Process and Configuration Development for Tubular Reverse Osmosis Units

United States Department of the Interior

Office of Saline Water • Research and Development Progress Report No. 426
Process and Configuration Development for Tubular Reverse Osmosis Units

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Contract No. 14–01–0001–1764
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The Department works to assure the wisest choice in managing all our resources so each will make its full contribution to a better United States—now and in the future.

FOREWORD

This is one of a continuing series of reports designed to present accounts of progress in saline water conversion and the economics of its application. Such data are expected to contribute to the long-range development of economical processes applicable to low-cost demineralization of sea and other saline water.

Except for minor editing, the data herein are as contained in a report submitted by the contractor. The data and conclusions given in the report are essentially those of the contractor and are not necessarily endorsed by the Department of the Interior.
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I. INTRODUCTION AND SUMMARY

A. The overall objective of this program was to develop an economical tubular reverse osmosis system for desalination of brackish water. Major emphasis was placed on the following aspects of the system.

1. Engineering and parametric studies to optimize process and plant design parameters.

2. Design and development studies of tube headers and manifold systems for feed and product water.

3. Selection and development of materials and manufacturing techniques to produce reverse osmosis tubular elements on a continuous basis.

B. The work accomplished is summarized in the following paragraphs.

1. Analytical studies were prepared in which the independent variables were membrane properties, tube dimensions and arrangements, feed water quality, and Reynolds numbers. Two computer programs were developed so that the effects of using different design parameters could be established, and one computer program was prepared for the purpose of determining the effects of changes in membrane properties, pressure, feed rates, and feed composition. Curves were prepared to show the relationships between Reynolds number and membrane area and power requirements, and between overall recovery and membrane area.

2. A number of preliminary designs were prepared for tube headers and the mating tube connectors, and by means of photoelastic studies and flow tests the design which was considered to be most practicable was demonstrated to be satisfactory.

3. Several materials and fabrication methods were investigated, and a tubular support structure for the membrane was developed which consists of a paper substrate on the inside surface with approximately 20 mils of fiber glass resin composite to provide the required strength.

4. The laboratory equipment was employed to fabricate several hundred feet of tubing into which membranes were subsequently extruded with separate apparatus. Laboratory tests of reverse osmosis properties showed that flaws in the membranes can be expected if the paper substrate is not free of protruding fibers or excessive overlap of scarfed edges. Moreover, in order to prevent premature local failure of the membranes, extreme care must be taken to avoid tear-drop shaped tubes, which can occur because of inadequate rounding of the paper substrate near the overlap of the edges. However, tubes which are free from such defects have produced up to 20 gallons of product per square
foot per day with rejection rates of about 80% of sodium chloride and 97% of sodium sulfate when operating at 800 psi.

5. The pilot plant was assembled at El Monte with a temporary spool piece in lieu of reverse osmosis tubes and tested to assure that there were no leaks. Then the assembly was transferred to the Laguna Beach test site where approximately one-half of the number of tubes for one module were installed and tested.
II. TECHNICAL DISCUSSION

A. PROCESS DESIGN

1. Plant Design Optimization

The objective of these studies was to determine the plant arrangements and parameters which would be best to meet particular sets of requirements. The parameters varied included the recovery desired, the tube internal diameter, membrane properties, plant capacity, quality of feed and product waters, and plant arrangement. Characteristics determined included the number of tubes in parallel and the series tube length per section, pressure drops, product concentration, maximum salt concentration at the membrane surfaces, Reynolds numbers, flow rates and pump duties. These parameters and characteristics were then used to guide the design of tube bundles for reverse osmosis plant in order to meet various sets of requirements.

(a) Theory

Technical Memorandum No. TM-8720-1, which is included herein as Appendix A, derives and describes the theory used in making computations for single stage, multi-section units operating on single salt feeds. This theory includes material tolerances and calculations of compositions, pressure drops, tube lengths, and correlation of membrane properties in a quantitative fashion so that they can be used for design purposes. A complete nomenclature is included.

