Suggested Short Title:

WATER PURIFICATION BY REVERSE OSMOSIS

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ABSTRACT

The object of this thesis was to investigate the operational feasibility of a variable power input reverse osmosis desalination system. This has been undertaken so that the reverse osmosis process can eventually be powered by a wind turbine for use in water provision in arid, developing areas. To simulate wind speed variations, the reverse osmosis membranes were subjected to a series of sinusoidal flow velocities at a constant system pressure of 600 psi. The brackish solution used was made up of tap water and pure sodium chloride, the salinity being 3450 ppm.

For the period of operation, it was found that the continuous variation in the feed velocity had no effect on the performance of the membranes. In fact, the product flux and salinity curves were similar to those obtained under steady state conditions.

The average output over the thirty nine days of operation was about 8.5 gals/sq.ft./day at an average recovery of about 22%. The salinity of the product water dropped from 450 ppm to 200 ppm during the first five days, with a trend toward stability in the next thirty four days.

WATER PURIFICATION BY REVERSE OSMOSIS

by

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LIST OF SYMBOLS

a_B = activity coefficient of water

A = water permeability coefficient, cm^3/cm^2 sec atm

B = salt permeability coefficient, cm/sec

C = concentration of solution, ppm

C_B = salt concentration in bulk saline solution on the saline side of membrane, gm/cm^3

C_D = salt concentration in desalinized water, gm/cm^3

D_r = desalination ratio, C_B/C_D

f = friction factor

F_1 = water flux, cm^3/cm^2 sec

F_2 = salt flux, gm/cm^2 sec

j_D = Chilton-Colburn mass transfer factor

K = concentration polarization exponent

m = molality of solution

M_B = molecular weight of water

N_{SC} = Schmidt number

P = applied pressure, atm

P_b = pressure resistance to solvent flow in the membrane supporting structure and any other back pressures, atm

ΔP = net driving pressure across the membrane, atm

R = interfacial salt rejection, $1-\frac{C_D}{C_W}$

T = absolute temperature, ^{o}K

U_B = bulk saline solution velocity, cm/sec

V_B = partial molal volume of water, liter per gram mole

Z = number of ions per mole of solute

ϕ = osmotic coefficient

π = osmotic pressure, atm

$\Delta\pi$ = osmotic pressure difference, atm

π_B = osmotic pressure of bulk saline solution, atm

π_D = osmotic pressure of desalinized water, atm

π_W = osmotic pressure of saline solution at interface between membrane and bulk saline solution, atm

gfd = gallons per square foot of membrane per day

gpm = gallons per minute

ppm = parts of solute per million parts of solution

1. INTRODUCTION

About three-quarters of the globe is covered with water, and, yet, shortages of drinking water are not uncommon in the developing countries as well as the advanced, industrial countries of the world. Water is more than a public utility. It is essential for all living things -- a building block of life itself. Its lack of purity or its shortage in the home imperils the health and lives of all people -- indeed, the very life of the community. Any improvement in living standards must begin with a safe and adequate water supply.

The developing parts of the world thirst for safe water, yet both in quality and quantity they have been slipping backward. (Good drinking water, according to the U.S. Public Health Service (1), should not contain more than 500 dissolved parts of salt per million parts of water.) The causes of this retrogression are many and complex.

Desalination has been practised for nearly a hundred years on board ships, but it is only in the last fifteen years that land-based units have been used to any significant extent. The total capacity of existing desalination plants throughout the world is very small (300 million gallons per day (2)) when compared with conventional water supply methods, but the ever-increasing demand indicates that desalination will eventually be recognised as the standard technique in many areas of the world. Indeed, Kuwait is at present almost entirely dependent on desalination for its supply of water.

The growing population of the world and the insatiable demand from industries have made it imperative that new supplies of fresh water be found. The greatest potential source for this new water supply has been found to lie in waters which are now brackish, saline or polluted.

A number of technically feasible means of desalting water have been advanced, but technical feasibility is not the only major problem in water desalination. The over-riding consideration is that of desalting water at a cost low enough to make it economically practical. In most parts of the world desalting costs are high compared with the charges made for water. It is for this reason that desalination has found application only in areas with negligible or limited natural sources and with the ability to afford high-cost water. Consequently, most of the plants have been located in rather special areas such as oil communities (Kuwait, Curaçao, Venezuela, etc.) and isolated island communities (Haiti, Virgin Islands, etc.).

A United Nations survey (3) revealed a number of areas where desalination could be applied, but few of the developing countries have the capital required to build large desalination plants to produce water relatively cheaply, nor can they afford the expensive water produced from smaller plants. Usually, where water is needed, power or energy is needed also. The water plants do not care where the power comes from, whether nuclear, fossil, wind, solar, waste heat or electricity. In the small, isolated communities of the West Indies, for example, conventional sources of power are limited or non-existent. Fortunately, however, an abundant amount of "free" energy in the form of the sun and wind is available. Chilcott (4) has shown that a windmill in the north east trade wind of the Caribbean can produce sufficient power for water pumping and desalination. It is for this reason that, in early 1967, the Brace Research Institute of McGill University, Canada, decided to look into the possibility of adapting a reverse osmosis desalination plant to the variable power output of the prototype windmill developed by Chilcott in Barbados. This rapidly improving method of water conversion is attractive because of its great simplicity, low operating and capital costs, low energy requirement, and the fact that no phase change is required in order to separate salt and water. The only kind of energy needed is pressure energy, and this can be obtained by connecting the pump directly to the windmill. However, since the wind speed is not steady, the power input to the pump will also be unsteady, thus giving rise to possible unforeseen problems.

This present project has been undertaken to find out, solve or minimise the problems that a reverse osmosis desalination plant will encounter when the power available is a fluctuating one.

It was decided that, for the purpose of analysis, and, since an actual wind speed fluctuation was difficult to simulate with the equipment available, the reverse osmosis unit should be run under several sinusoidally variable flow speeds at a constant operating pressure of 600 psi. This was made possible by the use of a positive displacement pump coupled to a variable speed motor, and a back-pressure regulator. The amplitude, as well as the period of each sinusoidal flow were varied to give as typical a wind speed fluctuation as possible.

The membranes used were commercial cellulose acetate membranes in tubular forms of 0.5 inch diameter, provided by American Standard Co., New Brunswick, New Jersey.

2. LITERATURE REVIEW

The process of osmosis is as old as life itself. In fact, the osmotic membranes form parts of the primary systems of living matter. They provide for the transport of water as well as of selected chemicals into and out of cells in both animals and plants. The birds, the trees, their leaves and their roots, all of them, use the process of osmosis in one way or another. The seagull, for example, extracts fresh water from sea water, and rejects the concentrated brine through the two holes in its beak.

Osmosis is the spontaneous flow of solvent from a dilute to a more concentrated solution when they are separated from each other by a semi-permeable membrane. This flow can be stopped by applying a pressure, the osmotic pressure, to the more concentrated solution, and can be reversed by applying a still higher pressure. Hence, the name "Reverse Osmosis" is applied to the process in which a pressure gradient is used to cause a solvent to flow out of a concentrated solution into a more dilute one across a semi-permeable membrane.

Historically, the reverse osmosis process has been investigated as a process for desalting sea water. It has long been recognized as one which holds promise of outstanding economy in the conversion of saline water to fresh water (5). Such predictions are based upon the premise that no phase change is involved, such as is necessary in many of the better known distillation processes, and that energy costs may be held to a very low value.

One salient advantage of this process is that it is reversible. This means that it can theoretically be operated as close to the required minimum thermodynamic energy input (the free energy of separation) as desired. The reversible process would consist of operating at a pressure infinitesimally greater than the osmotic pressure difference across the membrane (350 psig for sea water-fresh water). In practice, however, a considerably higher pressure (1500 psig) is necessary to attain appreciable fresh water flux.

In most of the early work, interest centered mainly on membranes that were permeable to water but relatively impermeable to alcohols, sugars and substances of still higher molecular weight and to colloids. It was also recognized, however, that membranes showed varying degrees of semipermeability to salt solutions, and a great deal of work on this phenomenon was done during the first half of the present century by workers such as Teorell (6) and Sollner (7).

In 1953, Reid, of the University of Florida (8), suggested to the Office of Saline Water of the U.S. Department of the Interior that a serious investigation of reverse osmosis as a potential desalination method be undertaken.

The result was a program at the University of Florida under the direction of Professor C.E. Reid and supported by the Office of Saline Water. The work resulted in a series of papers (9, 10, 11, 12) in which it was demonstrated that the purification of sea-water by this method is technically feasible. Economically, however, the utilization of reverse osmosis to desalt sea water was not a viable one because there were no membranes available that were highly permeable to water and yet impermeable to salt. Only one membrane material -- cellulose acetate -- was found by Reid and his co-workers to reject salt efficiently while allowing the permeation of water. Unfortunately the flux rates were too low to be useful.

In a parallel effort at the University of California at Los Angeles, Loeb and Sourirajan (13, 14) found that by using suitable preparative techniques, they could produce cellulose acetate membranes that not only had the excellent selectivity already demonstrated by Reid and Breton, but also had water permeabilities sufficiently high to be of real practical interest. In the preparation of these membranes, Loeb and Sourirajan utilized Mme. Dobry's (15) findings by including aqueous magnesium-perchlorate in the acetone-cellulose acetate casting solution. Mme. Dobry attributed to perchlorates the capability of solubilizing cellulose acetate; particularly effective were the perchlorates of calcium, magnesium, copper and zinc. Lithium, silver, and basic lead perchlorates were also solubilizing agents, but required warming.

Since April 15, 1962, one portion of the reverse osmosis program sponsored by the Office of Saline Water (O.S.W.) has been carried out at General Atomic's John Jay Hopkins Laboratory in San Diego, California. The work there has been primarily concerned with the study of the properties of semi-permeable membranes, and the derivation of phenomenological descriptions of flow through such membranes. Experimental investigations to synthesize ion-restraining films were also supported by the O.S.W. at Radiation Applications, Inc. (16) and at Monsanto Chemical Company (17).

In current membrane technology, cellulose acetate is considered the most suitable polymer for reverse osmosis. A lot of research efforts have been spent in the development of suitable new polymers that will provide a membrane material with a life and desalination properties exceeding those of cellulose acetate. Several interesting materials have turned up, but none of them appears to be competitive with cellulose acetate in the desalination application. Although present cellulose acetate membranes exhibit a declining flux under pressure, primarily due to compaction, a number of refinements in chemistry, casting, and fabrication techniques have produced a modified membrane with an improved life span of about two years (18). The Du Pont Company uses a nylon hollow fiber membrane with a rated flux of 0.15 gfd and an estimated lifetime of five years. However, the sodium chloride rejection characteristics of the fiber have not equalled those of cellulose acetate. The final report of Monsanto (19) reveals that they have successfully produced high-flux cellulose acetate hollow fibers by using a solution spinning technique. The results of field tests have shown that this hollow fiber system can efficiently and economically be used for the desalination of brackish water. In Britain, A.D. Little Ltd., has recently developed a new reverse osmosis membrane which is said to possess greater salt rejection and longer life characteristics than the Loeb-type membrane (20).

As a result of all these efforts, the structure, behaviour, and lifetime of cellulose acetate membranes are now much better understood. New design concepts for reverse osmosis systems have been formulated and small pilot plants have been built (21). In the module design, for example, there are now three membrane module concepts -- tubular, spiral-wound, and plate-and-frame -- that use cellulose acetate as the membrane material, and a fourth concept -- hollow fine fiber -- that uses "dense" cellulose acetate fiber (used by Dow Chemical), and nylon fiber (used by Du Pont). These modules have now been developed to the point of commercial application, and some of the manufacturers are:

Tubular: Havens Industries, American Standard, Inc., Aqua-Chem, Inc., Universal Water Corporation, Aerojet-General Corporation.

Spiral-wound: Gulf General Atomic, Inc., Desalination Systems, Inc.

Plate-and-Frame: Aerojet-General Corp.

Hollow Fine Fiber: E.I. Du Pont de Nemours & Co.,
Inc., Dow Chemical Co.

In construction, at present, is a 250,000 gallons per day reverse osmosis test-bed plant (18) for the Office of Saline Water, U.S. Department of the Interior. It will be the largest reverse osmosis plant in the United States, and perhaps the world, and will allow the development of data for the design and construction of multi-million gallons per day plants.

Other current research activities are in the mathematical and experimental investigations of salt build-up on the membrane surface (22, 23, 24, 25, 26, 27 and 28), and on the analysis and optimization of the entire system (22, 29). Many researchers (30, 31, 32) have investigated the effect of varying the feed flow rate on salt build-up. However, in these experiments, the feed flow variations were carried out only on a steady state basis; i.e., running the experiments at one steady feed flow for a while, then changing to another steady flow. Nobody has, to the author's knowledge, done any experiment where the feed flow is continuously changing, as it is in this project.

Finally, besides its application in the desalting of saline waters, the reverse osmosis process is also being used in the recovery of sewage effluent at, among other places, Azusa, California (33), Pomona, California (34), Bergen County, New Jersey (35), and Washington State University, Pullman, Washington (36). It is also being used in the purification of drugs, foods and industrial wastes. It can purify blood, remove bacteria out of solutions, and strontium 90 from milk. At the National Aeronautics and Space Administration laboratory (37), research is being done on water reuse in space vehicles by reverse osmosis.

3. THEORY

3.1. Osmosis

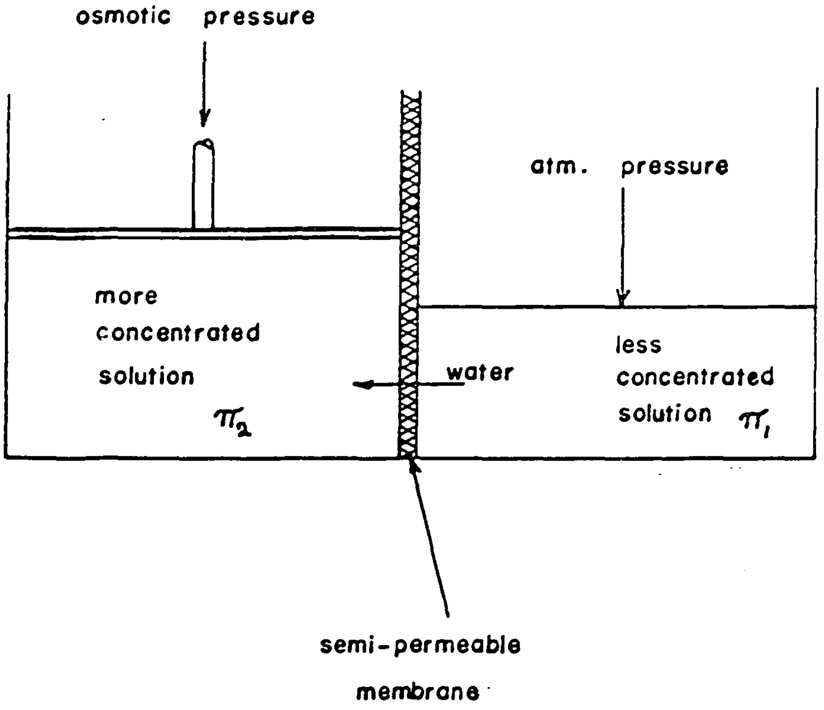
The term osmosis (Greek = push) is used to describe the spontaneous flow of water into a solution, or from a dilute into a more concentrated solution when they are separated from each other by a semi-permeable membrane, i.e., a membrane which allows the free passage of solvent but not of the solute.

This phenomenon was apparently first observed in 1748 by the Abbé Nollet (38) who worked with alcohol-water solutions. Knowledge of this process was considerably extended during the 19th century, particularly by Pfeffer (39) who made the first direct measurements of osmotic pressure. Pfeffer's results were used by Van't Hoff as the basis of a theory of solutions (40) published in 1886, and much of our present understanding of the phenomenon has its foundations in this work.

3.2. Osmotic Pressure

The osmotic pressure of a solution is defined by Glasstone (41) as the excess pressure which must be applied

Fig. 1. SIMPLE OSMOSIS



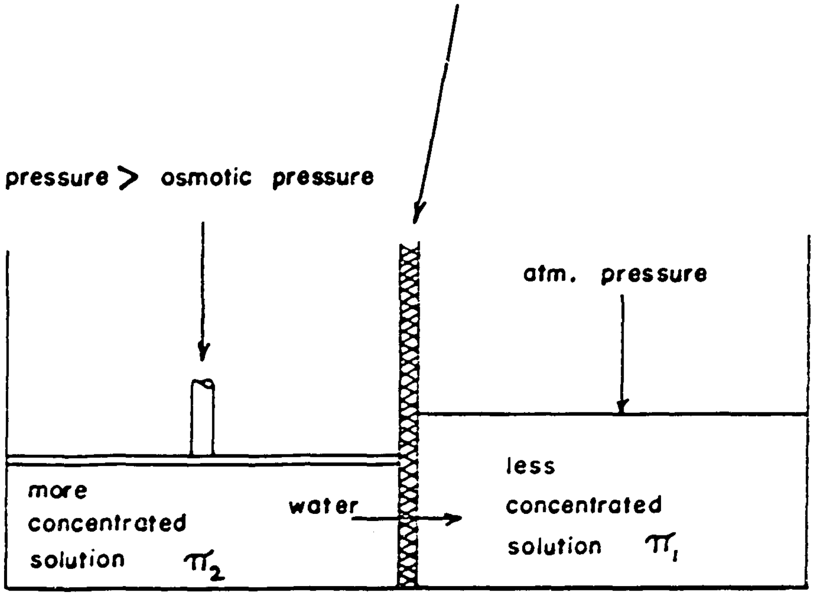


Fig. 2. REVERSE OSMOSIS

to a solution to prevent the passage into it of solvent when they are separated by a perfectly semipermeable membrane.

Consider a cell as in Fig. 1, containing two solutions of different concentrations separated by a semipermeable membrane. The left side of the cell is closed while the right hand side one is open to the atmosphere. Now, due to osmosis taking place, there is a net movement of solvent from the less concentrated solution across the membrane to the more concentrated solution. Pressure is built up in the left cell until an equilibrium is reached between pressure and concentration differences. If the solution on the right is pure solvent, the pressure reached at equilibrium will be the osmotic pressure of the solution on the left. The osmotic pressure is a property of every solution and it increases as the solute concentration increases.

In the system considered in Fig. 1, solvent will continue to flow towards the side containing the higher concentrated solution until the pressure built up equals the difference between the two osmotic pressures ($\Delta\pi = \pi_2 - \pi_1$) of the two solutions.

3.3. Calculation of Osmotic Pressure

The osmotic pressure of a solution can be given (42) as:

$$\pi = \frac{ZRTM_B}{V_B\ 1000} \quad m\phi \text{ (atmospheres)}$$

where Z = Number of ions per mole of solute.

For electrolyte solutions $Z = 1$, and

for non-electrolyte solutions $Z = 2$ (for sodium chloride)

R = Universal gas constant (liter atmospheres per gram mole per degree Kelvin) = 0.0815

M_B = Molecular weight of water

V_B = Partial molal volume of water (liter per gram mole).

m = Molality of the solution (gram mole per 1,000 grams)

T = Absolute temperature (^{o}K)

ϕ = Osmotic coefficient (At 25°C, $\phi = 0.936$ for one molecular weight of sodium chloride; $\phi = 1$ for an ideal dilute solution.)

The osmotic coefficient is defined as:

$$\phi = \frac{-1000}{Zm\ M_B} \cdot \ln a_B$$

where a_B = activity coefficient of water.

Tables 1 to 6 (43) give the osmotic pressure, specific volume, weight per cent of sodium chloride, mole fraction, molar density, molality, partial molal volume of sodium chloride, partial molal volume of water, and the kinematic viscosity for solutions of sodium chloride-water from 0.0005 molal to 6.0 molal.

To determine directly the osmotic pressure (in psi) of a solution, the following relationship exists (44):

$$\pi = 0.0115C$$

where π is in psi

C is in ppm of total solids.

3.4. Reverse Osmosis

Using the same system as described in Fig. 1, a reversal of solvent flow (reverse osmosis) can be made to take place by exerting a pressure to the more concentrated solution in excess of $(\pi_2 - \pi_1)$ Fig. 2. Ideally, only solvent should flow through the membrane. However, because the membranes available are not truly semi-permeable, some solute is also passed.

The equation for reverse osmosis is given by:

$$\Delta P = P - P_b - \Delta\pi$$

where ΔP = The net driving pressure across the membrane.

P = The applied pressure to the more concentrated solution.

P_b = The resistance to solvent flow (a pressure) in the membrane supporting structure and any other back pressures.

$\Delta\pi$ = The difference in osmotic pressure between the more concentrated solution and the less concentrated solution.

