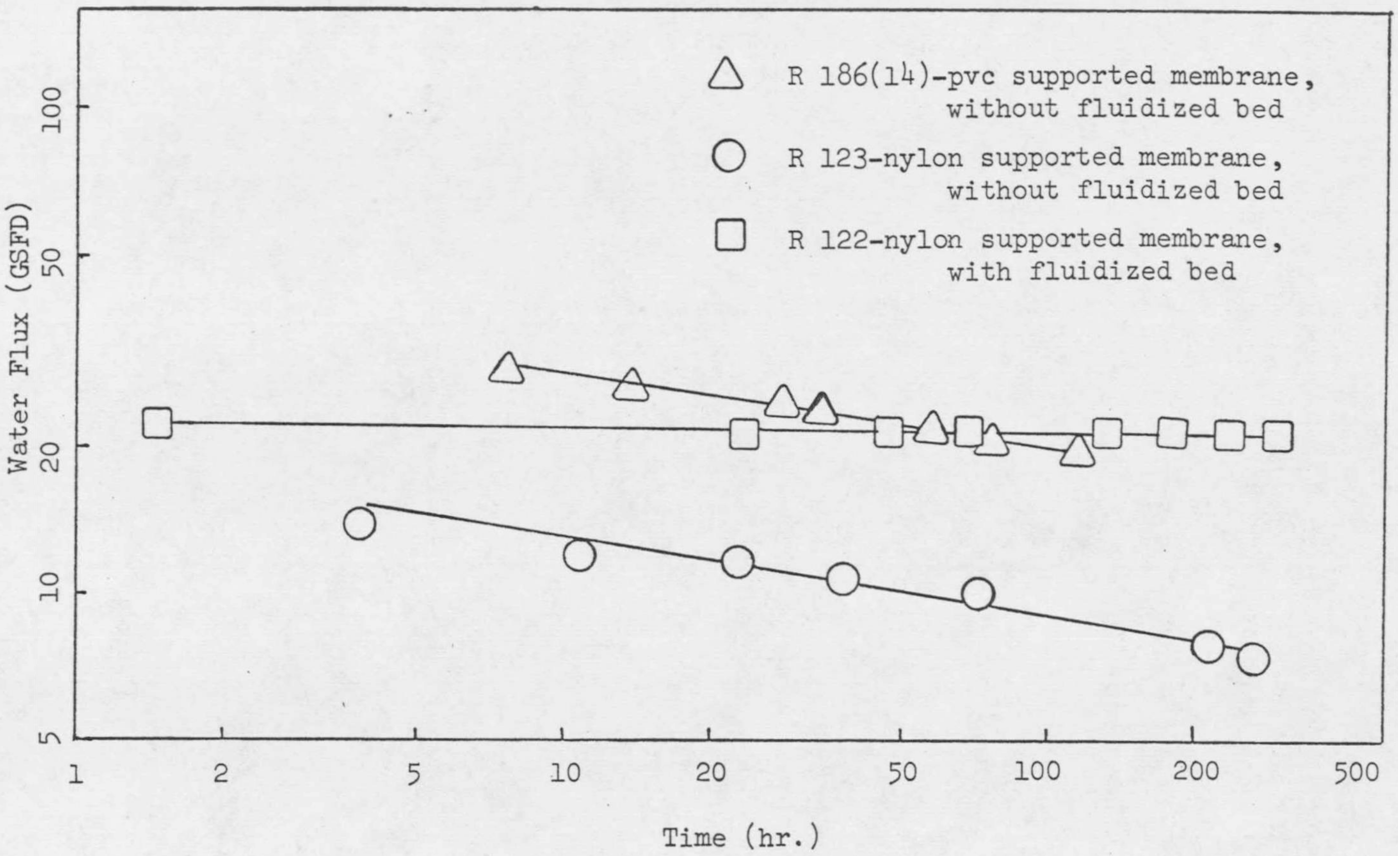

Figure 6. Comparison of the Time Effect on Water Flux of 398-10-86 Membrane with and without Fluidized Bed

of runs with PVC support and nylong support membranes are 26.2 and 28.6 percent, respectively. The slopes shown in this figure are both -0.158. Both of these runs were tested without the fluidized bed.

At the end of six months the water flux is projected to be about half of the original value. This is true for cellulose acetate membranes which were made of both polyvinyl chloride and nylon supports. When using a fluidized bed, the prediction of the water flux at the end of six months was only 10 percent less than the original value. Extrapolation of the lines on Figure 5 indicates the time needed to decrease the water to one-half its original value would be about twenty years. Such a prediction is not reliable based on the short length of the runs, but indicates that future work should include some long-term runs with the fluidized bed.

The result of this study is that by using the fluidized bed, the membrane life for cellulose acetate membranes on nylon supports is greatly increased.

SCALE FORMATION STUDY

Four different solutions containing 1/4, 3/8, 1/2, and 1 times the saturation concentration of $CaSO_4$ in a 1 wt.% NaCl-water solution, were used in this scale study. Only water flux was measured in these runs to avoid the recalibration necessary to determine the salt rejection.

The approximate minimum concentration of $CaSO_4$ which would cause precipitation on the membrane surface was studied first. Using a 398-10-82 membrane (Run 132), the water flux was 28.0 GSFD with a 1 wt.% CaCl feed solution. The membrane was washed with pure water before each test with a different $CaSO_4$ concentration solution in Runs 133, 134, and 135.

Results showed that there were no appreciable differences in water flux from original value when running with 1/4 or 3/8 the saturated $CaSO_4$ solution. There was an 8.6% reduction in flux when the solution was increased to half of the saturation concentration of the $CaSO_4$. The water flux of the membrane using a saturated $CaSO_4$ solution was about the same as that for the half-saturated $CaSO_4$ solution. It appears that precipitation on the membrane surface was caused when a minimum concentration of 1/2 the saturated value of $CaSO_4$ was present in the feed.

As shown in Table XIII, the significance of using the fluidized bed is to increase water flux 33.3% and 34.7% for half-saturated and saturated $CaSO_4$ solutions, respectively. Those values are higher than the percentage increase obtained in using the same kinds of membranes with brine water only. It seems the more scale content in the feed solution, the greater the increase in water flux when using a fluidized bed.

Two five-day-long runs with saturated $CaSO_4$ solution were tested to study the membrane life with scale formation. As shown in Figure 7, the slopes in the plot of log flux versus log time were -0.251 and -0.098 without fluidized bed and with fluidized bed cases, respectively. This means that after a six-month period, the water flux with the fluidized bed would be 2.5 times that without the fluidized bed.

This study shows that by using a fluidized bed system with a scale-forming feed, both the water flux and the membrane life are significantly improved.

ECONOMIC CONSIDERATIONS

In order to compare the cost difference between a system using a fluidized bed and one using only a membrane, a pilot plant capable of producing one million GPD of pure water was considered. The water flux and salt rejection of the membrane without a fluidized bed were assumed to be 20 GSFD and 95 percent, respectively. The main effects of using the fluidized bed will be to increase the water flux about one third while maintaining the same salt rejection, and to greatly increase the membrane life.