Plant design is very significantly influenced by membrane characteristics which are functions of membrane formulation and heat-treat temperature, applied pressure, salt concentration and type, operating temperature, and membrane age and past service history. Most of the data acquired at Aerojet that covers a range of heat-treat temperatures and operating conditions have been obtained in 3-in. cells. The concentration polarization behavior in these cells has not been known, and varying assumptions regarding concentration polarization have led to very different sets of membrane coefficients, and, as might be expected, the influence of these uncertainties on plant design has been significant. It was, therefore, considered important to obtain a good estimate of the concentration polarization in the 3-in. cells. This was done, and the derivations and results are shown in Appendix B.

(b) Membrane Data

Aerojet 3-in. cell data for triple salt membranes were analyzed, using the boundary layer modulus curve for 85% bypass on Figure 1 of Appendix B and methods described in Appendix A. Using the membrane equations
\[ J = \frac{k_w (P - \pi)}{(1 + k_p k_w P)(1 + k_c c_w)} \]  

(1)

\[ 1 - \lambda = \frac{k_1 \lambda}{J} + k_2 \]  

(2)

where \( \lambda \) is the salt retention, the following relations were obtained, in which \( \tau \) is the heat treat temperature, °C:

\[ k_1 = 1.388 \times 10^{19} \exp (-0.535 \tau) \text{ gal/(ft}^2\text{)(day)} \]  

(3)

\[ k_2 = 4.896 \times 10^{8} \exp (-0.289 \tau) \]  

(4)

\[ k_w = 9.280 \times 10^{7} \exp (-0.250 \tau) \text{ gal/(ft}^2\text{)(day)(psi)} \]  

(5)

\[ k_p = 8.72 \times 10^{-3} \text{ (ft}^2\text{)(day)/gal} \]  

(6)

\[ k_c = 3.9 \times 10^{-6} (1 + 3.6 \times 10^{-10} P^3) \text{ ppm}^{-1} \]  

(7)

The concentration correction given by \( k_c \) is of significance for high salt concentrations. The coefficient \( k_c \) is related to the major coefficients \( k_1 \) and \( k_w \) by

\[ k_2 = 1.862 \times 10^{-3} \exp (-0.004 \tau) \frac{k_1}{k_w} \]  

(8)

or, approximately

\[ k_2 = 1.352 \times 10^{-3} \frac{k_1}{k_w} \]  

(9)

Using the relationships for \( k_p \) and \( k_2 \) for triple-salt membranes, data for Aerojet brackish water membranes (T-series) were
analyzed. The 85% bypass boundary layer modulus curve of Figure 1, Appendix B, was employed. Initially, the concentration correction \( k_c \) from Equation (7) was also used. It did improve the fit at 35,000 ppm feed and 1500 psi, but it did not improve the prediction at lower pressures and concentrations, so it was omitted from the final analysis which gave

\[
k_1 = 3.3115 \times 10^4 \ exp\ (-0.1487 \tau) \ \text{gal/}(ft^2)(day) \quad (10)
\]

\[
k_2 = 1.1348 \ exp\ (-0.0563 \tau) \quad (11)
\]

\[
k_w = 39.396 \ exp\ (-0.0924 \tau) \ \text{gal/}(ft^2)(day)(psi) \quad (12)
\]

\[
k_p = 8.72 \times 10^{-3} \ (ft^2)(day)/\text{gal} \quad (13)
\]

The above coefficients, shown in Figure 1 as functions of heat treat temperature, do not include allowance for long-term flux decline.

(c) Plant Design and Performance Computer Programs

Two plant design computer programs and one plant performance computer program were developed, tested, and used. These programs are based on the mathematical developments shown in Technical Memorandum No. TM-8720-1, included herewith as Appendix A. These three programs are all based on single-stage, multisection units, as defined more fully in Appendix A. Each section consists of a number of tubes in parallel, and recirculation may be provided if desired to limit the pressure drop while maintaining the Reynolds number at an acceptable level. These programs are suitable for use with a feed containing a single dissolved salt, usually taken to be sodium chloride.