In practice $P_b \simeq 0$ since the membrane support resistance is negligible compared to that of the membrane itself, and the product is usually collected at atmospheric pressure.

3.5. Reverse Osmosis Mechanism

There have been many mechanisms hypothesized for the reverse osmosis phenomenon, but none adequately explains the semipermeability of cellulose acetate, although each of them may be valid for some systems. Several of the more significant theories will be reviewed and their bearing on present work will be indicated.

(a) Sieve Mechanism.

This theory was one of the earliest that was proposed (45). According to this theory, a semipermeable membrane possesses pores intermediate in size between the solvent and solute molecules. The solute molecules would thus be blocked and the smaller solvent molecules would be allowed to pass. Early in 1936, Ferry (46) showed this sieving action with synthetic membranes having pores in the 50 millimicron range. Recent work with ion exchange resins (47) has shown that partial exclusion of ions with sizes down to about ten Angstrom units (10^{-7} centimeters) can take place. However, these results are not enough to justify this sieving process because several semipermeable membranes have been found in which the pore size is larger than the solute molecules. In fact, the results of Breton (48) have indicated that the sieve mechanism could not account for the high semipermeability of cellulose acetate. Furthermore, the difference in size between water molecules (two Angstrom in diameter) and hydrated sodium ions (seven Angstrom in diameter) is too small (49) to permit the sieve mechanism to take place.

(b) Distillation Mechanism.

This theory was suggested by Callendar (50) who said that distillation occurs across a liquid-gas interface within the capillaries of the membrane. Bulk flow of the solution across the membrane is prevented by the walls of the capillaries which are nonwettable either to the solvent or to the solution. The solute molecules, being non-volatile, stay behind, while the volatile solvent molecules pass through the membrane as vapour and condense at the opposite membrane surface. Callendar's theory does not apply to cellulose acetate membranes, since they are hydrophilic rather than hydrophobic. The solution would meet the walls of the capillaries and be drawn into them.

(c) Adsorption Mechanism.

This theory of semipermeability is based upon the relative adsorption of solvent and solute molecules by the membrane. The solvent molecules are adsorbed positively and the solute molecules are adsorbed negatively. Loeb and

Sourirajan (51, 52, 53) used the Gibbs adsorption equation to show that there should be a layer of pure water of about four Angstrom (for sodium chloride) units thick at a solution-air interface. They postulated that, at a solution-cellulose acetate interface, this water layer is very much thicker, and, that if the pore size in the membrane is less than twice the thickness of this layer, only pure water can pass through the pores. They tried to test this theory by determining the rejection of various substances, the slope of the surface tension curve of these substances being known. Unfortunately, several of the substances that they predicted would be rejected actually passed through and vice versa. This type of semipermeability is more pronounced when the pore size is small and when surface flow predominates (54).

(d) Solubility Mechanism.

This theory is closely related to the adsorption theory and was first proposed by L'Hermite (55) in 1855. The theory proposes that semipermeability is an outgrowth of the solubility of the solvent and the insolubility of the solute in the membrane. Since the solvent is soluble in the membrane, it can pass but the solute cannot. L'Hermite, in his experiments, placed in a test tube a layer of water, a thin layer of castor oil and a layer of alcohol. After several days, he found that some of the alcohol had diffused through the separating layer of castor oil into the water layer at the bottom of the test tube. He postulated, after several other similar experiments, that substances passing through a membrane must first dissolve in it. Barres (56) also did some valuable work with gasses in rubbers. Although these experiments, as well as others (57, 58), suggest that the solution theory has some merits, Hartsung (59) pointed out that it is not easy to understand how a liquid can dissolve in a membrane without some of the membrane being dissolved in the liquid.

(e) Hydrogen Bonding Mechanism.

This mechanism was first proposed by Reid and his co-workers (60, 61, 62) for cellulose acetate. The membrane is here considered as a network of polymer chains. Some portions of the membrane are crystalline (the chains lie in an orderly pattern) and the other portions are amorphous (the chains are randomly placed and free to move). Reid suggested that the crystalline areas are impermeable to water and that the fibres in the amorphous areas are surrounded by water held by hydrogen bonding. Water molecules, through hydrogen bonding, cross-link the polymer chains and fill the voids in the amorphous regions with bound water. The extent of cross-linking depends upon the size of the voids. When they are large, as in the case of cellophane, the structure is weakly cross-linked. When they are small, as in the case of cellulose acetate, the cross-linking is extensive.

The diffusion through the membrane of ions that cannot enter into hydrogen bonding depends upon the probability of hole formation. In a weakly cross-linked structure, the voids are only partially filled with bound water leaving holes through which ions can pass. In a highly cross-linked structure, however, there is little or no free space through which ions can pass. Ions and molecules that can combine with the membrane through hydrogen bonding and that can fit into the bound water structure, are transported through the membrane by migrating from one hydrogen bonding site to another. Work at Aerojet General (63) in infra-red spectroscopy has added further evidence that hydrogen bonding does take place. Other researchers whose works tend to support the above theory are Gruner (64), Ott (65), Blunk (66) and Spence (67).

3.6. Boundary Layer Effects

It was suggested by Merten (68) that boundary layer phenomena in apparatus for water desalination by reverse osmosis will impose restrictions on the water throughput. When water is transported at a relatively high rate through the membrane, and salt in the feed flow is rejected, a boundary layer of salt solution more highly concentrated than the bulk feed solution forms at the membrane surface. This build-up of salt near the membrane surface is called concentration polarization and is a result of the inability of rejected salt ions to quickly diffuse back into the bulk solution.

If the salt build-up at the membrane surface becomes too great, four effects can be noted.

(i) The accumulation of salts will raise the effective osmotic pressure of the feed solution and will therefore decrease the force causing water to flow through the membrane, thus decreasing the water flux. This can be seen from the formula proposed by Merten (69) for water flux, F_1, through a membrane of constant permeability.

$$F_1 = A\ (\Delta P - \Delta \pi)$$

Increases in the osmotic pressure difference, $\Delta \pi$, require a higher applied pressure to obtain a specified water flux.

(ii) If the concentration of the feed water exceeds the saturation point of any one of the constituents of the feed solution, that constituent may precipitate and effectively limit the flow of water through the membrane.

(iii) The product water salinity will increase due to the fact that salt rejection depends on salt concentration difference, ΔC, across the membrane. Again, this can be demonstrated from the equation of salt flux, F_2, given by Merten (69).

$$F_2 = B \cdot \Delta C$$

where B, is the salt permeability coefficient.

(iv) The useful life of the membrane will be shortened by the increased salinity of the solution.

3.7. Concentration Polarization

Concentration polarization cannot be eliminated completely in any reverse osmosis process. Its magnitude, however, can be reduced in two ways: (a) the bulk solution can be made turbulent by having a high feed flow or by introducing turbulence promoters (plastic spheres) in the feed channel, (b) entrance effects can be utilized by using thin channels in the laminar flow region.

Sherwood, Brian, Fisher, and Dresner (70), have analyzed concentration polarization effects for both turbulent and laminar flow in tubular membranes rejecting salt completely, and for laminar flow in a two dimensional channel. This theory was then extended to membranes with less than complete rejection (71). Sherwood _et_ _al_. (72) have checked their equations and those of Brian through experiments carried out with cellulose acetate membranes supported on a rotating cylinder. Rosenfeld and Loeb (73) also found that performances at the Coalinga plant were consistent with the results predicted by the equations of Sherwood _et_ _al_. and Brian. A lot of the subsequent mathematical analyses, while focusing on important nuances of the theory and providing alternate methods of viewing the problem, in general consider second order correction factors which are outside the scope of present experimental techniques.

Since the tubular membranes used in this experiment contain turbulence promoters (plastic spheres), and the experiment was carried out with the flow in the turbulent range, it is proposed, here, to give the performance equations for turbulent flow only.

The model used by Sherwood <u>et</u> <u>al</u>. (70) and Brian (71) was the film-theory one in which the resistance to salt transport away from the membrane surface is controlled by molecular diffusion. The boundary layer is idealized as a thin, liquid film in which eddy motion is assumed to be negligible, and the bulk solution is considered to be well mixed. From this model, the concentration polarization ratio in the turbulent region is given by Brian (74) as:

$$\frac{C_W}{C_B} = \frac{\exp\left(\dfrac{F_1 N_{SC}{}^{0.67}}{U_B j_D}\right)}{R + (1 - R)\ \exp\left(\dfrac{F_1\ N_{SC}{}^{0.67}}{U_B j_D}\right)} \qquad (1)$$

and $$R = 1 - \frac{C_D}{C_W} \qquad (2)$$

where:

C_B is the salt concentration in the bulk saline solution on the saline side of the membrane

C_W is the salt concentration at the interface between the membrane and the saline solution

C_W/C_B is defined as the concentration polarization ratio.

C_D is the salt concentration in the desalinized water

F_1 is the water flux

N_{SC} is the (dimensionless) Schmidt No. for salt diffusion

U_B is the bulk saline solution velocity

R is the interfacial salt rejection

j_D is the Chilton-Colburn (dimensionless) mass transfer factor used in turbulent flow. For round tubes $j_D = f/2$, where f is the friction factor, and is some function of Reynolds number.

For R = unity, when the membrane rejects all salts, equation (1) reduces to that given by Sherwood et al. (70):

$$\frac{C_W}{C_B} = \exp\left(\frac{F_1 \, N_{SC}^{0.67}}{U_B j_D}\right) \qquad (3)$$

For conciseness, K, the concentration polarization exponent is defined as:

$$K \equiv \left(\frac{F_1 \ N_{SC}^{0.67}}{U_B j_D} \right) \qquad (4)$$

Although the concentration polarization ratio can be predicted by using equation (1), the latter is not a very practical equation to use because of the difficulty in measuring the term C_W, the concentration at the interface. To convert equation (1) into terms more readily measurable, a new term, D_r, called the desalination ratio is introduced (75). This new term is defined as:

$$D_r \equiv \frac{C_B}{C_D} \qquad (5)$$

Now, by combining equations (1), (2), (4) and (5), we get:

$$\frac{C_W}{C_B} = \left[(\exp K) \left(1 - \frac{1}{D_r} \right) + \frac{1}{D_r} \right] \qquad (6)$$

Equation (6) now gives the concentration polarization ratio in terms of variables that can be measured directly, and is thus a more practical one to use.

The equation for the interfacial salt rejection, R, can be similarly converted by rearranging equation (2) as:

$$R = 1 - \left(\frac{C_D}{C_B} \right) \left(\frac{C_B}{C_W} \right) \qquad (7)$$

and combining equations (5), (6) and (7) to give:

$$R = 1 - \left[\frac{1}{(\exp K)\ (D_r - 1) + 1} \right] \tag{8}$$

Although the assumptions used in the film-theory model are not quite correct, they are nevertheless good enough to permit one to predict the concentration polarization with good accuracy, especially with brackish water. Brian (76) has shown that an expression identical to equation (1) is obtained even when an eddy-diffusion model, which takes into consideration the eddy diffusivity within the film but which the film-theory assumes to be zero, is used.

3.8. Water Flux

Merten (69) proposed the following equation for the water flux through a membrane of constant permeability:

$$F_1 = A\ (\Delta P - \Delta \pi) \tag{9}$$

where:

$$\Delta \pi = \pi_W - \pi_D \tag{10}$$

when concentration polarization is present.

ΔP is the hydraulic pressure drop across the membrane

π_W is the osmotic pressure at the membrane-saline water interface

π_D is the osmotic pressure of the desalinized water

A is the water permeability coefficient.

Since the osmotic pressure at the membrane-saline water interface, π_W, is difficult to measure, equation (9) is expressed in terms of variables that can be measured directly. To do this, the desalination ratio term, D_r, is used and the concentration polarization ratio is expressed thus (75):

$$\frac{C_W}{C_B} \simeq \frac{\pi_W}{\pi_B} \qquad (11)$$

Now, by combining equations (6), (9) and (11) we have:

$$F_1 = A \left[\Delta P - \pi_B \left((\exp K) \quad (1 - \frac{1}{D_r}) + \frac{1}{D_r} \right) + \pi_D \right] \qquad (12)$$

where:

π_B is the osmotic pressure of the bulk feed water.

Simplifying equation (12) further by using $\pi_D / \pi_B = C_D / C_B$ we have:

$$F_1 = A \left[\Delta P - \pi_B \; (\exp K) \quad (1 - \frac{1}{D_r}) \right] \qquad (13)$$

For a perfectly semi-permeable membrane, $C_D = 0$ and $D_r = \infty$ from equation (5). Equation (13), then reduces to:

$$F_1 = A \; (\Delta P - \pi_B \exp K) \qquad (14)$$

If the membrane is completely non-selective ($D_r = 1$), or if pure water ($\pi_B = 0$) is used, then:

$$F_1 = A \cdot \Delta P \qquad (15)$$

In cases when the concentration polarization is small or negligible (exp K → 1), equation (13) reduces to:

$$F_1 = A \left[\Delta P - \pi_B \left(1 - \frac{1}{D_r} \right) \right] \qquad (16)$$

or

$$F_1 = A \left[\Delta P - (\pi_B - \pi_D) \right] \qquad (17)$$

Equation (17) is now similar to equation (9) except for π_B which replaces π_W.

3.9. Salt Flux

Merten (77) gave the following equation for salt flux.

$$F_2 = B\ (C_W - C_D) \qquad (18)$$

where F_2 is the salt flux

B is the salt permeability coefficient.

Equation (18) implies that the salt flux occurs through a simple diffusion mechanism.

To convert equation (18) into terms that are directly measurable, we divide it by C_D to give:

$$\frac{F_2}{C_D} = B \left(\frac{C_W}{C_D} - 1 \right) \qquad (19)$$

and using:

$$\frac{C_W}{C_D} = \frac{C_W}{C_B} \cdot \frac{C_B}{C_D} \qquad (20)$$

Now, after combining equations (5), (6), (19) and (20) and simplifying, we get:

$$F_2 = C_D\ B\ (\exp K)\ (D_r - 1) \qquad (21)$$

or

$$D_r = \left[\frac{F_2}{B \cdot C_D \cdot \exp K}\right] + 1 \qquad (22)$$

Loeb and Rosenfeld (75) use the following approximation:

$$\frac{F_2}{C_D} \simeq F_1$$

in equation (22) to get:

$$D_r = \left[\frac{F_1}{B \cdot \exp K}\right] + 1 \qquad (23)$$

This shows that the desalination ratio is also a function of the water flux F_1.

4. EXPERIMENTAL PROCEDURES

4.1. Preliminary Work

Since the purpose of this thesis is to test the possibility of adapting the reverse osmosis process to a windmill (variable speed), it was decided to simulate, as far as possible, a typical wind speed variation. To do this, an analysis of the data on wind speed in Barbados (4) was first carried out. As a result, it was found that the maximum ratio of the highest wind speed to the minimum wind speed in an average year is about 2.5 to 1. The maximum time taken for the wind to change from a maximum speed to a minimum speed (peak to peak) or vice versa, is about 45 seconds, and the minimum is about 15 seconds.

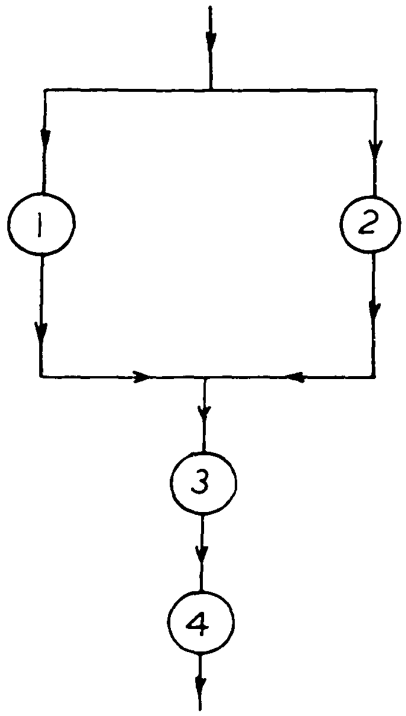
It was decided that, in order to simulate a wind speed variation, and, at the same time to keep the analysis fairly simple, sinusoidally variable flow speeds should be used as shown in Figs. 4 and 5. A "W" type variable flow is not appropriate because of the moment of inertia of the wind-mill which will tend to smooth out the curve at the peaks. This sinusoidal type of speed change was made possible by the use of the small motor and cam system shown in Figs. 19 and 21. The ratio of the maximum and minimum wind speeds corresponds to twice the amplitude of a sinusoidal flow curve, and the time between these two wind speeds corresponds to half the period of a sinusoidal flow curve.

In order to effect good control, the saline feed solution ($\simeq$ 3500 ppm) was made up of pure sodium chloride and tap water (pH = 7.1). In the later stages of the experiment a typical brackish water, or a solution approximating to a typical brackish water would be used. This might show up any problems that could arise from scaling, precipitation, excessive hydrolysis of the membrane, corrosion, etc. For reasons of economy and space, the system of flow was made a recirculatory one. This system, however, is (78) thermodynamically inefficient because of the mixing of solutions of different compositions. Mixing increases the average concentration of the saline solution and therefore its osmotic pressure. This phenomenon was noticed during the experiments and tap water had to be added to the feed solution from time to time to prevent its salinity from rising.

4.2. Preliminary Testing

The preliminary tests were carried out to check the major components of the system, i.e., flow measuring devices, piping, pumps, etc., and to gradually bring the reverse osmosis modules to their operating pressures of 600 psi. The tests started on October 19, 1970, on a steady flow basis, with the four modules connected in series. It was noticed that for a low reject brine flow of about 0.2 U.S.G.P.M., the totalizing flow-meter, T_2, was not accurate. The pressure difference between the inlet pressure to the first module and the outlet pressure of the fourth module was found to be too big -- 130 psi for a feed flow of only 0.6 U.S. gal/min when the system pressure was set at 400 psi. A new flow scheme was therefore tried so as to minimize the pressure drop across the modules. This flow scheme is shown in Fig. 3, when the first two modules were placed in parallel and the last two in series.

Fig. 3



Unfortunately, the pressure drop across the modules was still high (60 psi) when the flow was about 0.5 U.S. gal/min and the system pressure set at 600 psi. It was finally decided that the modules should be placed in parallel.

During the course of these tests, it was noticed, on a couple of occasions, that the feed flow recorder gave a zero flow reading although there was actually a flow. The reason for these false readings were found out when, on October 23, 1970, the recorder stopped recording. The plant was shut down and the turbine meter was dismantled. The bearings inside the turbine meter had seized, thus preventing the rotor from rotating.

On November 9, 1970, after the turbine meter had been repaired, the plant was started up again, only this time to find that the fourth module was leaking. Since the whole of the previous summer had been wasted due to faulty membranes and leaky modules, it was decided that the three remaining modules should be placed on a variable flow setting and that actual tests should begin. This was done on November 10, 1970.

4.3. Test Procedures

Test No. 1 was started on November 10 with a variable feed flow range of 0.54 and 1.0 U.S. gal/min. The period of the sinusoidal flow variation was set at 90 seconds. This test corresponds to a maximum change in the wind speed (amplitude) in a maximum time (period). In order that the flow in the modules be a turbulent one, the Reynolds Number at all points was maintained at 600 or greater (79). This Reynolds Number was based on open tubes. (Calculation of Reynolds Number with turbulence promoters is a problem being considered at present by American Standard Co., New Brunswick, New Jersey.)

On Wednesday, November 11, a set of readings of the product water flow was taken at every fifteen second interval on module 1. A similar one was again taken on module 1 on November 12, and one on each module on November 16. The flow was measured in a graduated cylinder and the data are shown in Tables 1A to 1E. The purpose of these readings was to check whether the product water flow did vary as the feed flow changed continuously.

Test No. 2 was started on November 17, 1970, and was terminated on November 25, 1970. The variable feed flow range was set at 0.60 U.S.G.P.M. and 0.94 U.S.G.P.M. and the period of the sinusoidal flow was kept at 90 seconds, as in the previous test.

At around 1400 hours on November 19, it was noticed that the fitting that holds the thermocouple in the flow circuit was leaking. The pump was therefore stopped for about five minutes to repair the leak. However, on restarting, it was found that the salinity of the product had jumped to a very high figure, as shown in Fig. 9. According to the author, the high product salinity was due to feed saline water permeating through the membranes while the pump had been stopped. The pump, being a positive displacement one, was still keeping the solution in the modules under the system pressure, and, since there was no flow through the back pressure regulator, the only flow that could take place was through the membranes. As the pressure in the system gradually decreased, so did the efficiency of the membranes, thus allowing more and more salt to pass through. This increase in product salinity could have been avoided or minimized by reducing the system pressure to atmospheric prior to stopping the pump.

