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Concentration of Dilute Industrial Wastes by Direct Osmosis

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CONCENTRATION OF DILUTE INDUSTRIAL WASTES BY DIRECT OSMOSIS

BY

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ABSTRACT

The purpose of this research was to study the feasibility of using direct osmosis with sea water to concentrate dilute industrial wastes.

Several continuous flow laboratory size osmosis units were designed, constructed, and operated successfully. Dilute waste solutions were concentrated by direct osmosis using simulated sea water on the other side of the membrane. With the reverse osmosis membranes currently available, permeation rates were much lower than expected based upon their reported reverse osmosis rates. Another problem was that the diffusion rate of sodium chloride from the sea water to the waste solution and of the metallic ions from the waste solution to the sea water were greater than could be tolerated in most applications.

This method of concentrating waste solutions does not appear to be practical until more selective high flux membranes than are currently available are developed. This method would be feasible if a suitable membrane were available. Membrane development was not within the scope of this investigation.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

LIST OF TABLES

LIST OF TABLES (Cont'd.)

LIST OF FIGURES

I. INTRODUCTION

There is a current need for more economical methods of treating industrial waste. If valuable products or raw materials can be recovered from the waste, the cost of the treatment will be partially offset by the value of these recovered materials (41, 33). In some cases, the value of the materials recovered may even be greater than the treatment cost.

Often industrial wastes are in the form of very dilute aqueous solutions and large volumes must be handled. These wastes would contain a relatively small amount of pollutant. For example, the rinse water used for washing nickel plated parts might contain only 500 milligrams per liter of nickel salts (41). Wash waters from a photographic processing laboratory may contain 10 to 100 milligrams per liter of silver salts (41). Recovery of valuable salts from these very dilute solutions would be expensive and might not be practical. An inexpensive method of concentrating dilute solutions of industrial wastes would be very useful in that it would make the recovery of many valuable dissolved materials economically practical. Even if the polluting material is not to be recovered, concen-

trating the solution will greatly reduce the volume to be handled in other treatment methods and may result in a reduction in the total treatment cost.

In the past decade, there has been considerable interest in the reverse osmosis process as a method of concentrating wastes and in the recovery of relatively pure water (1, 16, 17, 20, 26, 27, 33, 38, 41). Much recent work has been devoted to developing better reverse osmosis membranes and to reducing fouling of reverse osmosis membranes. In the reverse osmosis process, the solution is subject to a high pressure (100 to 600 psig) and relatively pure water flows through a semi-permeable membrane. In the direct osmosis process, when two solutions are separated by a suitable semi-permeable membrane, nearly pure water flows from the less concentrated to the more concentrated solution. No pressure differential is needed across the membrane. The need for a large pressure differential across the membrane in reverse osmosis requires that the equipment be constructed to withstand this high pressure. Also, the membranes, which are usually thin plastic film, must be supported by some strong porous backing material. This backing material often reduces the flow rate through the membrane. Another problem encountered in the reverse

osmosis process is the gradual reduction in the permeation rate through the membrane. This reduction in flow rate is attributed to the compaction of the membrane due to the high pressures.

Dilute solutions can be concentrated by direct osmosis at atmospheric pressure without the need for a pressure differential across the membrane. If the waste solution is separated by a suitable membrane from another more concentrated solution whose water osmotic pressure is less than that of the waste solution, water will flow from the dilute waste solution to the concentrated solution. Actually the factor governing the direction of flow is not the concentration of the solution but its osmotic pressure.

In those locations near the ocean, where sea water is available, it would be suitable for use as the concentrated solution. If a desalination plant is close by, the brine from this plant would be an even better source of a concentrated solution as its osmotic pressure would be even lower than sea water. A by-product benefit of using brine would be the dilution of the brine before it is discharged back into the ocean. If a proper membrane is used the only effect on the sea water or brine will be dilution, as most of the pollutant in the waste water should not pass through the membrane.

The direct osmosis process may be feasible in some industrial operations that do not have sea water available. Often in the same plant concentrated solutions are to be diluted by adding water. Instead of diluting the solutions by the direct addition of water, these solutions could be used as the concentrated solution in the direct osmosis process and would be diluted by the extraction of water from the waste solution.

Since the direct osmosis process operates at close to atmospheric pressure, the required equipment is relatively simple and inexpensive. Except for the membrane cost, units of fairly large area should be inexpensive to build. Because of their simple design, these osmosis units would be relatively easy to service.

The basic principle of the proposed direct osmosis process was tested in the laboratory. A small continuous flow osmosis unit was constructed and tested using a 1.5% sucrose solution as the waste solution and simulated sea water as the concentrated solution. The membrane tested was a sample of Eastman Kodak KP-98. Both solutions were at atmospheric pressure. As expected, water passed through the membrane from the sugar solution to the brine. The sugar solution was concentrated from 1.5 to 2.3% sucrose

and the brine was diluted from approximately 3.85% to 3.1% equivalent sodium chloride. The water flow rate through the membrane was 1.23 gal/ft^2/day.

It was the purpose of this research to make a study of the feasibility of using the direct osmosis process with sea water to concentrate dilute industrial wastes. The membranes used in this investigation were limited to those commercially available reverse osmosis membranes. Preliminary tests were made using distilled water as the waste solution in order to study the membrane's rejection of sodium chloride, but later simulated metallic wastes as well as an actual industrial waste were tested. The concentrating solution was limited to sea water.

The variables studied in addition to the different membranes and waste solutions were:

1. The flow rates of both sea water and the waste solution through the osmosis unit.
2. Concentration of the waste solution.
3. The rejection of the solute and of sodium chloride in the sea water by the different membranes.
4. The effect of solution concentration on permeation rate.
5. The effect of various techniques of supporting the membranes in the osmosis units.

6. The effect of different backing materials.

The principle measurements made in each test were the flow rates and the chemical analysis of each entering and leaving stream. From these measurements, it was possible to calculate the permeation rate through the membrane, the rejection of the pollutant by the membrane, and a material balance on all materials involved.

II. REVIEW OF LITERATURE AND THEORY

Review of Literature

There has been an interest in the permeation of liquids through membranes as early as 1831 (35). In 1907, Bigelow and Gemberling (12) made use of collodion membranes for dialysis and osmosis. They found that collodion membranes in the form of sacs, or flat films, for ordinary dialyzers, even of large size, were easily made. These membranes could be attached to supports more easily and more perfectly than parchment paper. Dialysis occurred through them more rapidly than through parchment paper. Membranes made from gold beaters' skin were still better for separations by dialysis. The quantity of water passing through the collodion membranes was nearly a linear function of pressure at a constant temperature. At 25°C, a change of one millimeter of mercury in pressure caused a change in the volume of water passing through the membrane equal to about 0.6 per cent of the quantity of water which passes through the membrane at a pressure difference of 150 millimeters of mercury. At a constant pressure of 150 millimeters of mercury, the quantity of water passing through the membrane was not

a linear function of temperature. An increase of 20-30 degrees was required to double the quantity of water passing through the membrane per unit time. Different samples of collodion membranes showed different permeabilities, but in spite of these differences in absolute values, a change in pressure or in temperature produced the same proportional effect in all samples of the membrane. It was also found that as a collodion membrane grows older, its permeability diminishes gradually, but it remains useful for one to three months.

Bartell (3) in 1914 made studies of osmosis using procelain membranes. Salt solutions of sulfates, chlorides, nitrates, and acetates were placed in osmotic cells which were constructed of procelain membranes of the same degree of porosity. Some of the solutions gave positive osmosis and others gave negative osmosis. Bartell defined positive osmosis as flow of liquid from more dilute to more concentrated solution and negative osmosis as flow of liquid from the concentrated solution to the dilute solution. Cells were set up with pure water inside and salt solutions outside. When set up in this manner, the solutions which had given decreased pressure within the cells when the salt solution was on the inside and the pure water on the out-

side, now gave increased pressure. The direction of flow was from the concentrated solution to the dilute solution even though it was opposed by hydrostatic pressure. The quantities of salt diffusing were determined. The order of the diffusion quantities of the salts through the procelain membranes was practically the same as the order of diffusion velocities when no membrane was present. The membranes which had the greatest negative osmosis had the smallest amounts of salt diffusing through them. In experiments using salt solutions of nitrates and chlorides, flow of the water was toward the dilute solution if the anion had a greater migration velocity than the cation. The greater the difference in migration velocity the greater the net flow. Negative osmosis was dependent on the pore diameter of the membrane. Negative osmosis was also found to be dependent on the electrical polarization of the capillaries of the membrane. This polarization was probably caused by ionic adsorption by the membrane.

Two years later, Bartell and Hocker (5) studied the relation between osmosis of solutions of electrolytes and membrane potentials. They used the following assumptions to explain the observed osmotic effects. Abnormal osmosis was due to an electrical effect. This osmosis was caused

by the passage of a charged liquid layer along the capillary tubes of the membrane. The passage of this liquid layer was caused by the driving force of the difference of potential which acts between the two faces of the membrane. The charge on the membrane (the charge on the liquid layer) may have been modified or the sign reversed by selective adsorption of ions of electrolytes. The potential difference depended upon a difference in migration velocity of the ions in the membrane. Osmosis was related to diffusion since the diffusion of ions determines the polarization of the membrane. The extent of the osmosis may have been affected by the relative volumes of water and salt solution on the two faces of the membrane. This factor may have affected the diffusion of salt through the membrane.

Bancroft (2) made a study of semipermeable membranes and negative adsorption in 1917. He concluded that one may have osmotic phenomena with a porous diaphragm provided that there is very marked negative adsorption and provided that the diameter of the pores is so small that the adsorbed films fill practically the whole of the pores. A porous diaphragm will act as a semipermeable membrane in the case where there is no measureable adsorption of the solute and in the case where the adsorbed films fill the pores com-

pletely. Semipermeability was due to the solvent dissolving in the diaphragm while the solute does not. Solubility does not depend on porosity.

In 1919, Loeb (28) studied the influence of the concentration of electrolytes on electrification and the rate of diffusion of water through collodion membranes. Solutions of non-electrolytes, sucrose, glucose, and glycerol separated from pure water by a collodion membrane influence the initial rate of diffusion through a membrane approximately in proportion to their concentrations.

Loeb (29) (1920) made a study of the influence of a slight modification of collodion membranes on the sign of the electrification of water. Collodion membranes which have been treated with a 1% gelatin solution show a different osmotic behavior than the untreated membranes when manifested only toward solutions of electrolytes, which tend to introduce negative electrification of water particles diffusing through the membranes. The behavior of gelatin-treated and untreated membranes is the same for solutions of salts and alkalies which introduce positive electrification of water particles.

By 1920, electro-endosmose was made use of technically in the purification of clays, removal of water from peat,

precipitation of silica gels from sodium silicate, electric tanning, concentration of ores, purification of gelatin for photographic purposes, and for separation of oil-water emulsions in the petroleum industry.

The study of anomalous osmosis of some solutions of electrolytes with gold beater's skin membranes by Bartell and Madison (6) in 1920 gave the following results. Osmosis of sugar solutions indicated that the rate of osmosis is nearly proportional to the concentration of the solution. If the solution side of the membrane has the same electrical sign as the capillary liquid layer the resulting osmosis will be abnormally low or negative. If the solution side has the opposite sign, the resulting osmosis will be abnormally high. The osmosis rate of solutions of salts of univalent and divalent cations was abnormally low. Salts of aluminum and thorium show abnormally great osmosis. An increase in concentration causes a small increase in osmosis for solutions of univalent cations, a marked increase for divalent, and an even greater increase for tri- and quadrivalent cations.

In another investigation by the same men in the same year (7), the effect of the presence of different concentrations of acids and bases upon the osmosis of chloride solu-

tions was studied. The object of the study was to test the hypothesis that by altering the sign of the charge of the membrane (by having acids and bases present), the osmotic effects may be greatly altered. The results show that the presence of acid or alkali not only may alter the electrical sign of the capillary wall system, but also may alter, or even reverse the electrical sign of the membrane system. The direction of the osmosis and its magnitude are closely related to electrical orientation of the cell system. Abnormal osmosis depends on the electrical orientation of the membrane system and the electrical orientation of the capillary wall.

Kahlenberg (24) used dialysis to separate crystalloids in 1921. Using pyridine as solvent and vulcanized rubber membranes as the septa, the following pairs were separated by dialysis: cane sugar and sulphur; silver nitrate and naphthalene; silver nitrate and camphor; silver nitrate and sulphur; cane sugar and camphor; cane sugar and naphthalene; lithium chloride and sulphur; lithium chloride and camphor; and lithium chloride and naphthalene. In each case, the last substance passed through the membrane.