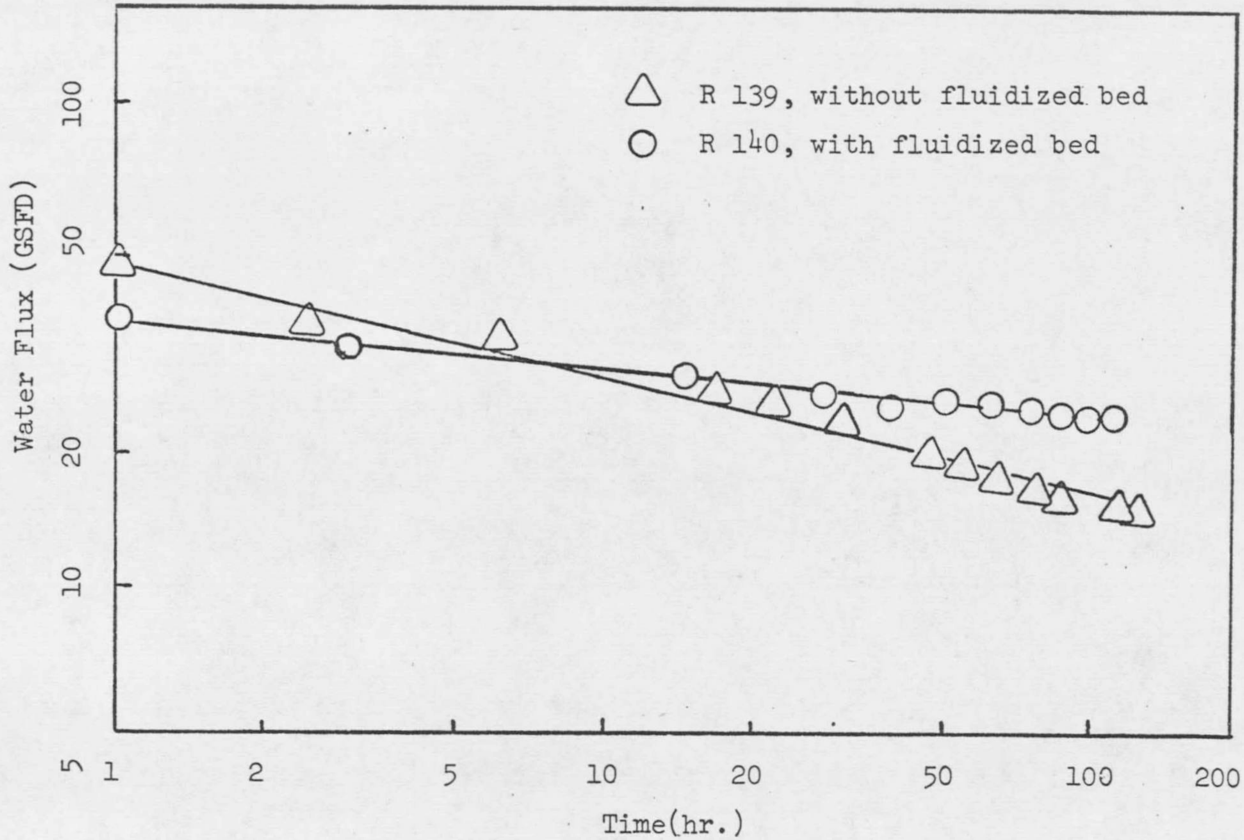

Figure 7. Effect of Time on Water Flux of 398-10-82 Membrane with Brine Solution Containing Saturated $CaSO_4$

Aerojet General Corporation (1) has made brief economic estimates (in 1966) for a shell and tube reverse osmosis pilot plant. The basic design variables were: \$0.25 per square foot membrane replacement cost, 20 years amortization, 4 percent annual interest rate, 330 operating days per year. The same values were used in this study. The number of operating cells and all auxiliary equipment were chosen to be the same for both systems.

The only difference in equipment for both cases is the cell. A cost summary of the cell is given in Table I. The cost per thousand gallons of product water for the fluidized bed and ordinary cells are 2.68 and 2.79 cents, respectively. Due to the increased water flux, the 25 percent reduction of required membrane area of the fluidized bed system more than offsets the increased cell costs due to the glass beads and porous stainless steel distributor plate. However, this difference is small compared to the reported total cost of 75.5 cents per thousand gallons (4).

Because the brine flow velocity of the fluidized bed system is much lower than that with the fluidized bed, the pumping cost of the fluidized bed system should be lower. However, because the total pumping energy is much greater than the kinetic energy due to brine flow, the difference between pumping costs of these two systems is negligible.

Table I. Economic Estimations of Reverse Osmosis Cell

Fluidized Bed:

No.	Item	Unit Cost	Total
2	Heads	$ 365	$ 730
4	Flanges	1,270	5,080
2	Tube sheets	3,000	6,000
1	30 ft, 42 in. shell	105/ft	3,150
2,300	30 ft-1/2-in. tube	6	13,800
9,500	Glass beads	0.15/lb	1,430
2	Porous stainless steel plate	1,260	2,520
			$32,710

Without Fluidized Bed:

No.	Item	Unit Cost	Total
2	Heads	$ 365	$ 730
4	Flanges	1,270	5,080
2	Tube sheets	3,000	6,000
1	40 ft, 39 in. shell	90/ft	3,600
2,300	40 ft-1/2-in. tube	8	18,400
			$33,810

Membrane life without the fluidized bed is about six months, according to the author's prediction from long runs using polyvinyl chloride membranes (15) and nylon membranes. If the membrane life were the same for both cases, using the fluidized bed could still save 25 percent of the membrane replacement cost due to the smaller required area. It would save 80 percent of the membrane replacement cost for 2 year's life and 93 percent for 5 year's life.

If the previous prediction for a 20 year membrane life is valid, the replacement cost, which is about one third of the total cost (3), could be entirely saved. Therefore, the most significant economic effect of using the fluidized bed is to decrease the considerable cost of membrane replacement.

IV. CONCLUSIONS

The experimental work of the author shows that it is feasible to use a fluidized bed to improve the performance of reverse osmosis desalination.

The significance of using the fluidized bed with No. 1 glass beads was to increase the salt rejection and to increase the water flux by 21.7, 29.6, and 35.8% for 398-10-86, 398-10-82, and 398-10-78 nylon-supported membranes, respectively. These results were based on a brine flow velocity of 0.97 cm/sec for the fluidized bed and a velocity of 11.0 cm/sec without the fluidized bed. The percentage increase in flux is actually higher for membranes which originally have a higher flux than for those of a lower flux. In other words, the more concentration polarization on the membrane, the more significant the effect of the fluidized bed becomes.

By using the fluidized bed with the dacron-supported membranes, the water flux also increased with an accompanying increase in salt rejection.

A glass bead size of approximately 0.0185-inch diameter appears best for this fluidized bed in the brine flow velocity range between 0.57 and 0.97 cm/sec. Glass beads much smaller than the above size are not recommended.

It was determined that different membrane positions and cell geometry affected the performance of the membranes.

By using the fluidized bed, the flux decline with time for cellulose acetate membranes on nylon supports was greatly decreased. The data were fitted by a straight line with a slope of -0.012 on a log flux versus log time plot.

A study conducted on scale formation shows that by employing a fluidized bed system with a scale-forming feed, both the water flux and the membrane life are significantly improved.

In view of the economics, the most significant effect of using the fluidized bed is to decrease the considerable cost of membrane replacement.

V. RECOMMENDATIONS

The determination of the optimum conditions will be necessary for this process to be commercially realized. An extensive study with higher brine flow velocities in a fluidized bed will be helpful to the understanding of this effect on cell performance. An optimum brine flow velocity and a new optimum glass bead size can be obtained from this study. A bead material other than glass should also be tried.

Additional work in the study of other membrane positions and cell geometry is also recommended. Tubular membranes positioned in a fluidized bed seem attractive.

A theoretical study should be undertaken to investigate the phenomenon wherein the salt flux increased when interface concentration decreased for loose membranes. This could include determination of mass transfer coefficients at the wall in a fluidized bed.