Test No. 3 was started on November 25 with a steady flow of saline solution. The flow was set at 0.77 U.S.G.P.M., which is the average flow rate of tests Nos. 1, 2, 4, 5, 6 and 7. The purpose of test No. 3 was to see whether the product water flow rate and salinity would be affected by a temporary, steady feed flow (simulating a constant wind speed) and back again on a variable state condition (test No. 4). This test was terminated after two days because no apparent change in the quality and quantity of the product water was noticeable.

An ultra violet lamp of short wavelength was installed on November 26 on the return line of the reverse osmosis unit to check the formation of bacteria. This method was used by Brun, Duriau and Dussaussoy (80), and, apparently, had a positive effect in preventing bacteria from forming. However, in the present experiment, the ultra violet lamp did not seem to have any effect on the salinity and flow rate of the product water. It was then decided that, since this was the case, it would be better, for the purpose of analysis, to remove this unknown variable (ultra violet). So, on November 30, the ultra violet lamp was removed.

Test No. 4, started on November 28, and, set at the same conditions as test No. 2, was terminated after one day for reasons similar to those of test No. 3.

Test No. 5 (November 29 - December 4), test No. 6 (December 4 - December 10), and test No. 7 (December 10 - December 16) were all set at the same variable flow of 0.66 U.S.G.P.M. and 0.88 U.S.G.P.M., but at periods of flow of 90 seconds, 60 seconds, and 30 seconds respectively, as shown in Figs. 4 and 5. These three tests were carried out so as to see the effects of the rate at which the wind changes speed (period of variation) on the product water.

The last two tests - test No. 8 (December 16 - December 18) and test No. 9 (December 18 - December 20) were performed to check the effect of varying the mean value of a variable flow on the product water. The feed flow of test No. 8 varied between 0.36 U.S.G.P.M. and 0.70 U.S.G.P.M., and that of test No. 9 varied between 0.53 U.S.G.P.M. and 0.87 U.S.G.P.M. However, they were both set at the same period of flow (30 seconds) and the same difference between their maximum and minimum speeds (same amplitude) as test No. 7. Test No. 8 was run for two days only because the author was informed on December 14 that due to some major electrical repairs, electricity would be cut off in the evening of December 20. Unfortunately, the warning came too late. No stand-by generators (110 volts, single phase for the instruments, and 240 volts, 3 phase for the high pressure pump) were available in the college and none was available for rent at such a short notice.

Test No. 9 had to be stopped prematurely because of a breakdown of the high pressure pump which occurred during the early morning (around 10.00 hours) of December 20. The breakdown was due to a return water hose which came loose and drained the system of all its feed solution.

The last set of readings before the breakdown occurred was taken at 23.30 hours on December 21, 1970.

5. DESCRIPTION OF REVERSE OSMOSIS UNIT

5.1. General

The flow diagram of the reverse osmosis unit is illustrated in Fig. 15. The saline feed water (around 3500 ppm) is made up of pure sodium chloride and tap water. A typical brackish water is not used at this stage because it is not practical and economical, with the space available, to store the huge volume that is necessary for the months-long series of tests. Moreover, a brackish water may contain other salts of lower saturation points than that of sodium chloride, and may thus precipitate in a recirculatory system such as is used in this project causing a change in the salinity of the feed water.

The saline feed water is stored in a 70 gallon plastic tank eight feet above the floor, and flows through 1 inch schedule 80 PVC (polyvinyl chloride) piping by gravity to the suction side of the high pressure pump. Prior to entering the pump, the feed water passes through an indicating rotameter, a totalizing meter, T1, and a 20 micron filter. The temperature of the feed water is measured by means of a thermometer inserted in the line just outside the feed water tank. A thermostat placed between the totalizing meter, T1, and the filter, activates a solenoid valve whenever the feed water temperature goes 1°F above or below the pre-set temperature. The solenoid valve is situated at the end of a cold tap water pipe and controls the flow of the cold water which flows through the heat exchanger.

After passing through the filter, the saline water is brought up to the system pressure (600 psi) by the positive displacement pump which is driven by a variable speed motor. The pressurized water from the discharge side of the pump is monitored by a turbine meter hooked to a Honeywell recorder, a pressure gauge, and a pressure recorder before being routed to the reverse osmosis modules through a valving arrangement. Immediately after the pump is located a pressure relief valve which opens and allows saline water to flow out of the high pressure system into the sump should the line pressure increase beyond the pre-set value.

The materials of all high pressure piping within the desalination unit are: 316 stainless steel 1/2 inch tube, 3/8 inch type "L" hard copper tube, and 1/2 inch (Internal Diameter) high-pressure synflex hose. The valves are high-pressure brass ones. To reduce galvanic action between copper, steel and brass, teflon tape is used.

The three modules that form the reverse osmosis assembly can be connected either in series or in parallel (or both) by means of the valving assembly shown in Fig 17.

The effluent water from each module collects in a plastic container surrounding the module and drains through an outlet in the bottom cover plate via a 0.5 inch plastic hose to a flow measuring tipping bucket, as shown in Fig 18. Each tipping bucket is calibrated to trip at 600 cu. cm., and each trip is registered on a digital counter so that the daily average flow can be computed by subtracting the figure registered at the start of the day from that registered at the end of the day. The salinity of the product water from each module is measured by diverting the flow from the tipping bucket into a beaker in which the salinity probe is placed. The product water thus collected is poured back into the tipping bucket, after the salinity has been measured, so that it can be registered. Each time a bucket trips, it pours its content into one of two manifolds placed on either side of the tipping buckets, and the water is then funnelled to a 20 gallon plastic sump.

The reject brine leaving the modules is monitored by a pressure gauge and a thermocouple, and is let down from 600 psi to atmospheric pressure through a nitrogen controlled back-pressure regulator. The latter keeps the system pressure at 600 psi even when the flow rate changes (within the capacity of the regulator). After leaving the back pressure regulator, the brine flows through an orifice plate which gives a measurement of the flow rate, and through a totalizing meter, T2. It then mixes with the product water leaving the manifold, and the mixture is subjected to ultra violet rays of short wavelength before going to the sump. The sump also contains an automatic, submersible, centrifugal pump which pumps the mixture of brine and product water back to the feed water tank which sits approximately 8 feet above the sump.

From a second opening at the bottom of the feed tank, feed water continuously flows down, by gravity, through the heat exchanger (double-pipe) where it is cooled and on into the sump. There, it mixes with the reject brine and product water and the cycle continues.

5.2. Subassembly Details

(a) Variable Speed Adjusting Mechanism.

This consists essentially of a motor (motor of a timer), a plastic disc, and a slotted plastic bar as shown in Fig. 19. One end of the bar fits tightly over the speed control knob of the pump electric motor, and the other end is connected to the plastic disc by means of a pin. The disc, which acts as a crank, in turn, is fixed onto the shaft of the small motor, and, by means of different gear racks the speed of the former can be varied. The speed of the motor is what, in fact, controls the period of the sinusoidal flow.

The plastic disc too has a slot machined into it in a radial direction, and the position of the pin along this slot controls the angular movement of the plastic bar (link) and hence the speed range or amplitude of the sinusoidal flow.

(b) Tipping Bucket.

This instrument was made in the college workshop to measure the low product water flow issuing out of each module and is shown in Figs. 23 and 24. The bucket is made out of 22 gauge galvanized sheet metal and coated both inside and outside with a sea water resistant paint. The bucket pivots about a horizontal bar which traverses the two legs of the bucket and which is supported by a rigid wooden frame. The angle through which the bucket can trip is controlled by a bolt below each side of the bucket and against which the latter comes to a rest. In order that the calibration is not affected by the constant banging against the bolt (causing a dent), the bottom of each bucket is reinforced with strips of hard steel. The more the bolt protrudes beyond its support the lower is the amount of water that the bucket can hold before it trips, and vice versa. (Each bolt controls the amount of water in the side of the bucket opposite to it.) In this experiment each bucket is calibrated at 600 cc and its accuracy is ± 1.5%.

At the tip of one leg of the tipping bucket is a metal disc which activates an electric switch, which, in turn, triggers a digital counter, each time the bucket trips.

(c) Reverse Osmosis Modules.

The four tubular reverse osmosis modules used (Figs. 25, 26) were donated by American Standard Co. of New Brunswick, New Jersey. Each module consists of a bundle of porous fiber-glass reinforced epoxy tubes (14 tubes), approximately one-half inch in diameter, into which have been inserted semi-permeable membranes of cellulose acetate (AS-197). These tubular membranes are formed from a continuous flat strip of cellulose acetate film which is curled into the shape of a cylinder with a slight overlap, and then placed into the fiber-glass support tubes by means of a mechanical device developed by American Standard for this purpose.

Both ends of the fourteen porous support tubes are bonded into stainless steel tube sheets by means of an epoxy adhesive leaving 50 inch tube bundles exposed. The tube sheets are, in turn, bolted to stainless steel end plates which contain liquid flow distribution channels. The flow channels are machined such that all the fourteen tubular membranes are in series in each module. The total membrane area in each module is 9.1 sq. ft.

The modules used in this experiment contain spherical turbulence promoters within the tubular elements. These are in the form of plastic spheres slightly smaller in diameter than the bore of the support tubes. They create additional turbulence in the feed water flow and thereby minimize the degree to which dissolved salts concentrate at the membrane surface.

Since in this system the membranes are not physically attached to the porous tubes, they can easily be removed on the site and replaced with fresh membranes. According to American Standard, the entire operation takes only a matter of minutes.

6. DISCUSSION OF RESULTS

The performances of the three modules are displayed graphically in Figs. 6 to 14, and tabulated in Tables 1 to 9. The product water flux (gallons/sq.ft./day) and the product salinity (ppm) are perhaps the major variables of interest in this experiment. These are plotted side by side in an overall graph, Fig. 16, to see if there exists any discontinuity in the curves, arising from the change in feed flow conditions. As can be seen, the curves do not show any discontinuity or sudden changes between each test run. The only sudden change in salinity was due to a pump stoppage which is indicated by "A" in Fig. 7 and by "B" in Fig. 16.

The product salinity versus time plot, shown in Fig. 16, exhibits a decrease in salinity from around 450 ppm to about 200 ppm during the first five days of the series of tests with a trend toward stability in the next thirty four days. The salinities of the product water from the three modules were never equal but were nevertheless very close to each other and were well below the accepted value of 500 ppm.

As for the product water flux, the curves for the three modules in Fig. 16 show a decline from about 10 gallons/ sq. ft./day (gfd) at the beginning of the experiment to about 6.7 gfd at the end of the series of tests. The drop in flux is more pronounced during the first 6 to 8 days than at any other period of the experiment. This is probably due to compaction of the membranes which takes place at a more rapid rate at the beginning of an experiment than at any subsequent stage. According to the author's point of view, the gradual decrease in product flux that takes place after the sixth day is due more to compaction than to concentration polarization. In fact, if concentration polarization did really take place, the salinity curves would have shown an upward trend and not a horizontal one. Besides, the average recovery of product water (around 19%, as shown in Fig. 8) is too low to cause any polarization to take place.

The use of a short wave ultra-violet lamp to kill bacteria (indicated by "C" in Fig. 16) did not seem to have had any positive effect either on the salinity or on the flux of the product water. In fact, the product water flux continued to decline. Perhaps, as mentioned in Chapter 4, the reason for the ineffectiveness of the ultra-violet lamp was that the saline solution was already bacteria free or contained a low level of bacteria, since it was made up of pure sodium chloride and potable tap water. If that was the case, then, any effect that the ultra-violet rays might have had on the bacteria would not result in an increase in the product water output.

The overall picture of product flux versus time and product salinity versus time in Fig. 16 shows that both the quality and quantity of the product water are not affected by the type of feed flow, be it variable or steady, provided, of course, that the flow is not reduced to zero. In fact, the curves look very much like the ones obtained for steady feed flow tests carried out by other researchers. Even when the mean of the varying feed velocity is changed, like in Tests No. 8 and 9, the product flux curves keep their trends. However, the salinity curves do show a temporary increase in these tests. It would have been very interesting to see how these curves would have looked like had these last two tests been of a longer duration.

The results shown in Tables 1A to 1E and Table 2A, indicate, once again, that the rate of product water flux is not affected by the varying velocity of the feed solution. Looking at Table 1A, for example, there is not any pattern in the product flow data that indicates that the flow is cyclical. The few figures that vary from the mean value of 60 were probably due to human error when taking readings. The results further show that the membranes, in restricting the flow to a steady but decreasing one, were behaving like baffles or pulsation dampeners.

The average product water flux (8.5 gfd) for the whole experiment is lower than 10 gfd -- considered by most researchers to be the minimum figure below which the reverse osmosis process is uneconomical. This, however, is due to the low flow limitations imposed by the high pressure pump and the back-pressure regulator. Since the quality of the product water (average ppm = 200) is much more superior than that accepted by the U.S. Public Health Service (500 ppm), the product flux can be further increased without detrimental effect on the quality of the water.

7. CONCLUSION

The following conclusions can be drawn from the results of this experiment:

1. The amplitude and period of the sinusoidal feed flow do not have any effect on the quality or quantity of the product water within the operating flow range.

2. Increasing or decreasing the mean feed velocity does not have any substantial effect on the quality of the product water.

3. No matter how the velocity of the feed flow varies (sinusoidal, saw-tooth, random, etc.), the membranes behave essentially as for a steady state condition, provided that at no time between the changing conditions is the feed velocity reduced to zero.

4. The intrinsic membrane properties of permeability and rejection are not affected by a variable feed velocity.

5. There exists a certain amount of evidence to indicate a time lag in the response of the membranes to a change in operating conditions. For example, about two days were required for the salinity of the product water to drop to its normal value, after the pump had been stopped in Test No. 2. For this reason, care must be taken to see that the pump is not stalled during an experiment.

6. Concentration polarization does not seem to be a problem in this experiment. American Standard Co. has some evidence to support the fact that the spherical turbulence promoters in the tubular membranes reduce fouling tendencies (79).

7. Finally, a wind powered reverse osmosis plant is technically feasible provided a way is found to circumvent the problem of zero flow.

RECOMMENDATIONS FOR FUTURE WORK

The following suggestions are made for future research.

1. The reverse osmosis unit should be hooked directly to a windmill on a typical site so that it would be subjected to an actual wind regime.

2. A typical West Indian brackish water should be used.

3. An investigation should be made to find a relationship between pressure and feed velocity, and from that, the optimum pressure for a given velocity or vice versa.

4. The feed flow velicty should be increased to a higher range to see the effect on concentration polarization.

5. Since the temperature of a typical brackish water varies throughout the day and night, an investigation should be made on the effect of temperature changes on product flux, concentration polarization and product salinity.

6. A comparative economic study of the cost of desalting brackish water by the wind-powered reverse osmosis process as opposed to other processes of desalination.

7. A long term study of the effect of ultra-violet rays on bacteria should be made.

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Table 1. Test 1: Performance log of reverse osmosis unit
Variable feed flow: 0.54-1.0 U.S. gpm
Inlet pressure: 620 psi (1)
Outlet pressure: 600 psi (2)
Period of sinusoidal flow: 90 secs.
(1) Measured at high pressure pump outlet
(2) Measured at outlet of last module.

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 10	21.30	77	3350	4350	--	--	--	680	670	600
Nov. 11	03.30	77	3345	4420	11.3	10.05	9.6	580	560	485
	09.30	77	3400	4300	--	--	--	500	528	480
	15.30	76	3410	4410	11.0	9.78	9.37	470	460	450
	21.30	76	3370	4350	--	--	--	418	457	400
Nov. 12	03.30	76	3370	4415	10.58	9.47	9.07	370	400	360
	09.30	76	3400	4370	--	--	--	340	380	300
	15.30	76	3405	4410	10.20	9.25	8.8	310	346	260
	21.30	76	3550	4660	--	--	--	290	327	290

Table 1. (continued)

Date	Time	Feed Temp (^{o}F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 13	03.30	77	3300	4320	10.06	8.97	8.6	276	290	275
	09.30	76	3300	4230	--	--	--	286	272	260
	15.30	77	3352	4420	9.95	8.80	8.60	300	255	265
	21.30	76	3305	4300	--	--	--	285	255	245
Nov. 14	03.30	76	3360	4400	9.75	8.72	8.48	285	255	225
	15.30	76	3395	4340	9.73	8.70	8.50	270	255	240
	21.30	77	3390	4395	9.70	8.70	8.46	260	255	238
Nov. 15	15.30	76	3380	4295	9.60	8.55	8.40	275	230	225
	21.30	76	3390	4420	9.58	8.60	8.40	280	270	220
Nov. 16	09.30	75	3300	4230	--	--	--	260	230	190
	15.30	77	3410	4405	9.50	8.50	8.33	260	245	185
	21.30	77	3415	4400	--	--	--	255	245	200
Nov. 17	03.30	77	3450	4405	9.48	8.38	8.25	255	245	192
	09.30	76	3370	4300	--	--	--	250	230	190
	15.30	76	3380	4300	9.35	8.20	8.15	240	205	230

Table 1A. Product water rate: Module No. 1
Date: November 11, 1970
Variable Feed Flow: 0.54-1.0 U.S. gpm
Period of sinusoidal flow: 90 seconds

Time (secs)	Cylinder Readings (cc)	Product Rate (cc/15 secs)
0	120	--
15	180	60
30	240	60
45	300	60
60	360	60
75	422	62
90	482	60
105	543	61
120	602	59
135	662	60
150	722	60
165	782	60
180	841	59

Table 1B. Product water rate: Module No. 1
Date: November 12, 1970
Variable Feed Flow: 0.54-1.0 U.S. gpm
Period of Sinusoidal Flow: 90 secs.

Time (secs)	Cylinder Readings (cc)	Product Rate (cc/15 secs)
0	110	--
15	170	60
30	228	58
45	288	60
60	348	60
75	408	60
90	466	58
105	527	61
120	587	60
135	647	60
150	709	62
165	769	60
180	828	59

Table 1C. Product water rate: Module No. 1
Date: November 16, 1970
Variable Feed Flow: 0.54-1.0 U.S. gpm
Period of Sinusoidal Flow: 90 secs.

Time (secs)	Cylinder Readings (cc)	Product Rate (cc/15 secs)
0	220	--
15	275	55
30	330	55
45	385	55
60	438	53
75	493	55
90	548	55
105	603	55
120	656	53
135	711	55
150	768	57
165	823	55
180	878	55

Table 1D. Product water rate: Module No. 2
Date: November 16, 1970
Variable Feed Flow: 0.54 U.S. gpm-1.0 U.S. gpm
Period of Sinusoidal Flow: 90 secs.

Time (secs)	Cylinder Readings (cc)	Product Flow (cc/15 secs)
0	120	--
15	168	48
30	220	52
45	270	50
60	320	50
75	370	50
90	420	50
105	470	50
120	520	50
135	573	53
150	623	50
165	675	52
180	725	50

Table 1E. Product water rate: Module No. 3
Date: November 16, 1970
Variable Feed Flow: 0.54 U.S. gpm-1.0 U.S. gpm
Period of Sinusoidal Flow: 90 secs.

Time (secs)	Cylinder Readings (cc)	Product Flow (cc/15 secs)
0	295	--
15	350	55
30	400	50
45	450	50
60	500	50
75	550	50
90	600	50
105	650	50
120	700	50
135	750	50
150	800	50
165	850	50
180	900	50

Table 2. Test 2: Performance log of reverse osmosis unit.
Variable Feed Flow: 0.60-0.94 U.S. gpm
Inlet Pressure: 615 psi
Outlet Pressure: 600 psi
Period of Sinusoidal Flow: 90 secs.

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 17	21.30	77	3450	4350	--	--	--	360	375	230
Nov. 18	03.30	75	3450	4400	9.20	8.35	8.25	360	280	227
	09.30	76	3450	4330	--	--	--	345	275	230
	15.30	77	3520	4400	9.15	8.33	8.20	325	257	220
	21.30	75	3300	4300	--	--	--	300	257	220
Nov. 19	03.30	76	3450	4350	9.00	8.30	8.10	280	240	210
	09.30	77	3450	4400	--	--	--	265	230	210
	15.30	77	3500	4420	8.70	8.10	8.00	490	600	335
	21.30	75	3350	4310	--	--	--	355	465	230

Table 2. (continued)

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 20	3.30	77	3450	4350	8.8	8.2	7.95	315	370	210
	9.30	76	3400	4200	--	--	--	300	360	212
	15.30	76	3300	4190	8.80	8.4	8.0	265	290	210
	21.30	76	3350	4200	8.70	8.22	8.00	255	262	190
Nov. 21	15.30	76	3350	4190	8.44	7.92	7.75	240	240	180
	21.30	76	3300	4190	8.40	8.0	7.80	230	240	180
Nov. 22	15.30	77	3450	4300	8.30	7.92	7.83	230	260	178
	21.30	75	3400	4220	--	--	--	220	268	170
Nov. 23	3.30	77	3420	4230	8.20	7.90	7.8	220	260	167
	9.30	76	3300	4190	--	--	--	218	245	165
	15.30	77	3450	4300	8.13	7.83	7.75	217	260	167
	21.30	77	3410	4220	--	--	--	218	245	162
Nov. 24	3.30	75	3300	4190	8.10	7.70	7.70	218	220	160
	9.30	77	3450	4300	--	--	--	222	200	170
	15.30	76	3450	4300	7.98	7.68	7.70	222	210	175

Table 2. (continued)

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 24	21.30	77	3390	4200	--	--	--	210	200	170
Nov. 25	3.30	77	3400	4220	7.90	7.60	7.65	210	200	167
	9.30	76	3330	4190	--	--	--	205	190	166
	15.30	75	3450	4330	7.90	7.50	7.62	205	188	170

Table 2A. Product water rate: Module No. 1
Date: November 24, 1970
Variable Feed Flow: 0.60-0.94 U.S. gpm
Period of Sinusoidal Flow: 90 secs.