In 1922 Bartell and Sims (8) found the relation of anomalous osmosis to the swelling of colloidal membranes.

The swelling effect corresponds to negative osmotic tendencies while a shrinking effect corresponds to a positive osmotic tendancy.

Loeb (1922) (30) worked with electrical charges of colloidal particles and anomalous osmosis. He found that when solutions of salts of different concentrations are separated by collodion-gelatin membranes from water, both electrical and osmotic forces take part in the transport of water across the membrane from the water to the salt solutions. Measurements of the potential difference across a collodion membrane which separates a salt solution from water show that when an electrical effect is added to the osmotic effect of the salt solution in the transport of water from the water side to the salt solution side of the membrane the salt solution possesses a considerable electrical charge. This charge increases with increasing valency of the anion and decreases with decreasing valence of the cation.

Bartell and Van Loo (9) studied the preparation of membranes with uniform distribution of pores in 1924. Membranes with different degrees of permeability were prepared with the same number of pores per given area of membrane. As a result of vortex action in drying, collodion membranes had a cellular structure. The number of cells determines the

number of pores. Membranes prepared from the same medium have the same number of cells per unit area. Permeability, which depended on pore diameter, was varied by arresting the vortex action at different states.

The effect of temperature on osmosis rate was observed by Traxler (45) in 1928. Pyridine was passed through a rubber barrier of one $cm.^2$ area into pure water. Temperature was varied from 5 to 85°C in 10° intervals. The osmosis rate increased by 100% for a 10 degree rise in temperature between 5° and 25°C, 50% from 25° to 45°C, 33% from 45° to 65°C, and 25% from 65° to 85°C. The initial osmosis rate increases as temperature increases. After 30 minutes the osmosis rate was the same for all temperatures.

Attempts were made to measure osmotic pressures with acetone as the solvent and rubber sheets as the semi-permeable membrane by Murray in 1929 (36). Osmotic pressures for a definite concentration of water in acetone were different for different rubber membranes. The pressure depended on the thickness of the membrane and the ease with which the water was prevented from passing through it. Osmotic flow of water through a rubber membrane resulted when concentrated sodium chloride solutions were separated from pure water by thin rubber sheets.

Burgess (13) worked with the selectivity of certain osmotic diaphragms. When either sodium alginate or soap was used in the construction of the diaphragm, the selective action favored potassium and retarded sodium ions or their corresponding salt molecules. These phenomena were explained by adsorption of ions or molecules at the surface of the diaphragm.

The feasibility of the reverse osmosis process was demonstrated by Reid and Breton (39) in 1956 with the finding that the passage of salt water over a supported dense film of cellulose acetate at elevated pressure resulted in the permeation of water with a salt rejection of 95% or better. The water flux was very low, less than 0.1 gallons per day per square foot membrane surface area. In 1960, Loeb and Sourirajan (32) discovered how to prepare an asymetric or skinned cellulose acetate membrane which enabled comparative salt rejection with an improvement in the flux by about two orders of magnitude at comparative pressures. This finding resulted in a surge of activity aimed at the development of practical systems for desalting brackish and sea water. In 1964, Havens Industry (23) announced the commercialization of a tubular system using a fiber support tube for the cellulose acetate membrane.

Thus, the reverse osmosis process became a commercial reality in a period of only about ten years.

It was the purpose of this research to investigate the feasibility of using direct osmosis to concentrate dilute industrial wastes using existing reverse osmosis membranes.

Definition of Terms

There are several terms which are commonly used in the study of membrane processes. Some of these basic terms are defined as follows: Concentration is defined as the amount of solute in a unit volume of solution. The units used for concentration are Milligrams per liter or parts per million. A membrane is a thin polymer film which is used in osmosis, reverse osmosis, and other separation processes. Osmosis (17) is the self-diffusion through a semi-permeable membrane of a solvent due to the differential pressure between two solutions of differing concentrations. Osmotic pressure is defined as the pressure that would have to be applied to the concentrated solution to completely stop the flow of liquid through the membrane. Osmotic pressure is the driving force for osmosis and varies with the type and concentration of the solute. The permea-

tion rate or flux is the amount of liquid penetrating the membrane in a given time for a unit cross section of membrane area. The basic units of flux are gallons per square foot per day.

Theory and Equations

There are many different kinds of membrane processes, but all have certain features in common. In all of them, a fluid containing two or more components is in contact with one side of a membrane that is more permeable to one component (or a group of like components) than to other components. The membrane is called a selective membrane. The other side of the selective membrane is in contact with a fluid that receives the components transferred through the membrane. To cause the transfer of components, there must be a driving force of some kind. Such a force may be transmembrane differences in concentrations, as in dialysis; electrical potential, as in electrodialysis; or hydrostatic pressure, as in reverse osmosis, ultrafiltration, and microfiltration.

It is convenient to picture a membrane as a jumble of polymer chains. The interstitial volume in a polymer through which transferring species pass is the void spaces between

the polymer chain. In transfers through polymers with short interchain distances, the transferring species must often push polymer segments apart to slide past them. Highly crystalline or highly crosslinked polymers are of this type. Other polymers with less interchain attraction have wider spaces between the polymer chains, or longer polymer segments that are more free to move aside. The resistance to transfer through such polymers is lower than that through polymers with very high interchain attractive forces, or through polymers that are highly crystalline or highly crosslinked.

The selectivity of cellulose acetate reverse osmosis membranes stems from the following mechanism (17). The surface of a cellulose acetate membrane, as formed, is comprised of both crystalline and amorphous areas. Prior to heat treatment, the amorphous areas are relatively large and represent the water soluble pores through which permeation takes place. Because of the loose arrangement and Brownian motion in the absence of crystalline constraints, the transmission of water involves weak bonding forces and leaves large areas through which ions can readily pass. Heat treating, or tempering the membrane, causes crystalite growth and a subsequent loss in amorphous or pore volume.

The hydrogen bonding, therefore, becomes much stronger and highly ordered, effectively excluding the ions. Figure 1 shows the cross section of a tempered membrane. Water molecules or ammonia molecules can hydrogen bond to the carbonyl groups in cellulose acetate but ions and non-hydrogen bonding substances cannot enter the organic matrix. The water molecules which enter the polymer by hydrogen bonding to it can move from one set of hydrogen bonding sites to another and thus be transported through the polymer if there is a driving force to cause the transfer. This type of transfer requires the making and breaking of hydrogen bonds and can only be accomplished with polymers that have the right combination of chemical groups in macromolecules that assume a highly organized structure.

The polymers must also be excellent film formers because even extremely tiny mechanical flaws in the film are enormously larger than the diameter of water like solvent molecules. Transfer of species through such highly organized tight membranes is similar to the previously mentioned transfer in which the moving species pushes aside the polymer strands. Therefore, the resistance to transfer is quite high. However, high fluxes through such materials have been achieved by making the effective thickness of the

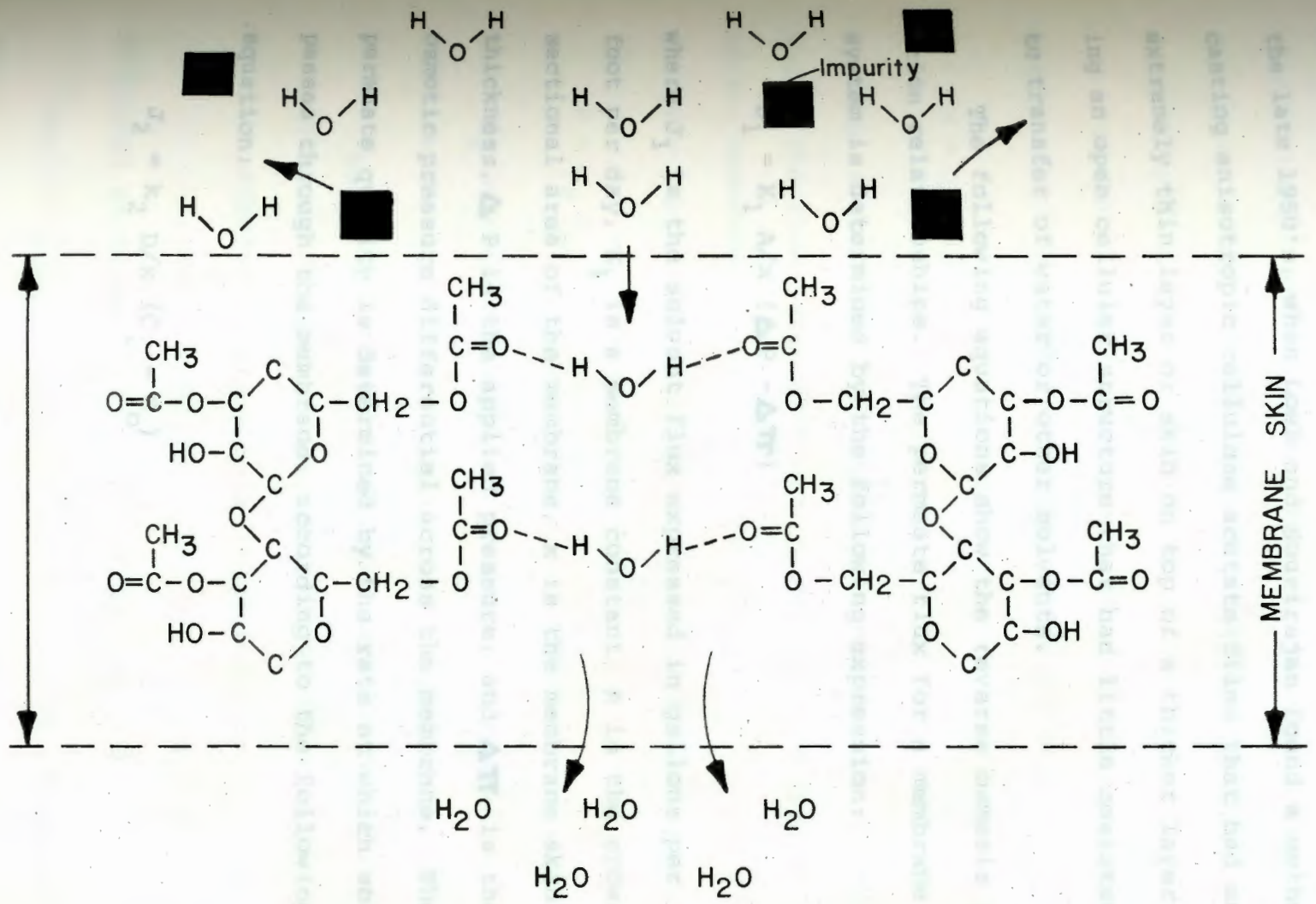


FIGURE 1. Cross Section of a Tempered Membrane

membranes extremely small. In fact, the reverse osmosis process did not appear to be economically practical until the late 1950's, when Loeb and Sourirajan found a method of casting anisotropic cellulose acetate films that had an extremely thin layer or skin on top of a thicker layer having an open cellular structure that had little resistance to transfer of water or other solvents.

The following equations show the reverse osmosis separation relationships. The permeate flux for a membrane system is determined by the following expression:

$$J_1 = K_1 A/x \ (\Delta P - \Delta \pi)$$

where J_1 is the solvent flux expressed in gallons per square foot per day, K_1 is a membrane constant, A is the cross sectional area of the membrane, x is the membrane skin thickness, ΔP is the applied pressure, and $\Delta \pi$ is the osmotic pressure differential across the membrane. The permeate quality is determined by the rate at which solute passes through the membrane, according to the following equation:

$$J_2 = k_2 D/x \ (C_i - C_o)$$

where J_2 is the solute flux, k_2 is the solute distribution coefficient between the membrane and solution, D is the diffusivity of solute in the membrane, and C_i and C_o are the concentration of solute in the feed and permeate, respectively (17).

For this direct osmosis work, the following expressions were used. The permeate or flux, J, is defined as:

$$J = Q/A\ t \qquad (1)$$

where Q is the amount of liquid passing through the membrane during the time interval t. A is the cross sectional area of the membrane.

The salt flux, F, is given by the equation below:

$$F = C_S\ V_{Wo}/A\ t \qquad (2)$$

where C_S is the concentration of sodium chloride in the dilute waste out of the osmosis cell in milligrams per liter, V_{Wo} is the volume of dilute waste leaving the cell in liters, and t is the time interval of the run in hours. A is the exposed membrane area in square feet.

Effect of Variables

The variables studied in addition to the different membranes and waste solutions were:

1. The flow rates of both sea water and the waste solution through the osmosis unit.
2. Concentration of the waste solution.
3. The rejection of the solute and of the sodium chloride in the sea water by the different membranes.
4. The effect of solution concentration on the permeation rate.
5. The effect of various techniques of supporting the membranes in the osmosis units.
6. The effect of different backing materials.