The first design program employs membrane with the same heat treat temperature throughout the several sections, which leads to the product compositions from the several sections being different. The plant product consists, of course, of a blend of all the section products. The second design program uses a different heat treat temperature for the membrane in each section, which is selected to give the same product concentration for each section. Input data for both programs are similar, including membrane properties, physical property data for the salt solution, tube diameter, the maximum product composition allowable and the tolerance, the overall recovery and the desired section recovery (which determines the number of sections) a maximum section pressure drop allowable without recirculation, the section pressure drop to be used if recirculation is employed, the minimum section feed
NEW BRACKISH WATER
MEMBRANE AT 25°C
NaCl SOLUTIONS
PRESSURE <1100 PSI
BASED ON THEORETICAL BOUNDARY
LAYER CORRECTIONS FOR 3" CELL

FOR "OLD", USE 1/2 kw;
2 (k/l/kw), OTHERS SAME

MEMBRANE COEFFICIENTS

FIGURE 1
pressure, feed composition and product flow rate. Originally the programs were designed to select Reynolds numbers to control boundary layer moduli to selected ranges, subject to the Reynolds number being larger than a prescribed minimum value. Later it was found more practical to specify the Reynolds numbers to be used, allowing the boundary layer moduli to be determined by the resulting conditions.

The design programs select membrane heat treat temperatures to give product of the specified composition, and determine the plant configuration, including number of sections, lengths of tubes and number of tubes in parallel in each section, pumps and duties, compositions of feed, inlet, discharge and product for each section, recirculation ratios, and total power and membrane area.

As the name implies, the plant performance program calculates the performance of a plant of specified physical arrangement for specified operating conditions. This is particularly useful in determining the behavior 1) as membrane characteristics change, and 2) for different operating pressures, feed rates, feed compositions, and so forth.

(d) Plant Operating Techniques

There are several ways of operating reverse osmosis plants to maintain recovery level, product quantity, and product quality despite membrane flux decline. Three methods are discussed below:

Plan 1. This involves starting with new membrane, and replacing membranes for the whole plant at one time. Operation is started at a relatively low pressure, and the pressure is gradually increased as necessary to maintain the average flux. When it is no longer possible to maintain product quantity without exceeding pressure limits, or when product quality deteriorates to an unacceptable level, the plant is shut down and remembraned.

This plan is probably most suitable for very small plants.

Plan 2. This is essentially a steady-state operation, with continuous replacement of membrane as it deteriorates, and would appear to be well suited to large capacity tubular element plants. The plant would be run at constant pressure. Each section would consist of a parallel arrangement of tube bundles of many different ages, ranging from new to fully declined. A regular replacement schedule would be followed, wherein the oldest bundles in each section are replaced by new bundles. With a proper replacement schedule the membrane properties averaged over a section will remain essentially the same with time so that constant product quality and quantity, and constant recovery, should be obtained with constant operating conditions.
This plan appears very advantageous in giving a constant level of both labor and materials for operating and maintenance. It also allows use of different membrane heat treat temperatures for different sections if this proves advantageous.

Plan 3. This plan approximates a steady-state operation of a multisection plant, although not as closely as does Plan 2. Periodically (the period being equal to membrane life divided by the number of sections) each section will be shifted downstream by one in the plant flow sheet: Section 1 will be all new membrane, the old Section 1 becomes Section 2, the old Section 2 becomes Section 3, and so forth. The last section is taken from service and remembraned. The rotation physically would no doubt be done by external manifolding, rather than by physically moving membranized elements.

This scheme requires all sections to have the same membrane area, which may introduce a slight performance penalty. It would be most applicable to a plant consisting of a small number of pressure-vessel type elements.

The plant design calculations reported herein are based on Plan 2, using membrane coefficients which are believed to represent the average over the membrane area and involve taking $k_w$ equal to half the value for new membrane. This results in the flux being approximately half that for a new membrane.