Time (secs)	Cylinder Readings (cc)	Product Flow (cc/15 secs)
0	150	--
15	200	50
30	245	45
45	290	45
60	335	45
75	380	45
90	425	45
105	470	45
120	515	45
135	560	45
150	608	48
165	650	42
180	695	45

Table 3. Test 3: Performance log of reverse osmosis unit
Steady Feed Flow: 0.77 U.S. gpm
Inlet Pressure: 610 psi
Outlet Pressure: 600 psi

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 26	3.30	76	3400	4250	7.80	7.47	7.60	212	180	168
	9.30	78	3450	4260	7.80	7.40	7.60	213	185	173
	21.30	77	3450	4255	7.7	7.35	7.55	210	185	165
Nov. 27	9.30	76	3400	4200	7.68	7.25	7.52	210	178	168
	15.30	76	3500	4400	7.52	7.22	7.43	202	188	165
	21.30	77	3380	4230	7.60	7.25	7.48	200	178	160

Table 3A. Test 3. Product recovery and salt rejection
Steady Feed Flow: 0.77 U.S. gpm
Inlet Pressure: 610 psi
Outlet Pressure: 600 psi

Date	Time	Feed Temp (^{o}F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Recovery (%)			Salt Rejection (%)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 26	3.30	76	3400	4250	19.2	18.4	18.7	93.9	94.9	95
	9.30	78	3450	4260	19.2	18.2	18.7	94	94.9	95.1
	21.30	77	3450	4255	19.0	18.1	18.6	94	94.9	95.1
Nov. 27	9.30	76	3400	4200	18.8	18.2	18.5	93.9	94.9	95
	15.30	76	3500	4400	18.75	17.9	18.45	94.2	94.8	95.3
	21.30	77	3380	4230	18.55	17.85	18.2	94.2	94.8	95.2

Table 4. Test 4: Performance of log of reverse osmosis unit
Variable Feed Flow: 0.60-0.94 U.S. gpm
Inlet Pressure: 615 psi
Outlet Pressure: 600 psi
Period of Sinusoidal Flow: 90 secs.

Date	Time	Feed Temp (^oF)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 28	1.30	76	3400	4200	7.62	7.32	7.52	194	176	166
	3.30	76	3425	4210	7.60	7.30	7.50	195	180	160
	10.30	77	3400	4208	7.60	7.30	7.50	205	188	160
	13.30	77	3450	4300	7.64	7.32	7.50	212	184	160
	15.30	75	3410	4250	7.63	7.29	7.50	208	188	158
	17.30	76	3450	4320	7.60	7.29	7.50	210	192	160
	19.30	77	3450	4250	7.60	7.29	7.50	208	190	160
	21.30	77	3400	4240	7.58	7.25	7.47	206	182	162
Nov. 29	00.30	76	3380	4210	7.58	7.27	7.47	210	184	157
	3.30	77	3390	4215	7.55	7.23	7.45	205	185	156
	9.30	77	3410	4245	7.55	7.22	7.45	205	180	160
	10.30	75	3400	4240	7.53	7.23	7.44	210	185	155
	11.30	76	3450	4260	7.54	7.22	7.44	210	180	160

Table 5. Test 5: Performance log of reverse osmosis unit
Variable Feed Flow: 0.66-0.88 U.S. gpm
Inlet Pressure: 615 psi
Outlet Pressure: 600 psi
Period of Sinusoidal Flow: 90 secs.

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Nov. 29	21.30	76	3410	4225	7.45	7.18	7.40	210	177	162
Nov. 30	9.30	76	3410	4224	7.45	7.21	7.36	202	172	160
	15.30	76	3450	4300	7.40	7.18	7.34	207	175	160
	21.30	75	3420	4220	--	--	--	212	177	155
Dec. 1	3.30	77	3420	4220	7.35	7.1	7.28	207	177	156
	15.30	77	3450	4220	7.37	7.13	7.32	207	177	158
	21.30	76	3450	4210	7.35	7.1	7.32	210	172	160
Dec. 2	15.30	76	3410	4205	7.24	7.0	7.25	205	172	162
	21.30	77	3420	4200	--	--	--	205	172	160
Dec. 3	3.30	77	3415	4205	7.19	6.96	7.24	203	172	160
	9.30	75	3350	4190	--	--	--	203	170	157
	15.30	76	3500	4310	7.14	6.95	7.21	207	173	159

Table 5. (continued)

Date	Time	Feed Temp (^{o}F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Dec. 4	3.30	77	3420	4219	7.12	6.92	7.19	215	175	156
	15.30	77	3400	4220	7.19	6.99	7.25	210	175	160

Table 6. Test 6: Performance log of reverse osmosis unit.
Variable Feed Flow: 0.60-0.94
Inlet Pressure: 620 psi
Outlet Pressure: 600 psi
Period of Sinusoidal Flow: 60 secs.

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Dec. 4	21.30	76	3430	4220	7.11	6.95	7.21	217	175	160
Dec. 5	3.30	76	3450	4250	7.19	6.97	7.25	235	180	165
	15.30	75	3480	4350	7.14	7.0	7.25	221	201	198
	21.30	76	3290	4180	--	--	--	218	189	172
Dec. 6	1.30	77	3410	4200	7.11	7.0	7.21	212	181	163
	15.30	76	3400	4200	7.08	6.92	7.20	225	180	162
	23.30	77	3412	4220	--	--	--	214	183	158
Dec. 7	3.30	75	3330	4150	7.05	6.9	7.14	220	184	157
	9.30	77	3415	4210	--	--	--	217	177	185
	15.30	77	3470	4290	7.02	6.88	7.16	212	181	177
	22.30	77	3460	4215	--	--	--	215	184	168
Dec. 8	3.30	77	3380	4205	6.98	6.86	7.13	213	178	163
	11.30	77	3465	4245	--	--	--	220	177	164

Table 6. (continued)

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Dec. 8	15.30	77	3450	4225	6.93	6.80	7.08	217	180	162
	21.30	77	3400	4200	--	--	--	216	179	160
Dec. 9	3.30	76	3400	4200	6.84	6.70	6.97	205	177	159
	9.30	76	3375	4100	--	--	--	204	175	160
	15.30	76	3430	4215	6.8	6.68	6.90	211	184	162
	21.30	75	3398	4190	--	--	--	210	184	165
Dec. 10	3.30	76	3430	4200	6.82	6.71	6.97	218	188	166
	9.30	76	3412	4200	--	--	--	210	194	165
	14.30	77	3470	4250	6.82	6.71	6.97	212	191	168

Table 7. Test 7: Performance log of reverse osmosis unit.
Variable Feed Flow: 0.60-0.94 U.S. gpm
Inlet Pressure: 620 psi
Outlet Pressure: 600 psi
Period of Sinusoidal Flow: 30 secs.

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Dec. 10	21.30	75	3410	4190	6.7	6.7	6.9	207	187	164
Dec. 11	3.30	75	3400	4140	6.7	6.62	6.9	212	187	163
	9.30	75	3360	4103	--	--	--	206	184	161
	15.30	75	3390	4110	6.7	6.62	6.87	210	195	164
	21.30	75	3350	4070	6.7	6.60	6.87	206	182	163
Dec. 12	12.30	76	3450	4195	--	--	--	208	191	168
	15.30	77	3450	4195	6.7	6.58	6.86	208	187	167
	21.30	75	3290	4030	6.7	6.58	6.84	210	187	164
Dec. 13	12.30	75	3400	4103	--	--	--	210	188	167
	15.30	75	3390	4072	6.7	6.57	6.84	210	183	165
	21.30	75	3345	4120	--	--	--	238	185	173
Dec. 14	03.30	75	3380	4100	6.66	6.50	6.8	245	186	171

Table 7. (continued)

Date	Time	Feed Temp (^{o}F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Dec. 14	09.30	75	3390	4100	--	--	--	240	187	168
	15.30	75	3360	4100	6.68	6.53	6.8	221	189	168
	23.30	77	3470	4230	--	--	--	219	195	171
Dec. 15	03.30	76	3390	4140	6.71	6.58	6.84	207	193	166
	09.30	76	3400	4150	--	--	--	202	194	166
	15.30	75	3300	4060	6.73	6.62	6.87	195	190	165
	21.30	75	3360	4103	--	--	--	216	195	167
Dec. 16	03.30	75	3360	4100	6.77	6.66	6.90	205	193	170
	09.30	76	3475	4220	--	--	--	210	200	172
	14.30	76	3360	4160	6.8	6.68	6.95	207	196	172

Table 8. Test 8: Performance log of reverse osmosis unit.
Variable Feed Flow: 0.36-0.70 U.S. gpm
Inlet Pressure: 615 psi
Outlet Pressure: 600 psi
Period of Sinusoidal Flow: 30 secs.

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Dec. 16	17.30	77	3425	4510	6.7	6.61	6.84	225	210	188
	19.30	74	3300	4408	6.67	6.67	6.86	219	208	184
	21.30	75	3375	4430	6.64	6.62	6.84	226	210	185
	23.30	77	3410	4505	6.69	6.63	6.86	227	215	187
Dec. 17	01.30	74	3300	4435	6.68	6.63	6.88	226	215	186
	03.30	75	3310	4440	6.66	6.62	6.84	226	214	186
	09.30	77	3475	4530	6.73	6.62	6.90	228	209	188
	13.30	75	3390	4440	6.7	6.62	6.87	226	207	187
	15.30	76	3395	4540	6.7	6.62	6.88	242	206	190
	17.30	75	3396	4530	6.7	6.62	6.87	250	210	190
	19.30	75	3350	4505	6.7	6.61	6.87	248	215	193
	23.30	75	3400	4440	6.68	6.61	6.87	242	210	191

Table 8. (continued)

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Dec. 18	01.30	75	3420	4500	6.68	6.59	6.86	246	214	194
	03.30	77	3412	4495	6.7	6.59	6.87	246	218	195
	09.30	77	3500	4560	6.66	6.57	6.84	246	236	196
	11.30	75	3373	4505	6.62	6.50	6.80	241	240	195
	14.30	77	3380	4508	6.60	6.52	6.78	243	238	194

Table 9. Test 9: Performance log of reverse osmosis unit.
Variable Feed Flow: 0.53-0.87 U.S. gpm
Outlet Pressure: 600 psi
Inlet Pressure: 620 psi
Period of Sinusoidal Flow: 30 secs.

Date	Time	Feed Temp (°F)	Feed Salinity (ppm)	Reject Brine Salinity (ppm)	Product Flux (gfd)			Product Salinity (ppm)		
					Mod. 1	Mod. 2	Mod. 3	Mod. 1	Mod. 2	Mod. 3
Dec. 18	17.30	75	3410	4245	6.68	6.49	6.74	225	205	181
	21.30	76	3412	4265	6.62	6.56	6.84	221	202	195
	23.30	76	3405	4245	6.59	6.53	6.80	222	203	184
Dec. 19	01.30	75	3400	4240	6.59	6.53	6.80	221	204	185
	14.30	75	3395	4235	6.60	6.53	6.80	221	205	183
	16.30	75	3400	4210	6.59	6.52	6.79	220	200	184
	17.30	77	3410	4250	6.60	6.53	6.80	218	202	185
	19.30	75	3450	4320	6.60	6.53	6.80	225	203	188
	23.30	77	3485	4270	6.60	6.53	6.80	221	208	187

Fig. 4: PICTORIAL DESCRIPTION OF TEST SERIES.

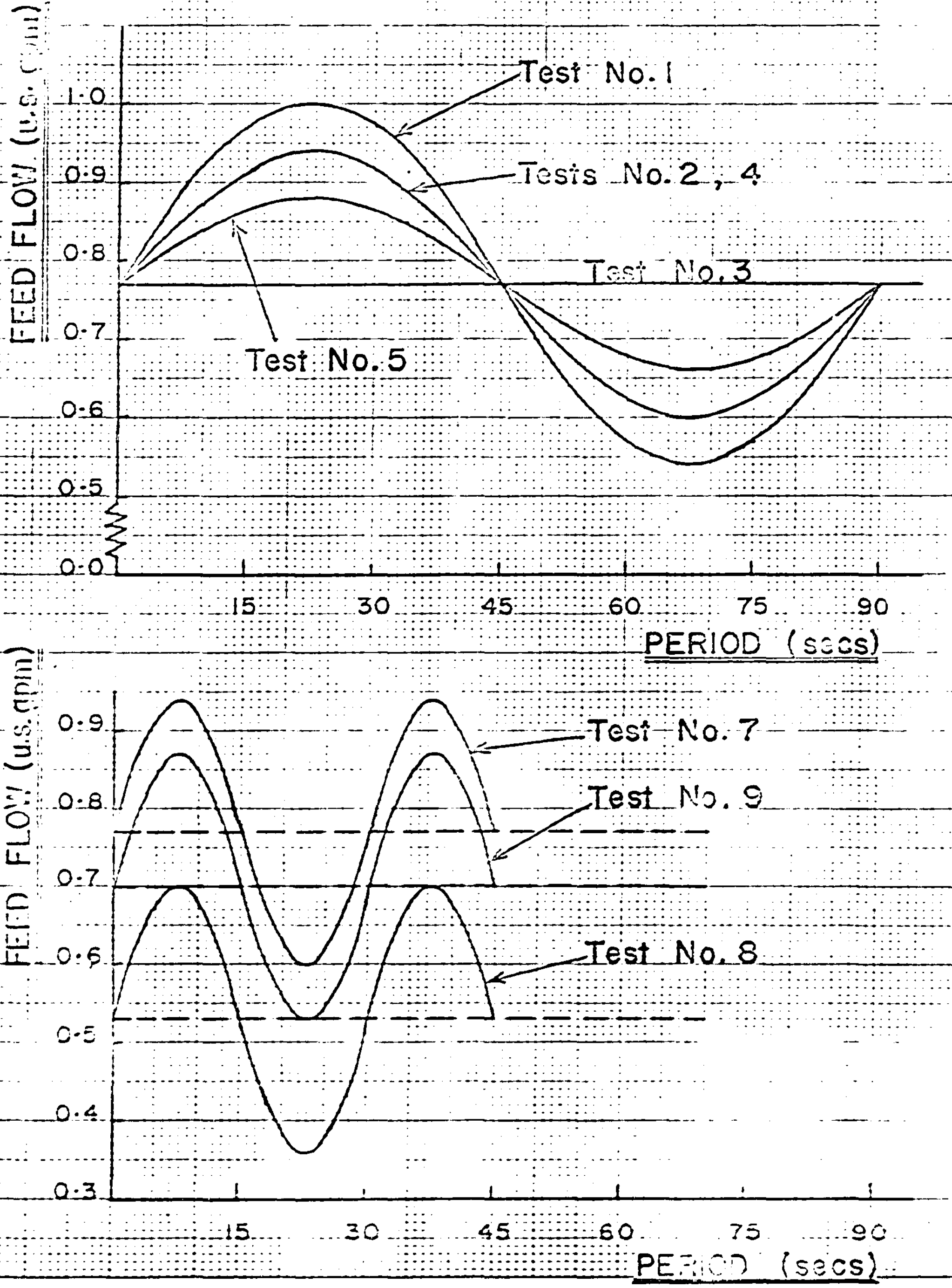


Fig. 5: PICTORIAL DESCRIPTION OF TEST SERIES

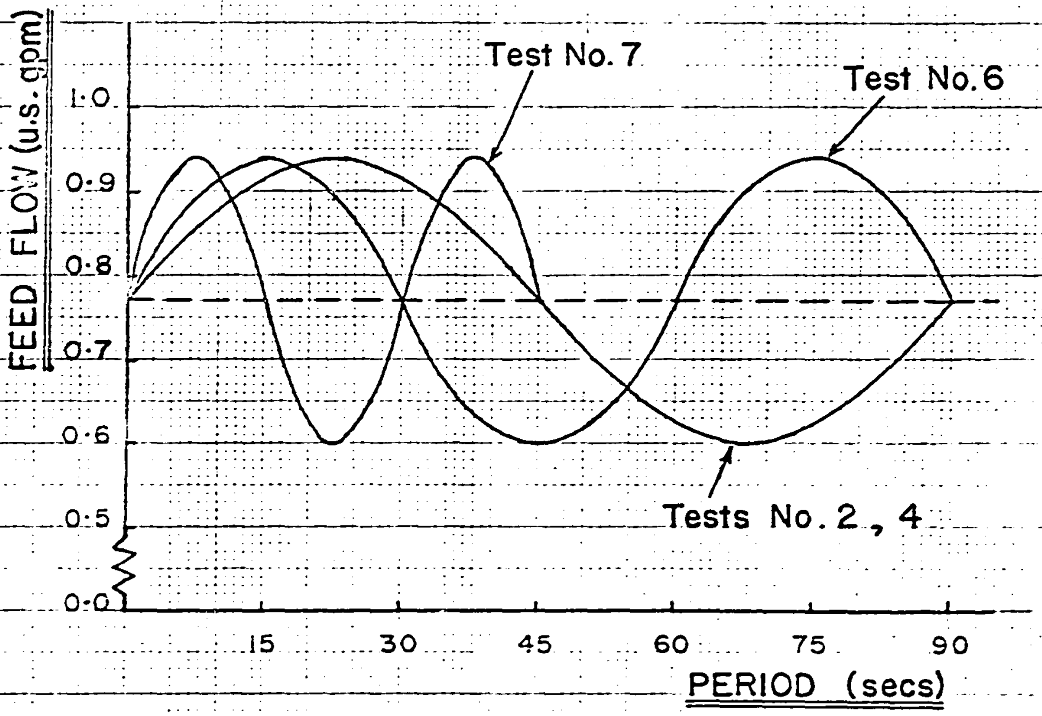
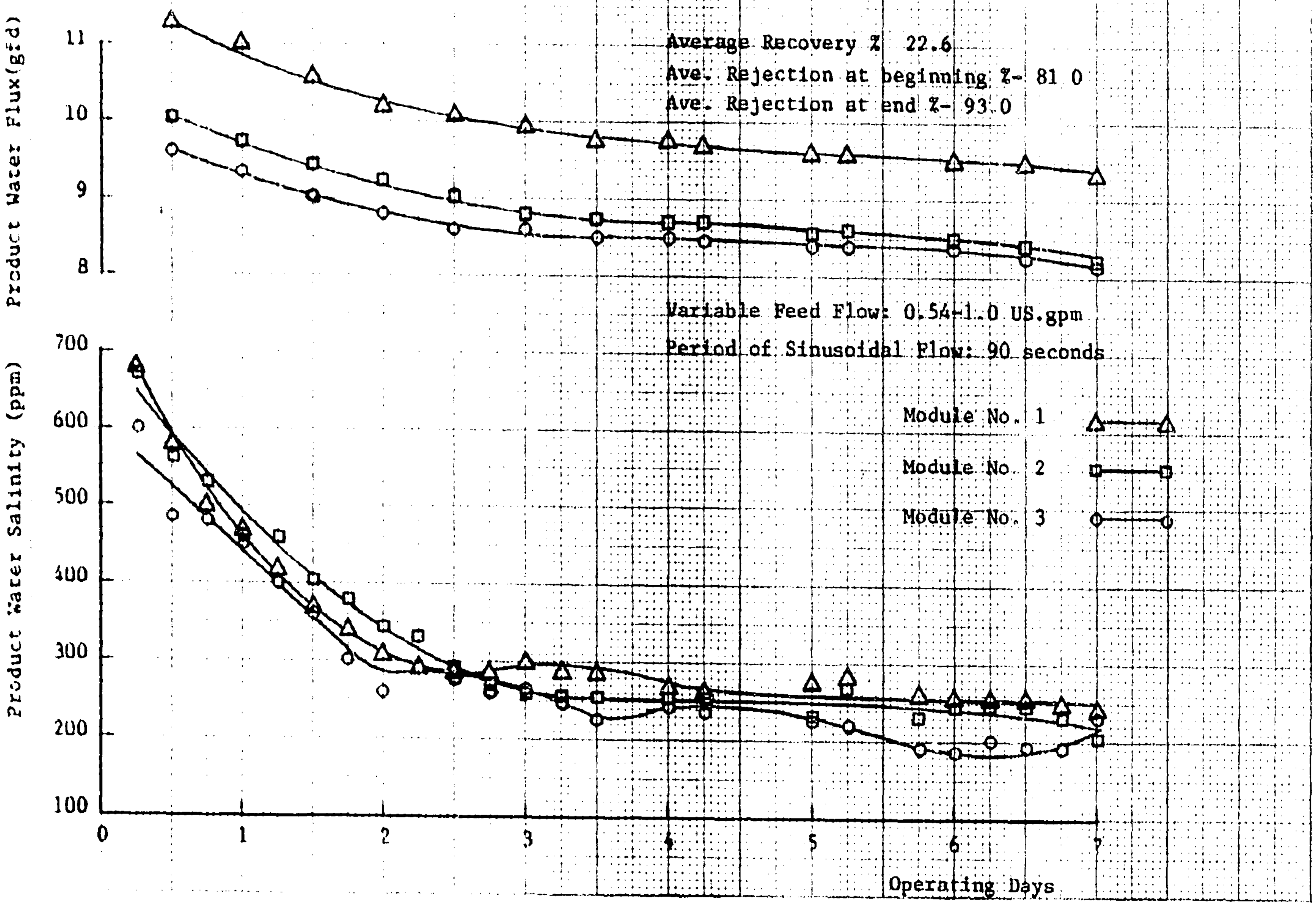