The permeation rate of the water, the flux of the sodium chloride, and the flux of metallic salts through the membrane are affected by the following factors: the type of membrane used; the flow rates of both the sea water and the dilute waste streams; the concentration of the dilute waste steam; and the interactions between the permeating solution and the membrane. The temperature dependence of the permeation rate was not studied as all work was done at room temperature.

The chemical structure of the polymer material from which the membrane is made can have an effect on the permeation rate. The addition of side groups and polar groups

to the polymer chain increases the activation energy for diffusion and decreases the permeation rate.

III. EXPERIMENTAL WORK

Equipment

The equipment needed for the experimental work was fairly simple. For the osmosis tests, a continuous flow laboratory size osmosis unit, tubing, two burettes, two constant head tanks, graduated cylinders, two rotameters, two pumps, two needle valves, membrane backing material, and a membrane were required. A conductivity meter was needed to analyze for sodium chloride concentration. An atomic absorption spectrophotometer was used to analyze for copper and chromium in the waste streams.

The only raw materials needed were distilled water, artificial sea salt, and copper and chromium salts.

Several continuous flow laboratory size osmosis units were designed and constructed. Continuous flow was possible on each side of the membrane in all of these units. These osmosis units were constructed from two five by five inch sections of 3/4 inch thick plexiglass. The flow channel for each section was formed by grinding a portion of one face of that section three by three inches by 0.025 inch deep. Two holes were drilled into the ends of each plexi-

glass section and connected to the flow channel. Short lengths of 1/4 inch plexiglass tubing were cemented into the holes, projected out of the ends of the five by five inch sections, and served as the inlet and outlet connection for that section. The osmosis unit was formed by clamping a flat piece of membrane between two sections separating the two flow channels. Rubber gaskets provided the seal and four bolts in the corners held the section together. These units had an exposed membrane area of 58.06 square centimeters. Since these units were made completely of plexiglass, they were not susceptible to chemical reaction between the osmosis unit and the solution used. A diagram of the osmosis unit appears in Figure 2.

The tubing used was Tygon tubing 3/16 and 1/4 inch inside diameters. The burettes used were 500 milliliter capacity with five milliliter graduations. In tests in which the permeation rate was small, a 50 milliliter capacity burette with one milliliter graduations was used for the dilute waste solution. The constant head tanks were made of plexiglass and were positioned at the top of the burettes. They allowed better flow control of the feed streams. The overflow from the constant head tanks was returned to the feed burettes and the side streams from the

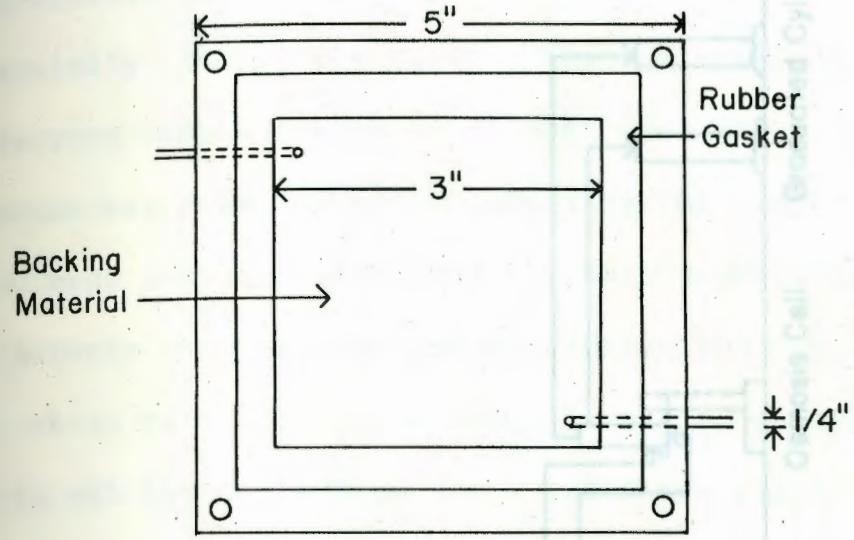
constant head tanks were used as the feed streams to the osmosis units. Graduated cylinders were used to collect the sea water and dilute waste streams leaving the osmosis unit. The graduated cylinders were 500 milliliter capacity with five milliliter graduations. A diagram of the experimental set-up appears in Figure 3.

Rotameters were used to minitor the flow rates of the sea water and dilute waste streams entering the osmosis unit. These rotameters were calibrated but were generally used only to set an approximate flow rate and to maintain constant flow. The rotameters used were Tru-Taper size 2-15-3 with both plastic and metal floats made by the Ace Glass Company.

Two Ministaltic pumps made by the Manostat Company were used to pump the feed streams from the burettes (feed tanks) to the constant head tanks. These pumps had a range of flow of 5 to 500 cubic centimeters per minute and could be connected to tubing of 1/4 to 3/8 inch inside diameter.

Needle valves were placed in the flow lines to provide better control of flow rates. The needle valves were Model B-2M2 made by the Nupro Company.

Originally several tests were made using no membrane support. However, the thin films were so flexible that they



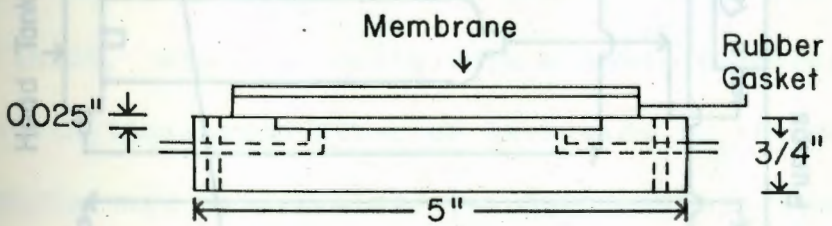


FIGURE 2. Osmosis Cell (One-Half)

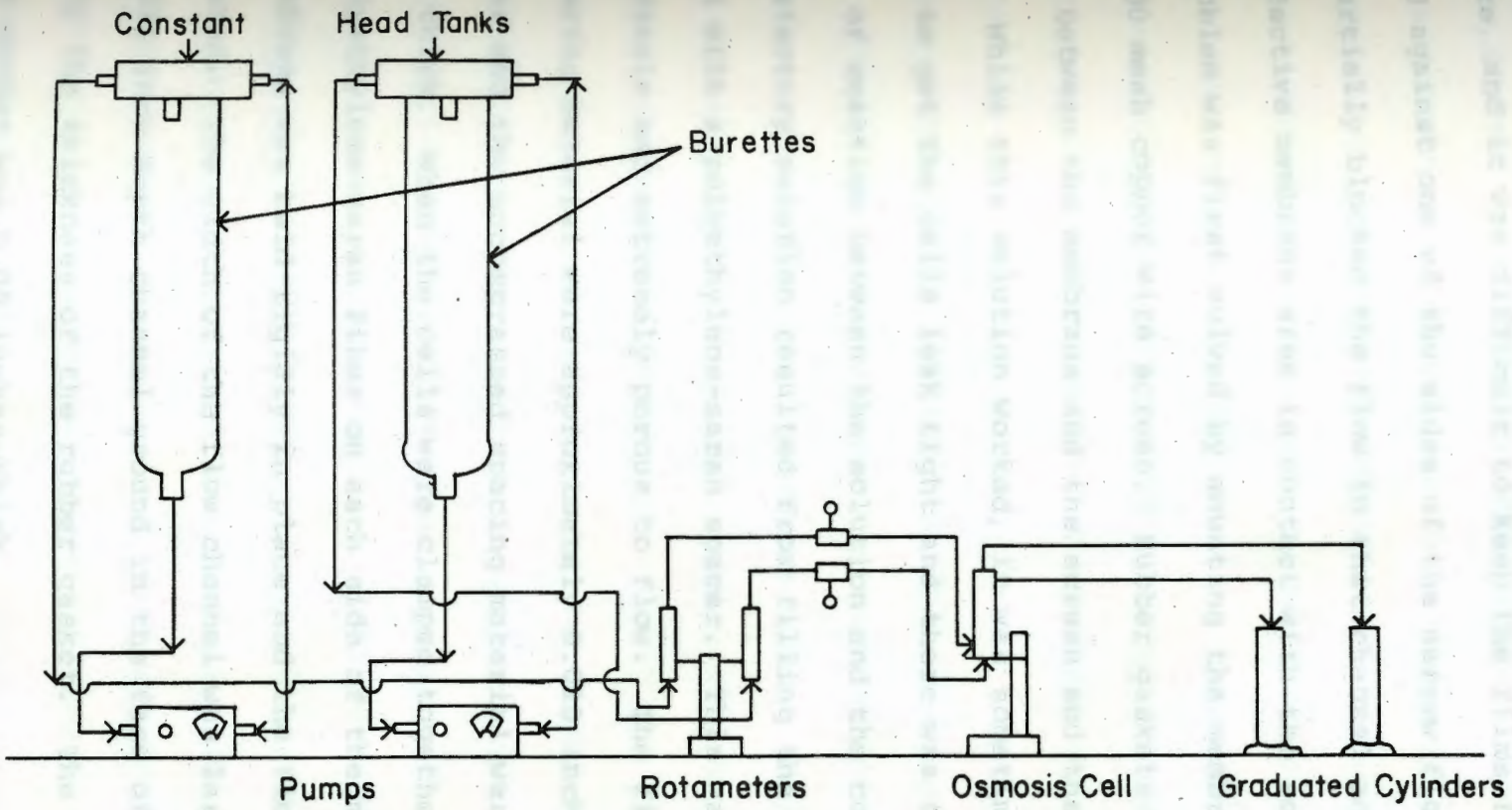


FIGURE 3. Direct Osmosis Equipment

were deflected and stretched by very slight differences in pressure, and it was difficult to keep the films from being pressed against one of the sides of the narrow flow channel. This partially blocked the flow in that channel and reduced the effective membrane area in contact with the solution. The problem was first solved by mounting the membrane between 30 mesh copper wire screen. Rubber gaskets were required between the membrane and the screen and the cell walls. While this solution worked, it was sometimes difficult to get the cells leak tight and there was the possibility of reaction between the solution and the copper screen. A satisfactory solution resulted from filling the flow channel with a polyethylene-saran spacer. This was a coarsely woven fabric and extremely porous to flow. The fibers in the spacing material were approximately 0.010 inches in diameter and the uncompressed spacing material was 0.070 inches thick. When the cells were clamped together, with the polyethylene-saran fiber on each side of the membrane, the membrane was held rigidly in place and the flow was unrestricted. The width of the flow channel was larger than the 0.025 inch depth channel ground in the face of the plexiglass by the thickness of the rubber gasket. The uncompressed gasket was 0.05 inches thick.

The membranes tested include: KP-98, KP-90, and KP-00 from the Eastman Kodak Company; SEPA-97 and SEPA-89 from Osmotics Company; Kesting Dry membrane; and both treated and untreated cellophane from Dupont Company.

The conductivity meter used to test for Sodium Chloride was Model 2511 made by the Hach Chemical Company.

An atomic absorption spectrophotometer available in Woodward Hall was used to analyze streams for metallic ion concentration.

Those commercially available cellulose acetate membranes from the Eastman Kodak Company have an active and an inactive side. The active side contains a dense thin surface layer in which the actual separation takes place. The rest of the membrane is very porous and its function is to support the dense surface layer of the active side. Tempering the membranes at a high temperature increases the thickness of the dense surface layer. In reverse osmosis, the solution to be concentrated is in contact with the active side. In direct osmosis, it was not apparent which solution, the sea water or the dilute waste solution, should be in contact with the active side. Runs were made with the active side toward both the sea water and toward the dilute waste solution. A slightly higher permeation rate was ob-

tained with the sea water next to the active side. The majority of the test runs were made this way.

Procedure

There were some preliminary steps required before running the tests. Sufficient amounts of sea water had to be prepared. This was done by mixing the correct amount of artificial sea salt with water. The totameters used to monitor the flow rates of the sea water and dilute waste inlet streams had to be calibrated. If a dilute metallic waste was to be used, sufficient amounts of this waste had to be prepared.

Next, an osmosis cell had to be prepared. A film or membrane was cut to the desired size to fit the cell. The film was then carefully placed between the two halves of the cell and, with the backing material and the rubber gaskets in place, the bolts at each corner of the cell were tightened to seal the cell. The cell was then connected to the rest of the experimental equipment.

One burette was filled with sea water and another burette filled with dilute waste. The pumps were started and the apparatus was allowed to run to check the cell for leakage. If there was no leakage from the cell, the apparatus was ready for use.

Data were taken at time intervals during the runs. This time interval was usually either one half hour or one hour. The quantities measured were the volume of sea water entering the cell, the volume of sea water leaving the cell, the volume of dilute waste entering the cell, and the volume of dilute waste leaving the cell.