(e) Preliminary Optimizations, Single-Stage Plants

A considerable number of runs were made with the plant design computer programs to determine the effects on total power and on total membrane area of various parameters. The principal parameters investigated included:

- Tube diameter - 0.125, 0.25, 0.50 and 1.0 in.
- Plant recovery - 0.5, 0.75, 0.9
- Reynolds number or boundary modulus
- Section recovery or number of sections
- Feed pressure - 500, 800, 1000 psig
- Recirculation or not
- Pressure drop when recirculating
- Design plan - No. 1 or No. 2

The following parameters were held constant for the calculations:
Feed composition - 5000 ppm NaCl
Product composition - 475 to 500 ppm NaCl
Capacity - $1.0 \times 10^6$ gal/day product
Operating temperature - 70°F (77°F on early runs)
Friction coefficient (factor multiplying computed skin friction to give total pressure drop):

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<th>Dia. in.</th>
<th>0.125</th>
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<th>0.5</th>
<th>1.0</th>
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<tr>
<td>$k_f$</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
<td>1.8</td>
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Feed pump - motor efficiency - 0.6 (0.8 used early)
Inlet pump - motor efficiency - 0.8
Recirculation pump - motor efficiency - 0.8
Turbine - alternator efficiency - 0.6 (0.75 used early)

Membrane type - old (declined flux) T-type
Inlet pump - always used

In the interests of brevity, no attempt will be made to catalogue the results of all the calculations which were made, but rather graphs showing the significant results will be shown. Except where specifically stated otherwise, design plan one was used; this is the plan which uses the same membrane heat treat temperature for each section.

The early runs were made with membrane coefficients which were estimated before the work discussed in Appendix B and paragraph (b) above was done and with the "early" experiences. Only the effect of recirculation pressure drop needs to be shown from these runs, and the actual levels of power and area are different from those obtained with the newer membrane coefficients and pump-motor efficiencies. The trends are valid, however.

A series of problems was run with $\Delta P_f$ set at 5, 20, and 50 psig for the four different tube diameters. 75% recovery, 6 sections, and 800 psig feed pressure were used. $C_w/C$ was set to assure recirculation and an acceptable Reynolds number for each case. The results of these problems are shown graphically in Figures 2 through 6. Figure 2 shows power vs $\Delta P_f$ at set values of $C_w/C$ for the various diameters. Figures 3, 4, 5, and 6 show membrane area vs $\Delta P_f$ at set $C_w/C$ for the 1.0, 0.5, 0.25, and 0.125-in. diameter tubes, respectively. As shown in Figure 2, power consumption increases only approximately 5% for a given diameter as $\Delta P_f$ increased from 5 to 50 psig. The significant change in power for different diameters is also evident. Figures 3 through 6 show that the area can increase or decrease by approximately 5% as
$10^6$ GPD PRODUCT
WITH RECIRCULATION

$C \sqrt{C} = 1.022$
0.5" DIAMETER

1.022
0.25"

1.022
0.125"

1.045
1.0"

1.045
0.5"

1.045
0.25"

1.068
1.0"

1.068
0.5"

POWER KW

$10^3$

$10^2$

$\Delta P_B$ - PSI

POWER VS SECTION PRESSURE DROP

FIGURE 2
Figure 3
AREA VS SECTION PRESSURE DROP FOR 0.25" DIAMETER TUBE

Area - ft²

\( \Delta p_{\beta} \) - PSI

- \( C_W / C = 1.022 \)  \( \bar{R}_o \approx 22,000 \)
- \( 1.045 \)  \( \bar{R}_o \approx 8,000 \)
Figure 6
\( \Delta P_e \) changes from 5 to 50 psi. This result is explainable from consideration of the effect that recirculation ratio and \( C_w/C \), in conjunction with \( \Delta P_e \), have on the water flux, that is, for a set value of \( C_w/C \) as \( \Delta P_e \) increases, a decrease in water flux (increased area) would be expected because of the lower average driving pressure; however, as \( \Delta P_e \) increases, the recirculation ratio decreases which tends to increase the water flux (reduced area) because of the reduction in average salt concentration which permits a looser membrane. It can be shown that the effect of recirculation ratio on the average salt concentration is not very significant if the recirculation ratio is above approximately 5. Thus, the curves in Figures 3 through 5 that show a decrease in area reflect those problems where the recirculation ratio was low. For example, in Figure 3 the recirculation ratio varies from approximately 9 to 0.4 for the curve where \( C_w/C \) is 1.069 and from 900 to 90 for the curve where \( C_w/C \) is 1.045.