Fig. 6: Product Salinity, Flux v/s Time (Test No.1)



Average Recovery % 22.6

Ave. Rejection at beginning %- 81.0

Ave. Rejection at end %- 93.0

Variable Feed Flow: 0.54-1.0 US.gpm

Period of Sinusoidal Flow: 90 seconds

Fig. 7: Product Salinity, Flux v/s Time (Test No.2)

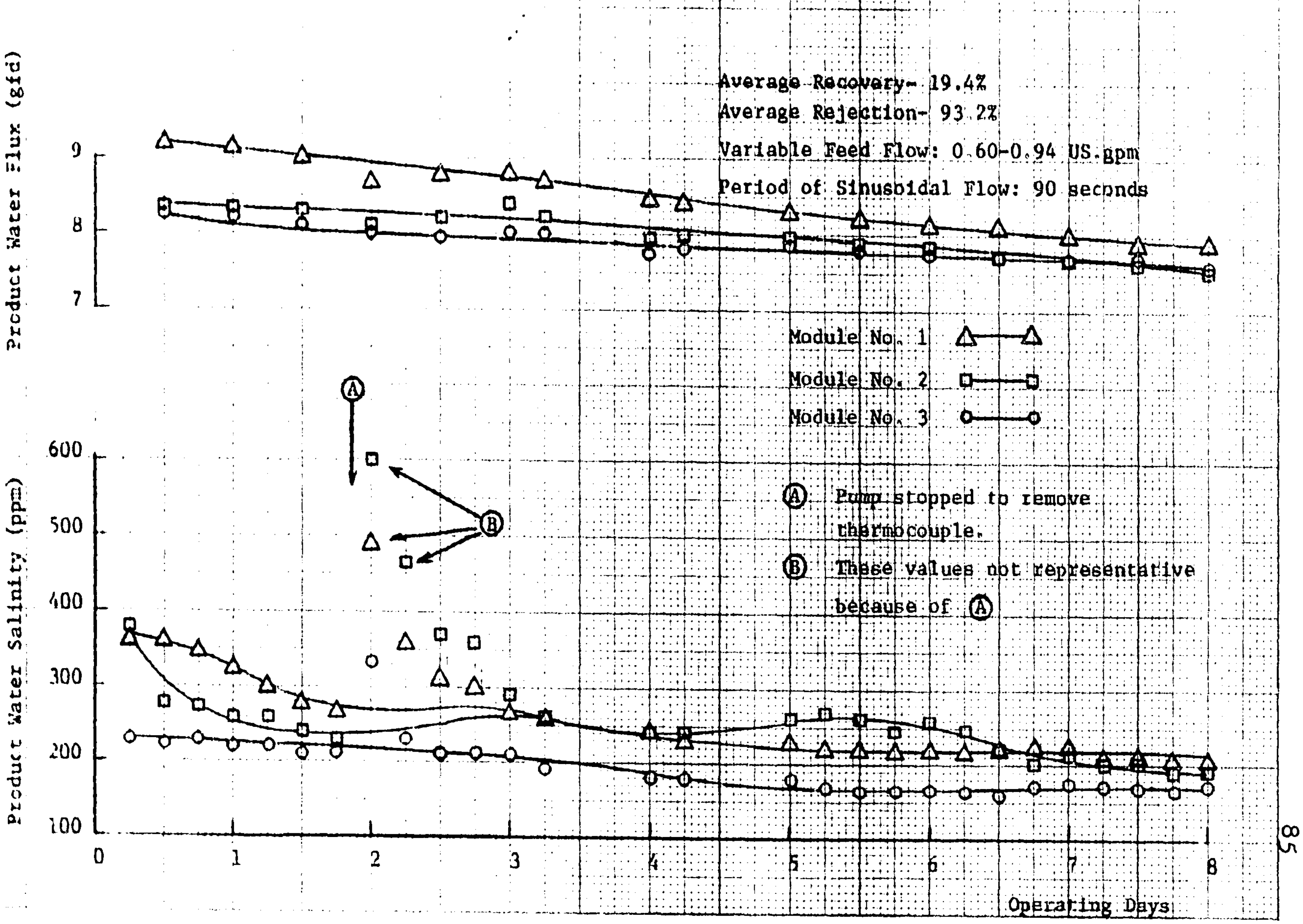


Fig. 8: Product Salinity, Flux v/s Time (Test No.3)

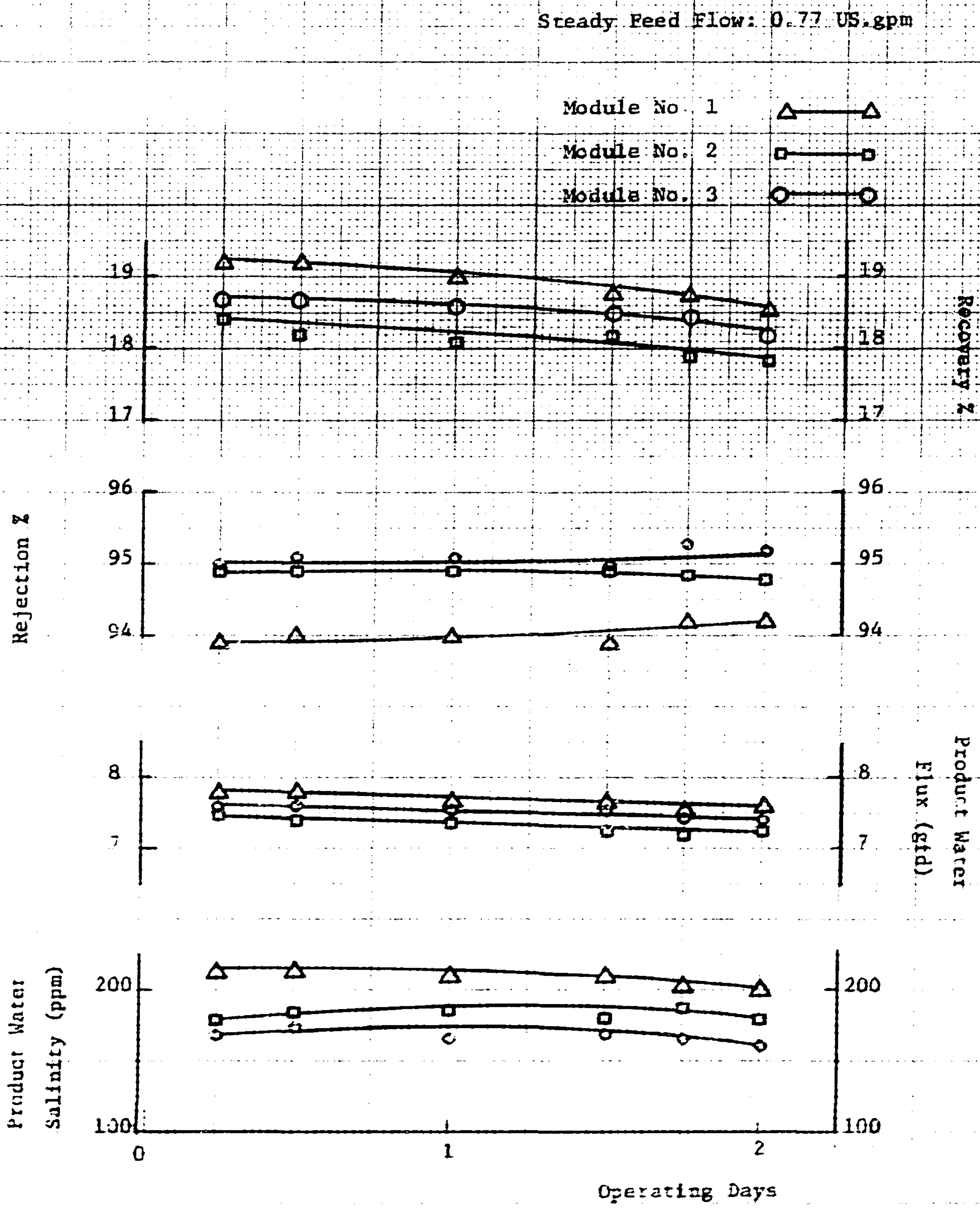
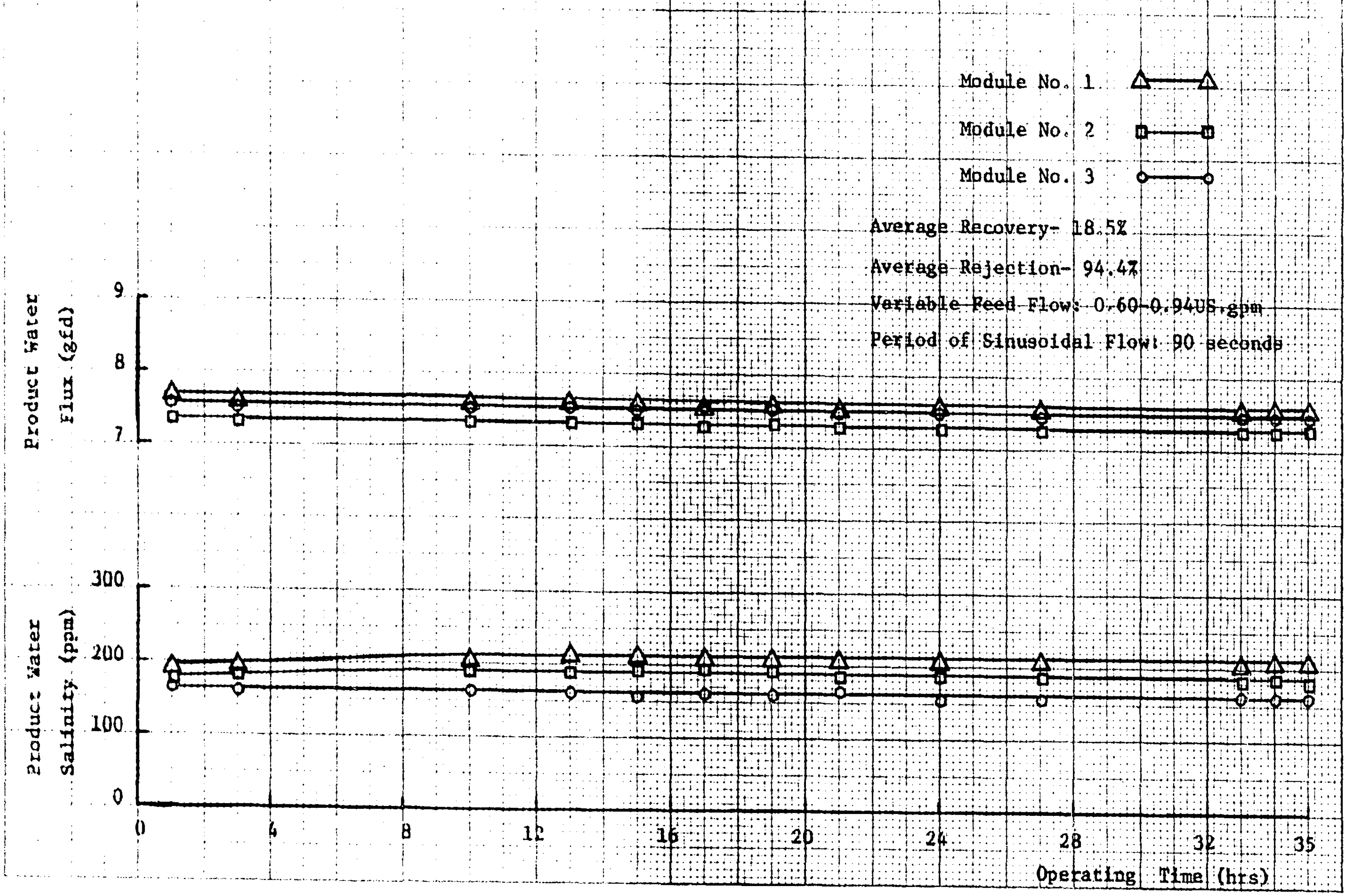


Fig. 9: Product Salinity, Flux v/s Time (Test No.4)



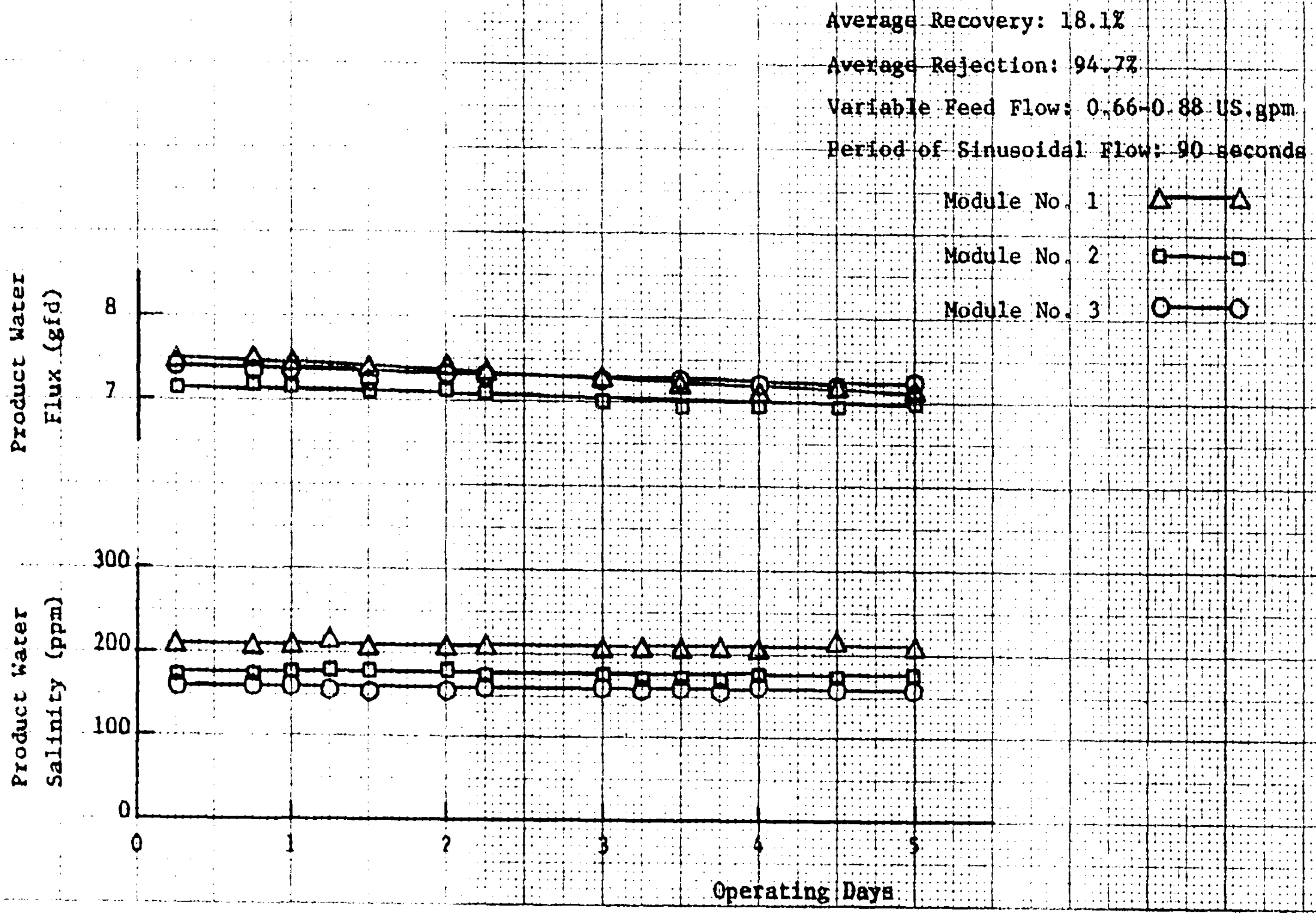
Average Recovery- 18.5%

Average Rejection- 94.4%

Variable Feed Flow: 0.60-0.94US.gpm

Period of Sinusoidal Flow: 90 seconds

Fig. 10: Product Salinity, Flux v/s Time (Test No.5)



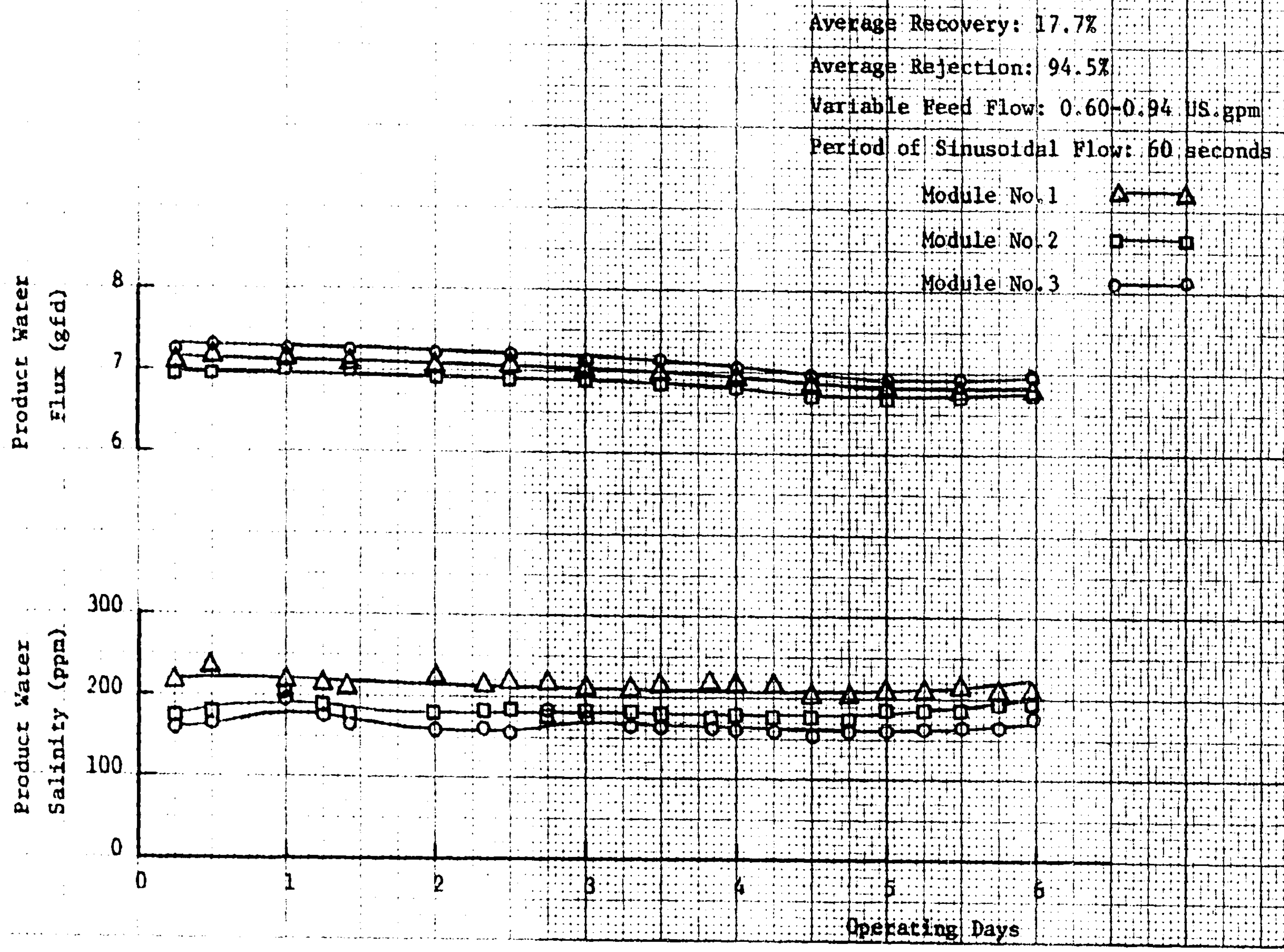
Average Recovery: 18.1%

Average Rejection: 94.7%

Variable Feed Flow: 0.66-0.88 US.gpm

Period of Sinusoidal Flow: 90 seconds

Fig. 11: Product Salinity, Flux v/s Time (Test No.6)