The volumes of the entering streams were determined by changes in the volumes in the burettes. The volumes of the leaving streams were determined by collection in graduated cylinders. The concentrations of sodium chloride and dilute metallic ions, if any, were also monitored. From these data, the osmosis rate and salt flux through the membrane could be obtained as well as the concentration of the dilute waste.

IV. DATA AND CALCULATIONS

Raw Data

In all of the runs, the volume of sea water or brine entering the cell, the volume of sea water or brine leaving the osmosis unit, the volume of dilute waste entering the cell, and the volume of dilute waste leaving the cell were measured at various times. The permeation rate was determined from these measurements.

The sodium chloride concentration of the dilute waste streams entering and leaving the osmosis unit were both obtained in order to determine the sodium chloride flux through the membrane.

In runs in which actual dilute metallic wastes were used, the dilute metallic ion concentration of the sea water streams entering and leaving the cell and the dilute waste streams entering and leaving the osmosis unit were obtained. These data allowed the determination of material balances for the metal ions.

The exposed membrane area was recorded for use in calculating both water and salt fluxes.

Calculations

The volume of liquid passing through the membrane was determined from the differences in the dilute waste streams in and out of the osmosis unit and the sea water streams in and out of the osmosis unit. In order to reach a steady state, data were not recorded until a reasonable time had elapsed after the osmosis unit had began to run.

The permeation rate or flux for the liquid was calculated from Equation 1,

$$J = Q/A\ t \qquad (1)$$

where Q is the volume of liquid passing through the membrane in time t and A is the exposed area of the membrane. The flux was expressed in gallons per square foot per day.

The rate of salt permeation, S, from the sea water through the membrane into the dilute waste solution is given by the following equation:

$$S = C_S\ V_{Wo}/t \qquad (4)$$

where C_S is the concentration of sodium chloride in the dilute waste out of the cell in milligrams per liter, V_{Wo} is the volume of dilute waste leaving the cell in liters, and t is the time interval of the run in hours. The units of salt rate are milligrams per hour.

The salt flux, F, is given by the equation below:

$$F = S/A \tag{5}$$

where S is the salt rate in milligrams per hour and A is the exposed area of the membrane in square feet. The salt flux is expressed as milligrams per hour per square foot.

The relative water to salt flux is given by the following equation:

$$R = Q\ (1000)/t\ S \tag{6}$$

where Q is the volume of liquid passing through the membrane in time t and S is the rate of salt permeation through the membrane. The relative water to salt flux is dimensionless.

Sample calculations of all types appear in the appendix.

V. EXPERIMENTAL RESULTS

Tabulated Results

The results of the experimental tests are presented in the following section. The calculations were made using the equations and methods presented in Chapter IV.

The nomenclature used in the tables and their units are given as follows:

J = permeation rate (gal/ft^2/day)

S = rate of diffusion of sodium chloride (mg/hr)

F = sodium chloride flux (mg/ft^2/hr)

R = relative water/sodium chloride flux (gm water/ gm sodium chloride)

It was first necessary to determine the amount of salt, that is, sodium chloride penetrating through the membrane from the sea water to the dilute waste solution. In these initial runs, two different membranes were tested. Distilled water was used as the waste solution. Runs were made with the active side of the membranes toward both sea water and distilled water.

TABLE I

Experimental Results for Kesting Dry Membrane

Run	Active Side	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
1	sea	2.03	28.1	448.	712.
2	sea	2.08	20.5	329.	1000.
3	sea	1.88	30.3	485.	610.
4	sea	1.83	31.8	509.	1044.
5	distilled	1.22	22.2	356.	540.
6	distilled	1.22	17.0	272.	706.

TABLE II

Experimental Results for KP-98 Membrane

Run	Active Side	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
7	distilled	2.11	53.6	858.	387.
8	distilled	2.17	59.5	952.	360.
9	sea	2.51	48.3	773.	511.
10	sea	2.61	58.2	931.	442.
11	sea	2.50	79.6	1273.	309.
12	sea	2.53	74.3	1188.	335.

In an attempt to limit the passage of sodium chloride through the membrane, the KP-98 membrane was tempered and the liquid and salt fluxes were studied. The membrane was tempered at four different temperatures. All temperings were four minutes.

TABLE III

Experimental Results for KP-98 Membrane

Tempered at 90°C

Run	Active Side	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
13	sea	2.69	23.0	368.	1152.
14	sea	2.44	19.5	312.	1231.
15	sea	2.40	21.4	343.	1103.
16	distilled	2.03	20.2	324.	991.

TABLE IV

Experimental Results for KP-98 Membrane

Tempered at 95°C

Run	Active Side	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
17	sea	1.52	22.0	352.	682.
18	sea	1.22	19.0	304.	632.
19	distilled	0.91	23.2	371.	388.

TABLE V

Experimental Results for KP-98 Membrane

Tempered at 92°C

Run	Active Side	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
20	sea	1.76	13.7	218.	1263.
21	distilled	1.50	14.6	233.	1014.
22	sea	1.41	16.3	261.	853.
23	sea	1.52	21.4	343.	701.

TABLE VI

Experimental Results for KP-98 Membrane

Tempered at 88°C

Run	Active Side	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
24	sea	2.54	34.0	544.	736.

Due to the large amounts of salt penetrating the membrane, the KP-98 membrane was treated with a 6 parts per million solution of polyvinyl methyl ether on the distilled water side of the membrane. It was hoped that the polymer would block the salt flow. Distilled water was used as the waste solution in these runs. The runs were made with

the active side toward both the sea water and the distilled water.

TABLE VII

Experimental Results for KP-98 Membrane

Six PPM Polyvinyl Methyl Ether Treatment

Run	Active Side	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
25	sea	3.27	74.6	1193.	432.
26	distilled	2.13	91.0	1456.	231.
27	distilled	2.06	102.0	1633.	199.

A 10 parts per million solution of polyvinyl methyl ether was then used on the sea water side of the membrane.

TABLE VIII

Experimental Results for KP-98 Membrane

Ten PPM Polyvinyl Methyl Ether Treatment

Run	Active Side	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
28	distilled	2.11	100.7	1611.	207.
29	sea	2.33	106.3	1701.	216.

Several runs were made using a dilute chromium waste with a concentration of approximately 50 parts per million. The membrane used was the KP-98 tempered in 88°C water for four minutes.

TABLE IX

Experimental Results for Chromium Waste

KP-98 Membrane

Tempered at 88°C

Run	Active Side	J gal/ft^2/day	Cr Concentration (mg/liter) waste in	waste out
30	sea	3.15	50.	54.
31	sea	2.24	50.	55.

Tests were then run to see if any of the chromium was passing through the membrane into the sea water.

TABLE X

Experimental Results for Chromium Waste

KP-98 Membrane

Tempered at 90°C

Run	Active Side	J gal/ft^2/day	Cr Concentration (mg/liter) sea water out	waste in	waste out
32	sea	1.06	1.2	51.5	57.
33	sea	1.43	1.2	51.5	61.

Since there was a substantial amount of chromium in the sea water out in the preceding set of runs, four runs were made to calculate the amount of chronium in all four streams entering and leaving the osmosis unit. All of these runs were made with sea water on the active side of the membrane.

TABLE XI

Experimental Results for Chromium

Waste With KP-98 Membrane

Run	J gal/ft^2/day	Chromium (mg) sea water in	sea water out	waste in	waste out
34	2.08	0.114	2.026	7.468	5.565
35	1.88	0.114	1.903	8.806	7.000
36	2.44	0.134	2.406	7.750	5.321
37	2.28	0.0724	1.170	3.400	2.016

Runs were also made using a dilute copper waste with a concentration of approximately 50 parts per million. The KP-98 membrane was used with the sea water facing the active side of the membrane.

TABLE XII

Experimental Results for Copper Waste

With KP-98 Membrane

Run	J gal/ft^2/day	Copper (mg) sea water in	sea water out	waste in	waste out
38	2.69	0.056	0.921	7.700	6.160
39	2.42	0.082	1.246	11.350	9.063

Two runs were made using a Universal Oil Products dry membrane with distilled water as the dilute waste solution. These runs gave no osmosis rate. Therefore, further tests with this membrane were not conducted. The data for these runs (runs 40 and 41) are found in the appendix.

The effect of tempering temperature on the KP-00 membrane was studied in the next series of runs. Tempering was done in water for four minutes. In all of these runs, the sea water on the active side of the membrane and distilled water was used as the waste solution.

TABLE XIII

[redacted]ct of Tempering Temperature on KP-00 Membrane

Run	Temperature °C	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
42	60	0.584	245.0	3920.	23.
43	60	0.711	276.8	4429.	25.
44	70	0.761	198.1	3170.	38.
45	70	0.812	183.0	2928.	44.
46	80	1.93	59.5	952.	319.
47	80	2.03	64.4	1030.	311.
48	85	2.03	37.4	598.	535.
49	85	1.83	42.1	674.	428.
50	90	1.63	18.1	290.	883.
51	90	0.609	9.7	155.	617.
52	90	1.02	14.3	229.	700.
53	90	1.08	11.6	186.	908.
54	93	0.61	6.6	106.	915.
55	93	0.56	5.8	93.	954.
56	96	0.41	3.3	53.	1199.
57	96	0.41	3.1	50.	1280.

The effect of tempering time on the KP-00 membrane was studied in the following series of runs. The tempering was done in 93°C water. The sea water was on the active side of the membrane and distilled water was used as the waste solution.

TABLE XIV

Effect of Tempering Time on KP-00 Membrane

Run	Time (minutes)	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
58	0.5	0.863	250.0	4000.	34.
59	0.5	0.914	129.2	2067.	70.
60	0.5	0.964	135.0	2160.	70.
61	1.0	0.914	11.0	176.	821.
62	1.0	0.863	16.0	256.	528.
63	1.0	0.812	15.9	254.	504.
64	1.0	0.863	14.8	238.	577.
65	2.0	0.609	7.4	118.	811.
66	2.0	0.609	7.2	115.	833.
67	2.0	0.761	11.4	93.	659.
54	4.0	0.610	6.6	106.	915.
55	4.0	0.560	5.8	93.	954.

Two cellulose acetate membranes from the Osmotics Company were tested for the amount of salt passing through the membrane and for liquid flux. Distilled water was used as the waste solution.

TABLE XV

Experimental Results for SEPA-97 Membrane

Run	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
68	0.431	26.6	426.	160.
69	0.634	13.6	218.	460.
70	0.660	8.7	139.	748.
71	0.457	23.8	381.	189.
72	0.406	26.0	417.	154.

TABLE XVI

Experimental Results for SEPA-89 Membrane

Run	J gal/ft^2/day	S mg/hr	F_2 mg/ft^2/hr	R
73	0.812	12.7	203.	630.
74	0.711	28.3	452.	248.

The effect of osmotic pressure on the permeation rate was studied in this series of runs. In the first two runs (75 and 76), sea water was on the active side and distilled water on the other side of the membrane. In runs 77 and 78, brine made of 50% sea water and 50% distilled water was used on the active side of the membrane.

TABLE XVII

Effect of Osmotic Pressure on Permeation Rate

KP-90 Membrane

Run	osmosis rate ml/hr	gal/ft^2/day
75	16.	1.624
76	14.	1.421
77	7.	0.710
78	7.	0.710

Several runs were made to determine the effect of flow rates of the waste and sea water streams on permeation rate. A summary of the results of these tests is given in Table XVIII. In all runs the sea water is on the active side of the membrane.

TABLE XVIII

Effect of Flow Rates on KP-90 Membrane

Run	Sea Water in ml/hr	Distilled Water in ml/hr	J gal/ft^2/day	R
79	345.	76.	1.22	37.
80	256.	74.	1.42	61.
81	254.	598.	2.33	28.
82	285.	1277.	2.84	34.
83	114.	590.	2.13	42.
84	292.	672.	2.59	35.
85	531.	596.	1.93	32.
86	582.	656.	2.74	39.
87	101.	656.	2.28	42.

An actual waste wash water from a fish and shellfish processing plant was concentrated. The KP-90 membrane was used with the active side toward the sea water solution. The results of this test are given below:

Run -- 88

Inlet waste salt concentration -- 2600 PPM

Outlet waste salt concentration -- 4000 PPM

Permeation rate -- 1.22 gal/ft^2/day

Relative flux, gm water/gm NaCl -- 42.

Cellophane obtained from Rhode Island Cellophane Company was used as a membrane. Tests were made using distilled water as the waste solution. These tests showed a very low or no permeation rate. The data for these runs (89-91) appear in the appendix.