From these results it was concluded that the effect of \( \Delta P_e \) on plant performance was rather insignificant and a value of 20 psig was used for subsequent calculations when recirculation was employed.

A series of runs was made with the corrected membrane coefficients, 75% recovery, 6 sections, and 800 psig feed pressure wherein the tube diameters and the boundary layer modulus \( C_w/C \) (and therefore the inlet Reynolds number) were varied. Results are plotted in Figures 7 through 9. In Figure 7, where power is shown for the several diameters as functions of Reynolds number, it is seen that as \( \bar{R}_e \) is decreased the power decreases to an asymptote which is feed pump power, and that there is no significant difference in power consumption, at a given value of \( \bar{R}_e \), whether recirculation pumps are used or not.

The equations used for boundary layer modulus are not believed valid below a Reynolds number of 8000, as discussed in Appendix A, so only the curves in the right hand region are believed valid. It can be seen that the power for 0.5-in. and 1.0-in. tubes is close to the minimum at \( \bar{R}_e \) of 10,000-15,000, while 0.125-in. and 0.25-in. tubes require much more power.

Figure 8 shows the tube area for no recirculation and Figure 9 shows the area with recirculation. In the region for \( \bar{R}_e \) of 10,000 or more there is little effect of diameter except for 1.0-in., which requires somewhat greater area.

Design plan two, which uses a different heat treat temperature for each section, was used for a series of runs at 75% recovery, 6 sections, and 800 psig feed pressure, in order to compare results with those from design plan one. The first 12 problems were run using the same constraints as those imposed on design plan one, i.e., constant \( C_w/C \). It was found that
\[ \Delta P_p = 20 \text{ PSI} \]

10^6 GPD PRODUCT

---

NO RECIRCULATION

---

WITH RECIRCULATION

---

\[ \text{POWER - KW} \]

\[ \log_{10}(\text{POWER - KW}) \]

---

\[ \text{POWER VS AVERAGE INLET REYNOLDS NUMBER } \bar{R}_o \]

---

\[ \text{PIAN ONE} \]

---

EQUATIONS ARE NOT VALID

EQUATIONS ARE QUESTIONABLE

PERFORMANCE PREDICTING EQUATIONS BELIEVED VALID IN THIS REGION

---

Diameter = 0.125"

0.25"

0.5"

1.0"

---

Figure 7
10^6 GPD PRODUCT
NO RECIRCULATION

EQUATIONS ARE NOT VALID
EQUATIONS ARE QUESTIONABLE
PERFORMANCE PREDICTING EQUATIONS
BELIEVED TO BE VALID IN THIS REGION

Diameter = 1.0"

AREA VS AVERAGE INLET REYNOLDS NUMBER $\overline{R}_o$ - PLAN ONE
$10^6$ GPD PRODUCT
$\Delta P_B = 20$ PSI
WITH RECIRCULATION

EQUATIONS ARE QUESTIONABLE

PERFORMANCE PREDICTING EQUATIONS
BELIEVED TO BE VALID IN THIS REGION

DIAMETER = 1.0"

0.125"
0.25"
0.5"

AREA VS AVERAGE INLET REYNOLDS NUMBER $\bar{R}_o$ - PLAN ONE

Figure 9
with this restriction the Reynolds number would vary by a factor of 10 throughout the 6 sections. This was unacceptable both from the standpoint of using an average $\bar{R}_o$ as a correlating parameter and from a standpoint of practical plant design. Therefore, design plan two was revised to hold $\bar{R}_o$ more nearly constant and allowing $C_w/C$ to vary accordingly. With this change the results shown in Figures 10 and 11 were obtained, which can be compared with Figures 7 and 8 for design plan one.