Average Recovery: 17.7%

Average Rejection: 94.5%

Variable Feed Flow: 0.60-0.94 US.gpm

Period of Sinusoidal Flow: 60 seconds

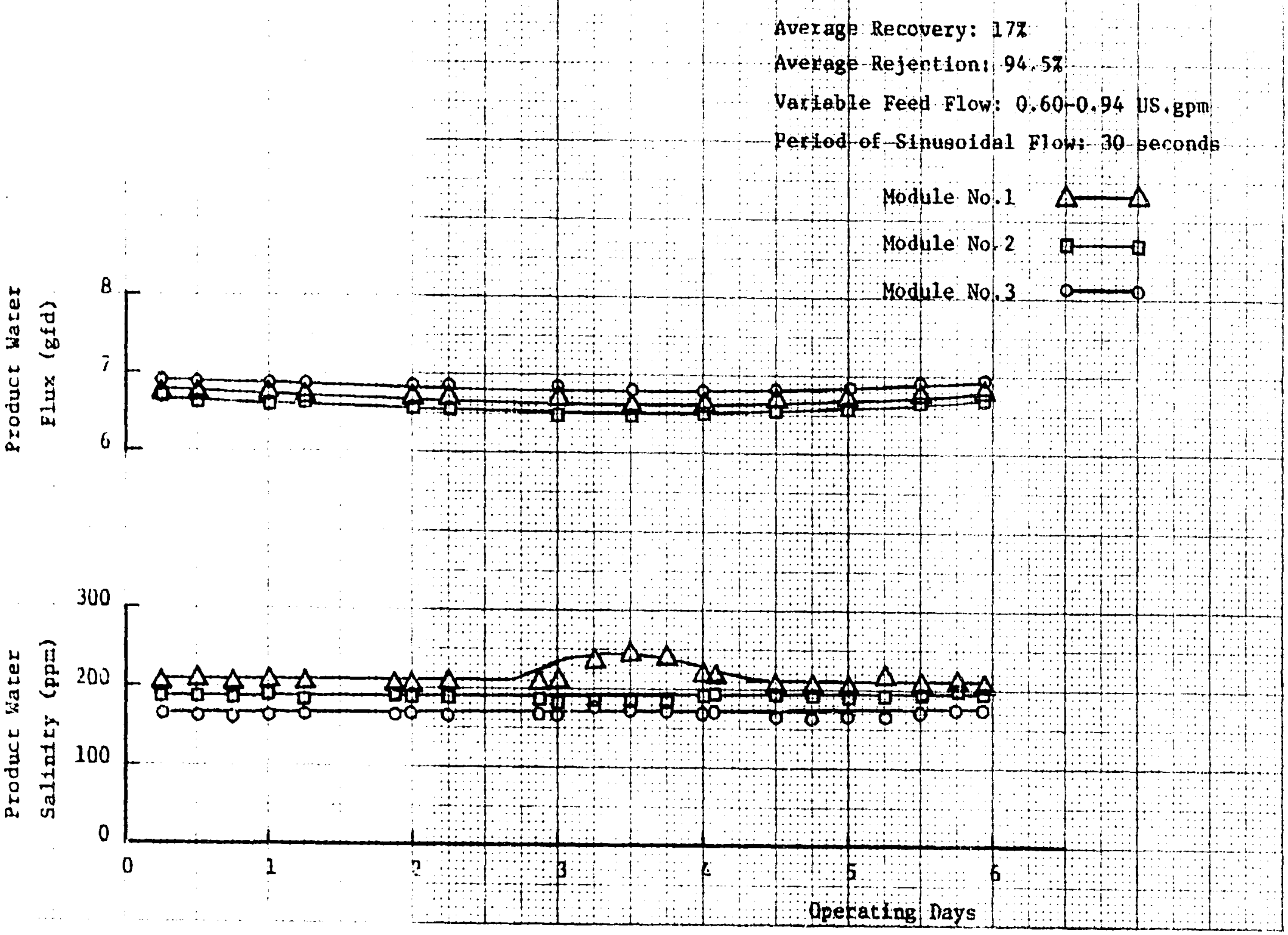
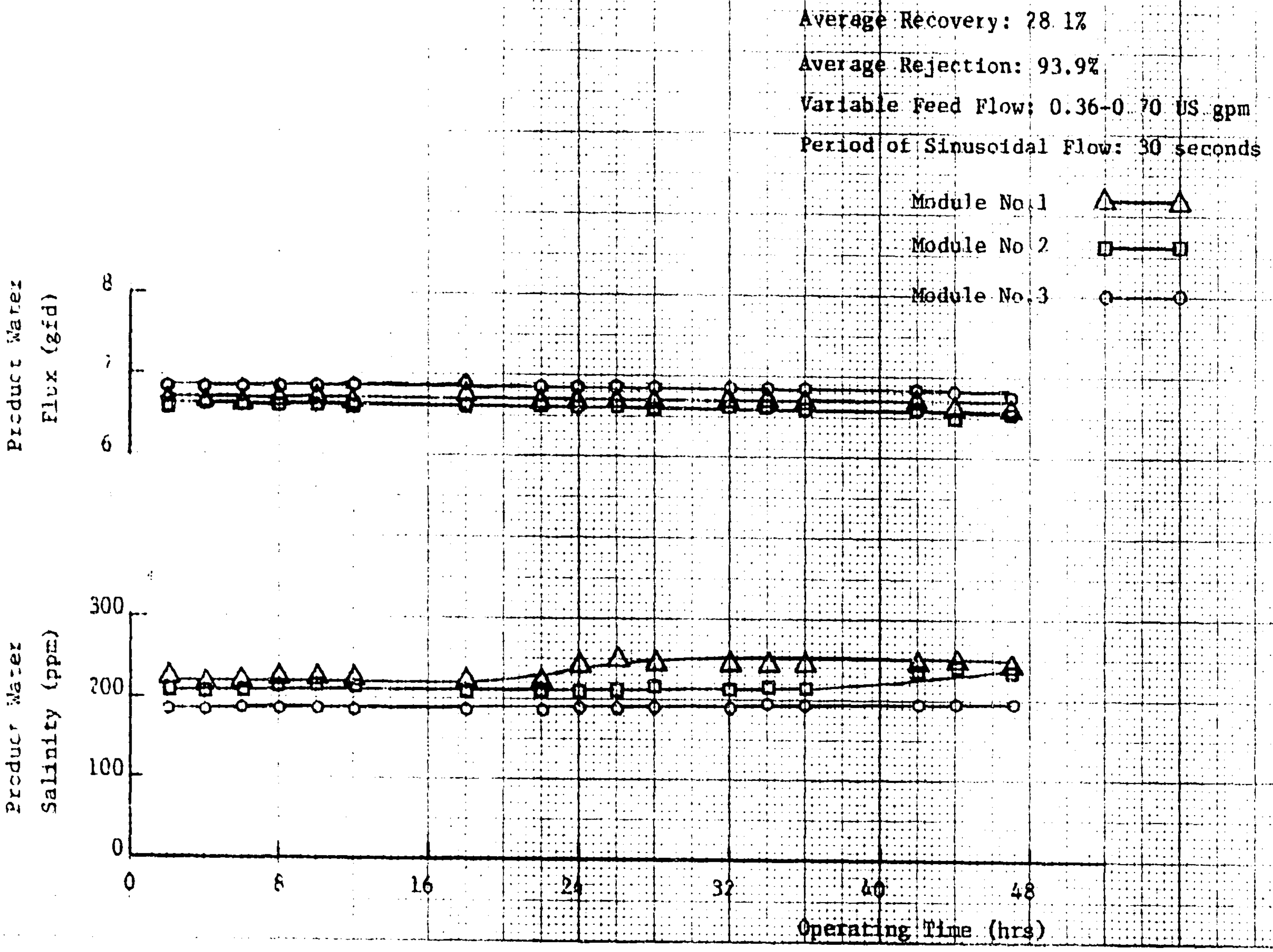


Fig 12: Product Salinity, Flux v/s Time (Test No.7)

Fig. 13: Product Salinity, Flux v/s Time (Test No.8)



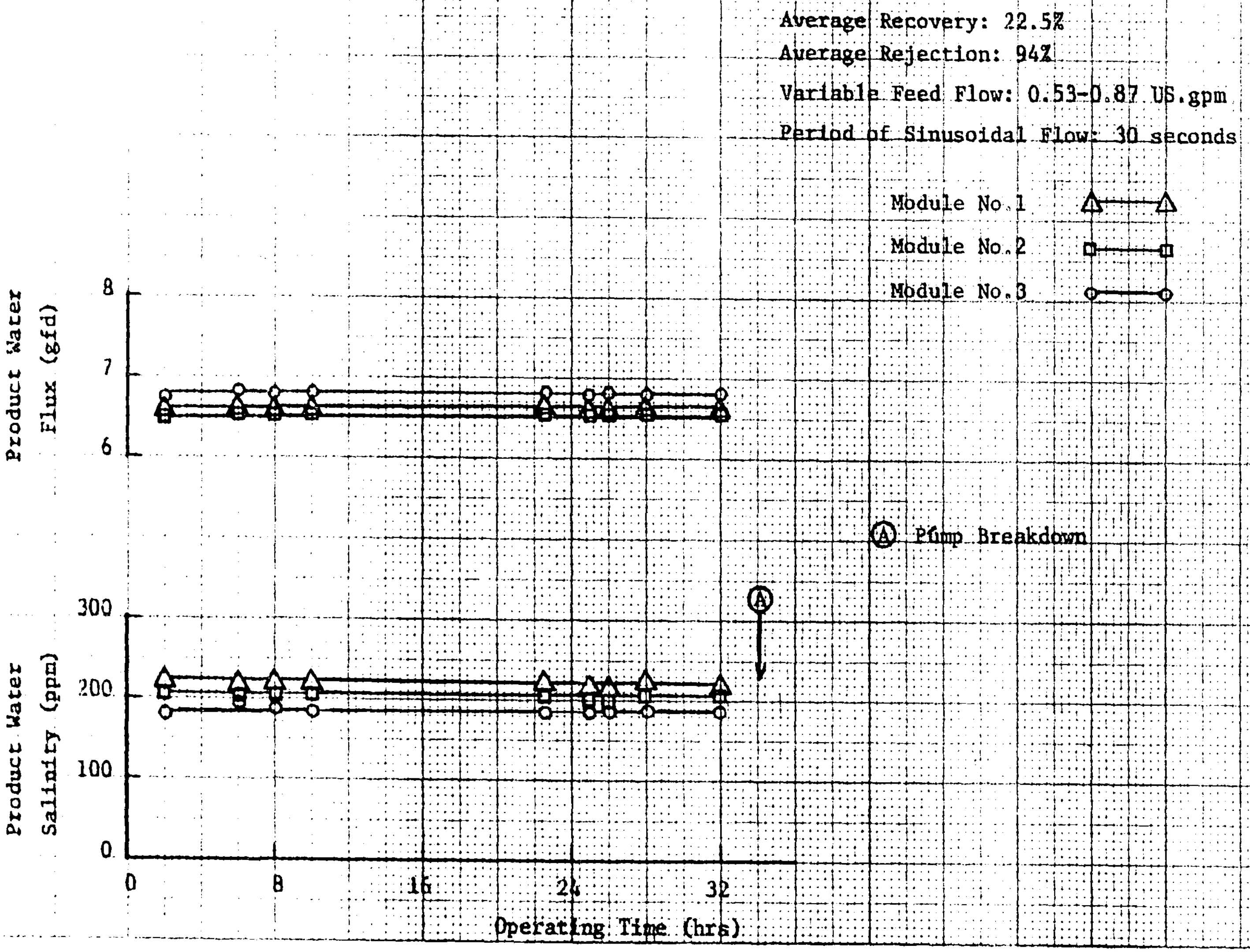
Average Recovery: 28.1%

Average Rejection: 93.9%

Variable Feed Flow: 0.36-0.70 US gpm

Period of Sinusoidal Flow: 30 seconds

Fig. 14: Product Salinity, Flux v/s Time (Test No.9)



Average Recovery: 22.5%
Average Rejection: 94%
Variable Feed Flow: 0.53-0.87 US.gpm
Period of Sinusoidal Flow: 30 seconds

Fig. 15: FLOW DIAGRAM OF REVERSE OSMOSIS UNIT

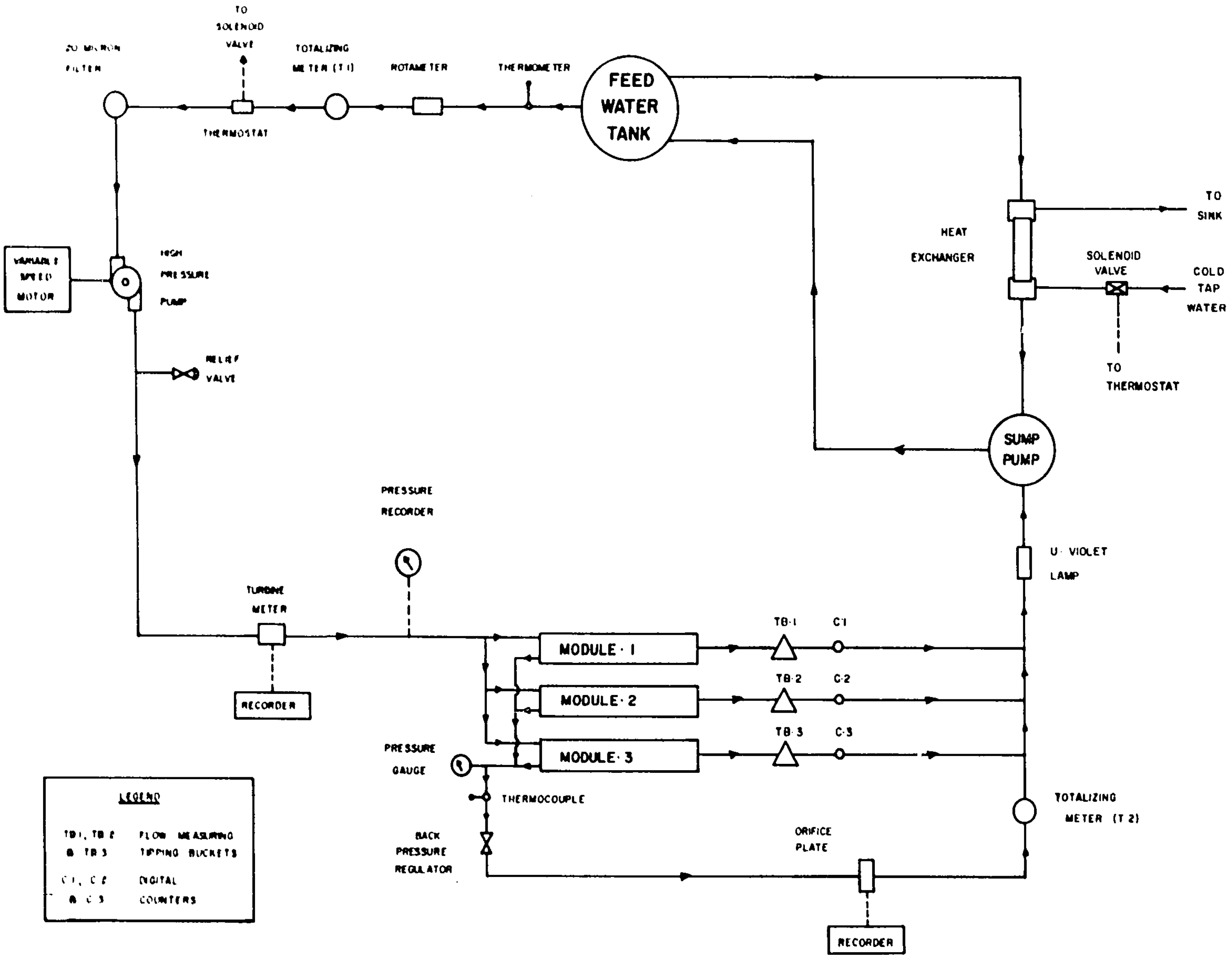
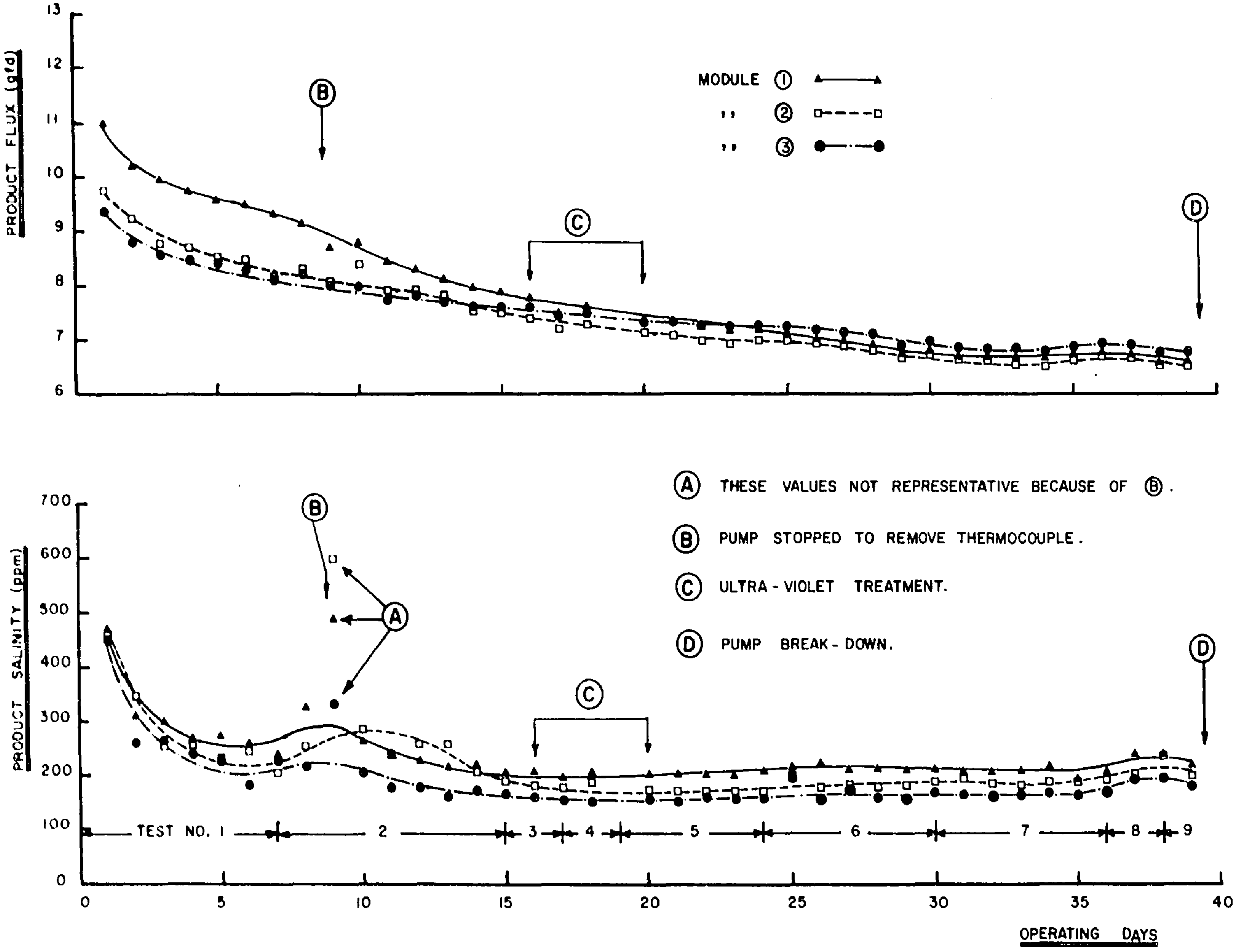


Fig. 16: PERFORMANCE OF REVERSE OSMOSIS UNIT (10-11-70 to 20-12-70)



Ⓐ THESE VALUES NOT REPRESENTATIVE BECAUSE OF Ⓑ.