It was found that the cellophane from Rhode Island Cellophane had been treated with either nitrocellulose wax or a seran polymer to prevent water permeation. Two types of untreated cellophane were received from the Dupont Company. These were 150 PD cellophane (1.3 mil thick) and 215 PD cellophane (0.9 mil thick). Initial runs (92-94) with 215 PD cellophane showed a negligible permeation rate. The experimental apparatus was then changed by closing the distilled water stream out and using a burette calibrated to 0.1 ml graduations for the distilled water stream in. The results of these tests appear in Table XIX.

TABLE XIX

Experimental Results for 215-PD and 150-PD Cellophane

Run	Type	J gal/ft^2/day
95	215 PD	0.156
96	150 PD	0.066
97	150 PD	0.066

Graphical Presentation of the Results

Some of the experimental results are presented graphically below. Figures 4, 5, and 6 show the effects of tempering temperature on the permeation rate, salt flux, and relative water to salt flux. Figures 7, 8, and 9 show the effect of time of tempering on the permeation rate, salt flux, and the relative water to salt flux.

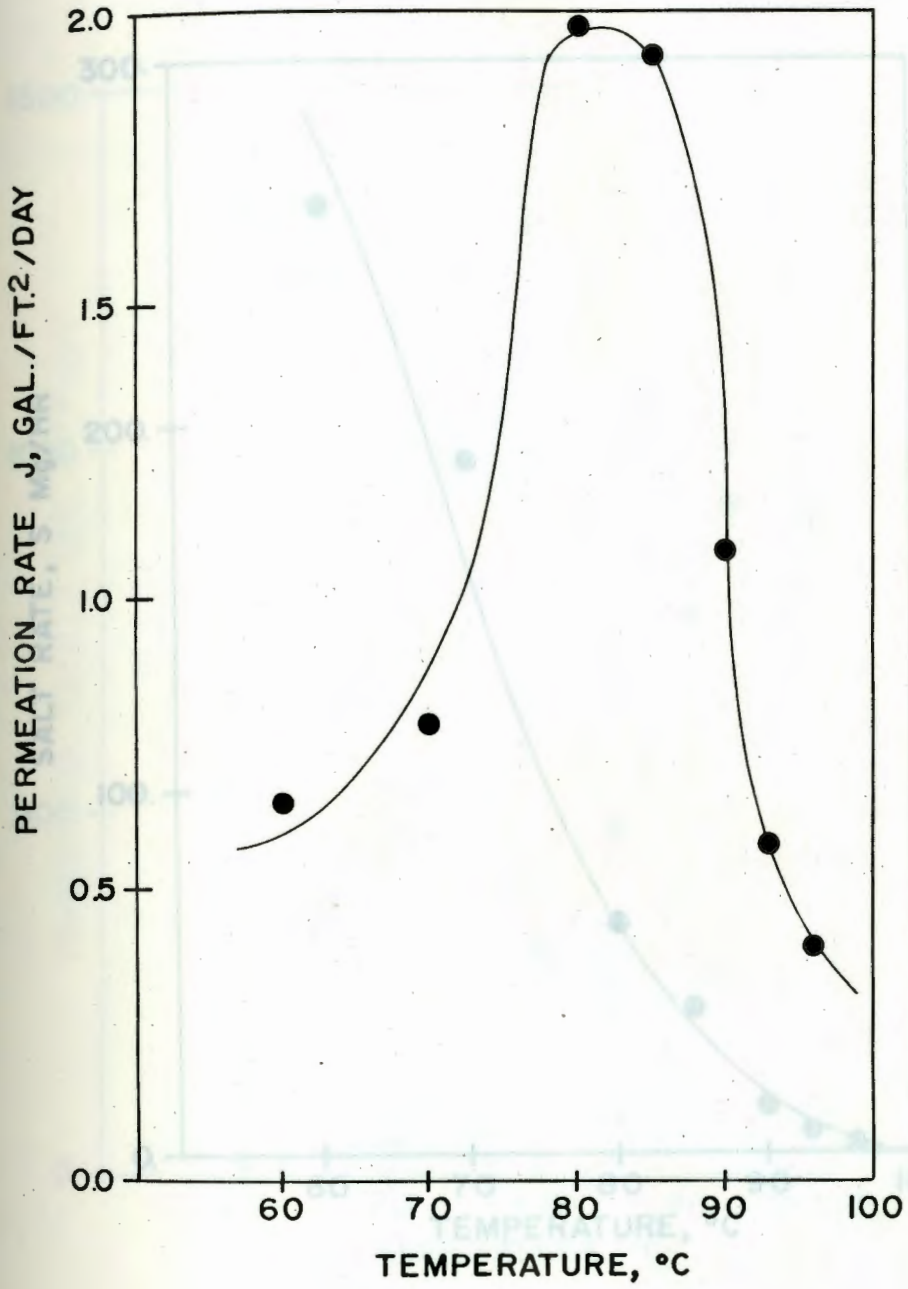


FIGURE 4. Effect of Tempering Temperature on Permeation Rate

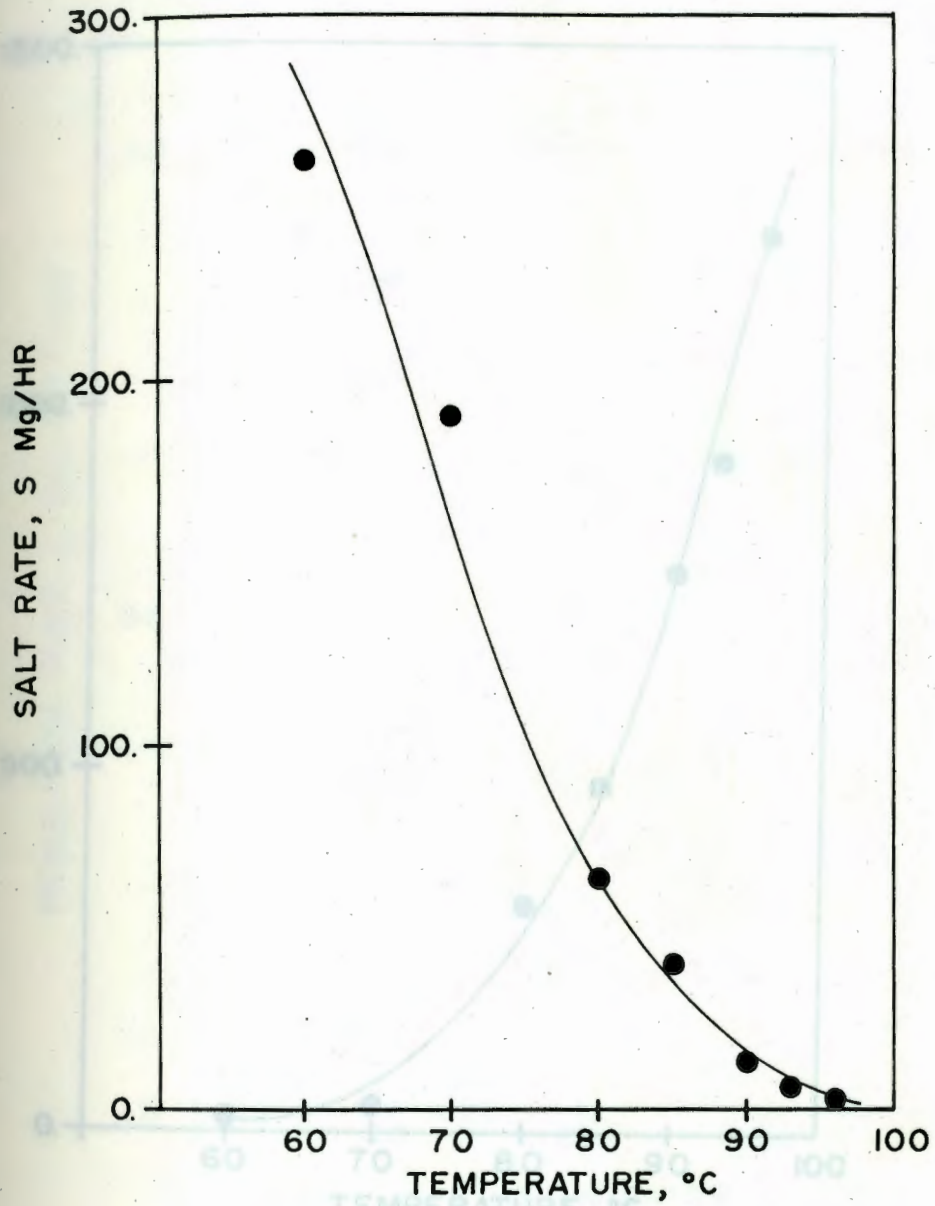


FIGURE 5. Effect of Tempering Temperature on Salt Rate

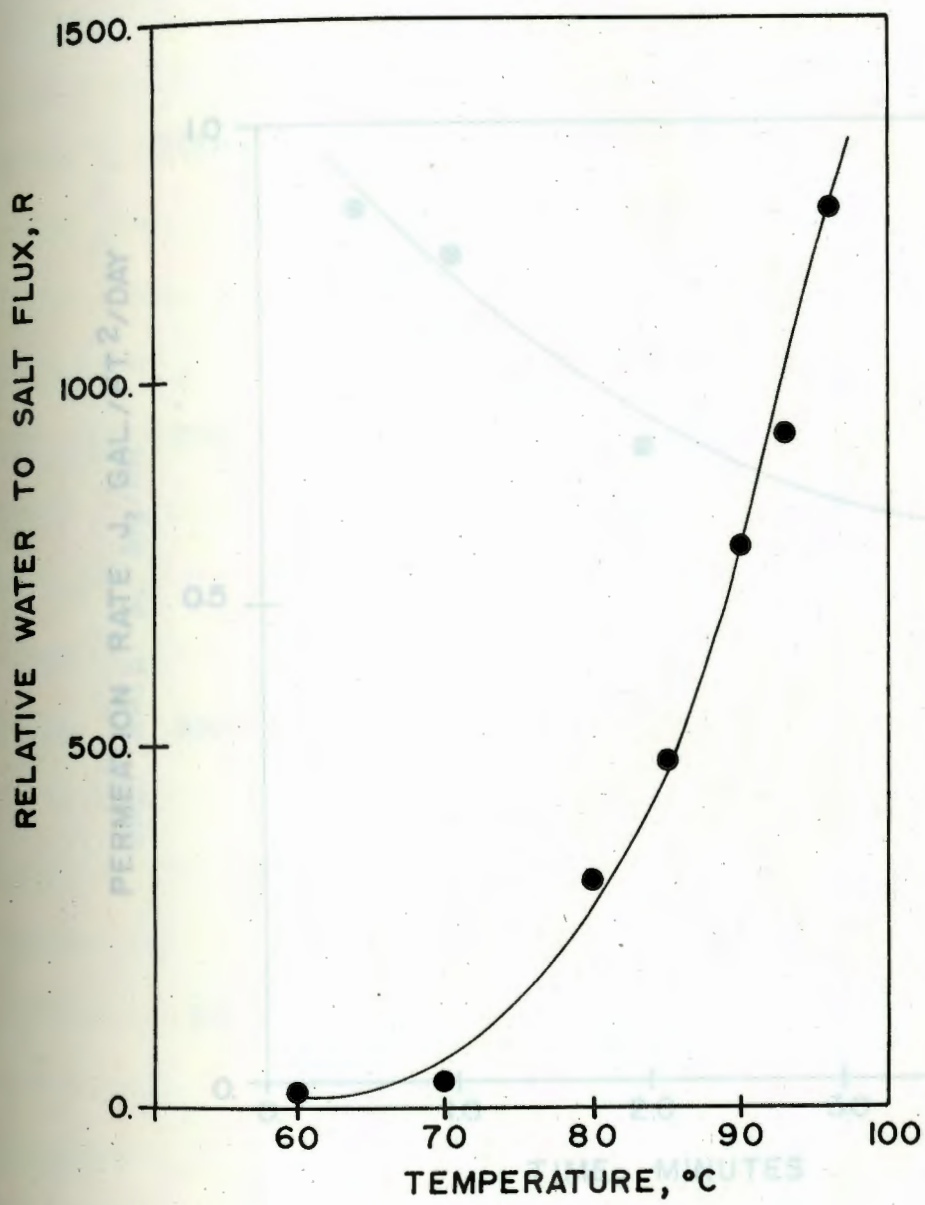


FIGURE 6. Effect of Tempering Temperature on Relative Water to Salt Flux

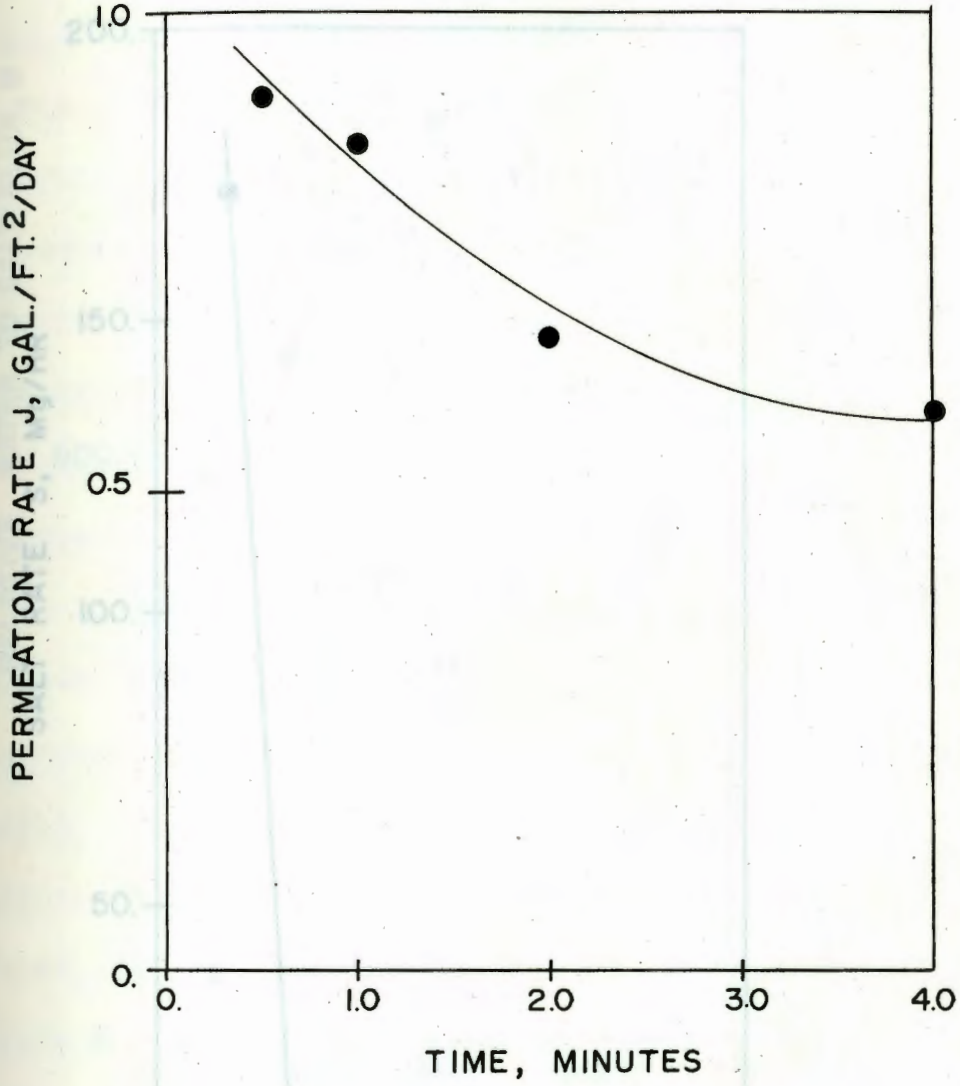


FIGURE 7. Effect of Tempering Time on Permeation Rate

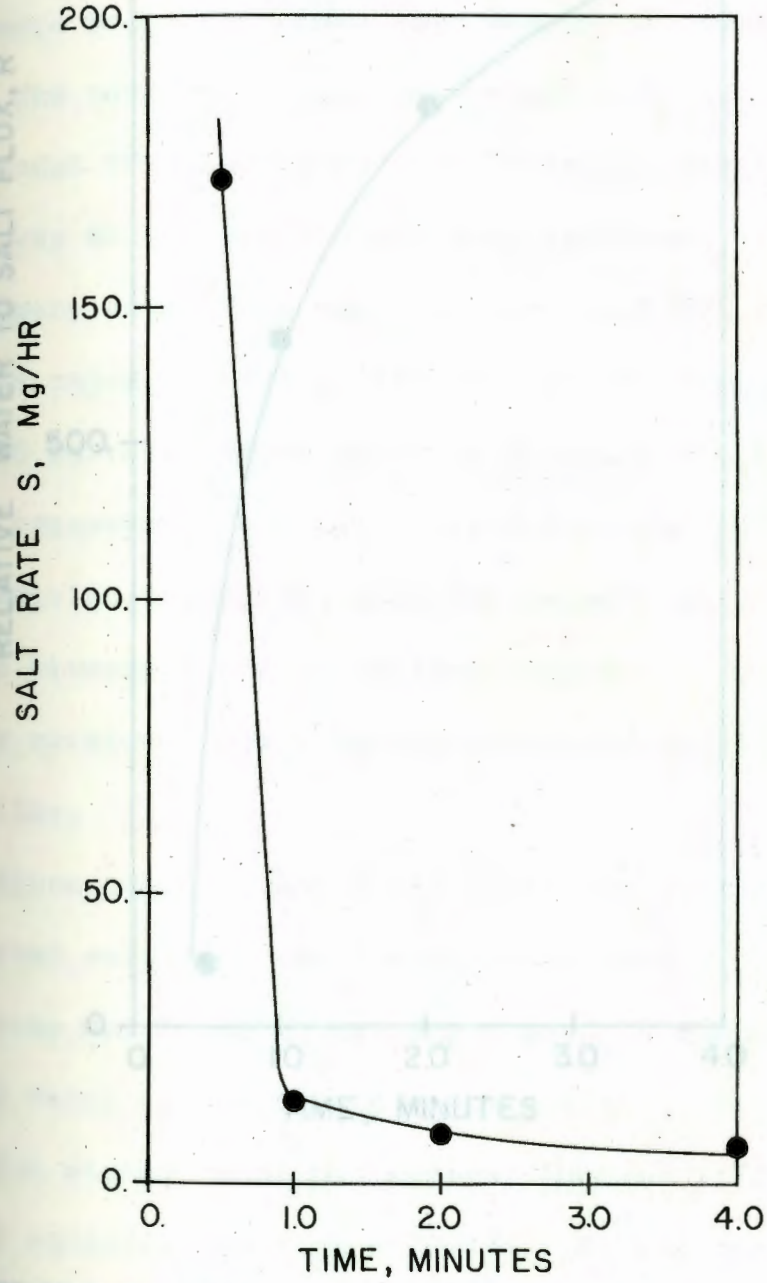


FIGURE 8. Effect of Tempering Time on Salt Rate

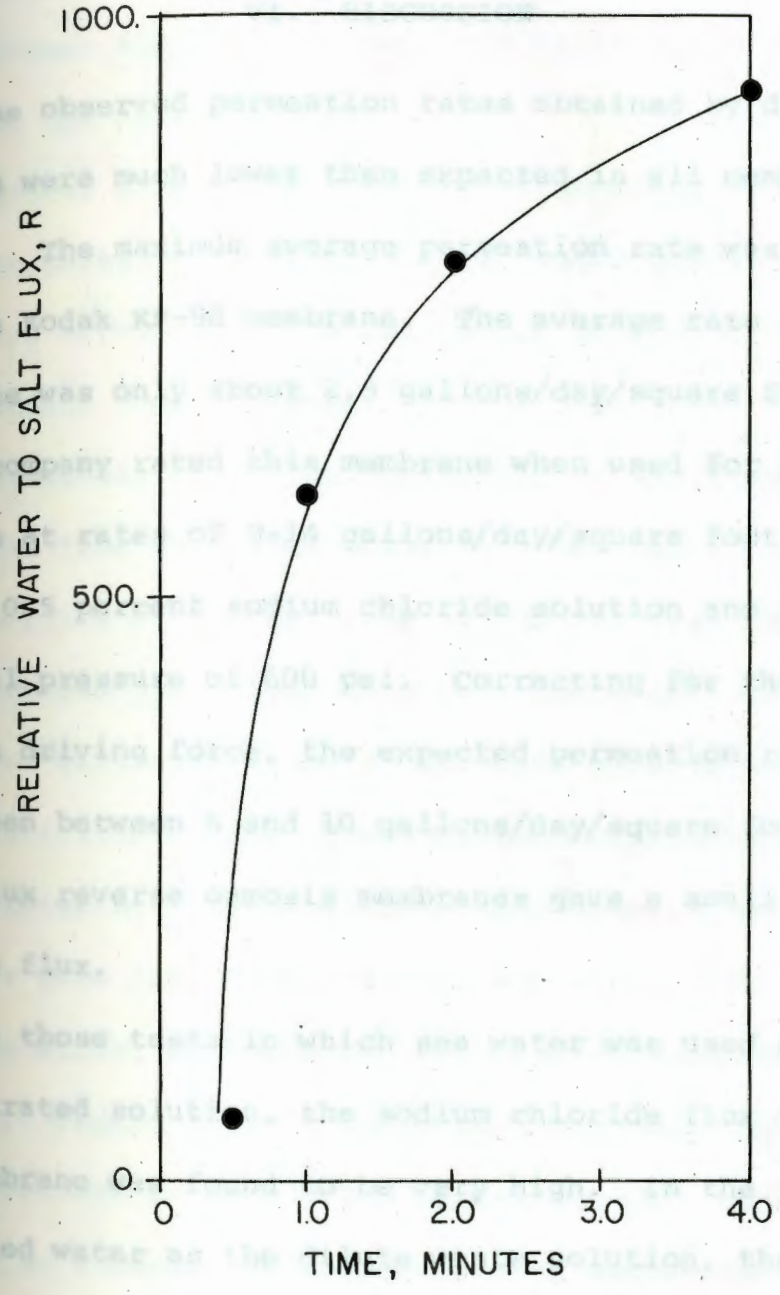


FIGURE 9. Effect of Tempering Time on Relative Water to Salt Flux

VI. DISCUSSION

The observed permeation rates obtained by direct osmosis were much lower than expected in all membranes tested. The maximum average permeation rate was obtained for the Kodak KP-98 membrane. The average rate for this membrane was only about 2.5 gallons/day/square foot. The Kodak company rated this membrane when used for reverse osmosis at rates of 9-14 gallons/day/square foot when used with a 0.5 percent sodium chloride solution and an applied external pressure of 600 psi. Correcting for the difference in driving force, the expected permeation rate should have been between 6 and 10 gallons/day/square foot. These high flux reverse osmosis membranes gave a small direct osmosis flux.

In those tests in which sea water was used as the concentrated solution, the sodium chloride flux through the membrane was found to be very high. In the tests using distilled water as the dilute waste solution, the exit waste water stream contained several hundred milligrams per liter equivalent sodium chloride. It had been expected that since the salt permeation would be against the flow