VI

APPENDIX

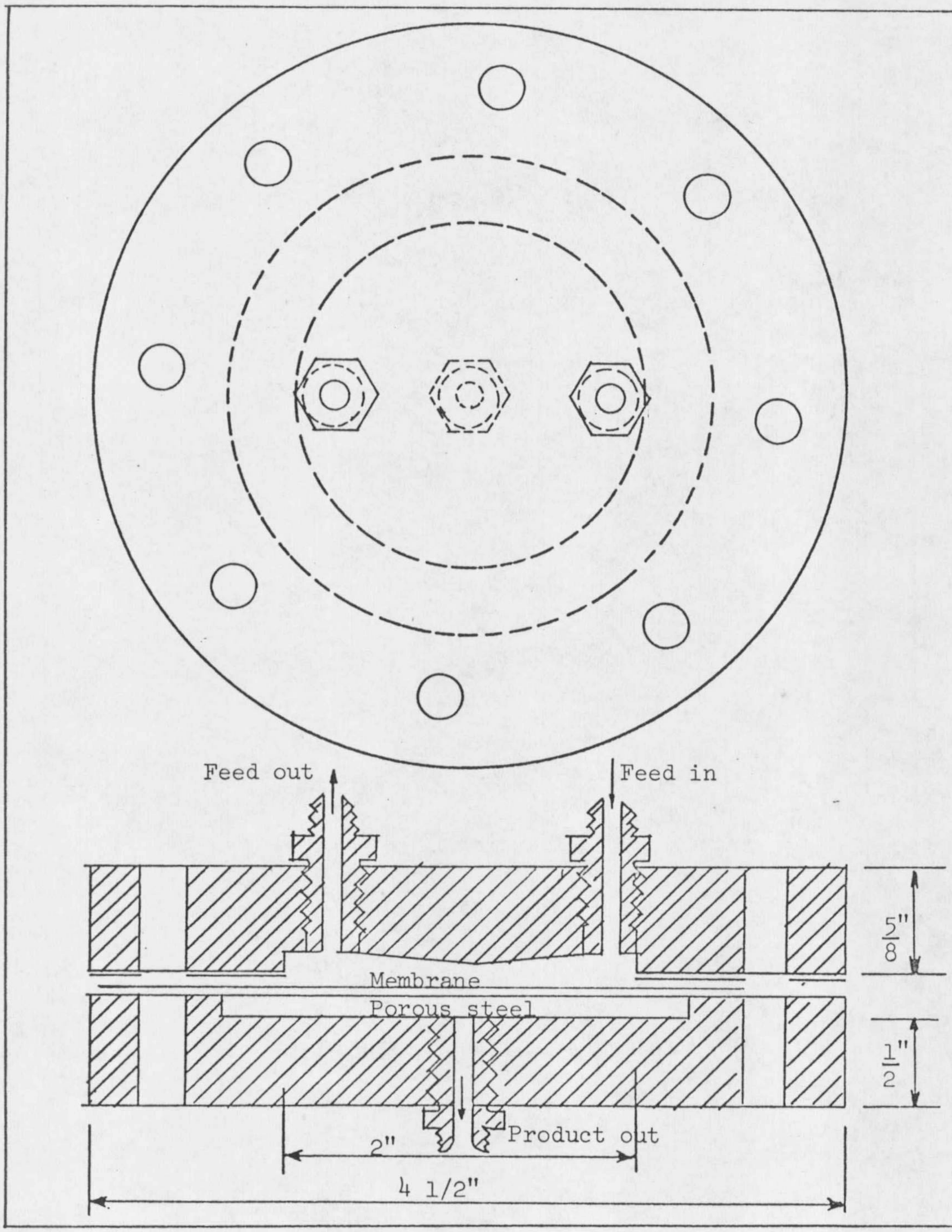

Figure 8. Reverse Osmosis Cell

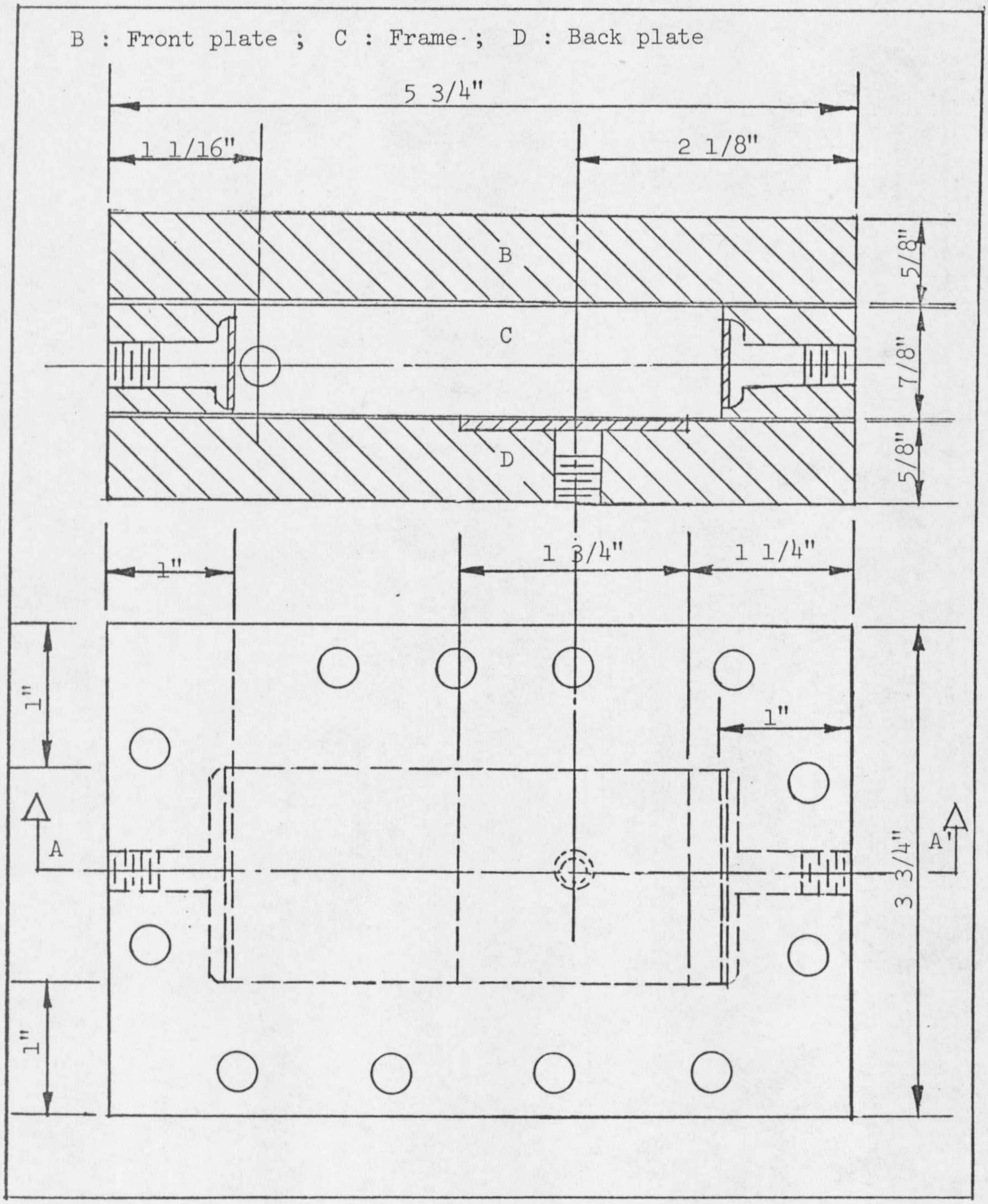

Figure 9. Fluidized Bed Reverse Osmosis Cell

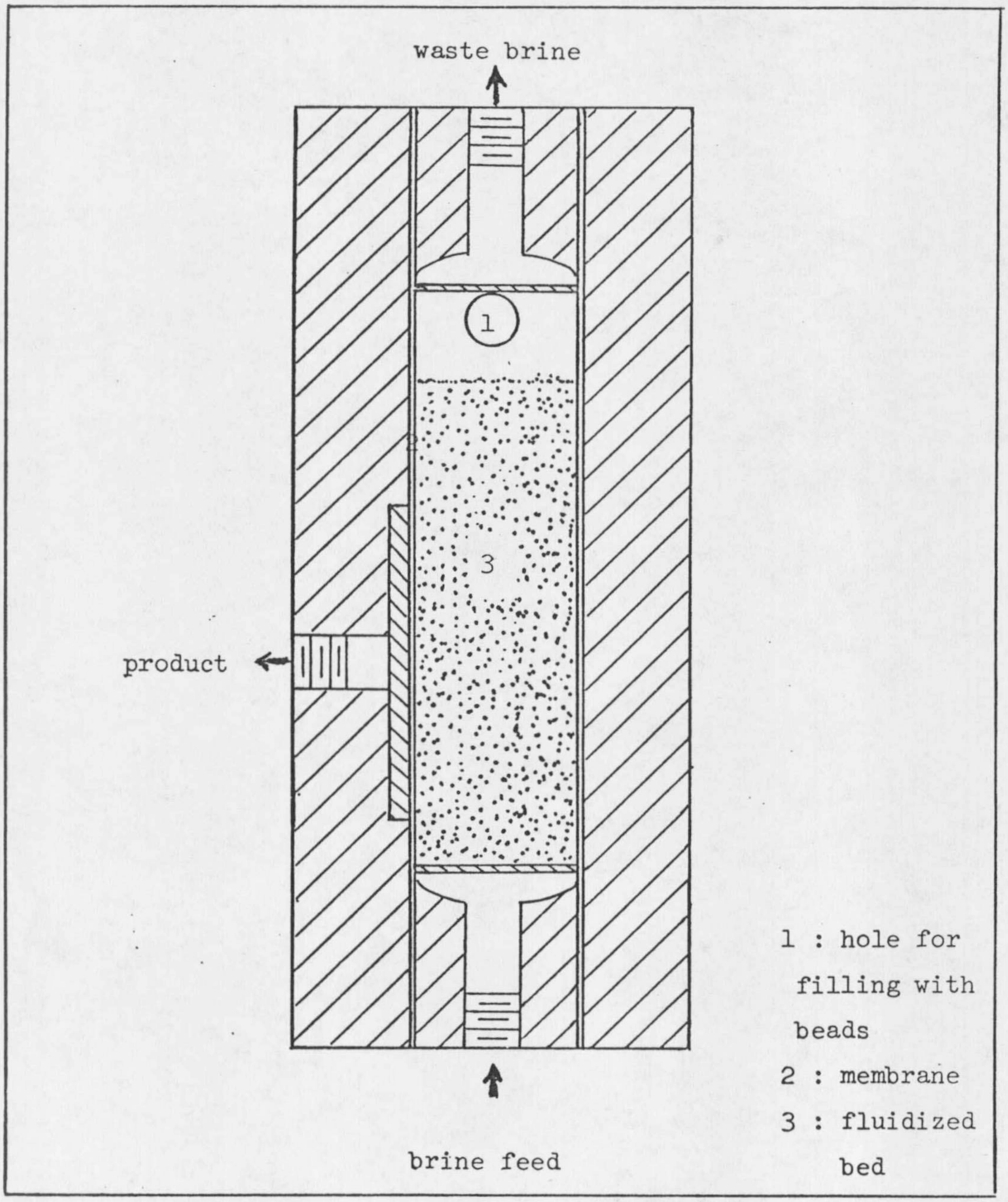

Figure 10. Conceptual Diagram of Fluidized Bed Reverse Osmosis

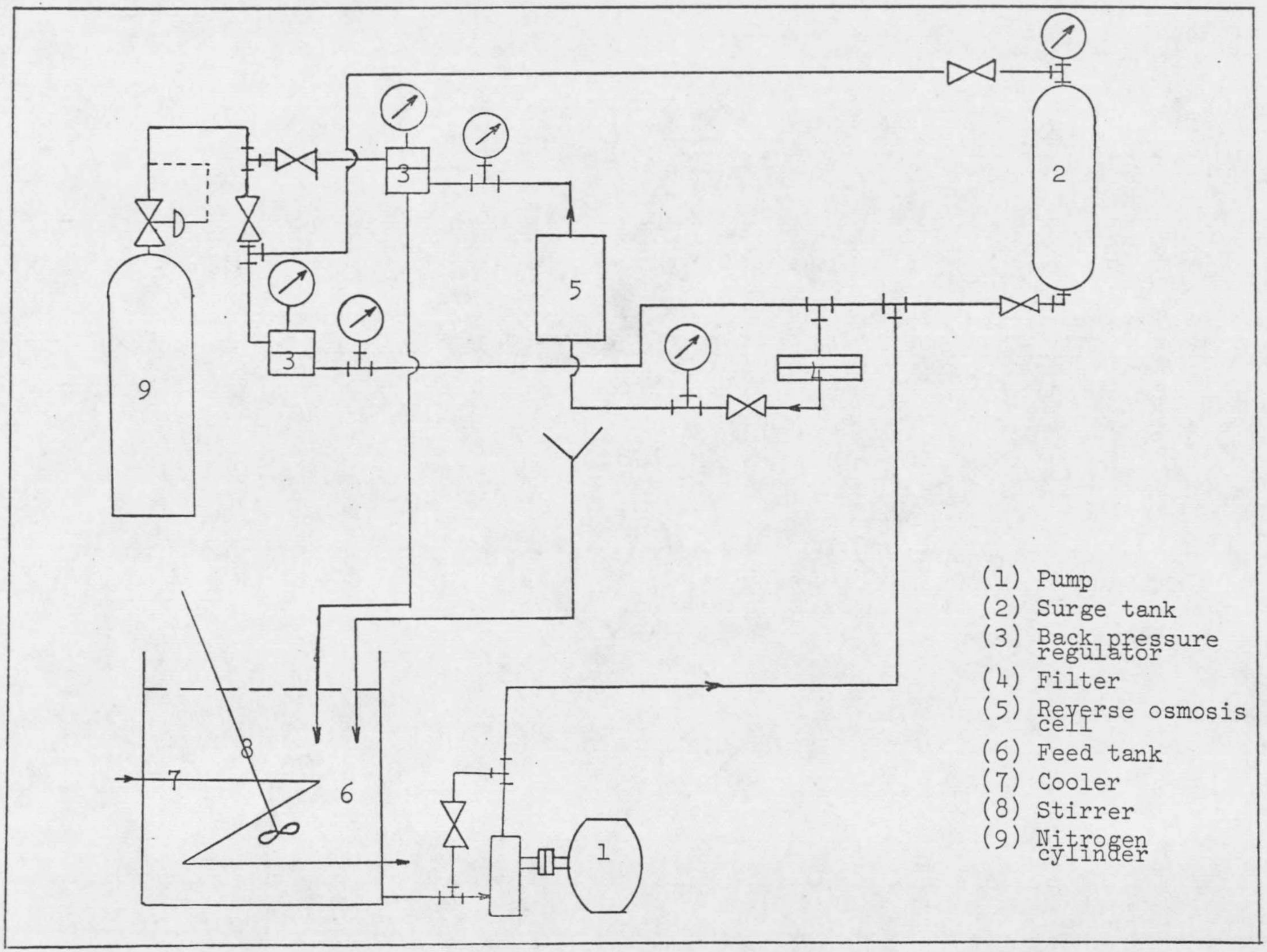

Figure 11. Test System and Flow Diagram

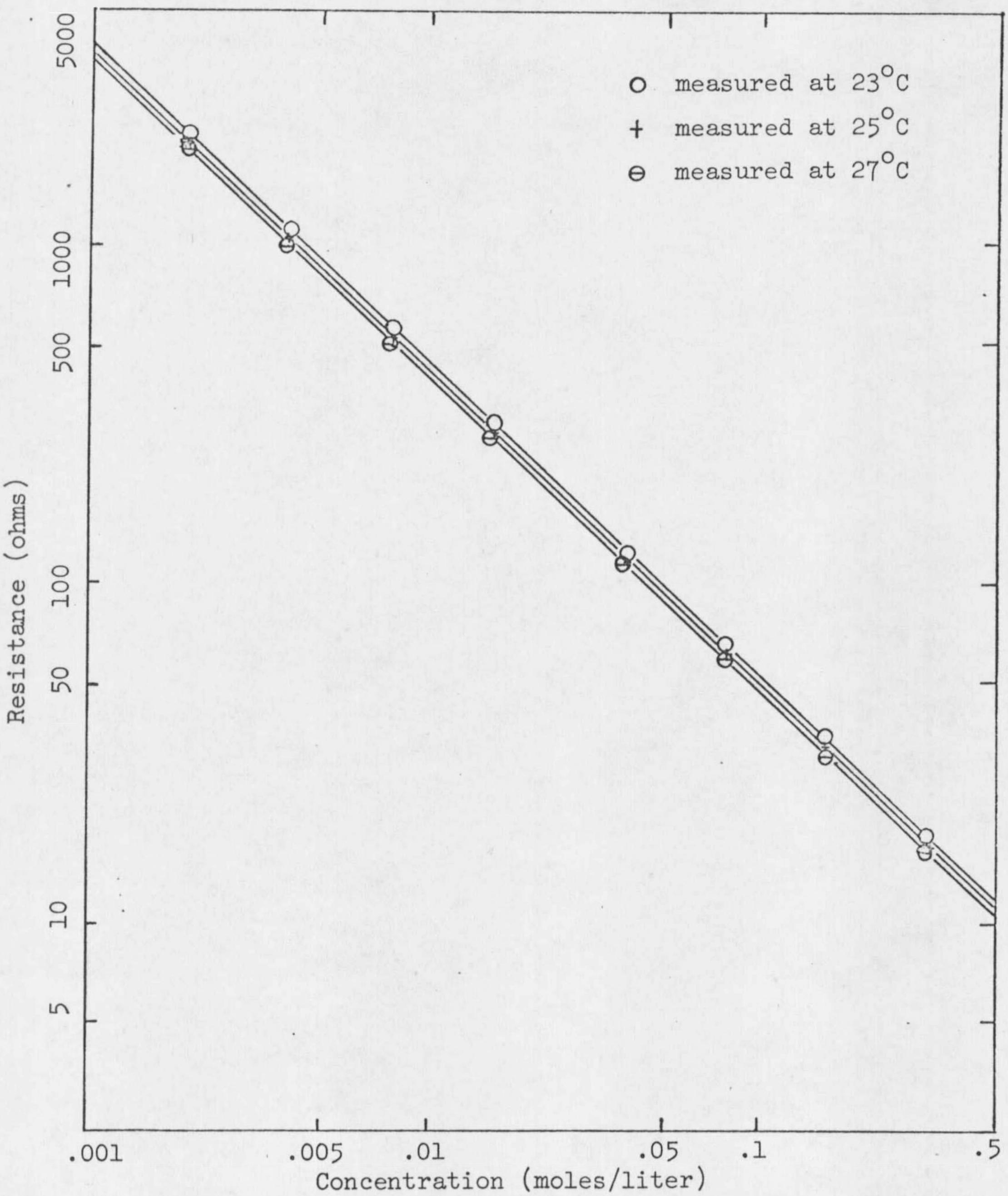

Figure 12. Calibration of Conductivity Cell

Table II. Results Using a Fluidized Bed for 398-10-86-Nylon Membranes.

Run No.	Glass Bead Type	Water Flux (GSFD)	Salt Rejection (%)
44	None	24.1	90.6
46	"	21.0	91.0
49	"	21.5	94.2
70	"	21.8	92.0
		Av. 22.1 ± 2.18	92.0
44	No. 1	28.7	93.7
46	"	25.6	93.4
49	"	26.8	95.5
70	"	26.5	94.3
		Av. 26.9 ± 2.07	94.2

Av. water flux increased with fluidized bed was 21.7% ± 4.2%

Diameter of bead No. 1: 0.0185 in.

Brine flow velocity with fluidized bed: 0.97 cm/sec.

Brine flow velocity without fluidized bed: 11.0 cm/sec.

Table III. Effect of Bead Sizes on Performance of 398-10-86-Nylon Membrane (A)

Run No.	Glass Bead Type	Water Flux (GSFD)	Salt Rejection (%)
44	No. 1	28.7	93.7
46	"	25.6	93.4
49	"	26.8	95.5
70	"	26.5	94.3
		Av. 26.9 ± 2.07	94.2
62	No. 2	28.9	93.5
63	"	25.3	95.1
64	"	25.8	92.7