Ⓑ PUMP STOPPED TO REMOVE THERMOCOUPLE.

Ⓒ ULTRA - VIOLET TREATMENT.

Ⓓ PUMP BREAK - DOWN.

Fig. 17 Valve Assembly, Pressure Recorder and Feed Flow Recorder

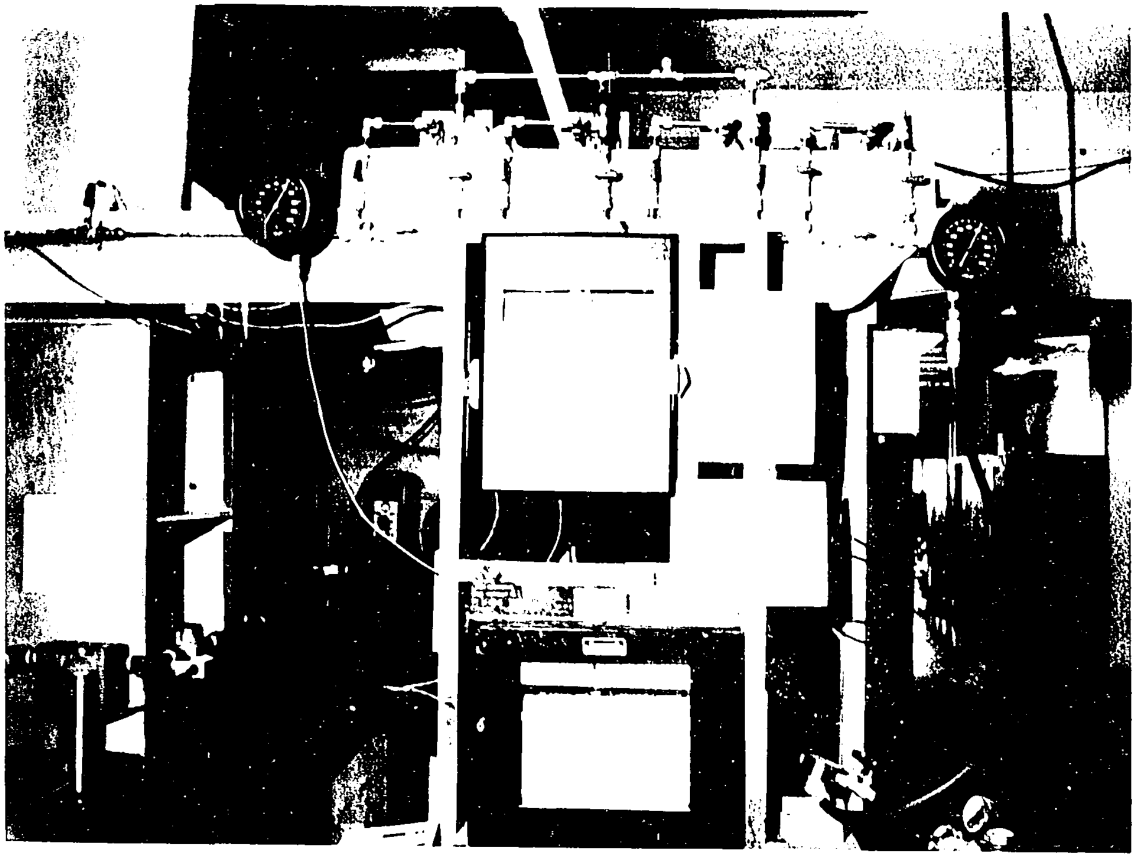


Fig. 18: Product water measurement

(a) Water manifold

(b) Water outlet system

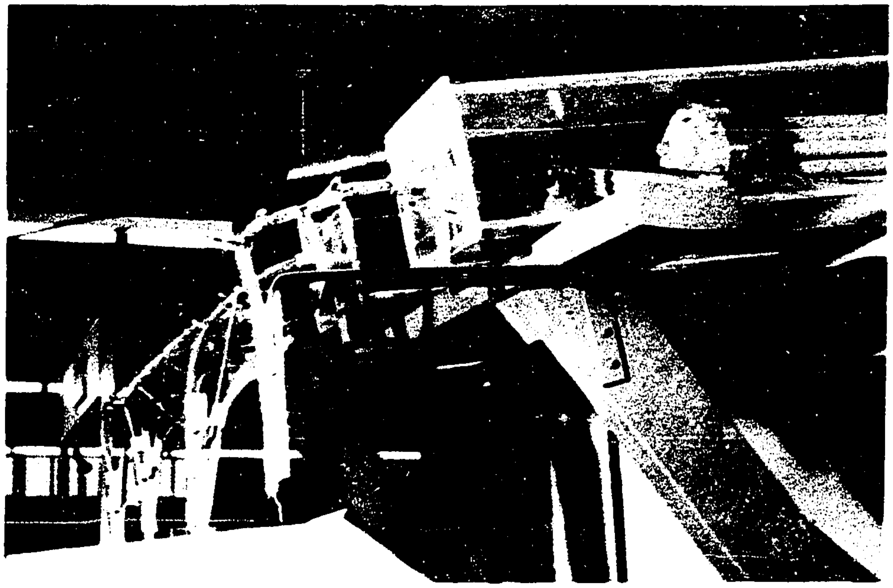
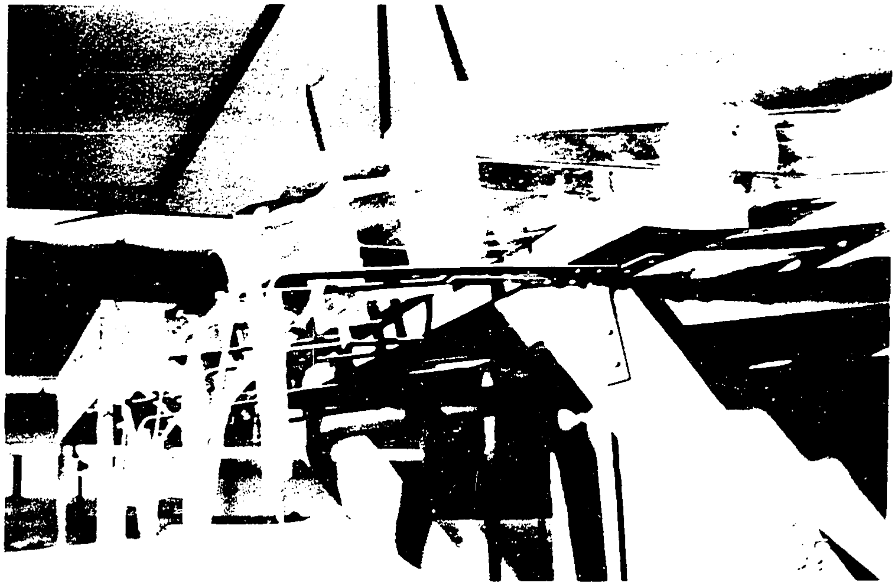


Fig. 18: Product water measurement

(a) Water manifold

(b) Water outlet system



VARIABLE FLOW ADJUSTING MECHANISM

Fig. 19

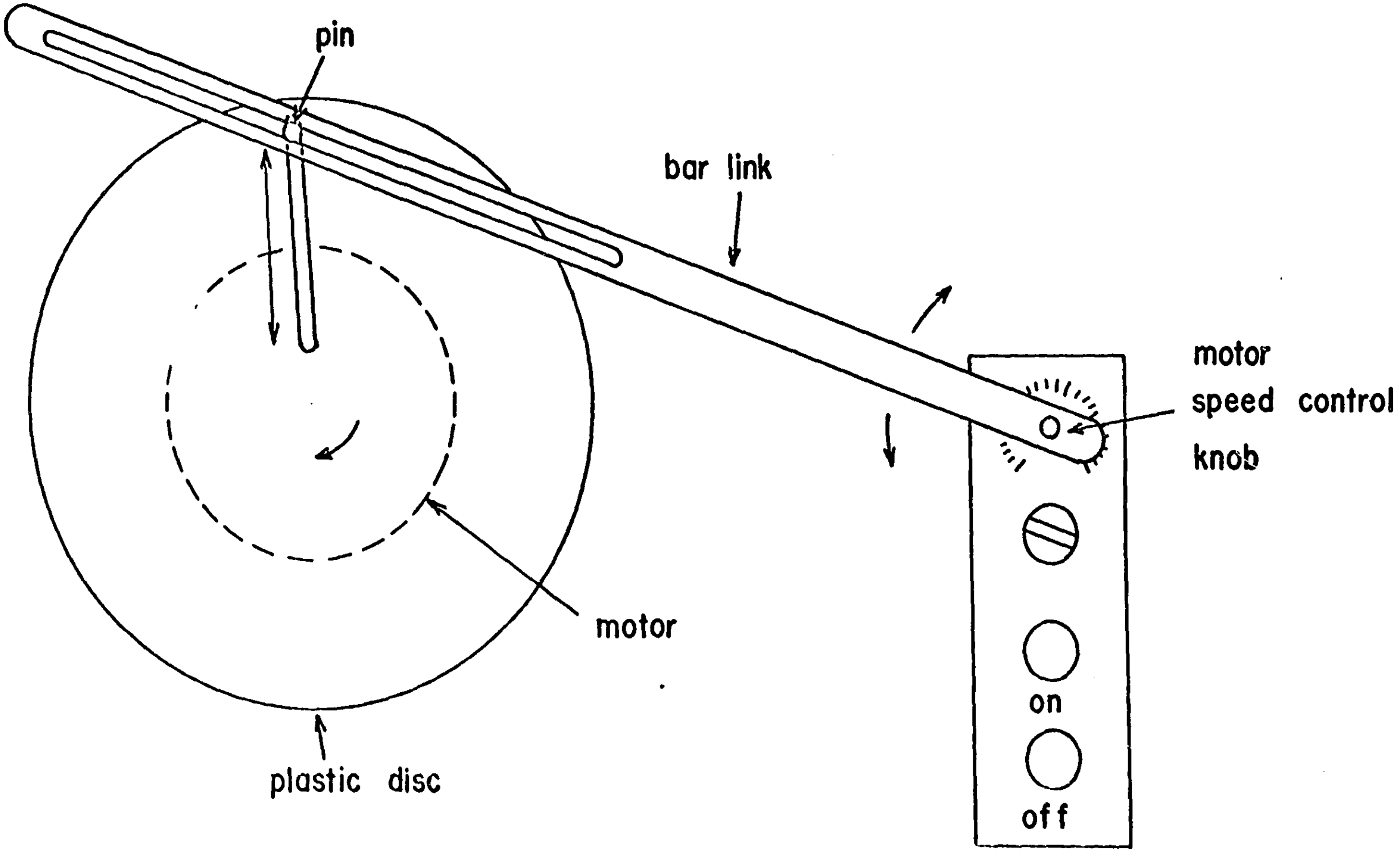


Fig. 20: Feed water tank and heat exchanger

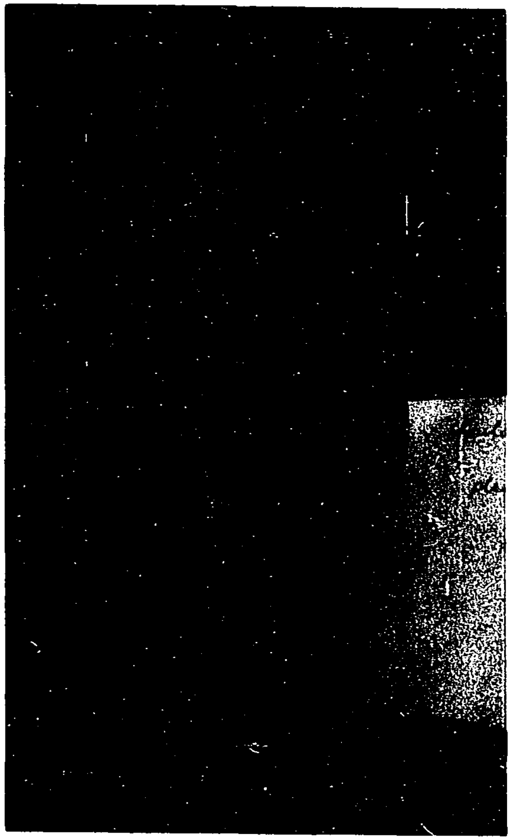


Fig. 21: Variable flow adjusting mechanism

[illegible] water tank and
[illegible]

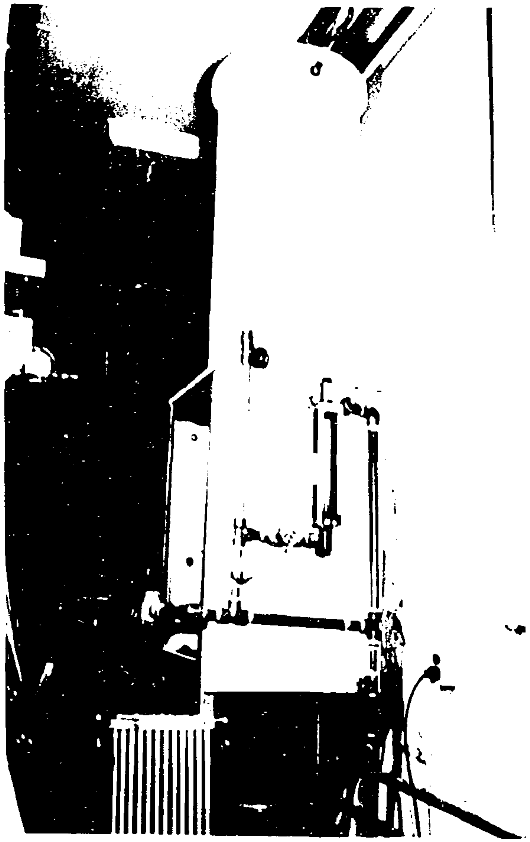
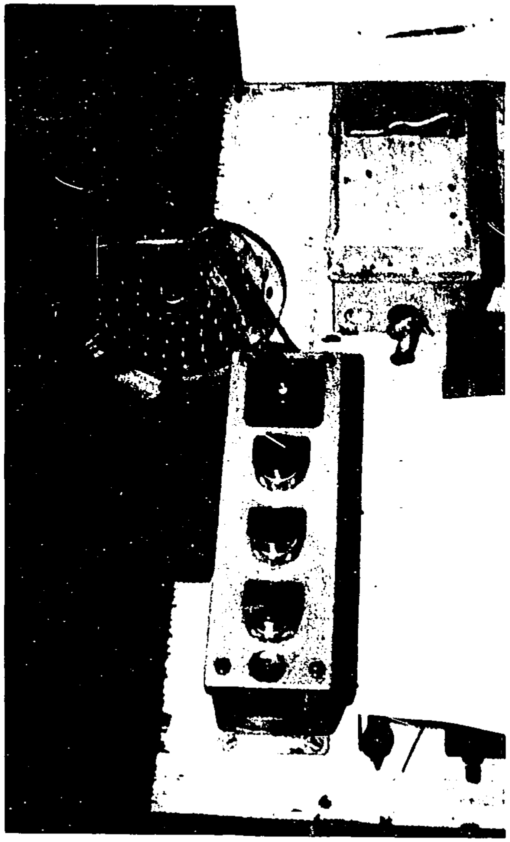
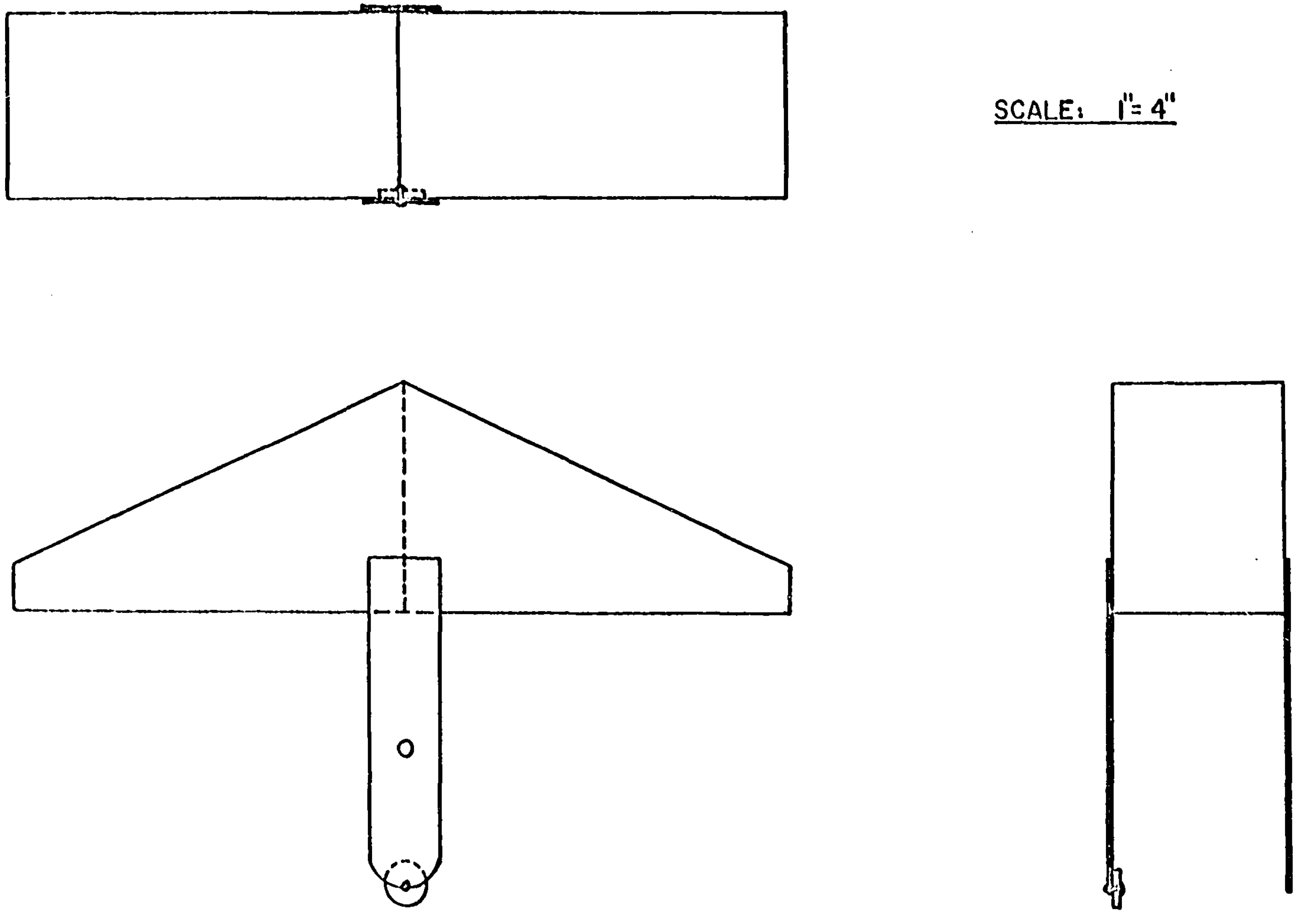


Fig. 21: Variable flow
adjusting mechanism



FLOW MEASURING TIPPING BUCKET Fig. 22



SCALE: 1" = 4"

Fig. 23: Orifice plate

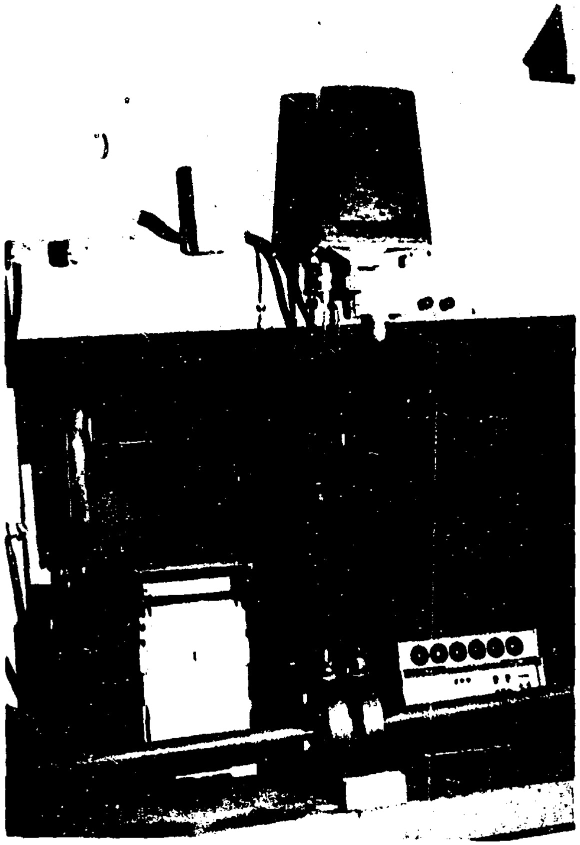


Fig. 24: Tipping bucket assembly

[illegible]