of the diffusing water, the salt flux would be small. The results obtained indicate that the high sodium chloride flux through the membrane may have blocked the pores, thus reducing the permeation rates.

Several samples of Kodak KP-98 membrane were treated with six parts per million and ten parts per million of polyvinyl methyl ether in an attempt to reduce the salt flux through the membranes. It was hoped that the inter-chain distances in the polymer would be small enough to block the flow of sodium chloride. No significant change in either the permeation rate or the salt flux was found.

Chromium and copper ions from the simulated waste solutions were also found to permeate through the membrane at a significant rate. These dilute waste solutions were concentrated but a relatively high proportion of the metallic ions were lost in the dilute sea water.

The effect of tempering on the KP-00 membrane was studied. Figure 4 shows the effect of tempering temperature on the permeation rate. The permeation rate reached a maximum at a tempering temperature of approximately 80°C. The manufacturer (19) found that the permeation rate decreased with increasing temperature of tempering when the membrane was used for reverse osmosis with an 0.5 percent

sodium chloride solution and an external applied pressure of 600 psi. The shape of the curve of Figure 4 is the result of the product of two effects. Refer to the equation,

$$J_1 = K_1/x \; A \; (\Delta P - \Delta \pi)$$

which can be rewritten for direct osmosis as,

$$J_1 = K_1/x \; A \; (- \Delta \pi)$$

where J_1 is the water flux in gallons per square foot per day, K_1 is a membrane constant, A is the cross sectional area of the membrane, x is the membrane skin thickness, and $\Delta \pi$ is the effective osmotic pressure differential.

The osmotic pressure reaches its maximum value as the membrane approaches ideal semi-permeability. The effective osmotic pressure increased with tempering temperature. The membrane skin thickness increases as the tempering temperature increases. The resistance term, K_1/x, therefore, decreases as the tempering temperature increases. It is the product of these two effects which leads to the results of Table XIII and Figure 4.

Figure 5 shows the effect of the tempering temperature on the salt rate. The salt rate through the membrane decreased with increasing temperature of tempering as was expected.

The effect of the time of tempering on the KP-00 membrane is shown in Figures 7, 8, and 9. Both the permeation rate and the salt flux decreased as the tempering time increased to four minutes as expected.