65	"	24.1	95.4
		Av. 26.0 ± 3.87	94.2
66	No. 3	20.3	93.5
67	"	18.6	94.9
68	"	21.3	92.4
69	"	19.8	94.4
		Av. 20.0 ± 1.79	93.8
110	No. 4	26.3	91.9
111	"	28.0	91.6
112	"	26.3	92.7
113	"	27.0	94.1
		Av. 26.9 ± 1.28	92.6

Brine flow velocity: 0.97 cm/sec.

Diameter of beads: No. 1 ..... 0.0185 in.
No. 2 ..... 0.0110 in.
No. 3 ..... 0.0080 in.
No. 4 ..... 0.0394 in.

Table IV. Effect of Bead Sizes on Performance of 398-10-86 Nylon Membrane (B)

Run No.	Glass Bead Type	Water Flux (GSFD)	Salt Rejection (%)
44	No. 1	28.9	92.0
46	"	25.1	92.0
49	"	24.8	95.4
70	"	25.1	94.1
		Av. 26.0 $\pm$ 2.30	93.4
62	No. 2	27.0	93.4
63	"	23.4	94.5
64	"	25.3	92.4
65	"	23.2	94.0
		Av. 24.7 $\pm$ 3.50	93.3
66	No. 3	19.3	93.0
67	"	17.4	94.6
68	"	20.1	91.9
69	"	19.1	94.1
		Av. 19.0 $\pm$ 0.24	93.4

Brine flow velocity: 0.57 cm/sec.

Diameter of beads: No. 1 ..... 0.0185 in.
No. 2 ..... 0.0110 in.
No. 3 ..... 0.0080 in.

Table V. Results Using a Fluidized Bed for 398-10-82-Nylon Membranes

Run No.	Glass Bead Type	Water Flux (GSFD)	Salt Rejection (%)
26	None	26.8	85.5
27	"	33.4	83.0
28	"	24.1	88.1
33	"	27.8	85.5
		Av. 28.0 ± 6.20	85.5
26	No. 1	35.6	87.6
27	"	40.0	85.0
28	"	33.9	90.5
35	"	35.8	85.0
		Av. 36.3 ± 4.13	87.0

Av. water flux increased with fluidized bed: 29.6% ± 16.0%