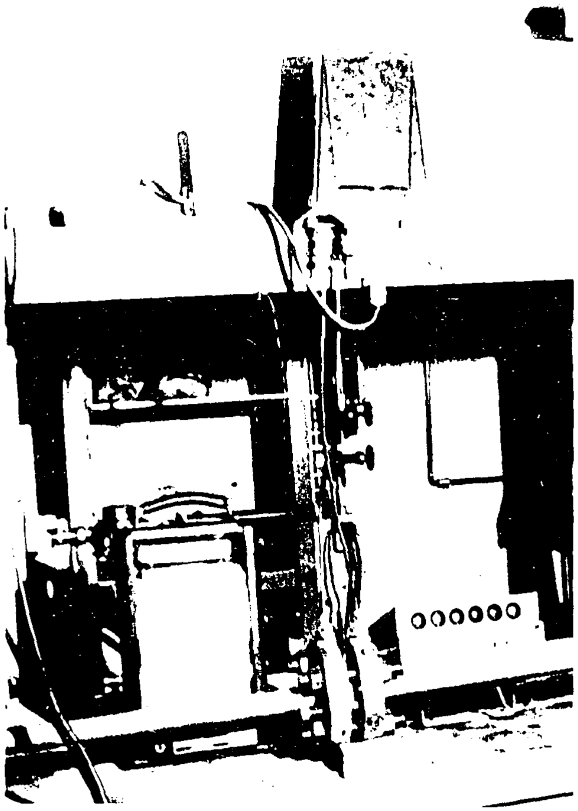


Fig. 24: Tipping bucket assembly

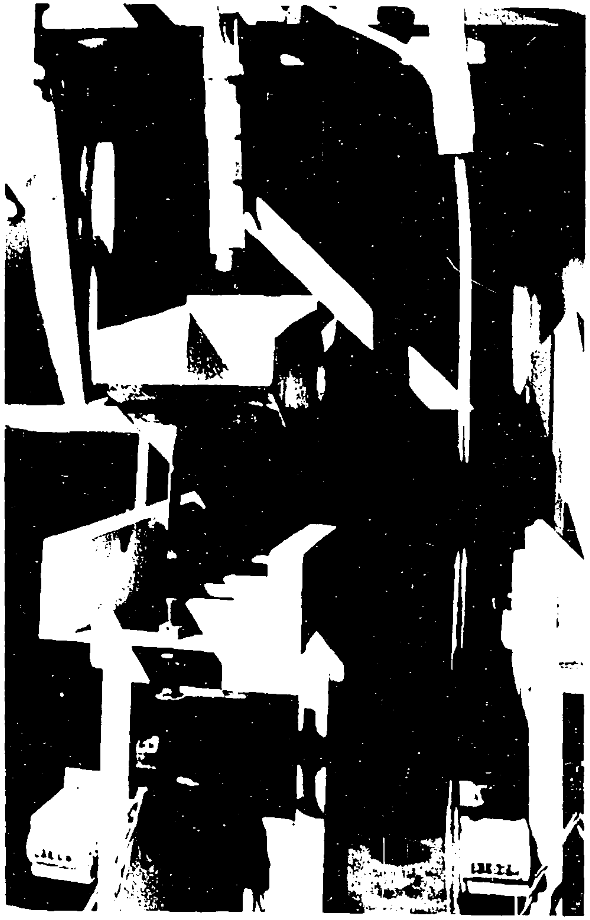


Fig. 25: TUBULAR MODULE

(NOT TO SCALE)

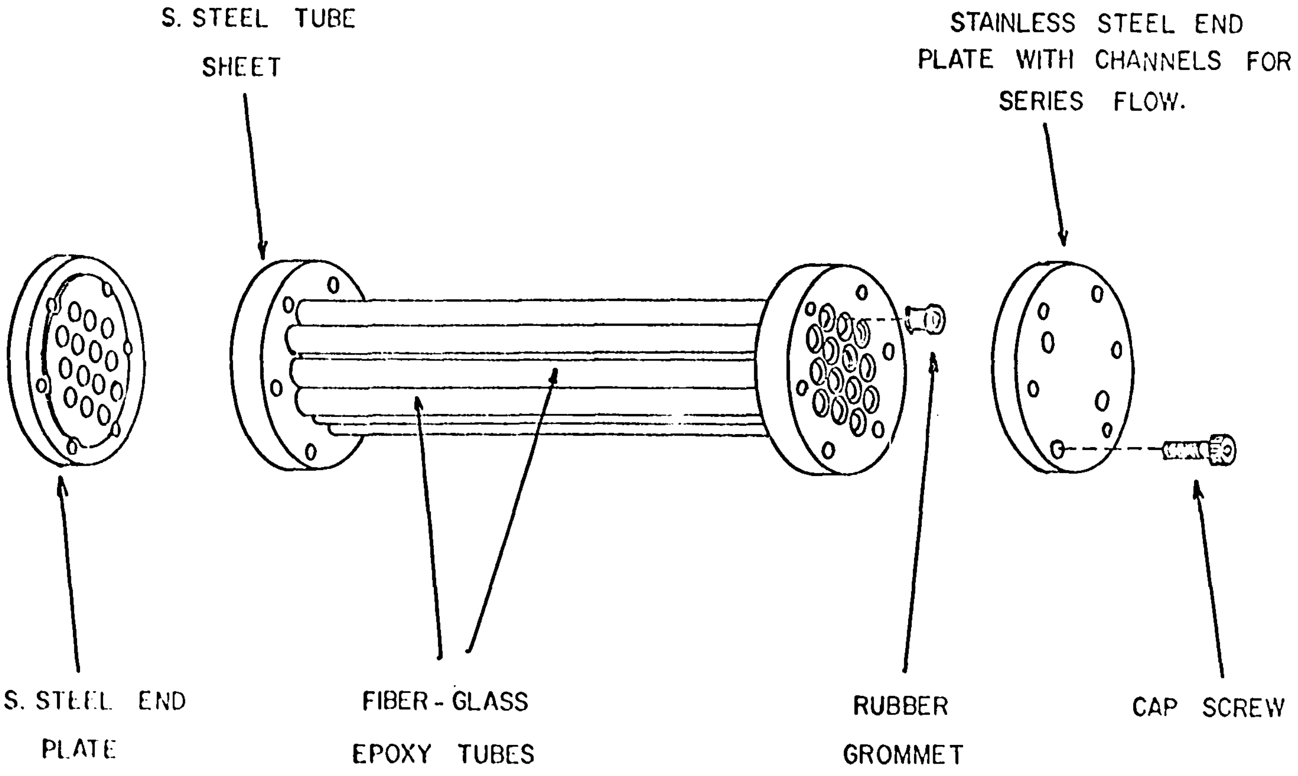


Fig. 26: Reverse Osmosis Module

Fig. 27: Back pressure regulator

Fig. 28: Ultra-violet lamp

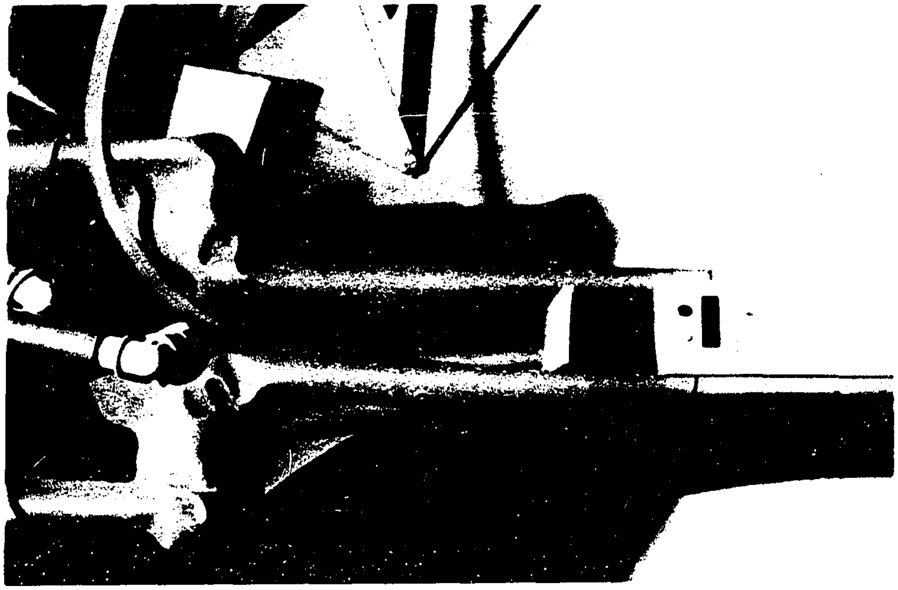


Fig. 27: Back pressure regulator

Fig. 28: Ultra-violet lamp

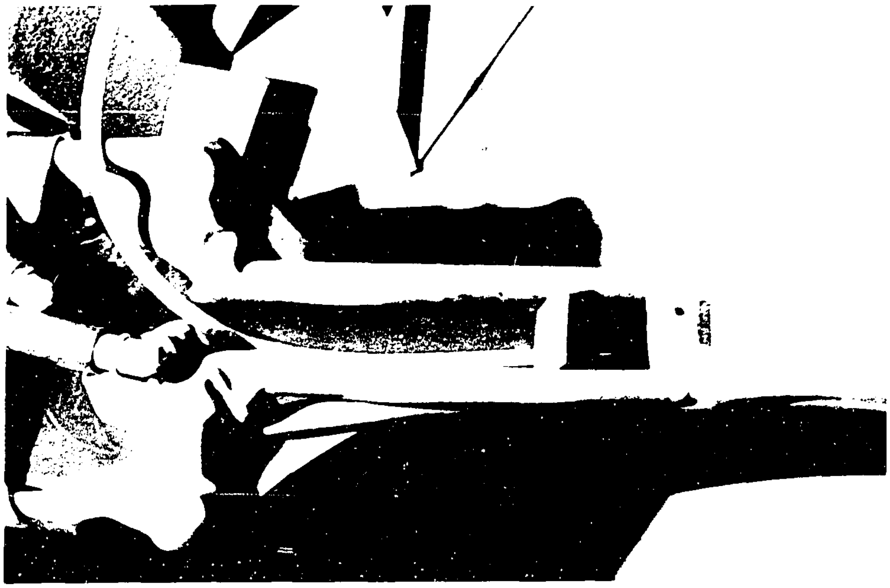


Fig. 29: Pump-motor assembly

Fig. 30: Pump rpm recorder

Fig. 29: Pump-motor assembly

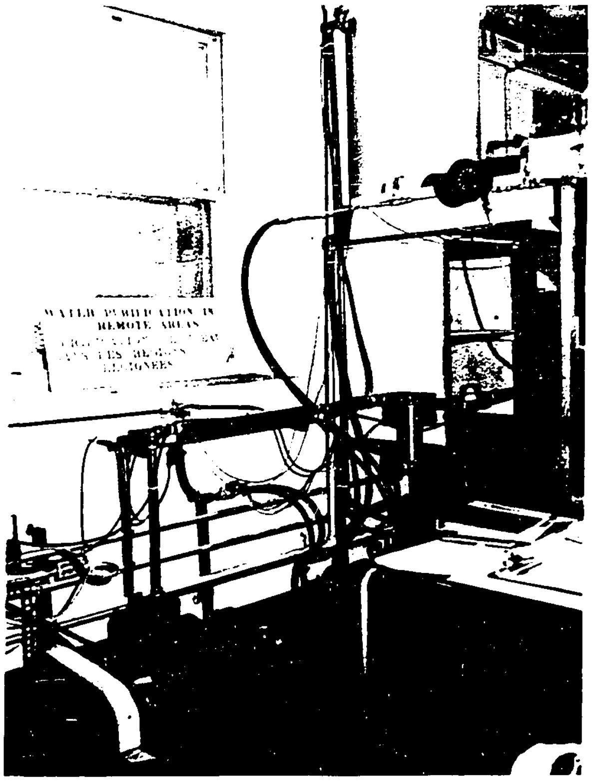


Fig. 30: Pump rpm recorder

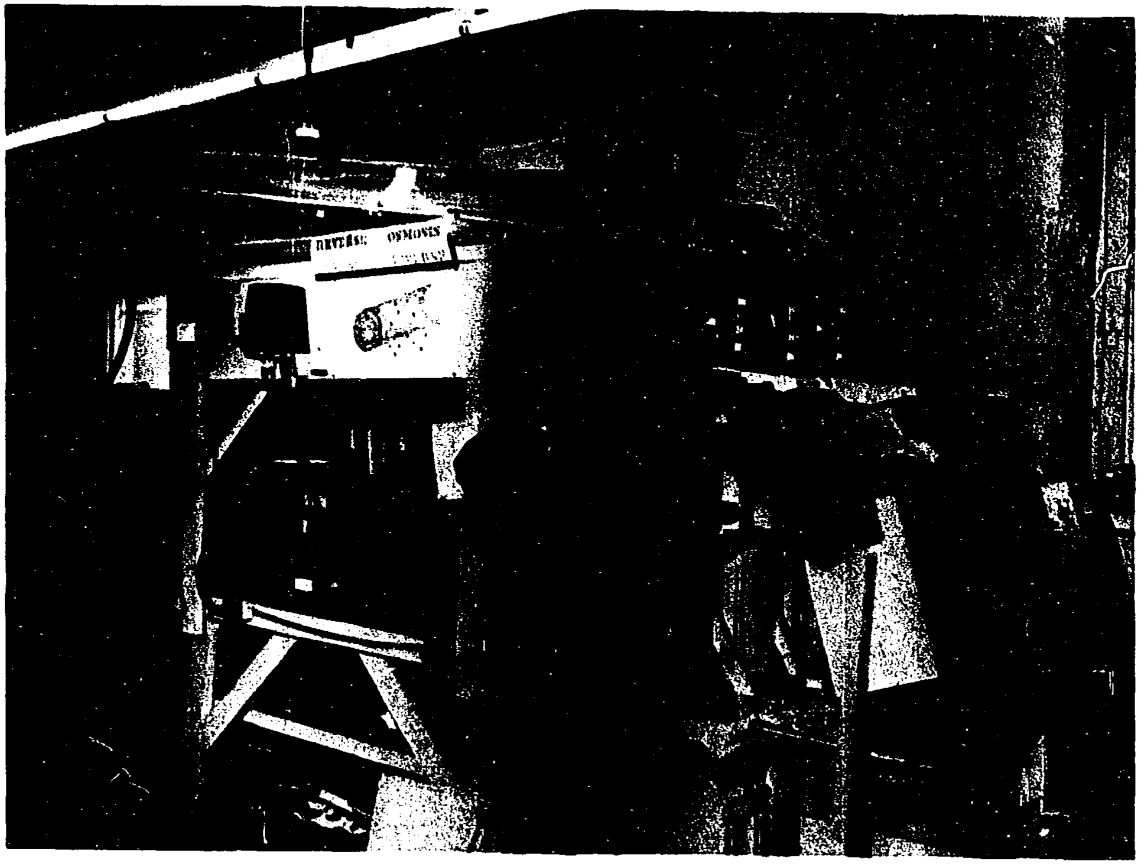
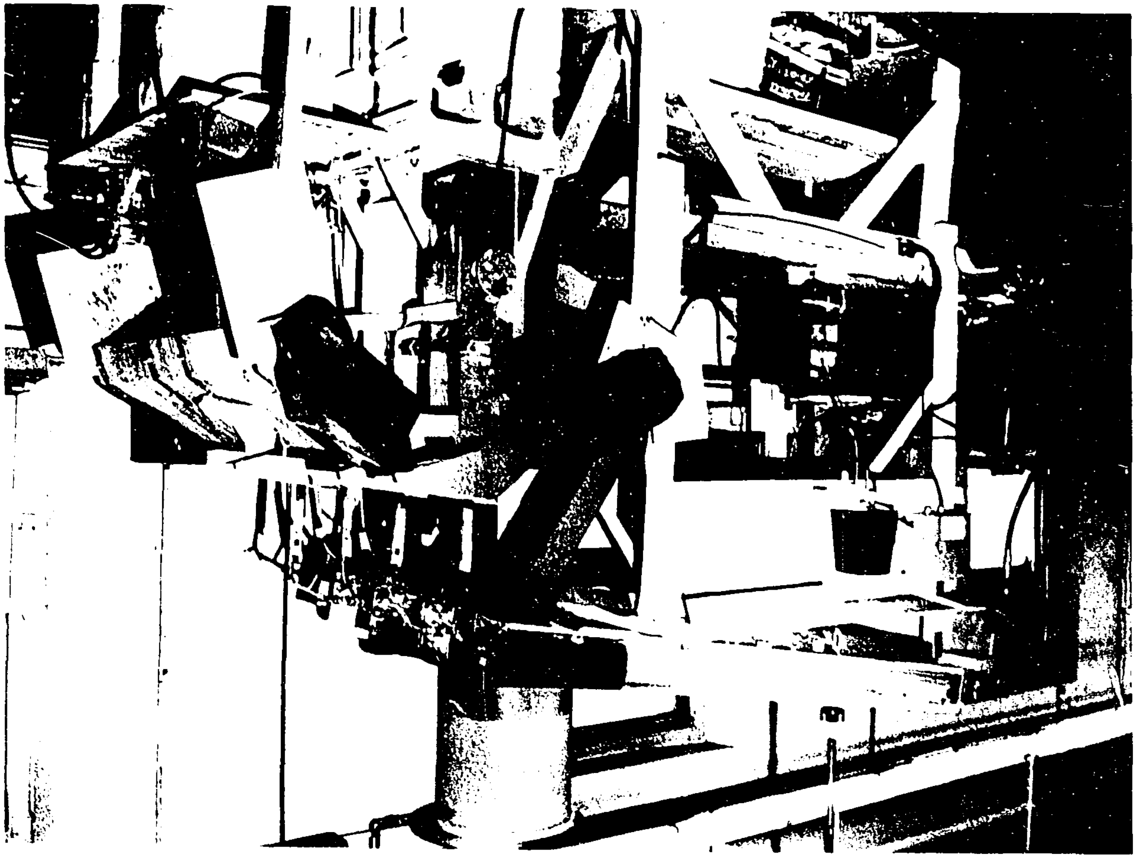


Fig. 31: Reverse osmosis assembly

[illegible]



APPENDIX I.

CHRONOLOGY OF TEST SERIES

Test No. 1: November 10-17
Variable Flow: 0.54-1.0 U.S. gpm
Average Flow: 0.77 U.S. gpm
Period of Sinusoidal Flow: 90 secs.

Test No. 2: November 17-25
Variable Flow: 0.60-0.94 U.S. gpm
Average Flow: 0.77 U.S. gpm
Period of Sinusoidal Flow: 90 secs.

Test No. 3: November 25-27.
Steady Flow: 0.77 U.S. gpm

Test No. 4: November 27-29
Same Flow conditions as in Test No. 2

Test No. 5: November 29-December 4
Variable Flow: 0.66-0.88 U.S. gpm
Average Flow: 0.77 U.S. gpm
Period of Sinusoidal Flow: 90 secs.

Test No. 6: December 4-10
Variable Flow: 0.60-0.94 U.S. gpm
Average Flow: 0.77 U.S. gpm
Period of Sinusoidal Flow: 60 secs.

Test No. 7: December 10-16
Variable Flow: 0.60-0.94 U.S. gpm
Average Flow: 0.77 U.S. gpm
Period of Sinusoidal Flow: 30 secs.

Test No. 8: December 16-18
Variable Flow: 0.36-0.70 U.S. gpm
Average Flow: 0.53 U.S. gpm
Period of Sinusoidal Flow: 30 secs.
Amplitude of Sinusoidal Flow: same as in Test No. 7.

Test No. 9: Dec. 18-20
Variable Flow: 0.53-0.87 U.S. gpm
Average Flow: 0.70 U.S. gpm
Period of Sinusoidal Flow: 30 secs.
Amplitude of Sinusoidal Flow: same as in Test No. 7.

APPENDIX II.

DEFINITIONS OF TERMS USED

Product Water:	The fresh water produced after passage through the membranes.
Reject Brine:	The concentrated salt solution rejected by the membranes.
Feed Water:	The saline solution fed to the membranes for desalination.
Recovery(%):	The percentage of product water recovered in relationship to the feed water input.
Rejection(%):	$\frac{\text{Salinity of Feed Water-Salinity of Product Water}}{\text{Salinity of Feed Water}} \text{x}100$
Salinity:	Amount of salt in the solution (grams/cm^3 or ppm)