A diluted simulated sea water solution, when used as the concentrated solution, gave a reduced permeation rate which was proportional to the sea water osmotic pressure.

The effect of variation in flow rates was studied in several tests. The results of these tests appear in Table XVIII. With the sea water entering the osmosis cell kept at an approximately constant rate, the permeation rate increased with increasing rate of distilled water entering the cell. The salt flux, however, also increased. In tests in which the rate of the distilled water entering the cell was approximately constant, the permeation rate and the salt flux did not show substantial variation as the rate of the sea water entering the cell increased.

An actual waste wash water from a fish and shellfish processing plant was tested. The sodium chloride flux from the sea water to the waste water was high even though the initial waste solution contained a relatively high salt concentration.

The types of cellophane tested showed very small perm-

eation rates and would not appear to be practical for this application.

Based on the results obtained, the reverse osmosis membranes tested do not appear to behave in the same manner for direct osmosis as they do for reverse osmosis applications. The generally accepted mechanism described in Chapter II does not appear to be applicable at the lower pressures used during direct osmosis. Heat treating, or tempering, the membrane did reduce the salt flux but the osmosis rate (water flux) was also reduced. The low permeation rates and high salt fluxes indicate a different mechanism for direct osmosis with reverse osmosis membranes.

In summary, these reverse osmosis membranes do not behave as expected when used for direct osmosis. The concentration of industrial wastes by direct osmosis using existing reverse osmosis membranes does not appear to be feasible based on the results presented here.

VII. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Concentration of dilute industrial wastes using existing commercially available reverse osmosis membranes does not appear promising based on the reverse osmosis membranes tested. Low water permeation rates and high salt fluxes through the membrane would make the process impractical. If valuable materials were being concentrated, their recovery would be complicated by the addition of a high concentration of sodium chloride. In concentrating dilute solutions of metal ions, a high proportion of metallic ions would be lost in the sea water. It might be feasible to use the proposed method with an existing reverse osmosis membrane to concentrate a waste which would not be affected by the addition of sodium chloride or where the only desired effect was to reduce the total volume of waste to be handled. The waste water from a shellfish processing plant is such a waste. This waste water already contains a high concentration of sodium chloride and the addition of a little more will not hurt it.

[redacted]mendations

The concentration of wastes by direct osmosis might be practical if a suitable membrane were available. The membrane should permit a high water permeation rate under direct osmosis and have a much lower salt flux than existing membranes.

LIST OF SYMBOLS

A	exposed membrane cross section area
C_S	concentration of sodium chloride in dilute waste stream leaving cell
F	salt flux
J	permeation rate of water
K	membrane constant
Q	volume of liquid passing through the membrane
R	relative water to salt flux
S	salt permeation rate
V_{Wo}	volume of dilute waste leaving the cell
x	membrane thickness
π_{eff}	effective osmotic pressure
π_{th}	theoretical osmotic pressure
σ	reflection coefficient of membrane

APPENDIX I

Kesting Dry Membrane

Dilute Waste Solution-Distilled Water

Run 1

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	123	35	133	25
60	223	70	244	50
90	309	106	342	75
120	386	142	429	100
150	459	175	514	125
180	538	210	599	150

Osmosis Rate = 20.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	460
120	610
180	560

Run 2

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	104	39	116	25
60	202	75	223	50
90	295	111	324	75
120	383	146	422	100
150	496	183	546	127
180	598	218	657	154

Osmosis Rate = 20.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	425
60	425
90	450
120	410
180	390

Run 3

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	86	36	99	27
60	152	72	173	53
90	224	107	252	81
120	291	137	325	106
150	354	174	398	133
180	406	215	456	158
210	478	250	541	184
240	564	283	636	209

Osmosis Rate = 18.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	1260
60	620
90	460
120	440
150	420
180	450
240	450
	580

Run 4

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	80	35	93	26
60	162	69	185	52
90	256	103	285	80
120	357	138	395	107
150	457	173	505	133
180	554	208	613	160
210	648	243	719	187
240	741	277	820	212

Osmosis Rate = 18.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	1120
60	440
90	400
120	350
150	350
180	320
210	325
240	370
	600

Run 5

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	113	35	120	30
60	212	70	225	60
90	299	106	314	90
120	349	143	375	119
150	416	179	450	144
180	474	212	515	174
210	657	247	700	203
240	732	283	780	234

Osmosis Rate = 12.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	350
120	330
180	470
240	300
	380

Run 6

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	76	35	84	29
60	134	70	150	59
90	186	105	209	90
120	246	140	274	120
150	310	176	345	150
180	379	210	419	180
210	441	246	488	212
240	497	282	552	242
300	628	355	695	301
360	747	426	829	364

Osmosis Rate = 12.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	275
120	300
180	280
240	275
300	275
360	275
	280

KP-98 Membrane

Dilute Waste Solution-Distilled Water

Run 7

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	105	34	119	19
60	192	68	217	41
90	276	102	310	63
120	358	137	402	87
150	438	172	496	112
180	516	205	585	138
210	594	240	671	162
240	664	275	750	195

Osmosis Rate = 20.75 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	430
60	860
90	1125
120	1240
150	1865
180	1600
210	1525
240	1490
	1100

Run 8

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	118	37	137	23
60	220	72	246	47
90	318	107	350	72
120	414	139	457	93
150	518	177	572	118
180	609	208	675	143
210	705	243	781	168
240	803	278	890	192

Osmosis Rate = 21.4 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	770
60	810
90	1110
120	1230
150	1490
180	1300
210	1300
240	1740
	1240

Run 9

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	100	36	115	20
60	201	71	231	40
90	302	106	345	63
120	406	141	463	86
150	511	166	582	109
180	618	201	697	133

Osmosis Rate = 24.7 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	400
60	820
90	1110
120	1125
150	1270
180	1290
	1090

Run 10

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	84	37	102	19
60	150	73	178	41
90	208	107	245	61
120	280	141	330	85
150	339	175	400	106
180	448	208	520	130
210	566	243	655	153
240	683	278	785	175

Osmosis Rate = 25.7 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	850
60	1050
90	1125
120	1380
150	1800
180	1610
210	1870
240	1860
	1330

Run 11

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	108	36	125	21
60	208	70	237	44
90	308	103	350	66
120	415	138	463	90
150	523	174	588	115
180	620	208	700	137
210	725	245	818	161
240	820	279	923	185

Osmosis Rate = 24.6 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	2600
60	1600
90	1730
120	1730
150	1900
180	1730
210	1800
240	1730
	1720

Run 12

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	107	36	125	21
60	209	72	245	46
90	300	106	345	67
120	394	142	450	91
150	493	172	560	110
180	583	206	664	133
210	676	238	770	156
240	759	273	865	180

Osmosis Rate = 24.9 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	2070
60	1460
90	1485
120	1575
150	1800
180	1780
210	1800
240	1780
	1650

KP-98 Membrane

Four Minute Tempering

Dilute Waste Solution-Distilled Water

Run 13

Tempered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	109	39	126	28
60	226	77	256	53
90	343	115	385	82
120	457	153	517	107

Osmosis Rate = 26.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	310
60	500
90	490
120	460
	430

Run 14

Tempered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	130	38	143	24
60	236	74	260	49
90	341	109	370	74
120	441	148	489	100

Osmosis Rate = 24.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	440
60	350
90	365
120	370
	390

Run 15

Tempered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	200	72	226	52
120	422	154	470	102
180	654	227	725	152
240	850	299	944	204

Osmosis Rate - 23.6 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	370
120	405
180	430
240	430
	420

Run 16

Tempered at 90°C

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	82	36	97	28
90	193	110	229	83
120	321	145	365	110
180	533	218	599	164

Osmosis Rate = 20.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	285
90	390
120	380
180	360
	370

[redacted]n 17

[redacted]mpered at 95°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
120	615	140	662	115
180	926	214	982	177
240	1204	286	1276	238

Osmosis Rate = 15.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
120	465
180	330
240	280
	380

Run 18

Tempered at 95°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	231	72	245	60
120	470	144	499	120
240	951	289	1002	245

Osmosis Rate = 12.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	330
120	290
240	360
	320

Run 19

Tempered at 95°C

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	253	71	264	65
120	508	145	528	129

Osmosis Rate = 9.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	370
120	370

Run 20

Tempered at 92°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	233	71	252	55
120	477	145	512	110
240	947	291	1017	223

Osmosis Rate = 17.3 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	360
120	240
240	255
	255

Run 21

Tempered at 92°C

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	234	74	249	62
120	472	152	502	126
240	940	310	1001	253

Osmosis Rate = 14.8 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	375
120	210
240	185
	240

Run 22

Tempered at 92°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	256	76	246	61
120	461	147	490	122
180	693	227	735	182
280	1096	347	1161	282

Osmosis Rate = 13.9 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	500
120	280
180	255
280	230
	280

Run 23

Tempered at 92°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	242	94	255	74
120	485	167	515	131
180	732	248	773	195
140	974	316	1028	252

Osmosis Rate = 15.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	380
120	370
180	320
240	345
	350

Run 24

Tempered at 88°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	246	77	275	50
120	498	155	550	101
180	742	227	821	151

Osmosis Rate = 25.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	1040
120	760
180	680

KP-98 Membrane

Polyvinyl Methyl Ether Treatment

Dilute Waste Solution-Distilled Water

Run 25

Distilled Water - Six Parts Per Million

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	266	92	303	58
180	747	219	890	117
270	1226	340	1373	187
360	1631	445	1823	250

Osmosis Rate = 32.25 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	1690
180	1890
270	1890
360	1790

Run 26

Distilled Water - Six Parts Per Million

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	256	75	284	50
120	519	146	568	100
180	794	222	865	155
240	1065	297	1155	210
300	1353	368	1465	265
390	1791	479	1935	350

Osmosis Rate = 21.0 ml/hr

Sodium Chloride in Distilled Water Our

Time (min)	Concentration (mg/lit)
60	1780
120	1780
180	1630
240	1600
300	1710
390	1660
	1690

Run 27

Distilled Water - Six Parts Per Million

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	271	74	289	55
120	551	139	589	101
180	831	216	889	161
240	1091	284	1169	210
300	1313	354	1412	260
360	1568	439	1689	310

Osmosis Rate = 20.3 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	3230
120	1920
180	1580
240	1720
300	1760
360	1720
	2030

Run 28

Sea Water - Ten Parts Per Million

Active Side - Distilled Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	267	72	288	55
120	526	143	568	110
180	787	216	853	160
240	1047	289	1135	215
300	1309	362	1420	265

Osmosis Rate = 20.8 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	2100
120	1770
180	1950
240	1680
300	1905
	1920

Run 29

Sea Water - Ten Parts Per Million

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	334	68	357	45
120	669	140	718	97
180	984	211	1055	147
240	1294	284	1389	196

Osmosis Rate = 23.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	2720
120	2115
180	2090
240	2090
	2200

KP-98 Membrane

Dilute Chromium Waste

Run 30

Tempered at 88°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
90	430	119	472	74
150	725	194	802	116
210	993	267	1104	157

Osmosis Rate = 31.0 ml/hr

Chromium concentration in waste in = 50 mg/lit

Chromium concentration in waste out = 54 mg/lit

Run 31

Tempered at 88°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
45	193	60	205	45
105	449	133	483	102
165	681	208	728	157
260	1090	331	1200	250

Osmosis Rate = 22.1 ml/hr

Chromium concentration in waste in = 50 mg/lit

Chromium concentration in waste out = 55 mg/lit

Run 32

Tempered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
42	161	53	170	50
109	415	142	435	127
167	637	220	670	195

Osmosis Rate = 10.4 ml/hr

Chromium concentration in waste in = 51.5 mg/lit

Chromium concentration in waste out = 57 mg/lit

Chromium concentration in sea water out = 1.2 mg/lit

Run 33

Tempered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
36	150	45	159	36
96	401	121	425	100

Osmosis Rate = 14.1 ml/hr

Chromium concentration in waste in = 51.5 mg/lit

Chromium concentration in waste out = 61 mg/lit

Chromium concentration in sea water out = 1.2 mg/lit

Run 34

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
62	287	75	315	52
121	572	145	614	105

Osmosis Rate = 20.5 ml/hr

Chromium Analysis

Sea water in = 0.2 mg/lit

Sea water out = 3.3 mg/lit

Waste water in = 51.5 mg/lit

Waste water out = 53 mg/lit

Run 35

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
85	430	102	460	75
140	721	171	760	125