Brine flow velocity with fluidized bed: 0.97 cm/sec.

Brine flow velocity without fluidized bed: 11.0 cm/sec.

Table VI. Effect of Bead Sizes on Performance of 398-10-82-Nylon Membrane (A)

Run No.	Glass Bead Type	Water Flux (GSFD)	Salt Rejection (%)
26	No. 1	35.6	87.6
27	"	40.0	85.0
28	"	33.9	90.5
35	"	35.8	85.0
		Av. 36.3 ± 4.13	87.0
36	No. 2	37.3	90.3
40	"	38.7	83.0
41	"	36.1	85.5
		Av. 37.4 ± 2.07	86.3
38	No. 3	35.8	80.5
42	"	31.0	84.5
43	"	34.2	87.0
		Av. 33.7 ± 3.89	84.0
114	No. 4	29.8	90.5
115	"	31.0	90.0
116	"	38.5	85.5
117	"	37.0	89.2
		Av. 34.1 ± 6.86	88.8

Brine flow velocity: 0.97 cm/sec.

Diameter of beads: No. 1 ..... 0.0185 in.
No. 2 ..... 0.0110 in.
No. 3 ..... 0.0080 in.
No. 4 ..... 0.0394 in.

Table VII. Effect of Bead Sizes on Performance of 398-10-82-Nylon Membrane (B)

Run No.	Glass Bead Type	Water Flux (GSFD)	Salt Rejection (%)
26	No. 1	36.6	87.0
27	"	41.4	84.5
28	"	33.0	89.8
35	"	33.9	85.0
		Av. 36.2 ± 6.48	86.6
36	No. 2	37.3	88.1
40	"	36.3	80.5
41	"	36.1	83.0
		Av. 36.6 ± 1.02	83.9
38	No. 3	33.4	76.5
42	"	30.6	83.0
43	"	33.2	85.5
		Av. 32.4 ± 2.49	81.7

Brine flow velocity: 0.57 cm/sec.

Diameter of beads: No. 1 ..... 0.0185 in.
No. 2 ..... 0.0110 in.
No. 3 ..... 0.0080 in.