These problems were run for the 0.25 and 0.5-in. diameter tubes only as it was felt that this would provide sufficient information for comparison. The results show that power consumption is nearly the same. However, design plan two requires approximately 11% more membrane area. This suggests that design plan one may provide more efficient reverse osmosis plants. However, this is by no means a firm conclusion since a different set of membrane properties might reverse the ordering.

Returning to design plan one, which was now revised to control Reynolds numbers rather than boundary modulus, the effect of product recovery was investigated with 800 psig feed pressure, 6 sections, and 0.5-in. diameter tubes. The effects of variations in overall recovery ($\gamma$) on plant membrane area are shown in Figure 12. Both the recirculation and no recirculation cases are presented. A significant point to notice in this figure is the membrane area requirement for two stage design at 90% recovery. A complete discussion of the two stage design will be made in subsequent paragraphs. The reduction in membrane area requirement as $\gamma$ is reduced results from the decrease in the stream salt concentration which permits looser membrane and higher water flux. The area is not linear with recovery, however. This is shown in Figure 13 where plant area versus overall recovery is plotted for a given ($\bar{R}_o$) average inlet Reynolds number. It is apparent that as $\gamma$ is increased a point will be reached where plant membrane area requirements will become prohibitive.

Figure 14 shows power versus $\bar{R}_o$ for various values of overall recovery. At low $\bar{R}_o$, and consequently no recirculation, the feed pump power is predominant and, therefore, as $\gamma$ is increased the total power will decrease due to the reduction in feed flow rate. However, as $\bar{R}_o$ increases the power level curves cross showing that above $\bar{R}_o$ of approximately 19,000 the lower values of recovery will require less power. This is a result of the increase in either section pressure drop, or in recirculation ratio if recirculation is used, which requires an increase in either inlet pump power or recirculation pump power (since these problems were run with recirculation at the higher $\bar{R}_o$ it is the recirculation pump power that increased). Now, as the recirculation pump power increases the feed pump power no longer predominates and since the lower recovery plants have lower recirculation ratios because of both the higher flux and lower section recovery, the total power requirement is less.
$10^6$ GPD PRODUCT
\(\Delta P_B = 20 \text{ PSI}\)

- **NO RECIRCULATION**
- **WITH RECIRCULATION**

**POWER VS AVERAGE INLET REYNOLDS NUMBER** $\overline{R}_o$  - PLAN TWO
AREA VS AVERAGE INLET REYNOLDS NUMBER $\overline{R_o}$ - PLAN TWO

$10^6$ GPD PRODUCT
NO RECIRCULATION

EQUATIONS ARE QUESTIONABLE

PERFORMANCE PREDICTING EQUATIONS
BELIEVED TO BE VALID IN THIS REGION

DIAMETER = 0.25"

0.5"

Figure 11
AREA VS AVERAGE INLET REYNOLDS NUMBER $R_{in}$

PLANT AREA - FT$^2$

AVERAGE INLET REYNOLDS NUMBER ($R_{in}$)

$\gamma = 90\%$ (SINGLE STAGE)

$\gamma = 75\%$

$\gamma = 90\%$ (TWO STAGE)

$\gamma = 50\%$
Area vs Overall Recovery - Plan One Revised

ΔPb = 20 PSI
10^6 GPD Product
With Recirculation

SINGLE STAGE DESIGN

TWO STAGE DESIGN

PLANT AREA - ft^2

OVERALL RECOVERY, % (γ)
POWER VS AVERAGE INLET REYNOLDS NUMBER $\bar{R}_o$

PLAN ONE REVISED
Next, comparisons were made of the effects of inlet pressure on plant membrane area and power. Figures 15 and 16 show respectively, area and power versus average inlet Reynolds number at various levels of inlet pressure. As the pressure is increased the area requirement decreases, irrespective of $R_0$, because of the higher flux caused by the higher driving pressure. The power requirement as a function of operating pressure is, however, dependent on the Reynolds number. At values of $R_0$ below approximately 13,000 the higher the pressure the more power that is required, but at higher values of $R_0$ this reverses and the lower operating pressure requires more power. This condition is a result of the higher water flux obtained at higher pressures. At low $R_0$, the total power requirement is essentially all feed pump power which increases as pressure is increased. At higher $R_0$, the inlet and/or recirculation pump power becomes increasingly predominant and since the higher pressure (increased water flux) tends to reduce this power requirement the condition shown in Figure 16 results.