Osmosis Rate = 18.5 ml/hr

Chromium Analysis

Sea water in = 0.2 mg/lit

Sea water out = 2.5 mg/lit

Waste water in = 51.5 mg/lit

Waste water out = 56.0 mg/lit

Run 36

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
150	670	155	729	95

Osmosis Rate = 24.0 ml/hr

Chromium Analysis

Sea water in = 0.2 mg/lit

Sea water out = 3.3 mg/lit

Waste water in = 50.0 mg/lit

Waste water out = 56.0 mg/lit

Run 37

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
80	362	68	390	36

Osmosis Rate = 22.5 ml/hr

Chromium Analysis

Sea water in = 0.2 mg/lit

Sea water out = 3.0 mg/lit

Waste water in = 50.0 mg/lit

Waste water out = 56.0 mg/lit

KP-98 Membrane

Dilute Copper Waste

Run 38

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
80	298	81	330	54
120	560	154	614	101

Osmosis Rate = 26.5 ml/hr

Copper Analysis

Sea water in = 0.1 mg/lit

Sea water out = 1.5 mg/lit

Waste water in = 50.0 mg/lit

Waste water out = 61.0 mg/lit

Run 39

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste Water In (ml)	Sea Water Out (ml)	Waste Water Out (ml)
60	267	77	295	54
180	815	227	890	159

Osmosis Rate = 23.8 ml/hr

Copper Analysis

Sea water in = 0.1 mg/lit

Sea water out = 1.4 mg/lit

Waste water in = 50.0 mg/lit

Waste water out = 57.0 mg/lit

Universal Oil Products Dry Membrane

Dilute Waste Solution-Distilled Water

Run 40

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
100	486	129	485	126
180	824	223	825	224

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (gm/lit)
100	13
180	24

Run 41

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	243	80	242	77
132	564	173	565	171

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	25
132	20

KP-00 Membrane

Effect of Temperature of Tempering

Four Minute Temperings

Run 42

Tempered at 60°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	275	70	284	65
120	545	151	555	140

Osmosis Rate = 5.75 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	3450
120	3540
	3500

Run 43

Tempered at 60°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	299	84	300	70
120	559	164	565	150

Osmosis Rate = 7.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	4140
120	3240
	3690

Run 44

Tempered at 70°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	247	79	255	72
120	512	157	527	142

Osmosis Rate = 7.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	2940
120	2640
	2790

Run 45

Tempered at 70°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	279	82	288	71
120	531	163	547	147

Osmosis Rate = 8.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	2490
120	2490
	2490

Run 46

[redacted]pered at 80°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	270	80	308	60
120	570	152	608	115

Osmosis Rate = 19.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	1140
120	930
	1035

[redacted]n 47

[redacted]mpered at 80°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	287	84	308	63
120	580	169	620	125

Osmosis Rate = 20.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	1040
120	1020
	1030

Run 48

Tempered at 85°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
93	425	116	454	85
120	539	151	579	110

Osmosis Rate = 20.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
93	690
120	650
	670

Run 49

Tempered at 85°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
65	306	78	325	58
120	552	141	586	104

Osmosis Rate = 18.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
65	850
120	750
	810

Run 50

Tempered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	295	74	304	57
120	612	150	625	125

Osmosis Rate = 16.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	440
120	150
	290

Run 51

Tempered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	308	76	310	69
120	621	154	630	139

Osmosis Rate = 6.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	140
120	140

[redacted]n 52

[redacted]mpered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	311	74	320	64
120	625	153	644	133

Osmosis Rate = 10.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	250
120	180
	215

Run 53

Tempered at 90°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	303	78	312	66
120	606	159	626	136

Osmosis Rate = 10.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	170
120	170

Run 54

Tempered at 93°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	275	75	280	69
120	564	152	573	138

Osmosis Rate = 6.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	110
120	85
	95

Run 55

Tempered at 93°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	261	75	266	70
120	515	150	526	139

Osmosis Rate = 5.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	82
120	83

Run 56

Tempered at 96°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	255	75	259	72
120	506	149	515	142

Osmosis Rate = 4.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	55
120	41
	47

Run 57

Tempered at 96°C

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	260	75	265	70
120	515	148	526	142

Osmosis Rate = 4.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	44
120	44

KP-00 Membrane

Effect of Time of Tempering

Temperature 93°C

Run 58

Tempered for 30 Seconds

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	254	78	264	68
120	509	152	526	135

Osmosis Rate = 8.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	4500
120	3200
	3700

Run 59

Tempered for 30 Seconds

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	254	75	264	66
120	507	154	525	136

Osmosis Rate = 9.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	2300
120	1400
	1900

Run 60

Tempered for 30 Seconds

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	275	78	285	70
120	550	155	569	135

Osmosis Rate = 9.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	2400
120	1600
	2000

Run 61

Tempered for One Minute

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	281	75	290	68
120	557	154	575	137

Osmosis Rate = 9.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	170
120	150
	160

Run 62

Tempered for One Minute

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	275	76	285	70
120	553	154	570	137

Osmosis Rate = 8.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	230
120	240
	235

Run 63

Tempered for One Minute

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	273	75	281	67
120	546	151	561	135

Osmosis Rate = 8.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	240
120	230
	235

Run 64

Tempered for One Minute

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	279	77	287	69
120	559	150	577	134

Osmosis Rate = 8.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	220
120	220
	220

Run 65

Tempered for Two Minutes

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	294	76	300	70
120	590	152	600	137

Osmosis Rate = 6.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	105
120	110
	108

Run 66

Tempered for Two Minutes

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	299	75	306	70
120	571	144	583	131

Osmosis Rate = 6.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	110
120	110

Run 67

Tempered for Two Minutes

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	267	77	275	70
120	525	148	540	134

Osmosis Rate = 7.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	170
120	170

SEPA-97 Membrane

Dilute Waste Solution-Distilled Water

Run 68

Smooth Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
54	211	66	215	62
120	465	146	475	139

Osmosis Rate = 4.25 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
54	620
120	180
	385

Run 69

Smooth Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	286	76	292	70
120	572	158	586	147

Osmosis Rate = 6.25 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	230
120	150
	185

Run 70

Smooth Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	324	74	330	67
120	615	151	630	139

Osmosis Rate = 6.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	120
120	130
	125

Run 71

Smooth Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	269	70	275	71
120	530	152	538	142

Osmosis Rate = 4.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	460
120	210
	335

Run 72

Smooth Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	276	73	280	70
120	530	146	538	139

Osmosis Rate = 4.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	540
120	210
	375

SEPA-89 Membrane

Dilute Waste Solution-Distilled Water

Run 73

Smooth Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	206	78	215	70
120	440	156	457	141

Osmosis Rate = 8.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	180
120	175

Run 74

Smooth Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	183	80	189	71
120	326	159	339	145

Osmosis Rate = 7.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
60	450
120	340
	390

Effect of Osmotic Pressure on Osmosis Rate

KP-90 Membrane

Run 75

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
60	168	76	185	59
120	327	157	360	125

Osmosis Rate = 16.0 ml/hr

Run 76

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
65	212	76	228	60
120	408	137	445	109

Osmosis Rate = 14.0 ml/hr

Run 77

Active Side - Brine (50 per cent sea water and 50 per cent distilled water)

Time (min)	Brine In (ml)	Distilled Water In (ml)	Brine Out (ml)	Distilled Water Out (ml)
62	242	84	250	75
120	465	152	480	139

Osmosis Rate = 7.0 ml/hr

Run 78

Active Side - Brine (50 per cent sea water and 50 per cent distilled water)

Time (min)	Brine In (ml)	Distilled Water In (ml)	Brine Out (ml)	Distilled Water Out (ml)
60	224	84	233	75
120	436	159	499	144

Osmosis Rate = 7.0 ml/hr

Effect of Flow Rates on Permeation Rate

KP-90 Membrane

Run 79

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	179	37	184	34
60	345	76	357	64

Osmosis Rate = 12.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	4500
60	5700
	5100

Run 80

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	129	36	135	33
60	256	74	271	61

Osmosis Rate = 14.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	3900
60	3600
	3750

Run 81

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	137	302	145	294
60	254	598	274	572

Osmosis Rate = 23.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	1500
60	1400
	1450

Run 82

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	638	143	626	163
60	1277	285	1253	316

Osmosis Rate = 28.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	720
60	600
	660

Run 83

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	58	294	65	280
60	114	590	133	567

Osmosis Rate = 21.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	890
60	860
	875

Run 84

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	154	341	167	325
60	292	672	316	645

Osmosis Rate = 25.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	1300
60	960
	1130

Run 85

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	267	290	279	279
60	531	596	552	579

Osmosis Rate = 19.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	1100
60	980
	1040

Run 86

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	291	327	300	310
60	582	656	607	628

Osmosis Rate = 27.0 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	1100
60	1100

Run 87

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	53	327	65	315
60	101	656	125	635

Osmosis Rate = 22.5 ml/hr

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	870
60	800
	835

Waste Wash Water

Fish and Shell Fish Processing Plant

KP-90 Membrane

Run 88

Active Side - Sea Water

Time (min)	Sea Water In (ml)	Waste In (ml)	Sea Water Out (ml)	Waste Out (ml)
30	144	104	151	98
60	290	239	302	227

Osmosis Rate = 12.0 ml/hr

Sodium Chloride in Waste Water

Waste in 2600 mg/liter

Waste out 4000 mg/liter

Treated Cellophane

Rhode Island Cellophane Company

Dilute Waste Solution-Distilled Water

Run 89

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	217	223	220	220
60	435	466	437	466

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	30
60	27

Run 90

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	209	228	212	225
60	415	466	412	464

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	22
60	10

Run 91

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	202	216	203	215
60	397	446	395	448

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	22
60	8

Untreated Cellophane

Dupont Company

Dilute Waste Solution-Distilled Water

Run 92

215-PD Cellophane

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	195	175	195	174
60	387	348	386	347

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	2100
60	2100

Run 93

215-PD Cellophane

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	188	192	190	193
60	384	377	385	378

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	1800
60	1800

Run 94

215-PD Cellophane

Time (min)	Sea Water In (ml)	Distilled Water In (ml)	Sea Water Out (ml)	Distilled Water Out (ml)
30	196	171	195	171
60	390	370	392	371

Sodium Chloride in Distilled Water Out

Time (min)	Concentration (mg/lit)
30	2100
60	1900

Run 95

215-PD Cellophane

Distilled Water Out Closed Off

Time (min)	Sea Water In (ml)	Sea Water Out (ml)	Distilled Water In (ml)
30	185	186	1.0
60	373	375	1.7
90	580	582	2.3

Run 96

150-PD Cellophane

Distilled Water Out Closed Off

Time (min)	Sea Water In (ml)	Sea Water Out (ml)	Distilled Water In (ml)
30	171	172	0.4
60	344	345	0.7
90	515	518	1.0
120	685	689	1.3

Run 97

150-PD Cellophane

Distilled Water Out Closed Off

Time (min)	Sea Water In (ml)	Sea Water Out (ml)	Distilled Water In (ml)
30	182	185	0.4
60	366	367	0.8
90	559	559	1.1
120	739	740	1.3

APPENDIX II

SAMPLE CALCULATION

Run 1

1. $J = Q/At$

$J = 60.0 \text{ ml}/(58.06 \text{ cm}^2)\ 3 \text{ hr} \times 0.00264 \text{ gal/l ml} \times 24 \text{ hr/1 day} \times 929.03 \text{ cm}^2/1 \text{ ft}^2$

$J = 2.03 \text{ gal/ft}^2/\text{day}$

2. $S = C_S V_{Wo}/t$

$S = 560 \text{ mg/lit} \times .150 \text{ lit}/3 \text{ hr}$

$S = 28.1 \text{ mg/hr}$

3. $F = S/A$

$F = 28.1 \text{ mg/hr}/0.0625 \text{ ft}^2$

$F = 448.8 \text{ mg/hr/ft}^2$

4. $R = Q\ (1000)/t\ S$

$R = 60 \text{ ml } (1000)/3 \text{ hr} \times 28.1 \text{ mg/hr}$

$R = 712.$

SAMPLE CALCULATION

Run 34

Chromium Material Balance

sea water in	waste in
(0.572)(0.2) = 0.114 mg	(0.145)(51.5) = 7.468 mg
sea water out	**waste out**
(0.614)(3.3) = 2.026 mg	(0.105)(53) = 5.565 mg

SAMPLE CALCULATION

Run 88 -- Fish Waste

waste in

(0.239) (2600) = 621.4 mg sodium chloride

waste out

(0.227) (4000) = 908.0 mg sodium chloride

salt through membrane

(908.0-621.4) = 286.6 mg

S = 286.6 mg/hr

$F = 286.6 \text{ mg/hr}/0.0625 \text{ ft}^2$

$F = 4585.6 \text{ mg/hr/ft}^2$

R = 12.0 ml/hr x 1000/286.6 mg/hr

R = 41.9

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