Table VIII. Membrane Performance with Varied Histories (without a fluidized bed)

Run No.	Brine Flow Velocity (cm/sec)	Water Flux (GSFD)	Salt Rejection (%)
26 (*)	8.7	26.3	85.0
27 (*)	"	33.7	83.0
		Av. 30.0 ± 8.33	84.0
31 (**)	"	26.0	86.5
32 (**)	"	30.4	80.5
33 (**)	"	28.2	85.5
34 (**)	"	33.7	83.0
		Av. 29.6 ± 4.72	83.9
26 (*)	11.0	26.8	85.5
27 (*)	"	33.4	83.0
		Av. 30.1 ± 7.43	84.3
31 (**)	"	26.3	87.0
32 (**)	"	31.0	81.7
33 (**)	"	27.8	85.5
34 (**)	"	34.6	81.7
		Av. 29.9 ± 6.27	84.0

* ..... Membranes which were tested with glass beads first

** ..... New membranes

Table IX. Results Using a Fluidized Bed for 398-10-78-Nylon Membranes

Run No.	Glass Bead Type	Water Flux (GSFD)	Salt Rejection (%)
96*	None	45.4	38.0
97*	"	53.7	35.0
100**	"	32.5	67.0
101**	"	59.6	26.0
		Av. 47.8 ± 18.6	41.5
96*	No. 1	65.5	44.2
97*	"	70.5	41.3
100**	"	49.5	68.0
101**	"	74.0	43.2
		Av. 64.9 ± 17.0	49.2

*Run with glass beads first, then without beads

**Run without glass beads first, then with beads

Average water flux increased with glass beads: 35.8% ± 14.2%

Brine flow velocity: 0.97 cm/sec.

Table X. Effect of Bead Size on Performance of 398-10-78-Nylon Membrane

Run No.	Glass Bead Type	Water Flux (GSFD)	Salt Rejection (%)
92	No. 1	43.0	81.7
93	"	43.2	75.0
104	"	46.2	77.0
105	"	58.0	72.0
106	"	54.0	76.5
107	"	48.0	72.0
		Av. 48.7 ± 9.65	75.7
84	No. 2	58.0	55.0
85	"	46.8	77.5
86	"	48.0	78.5
87	"	44.2	73.5
		Av. 49.3 ± 9.62	71.1
88	No. 3	45.3	73.5
89	"	53.3	63.0
90	"	48.0	73.5
91	"	45.4	70.0
		Av. 48.0 ± 5.96	70.0
102	No. 4	62.0	65.0
108	"	38.2	76.7
109	"	43.0	76.7
118	"	51.4	70.5
119	"	53.7	76.5
		Av. 49.7 ± 14.8	73.2

Table XI. Salt Fluxes With and Without the Fluidized Bed

Run No.	H.T.T. (°C)	Glass Bead Type	W.F. (GSFD)	S.R. (%)	Ns $\frac{g\ NaCl}{cm^2 sec} \times 10^8$
44	86	None	24.1	90.6	1.91
46	86	"	21.0	91.0	1.53
49	86	"	21.5	94.2	1.11
70	86	"	21.8	92.0	1.41
					Av. 1.49
44	86	No. 1	28.7	93.7	1.46
46	86	"	25.6	93.4	1.36
49	86	"	26.8	95.5	0.97
70	86	"	26.5	94.3	1.21
					Av. 1.25
128	82	None	29.8	85.0	3.60
129	82	"	29.2	81.7	4.30
130	82	"	26.8	84.8	3.28
131	82	"	29.8	85.0	3.60
					Av. 3.70
128	82	No. 1	37.3	86.5	4.05
129	82	"	38.2	84.5	4.75
130	82	"	34.4	85.0	4.15
131	82	"	37.3	85.5	4.35
					Av. 4.32
96	78	None	45.4	38.0	22.7
97	78	"	53.7	35.0	28.2
100	78	"	32.5	67.0	8.7
101	78	"	59.6	26.0	35.7
					Av. 23.8

Table XI (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	W.F. (GSFD)	S.R. (%)	Ns $\frac{\text{g NaCl}}{\text{cm}^2\text{sec}} \times 10^8$
96	78	No. 1	65.5	44.2	29.5
97	78	"	70.5	41.3	33.4
100	78	"	49.5	68.0	12.7
101	78	"	74.0	43.2	33.9
					Av. 27.4

H.T.T. : Heat Treatment Temperature

W.F. : Water Flux

S.R. : Salt Rejection

Table XII. Results Using a Fluidized Bed for 398-10-82-Nylon Membrane with Brine Solution Containing $CaSO_4$

Run No.	Fraction of Saturate $CaSO_4$ Solution	Water Flux (GSFD) Without Beads	With Beads	Water Flux Increase (%)
135	1/2	25.6	34.2	33.6
136	1/2	34.6	46.0	33.0
				Av. 33.3
137	1	33.9	45.3	33.6
138	1	24.6	33.4	35.8
				Av. 34.7

Brine flow velocity: without fluidized bed ..... 11.0 cm/sec.

with fluidized bed ..... 0.97 cm/sec.

Table XIII. Results of All Runs

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr.)	Comments
1	82	None	9.8	16.4	85.5		
		No. 1	14.8	15.2	92.4		
		No. 1	3.1	9.0	85.0		
2*	82	None	2.2	6.3	90.6		
			9.8	9.4	91.6		
3	82	No. 1	14.8	11.6	90.0		
				6.8	87.0	124	
4	86	No. 1	6.5	17.5	88.6		
			3.1	10.5	76.5		
			14.8	21.2	94.1		
		None	9.8	18.9	94.0		
			2.2	17.2	53.2		
			4.3	10.3	88.0		
5	86	None	2.2	9.3	92.7		
		No. 1(3gr)	3.1	10.0	94.2		
		No. 1(5gr)	3.1	10.0	91.6		
6	84	No. 1(3gr)	3.1	12.3	87.6		
		None	2.2	10.7	86.5		
		No. 1(2gr)	3.1	13.8	87.6		

Round test cell was used for Runs No. 1 to No. 6

One layer masking tape was used when preparing above membrane

*Operating pressure at 350 psi; remaining runs were at 800 psi

B.F.V. : Brine Flow Velocity

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
7	82	No. 3	0.57	46.5	81.7		a
			0.76	47.7	84.5		
8	82	No. 3	1.0	53.7	80.5		a
9	84	No. 1	0.77	33.0	94.4		a
10	84	No. 3	0.77	33.4	70.5		a
11	84	No. 3	0.57	27.5	54.3		a
12	84	No. 1	0.57	28.7	60.5		a
13	82	No. 1	0.57	42.2	91.0		
14	82	No. 2	0.57	41.8	90.3		
15	82	None	1.77	39.4	87.6		
			1.1	32.5	84.5		
16	82	No. 1	0.77	41.6	90.3		
			0.57	39.7	88.6		
17	86	No. 1	0.57	18.9	94.4		
			0.77	19.1	95.4		
18	86	None	2.7	15.3	94.1		
			2.0	15.3	94.1		
			1.3	15.0	92.6		
			0.5	13.2	92.0		
19	86	No. 1	0.57	15.8	95.5		Dacron support
			0.77	16.2	95.8		
			0.97	16.5	96.2		
		None	0.51	10.5	91.0		
			1.27	12.4	93.0		

a: 0.005-inch thick membrane

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
19	86	None	1.98	12.9	94.7		
			3.41	13.4	95.0		
			6.82	13.4	95.1		
			7.54	13.6	94.7		
			11.0	14.3	94.9		
20	86	No. 1	0.57	19.6	92.4		Dacron support
			0.97	21.5	93.5		
21	82	No. 1	0.57	22.7	87.0		"
			0.97	25.3	89.8		
22	84	No. 1	0.57	18.2	93.4		"
		None	11.0	14.1	88.1		
			8.7	14.1	88.6		
			6.4	13.2	87.6		
			4.1	11.5	86.5		
			1.0	9.6	80.5		
23	84	No. 1	0.14	16.0	88.1		"
			0.36	19.1	90.5		
			0.57	19.8	90.5		
			0.77	19.6	92.4		
		None	1.0	13.6	76.5		
			4.1	15.5	83.0		
			6.4	18.6	83.0		
24	82	No. 1	0.57	26.8	88.6		"
			0.77	27.2	89.2		
		None	6.4	24.4	81.7		
25	86	No. 1	0.97	16.5	95.1		
			0.57	15.0	93.0		
		None	11.0	13.2	87.0		
			8.7	13.1	87.6		
			6.4	12.2	88.1		
			1.0	10.8	85.5		