Several problems were run to determine the effect of varying the number of sections on plant power and area. The results of these problems are shown graphically in Figure 17. It can be seen that not much savings in power consumption is achieved by increasing the number of sections (N) beyond 4. However, a significant reduction in membrane area is attained by adding sections up to approximately 8.

(f) Preliminary Optimization, Two-Stage Plants

A small amount of work was done on two-stage plants in order to see whether they appeared to offer any advantage for brackish waters, and the results appeared very encouraging. The plant arrangement studied, which is identified as reverse staging, is shown in Figure 18. This arrangement is designed for a high recovery on brackish feed. The more usual forward staging shown in Figure 19, is suitable for relatively low recovery on a very saline feed water, such as sea water.

As shown in Figure 12 and 13, it has been found that for high recovery a two stage design has a significant advantage over single stage design in terms of membrane area.

The performance of the two stage design shown in Figure 18 was obtained by running several problems wherein the second stage product ($C_{P2}$) and the first stage recovery ($y_1$) were set at various levels. Either first stage recovery ($y_1$) or second stage recovery ($y_2$) could have been chosen as the parameter to be set, since to obtain a specified overall recovery ($y$) they are related by the following equation.

$$y_2 = \frac{y_1 (1 - y)}{y (1 - y_1)}$$

A graphical solution of this equation is shown in Figure 20.
Figure 15

Area vs average inlet Reynolds number $\bar{R}_o$

At various levels of feed pressure.
Figure 16

Power vs average inlet Reynolds number ($R_e$) at various levels of feed pressure.
$\bar{E} = 15600$
$\varphi = 75\%$

$10^6 \text{ GDP PRODUCT WITH RECIRCULATION}$

POWER

AREA

$10^2$

$10^3$

$10^2$

$10^3$

POWER AND AREA VS NUMBER OF SECTIONS $N$

Figure 17
REVERSE-STAGE PLANT
RELATIONSHIP BETWEEN RECOVERIES OF FIRST AND SECOND STAGES
C\text{P}_2 was maintained equal to or less than the plant feed composition (C\text{P}_0) for all problems. This initial selection of C\text{P}_2 was somewhat arbitrary except that it seemed logical to assume that if C\text{P}_2 were greater than C\text{P}_0, too high a salt retention capability would be required in the first stage to effect a significant improvement in plant design. This assumption was verified by the problem results, that is, for a given value of \( Y_1 \), minimum area is achieved at C\text{P}_2 of approximately 3500 for 90\% plant recovery. This result is shown in Figures 21 and 22.

Plots of plant area and plant power vs \( Y_1 \), are shown in Figures 23 and 24 for plant recoveries of 90 and 75\% respectively. These figures show that as \( Y_1 \) is decreased the power continually increases but the area will decrease to a minimum and then increase. Because there is very little difference in power level as C\text{P}_2 is varied, only one power curve is shown in these figures.

The continual increase in power as \( Y_1 \) is decreased is due to the increase in feed flow rate to the first stage. This causes both the feed pump and inlet pump power to increase. The recirculation pump power decreases as \( Y_1 \) decreases, however, its relative magnitude is small except at the higher values of \( Y_1 \); for example, at \( Y_1 \) of 80\% the feed pump power is 501 kw and the recirculation pump power is 147 kw, whereas, at \( Y_1 \) of 40\% the feed pump power is 1004 kw and recirculation pump power is 34 kw.