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
26	82	No. 1	0.57	36.6	87.0		
			0.14	28.6	83.0		
			0.97	35.6	87.6		
		None	11.0	26.8	85.5		
			8.7	26.4	85.0		
			6.4	26.4	83.0		
			1.0	23.0	76.5		
27	82	No. 1	0.14	38.0	80.5		
			0.57	41.4	84.5		
			0.77	40.2	85.0		
			0.97	40.0	85.0		
		None	1.0	29.4	75.0		
			6.4	33.0	84.5		
			8.7	33.7	83.0		
			11.0	33.4	83.0		
28	82	No. 1	0.14	28.7	81.7		
			0.57	33.0	89.8		
			0.97	33.9	90.5		
			6.4	25.8	88.1		
			8.7	25.8	88.1		
			11.0	24.1	88.1		
29	84	No. 1	0.14	28.9	79.5		
30	84	No. 1	0.57	31.6	79.5		
			0.97	29.2	83.0		
			0.57	28.2	75.0		b
			0.57	30.4	85.0		c
31	82	None	6.4	25.8	86.0		
			8.7	26.0	86.5		
			11.0	26.3	87.0		
			4.1	24.8	84.5		
			1.0	20.5	79.5		

b: +30° from the vertical with the membrane facing upward
c: -30° from the vertical with the membrane facing downward

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
32	82	None	11.0	31.0	81.7		
			8.7	30.4	80.5		
			6.4	28.9	79.5		
			4.1	27.0	77.0		
			1.0	22.7	68.2		
33	82	None	1.0	23.9	67.0		
			4.1	27.0	82.4		
			6.4	27.0	85.2		
			8.7	28.2	85.5		
			11.0	27.8	85.5		
34	82	None	11.0	34.6	81.7		
			8.7	33.7	83.0		
			6.4	32.7	81.7		
			4.1	30.4	79.5		
			1.0	26.8	70.5		
35	82	No. 1	0.97	35.8	85.0		
			0.57	33.9	85.0		
		No. 2	0.97	34.9	80.5		
			0.77	33.4	80.5		
			0.57	32.3	80.5		
36	82	No. 2	0.36	36.1	86.0		
			0.57	37.3	88.1		
			0.97	37.3	90.3		
		No. 1	0.97	35.8	89.8		
37	82	No. 3	0.57	42.8	67.0		
			0.77	44.5	64.0		
			0.97	45.4	64.0		
38	82	No. 3	0.57	33.4	76.5		
			0.77	33.7	79.5		
			0.97	35.8	80.5		
39	82	No. 2	0.97	25.1	86.5		

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
40	82	No. 2	0.97	38.4	83.0		
			0.57	36.3	80.5		
			0.36	33.7	79.5		
41	82	No. 2	0.36	35.8	81.0		
			0.57	36.1	83.0		
			0.77	36.3	85.0		
			0.97	36.1	85.5		
42	82	No. 3	0.97	31.0	84.5		
			0.77	30.8	84.5		
			0.57	30.6	83.0		
			0.36	27.8	81.7		
43	82	No. 3	0.14	30.4	77.5		
			0.36	29.6	82.4		
			0.57	33.2	85.5		
			0.97	34.2	87.0		
44	86	No. 1	0.14	27.5	90.0		
			0.36	28.2	91.4		
			0.57	28.9	92.0		
			0.77	28.7	93.0		
			0.97	28.7	93.7		
44	86	None	11.0	24.1	90.6		
			8.7	24.4	91.4		
			6.4	23.7	90.3		
			4.1	21.8	88.6		
			1.0	18.4	87.6		
45	86	None	1.0	23.3			
			4.1	23.9			
			6.4	23.9			
			11.0	23.9			

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
46	86	No. 1	0.36	24.4	91.9		
			0.57	25.1	92.0		
			0.97	25.6	93.4		
		None	4.1	17.7	87.0		
			6.4	21.3	90.3		
			8.7	21.3	91.0		
			11.0	21.0	91.0		
47	86	None	11.0	26.0			
			6.4	25.1			
			8.7	25.8			
48	86	None	0.57	21.5			d
			0.97	21.5			
			6.4	23.4			
			11.0	23.4			
49	86	No. 1	0.97	26.8	95.5		
			0.57	24.8	95.4		
		None	11.0	21.5	94.2		
			8.7	21.0	94.2		
50	86	No. 1	0.97	30.1			d
		None	11.0	30.1			
			6.4	27.5			
			4.1	24.1			
51	86	None	4.1	20.5			d
			6.4	20.3			
			11.0	20.3			
		No. 1	0.97	20.5			
52	82	No. 1	0.97	43.2			d
			11.0	43.2			
			6.4	39.0			
53	86	No. 1	0.97	28.0			d
		None	11.0	26.5			
			6.4	24.1			
			1.0	19.8			

d: Feed solution content 150 ppm salt

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
54	82	No. 1	0.97	41.4			d
		None	11.0	40.9			
			6.4	37.5			
55	82	None	6.4	45.4			d
			11.0	45.9			
		No. 1	0.97	45.9			
56	82	None	1.0	44.2			d
			6.4	46.8			
			11.0	47.2			
		No. 1	0.97	47.5			
57	82	No. 2	0.97	49.6			d
		None	11.0	48.8			
			6.4	43.7			
58	86	No. 1	0.97	32.0			d
		None	11.0	31.8			
59	86	None	6.4	32.7			d
			11.0	34.2			
		No. 1	0.97	34.4			
60	86	No. 1	0.97	32.7			d
		None	11.0	33.0			
			6.4	30.0			
61	86	No. 1	0.97	36.3			
		None	11.0	36.6			
			6.4	33.4			
62	86	No. 2	0.97	28.9	93.5		
			0.57	27.0	93.4		
			0.36	25.1	93.0		
63	86	No. 2	0.97	25.3	95.1		
			0.77	25.1	94.8		
			0.57	23.4	94.6		
			0.36	20.8	94.2		

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
64	86	No. 2	0.36	24.1	91.6		
			0.57	25.3	92.4		
			0.97	25.8	92.7		
65	86	No. 2	0.97	24.1	95.4		
			0.57	23.2	94.0		
66	86	No. 3	0.97	20.3	93.5		
			0.57	19.3	93.0		
67	86	No. 3	0.97	18.6	94.9		
			0.57	17.4	94.6		
			0.36	14.6	94.1		
			0.14	12.0	92.7		
68	86	No. 3	0.14	17.4	89.2		
			0.36	19.8	91.0		
			0.57	20.1	91.9		
			0.97	21.3	92.4		
69	86	No. 3	0.14	16.2	90.3		
			0.36	18.6	93.4		
			0.57	19.1	94.1		
			0.77	19.6	94.3		
			0.97	19.8	94.4		
70	86	No. 1	0.97	26.5	94.3		
			0.57	25.1	94.1		
		None	11.0	21.8	92.0		
			6.4	20.8	91.7		
			1.0	16.7	90.0		
71	86	None	1.0	31.8			e
			4.1	30.4			
			6.4	31.0			
			8.7	30.4			
			11.0	30.6			

e: Feed solution content 8 ppm salt

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
72	86	None	1.0	31.3			e
			4.1	31.0			
			6.4	31.0			
			11.0	30.8			
73	86	None	11.0	25.8			e
			8.7	25.8			
			6.4	24.6			
			4.1	23.9			
			1.0	23.2			
74	86	None	11.0	24.4			e
			8.7	22.9			
			6.4	21.3			
			4.1	21.5			
			1.0	20.8			
75	82	None	11.0	33.0			e
			8.7	32.7			
			6.4	31.8			
			4.1	31.0			
			1.0	30.4			
76	82	None	11.0	35.8			e
			6.4	35.1			
			4.1	33.4			
			1.0	32.7			
77	82	None	1.0	37.0			e
			4.1	37.3			
			6.4	37.5			
			11.0	37.5			
78	82	None	4.1	29.2			e
			6.4	28.0			
			11.0	28.7			
			11.0	18.6	91.7		
79	78	No. 5	0.97	57.4	60.5		

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
80	78	No. 5	0.97	58.5	67.0		
81	82	No. 5	0.97	31.8	90.5		
			0.57	30.6	90.3		
82	86	No. 5	0.97	20.8	95.0		
			0.57	18.9	94.6		
83	86	No. 5	0.97	20.3	94.6		
84	78	No. 2	0.97	58.0	55.0		
			0.57	48.0	55.0		
			0.36	42.5	52.0		
			0.14	32.3	46.0		
85	78	No. 2	0.97	46.8	77.5		
			0.57	43.0	77.0		
			0.14	38.2	69.0		
86	78	No. 2	0.97	48.0	78.5		
			0.57	41.3	77.0		
			0.14	36.1	72.0		
87	78	No. 2	0.97	44.2	73.5		
			0.57	44.2	72.0		
88	78	No. 3	0.97	45.3	73.5		
			0.57	41.8	73.3		
89	78	No. 3	0.97	53.3	63.0		
			0.57	46.0	60.0		
90	78	No. 3	0.97	48.0	73.5		
91	78	No. 3	0.57	40.6	65.3		
			0.97	45.4	70.5		
92	78	No. 1	0.97	43.0	81.7		
93	78	No. 1	0.97	43.2	75.0		
			0.57	41.6	69.0		

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
94	78	None	11.0	40.4	65.3		
			6.4	38.7	60.5		
95	78	None	1.0	31.0	26.0		
			6.4	41.8	35.0		
			11.0	42.0	34.0		
96	78	No. 1	0.97	65.5	44.2		
		None	11.0	45.4	38.0		
97	78	No. 1	0.97	70.5	41.3		
		None	11.0	53.7	35.0		
98	78	No. 4	0.97	64.5	43.2		
99	78	No. 4	0.97	67.0	41.3		
			0.57	62.0	38.3		
100	78	None	11.0	32.5	67.0		
		No. 1	0.97	49.5	68.0		
101	78	None	11.0	59.6	26.0		
		No. 1	0.97	74.0	43.2		
102	78	None	11.0	47.2	64.5		
		No. 4	0.97	62.2	64.5		
103	78	None	11.0	58.5	50.0		
104	78	No. 1	0.97	46.2	77.0		
105	78	No. 1	0.97	58.0	72.0		
106	78	No. 1	0.97	54.0	76.5		
107	78	No. 1	0.97	48.0	72.0		
108	78	No. 4	0.97	38.2	76.7		
		None	11.0	28.2	72.0		
109	78	No. 4	0.97	43.0	77.3		
110	86	No. 4	0.97	26.3	91.9		

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
111	86	No. 4	0.97	28.0	91.6		
112	86	No. 4	0.97	26.3	92.7		
113	86	No. 4	0.97	27.0	94.1		
114	82	No. 4	0.97	29.8	90.5		
115	82	No. 4	0.97	31.0	90.0		
116	82	No. 4	0.97	38.5	85.5		
117	82	No. 4	0.97	37.0	89.2		
118	78	No. 4	0.97	51.4	70.5		
119	78	No. 4	0.97	53.7	76.5		
120	86	No. 1	0.97	25.4	91.7	2	
				23.7	92.0	25	
				23.4	91.9	36	
				23.4	91.9	55	
				23.4	91.9	72	
				23.4	91.9	103	
				23.9	91.6	220	
				22.9	90.3	251	
121	86	No. 1	0.97	16.2	93.0	1	
				15.0	93.5	14	
				15.0	93.5	36	
				15.0	93.5	46	
				15.0	93.5	60	
				15.0	93.5	71	
				15.0	93.5	83	
				14.8	93.8	107	
122	86	No. 1	0.97	23.9	95.4	1.5	
				21.5	95.4	24	
				21.5	95.1	48	
				21.5	95.0	71	

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
122	86	No. 1	0.97	21.5	95.0	139	
				21.5	94.9	184	
				21.0	95.0	242	
				20.8	95.0	303	
123	86	None	11.0	14.3	92.7	2	
				14.6	94.6	4	
				13.2	94.6	11	
				12.0	94.5	24	
				11.5	94.2	36	
				10.8	93.8	50	
				10.7	93.0	74	
				10.5	92.4	105	
				9.1	91.4	214	
				8.9	91.0	256	
124	82	None	11.0	44.0	(P2)	25	e
125	82	No. 1	0.97	44.2	(P2)	21	e
			0.36	43.0	(P2)	22	
126	82	None	11.0	45.5	(P2)	23	e
		No. 1	0.97	46.7	(P2)	24	
127	82	No. 1	0.57	44.0	(P2)	4	e
			0.97	44.7	(P2)	5	e
		None	11.0	44.0	(P2)	21	
128	82	None	11.0	29.8	85.0		Same membrane as Run-127
			4.1	26.0	81.7		
		No. 1	0.97	37.3	86.5		
			0.57	34.6	85.5		
129	82	No. 1	0.97	38.2	84.5		Same membrane as Run-126
			0.57	37.0	83.0		
		None	4.1	28.0	81.1		
			11.0	29.2	81.7		

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
130	82	No. 1	0.97	34.4	85.0		Same membrane as Run-125
			0.57	32.7	83.8		
		None	11.0	26.8	84.8		
			4.1	24.6	83.0		
131	82	None	4.1	28.2	84.5		Same membrane as Run-124
			11.0	29.8	85.0		
		No. 1	0.97	37.3	85.5		
			0.57	34.2	85.0		
132	82	None	11.0	34.9	85.5	0.5	
				33.4	86.5	1.0	
				31.3	87.0	1.5	
				29.8	87.0	2.5	
				28.7	86.8	5.5	
				28.7	86.5	6.5	
				28.0	86.5	7.5	
133	82	None	11.0	29.8		1.0	Content 1/4 conc. of sat. $CaSO_4$ sol'n.
				28.7		2.0	
				28.2		4.0	
134	82	None	11.0	29.8		1.0	3/8 conc. of sat. $CaSO_4$ sol'n.
				28.0		2.0	
				28.0		6.0	
135	82	None	11.0	29.8		0.5	1/2 conc. of sat. $CaSO_4$ sol'n.
				27.8		1.5	
				26.0		2.5	
				25.6		5.0	
		No. 1	0.97	35.8		0.5	
				34.6		1.0	
				34.4		3.0	
				34.2		5.0	
				34.2		6.0	

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
136	82	No. 1	0.97	53.8		0.5	
				49.0		1.0	
				47.8		2.0	
				46.0		6.0	
		None	11.0	44.2		0.5	
				40.6		1.5	
				35.8		3.5	
				34.6		6.0	
137	82	None	11.0	39.4		1.0	Sat. $CaSO_4$
				35.8		2.5	sol'n,
				34.6		3.5	membrane
				33.9		5.0	same as
		No. 1	0.97	45.0		2.5	Run-136
				45.3		5.5	
138	82	No. 1	0.97	35.8		0.5	Sat. $CaSO_4$
				34.6		3.0	sol'n,
				33.4		5.0	membrane
		None	11.0	26.3		1.5	same as
				25.1		3.5	Run-135
				24.6		5.5	
139	82	None	11.0	47.8		1.0	
				35.8		2.5	
				33.4		6.0	
				31.0		10.0	
				29.8		17.0	
				27.5		22.5	
				23.9		31.5	
				20.8		42.5	
				20.3		49.0	
				20.1		55.0	
				19.3		67.0	
				19.1		73.0	
				17.9		78.0	

Table XIII (continued)

Run No.	H.T.T. (°C)	Glass Bead Type	B.F.V. (cm/sec)	W.F. (GSFD)	S.R. (%)	Time (hr)	Comments
139	82	None	11.0	16.2		88.5	
				15.5		101.5	
				15.3		113.0	
				15.0		120.0	
140	82	No. 1	0.97	38.2		1.0	Sat. $CaSO_4$
				33.4		3.0	sol'n,
				38.7		14.5	membrane
				25.1		28.0	same as
				24.4		39.0	Run-135
				24.6		51.0	
				24.4		63.0	
				23.9		75.0	
				23.9		86.0	
				23.9		94.0	
				23.9		100.0	
				23.9		110.0	
				23.4		120.0	
141	82	No. 1	0.57	33.9	83.0		Cell space
			0.97	35.8	84.5		3-3/4" x
			2.49	38.0	85.5		1-3/4" x
			2.0	38.2	85.5		3/8"
			0.97	33.7	84.5		Regular space

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