The variation in area results from the interaction of feed composition and recovery in each stage. That is, as \( Y_1 \) is decreased a corresponding increase in \( Y_2 \) must occur to maintain a particular plant recovery (see Figure 20) and since C\text{P}_2 is specified to be lower than (C\text{P}_0) the increase in \( Y_2 \) causes a net reduction in C\text{P}_1. This permits higher water flux and reduced area for the first stage. Now, the second stage area is increasing during this time but not as rapidly as the first stage area is decreasing, however, there is a point where the effect of high feed concentration to the second stage and higher \( Y_2 \) does cause second stage area to increase faster than the first stage area is decreasing. This appears to occur in the range of \( Y_1 \) equal to 45 to 50\% for the two overall recoveries studied.

The other feature of two stage design is that there appears to be an optimum second stage product composition. For a plant recovery of 90\% there is very little difference in plant area between C\text{P}_2 of 3000 and 4000 ppm. However, as C\text{P}_2 is changed in either direction from these values, a noticeable increase in plant area occurs. Similarly, the minimum area for a plant recovery of 75\% is obtained at C\text{P}_2 between 2000 and 3000 ppm.

A comparison of single stage and two stage design for a plant recovery of 90\% shows that a \( R_0 \) of approximately 17,000, C\text{P}_2 of 4000 ppm, and \( Y_1 \) 50\%, the single stage design requires 237\% more membrane area.
500 PPM PRODUCT CONCENTRATION
10^6 GPD PRODUCT
0.5" DIAMETER TUBE
TWO STAGE PLANT
90% PLANT RECOVERY
6 SECTIONS/STAGE

PLANT AREA VS SECOND-STAGE PRODUCT COMPOSITION - 90% PLANT RECOVERY
500 PPM PRODUCT COMPOSITION
$10^6$ GPD PRODUCT
0.5" DIAMETER TUBE
TWO STAGE PLANT
75% PLANT RECOVERY

PLANT AREA VS SECOND-STAGE PRODUCT COMPOSITION - 75% PLANT RECOVERY

Figure 22
PERFORMANCE OF SINGLE STAGE PLANT AT 90% RECOVERY

\( R_0 = 16,900 \)

POWER = 900

area = \( 0.32 \times 10^6 \)

\( R_0 = 15,500 - 17,600 \)

500 PPM PRODUCT COMPOSITION

\( 10^6 \) GPD PRODUCT

0.5" DIAMETER TUBE

TWO STAGE PLANT

90% PLANT RECOVERY

\( C_{P2} = 2000 \)

\( C_{P2} = 5000 \)

\( C_{P2} = 4000 \)

PLANT AREA AND POWER VS FIRST STAGE RECOVERY
PERFORMANCE OF SINGLE STAGE PLANT AT 75% RECOVERY

\( R_o = 17,500 \)

POWER = 720

AREA = 0.120 x 10^6

\( R_o = 16,000 \) TO 19,600

500 PPM PRODUCT COMPOSITION

10^6 GPD PRODUCT

0.5" DIAMETER TUBE

TWO STAGE PLANT

75% PLANT RECOVERY

PLANT AREA AND POWER VS FIRST STAGE RECOVERY
than the two stage design. The power requirements of both designs are approximately equal. A similar comparison for plant recovery of 75% at $C_{p2}$ of 2000 ppm, and $Y_1$ of 40% shows that the single stage design requires 51% more area and 22% less power than the two stage design. It is clear that as plant recovery is decreased the two stage design becomes less advantageous. In fact, Figure 13, while limited, indicates that a joining of the two curves is possible at a low recovery. The points for the two stage design in Figure 13 represent a best case, that is, the combination of parameters that gave the minimum membrane area required for the specified product. Now, if the two curves join, it will occur when the first stage recovery in the two stage design equals the overall recovery. Thus, if there is a point where the best case for a two stage design exists with $Y_1$ equal to $Y$ then the curves will join. Of course at this point the two stage design has degenerated into a single stage design. Prior to joining of the two curves, if this is possible, they will approach each other very closely and there will be a point where the increased cost associated with staging will negate any benefit derived from the reduced membrane area requirement. This point will represent the minimum overall recovery for which two stage design will be considered.

The dashed lines in Figures 21 through 24 represent the range where the constants used to predict membrane performance have not been completely determined; that is, this region represents an extrapolation of membrane data and as such could be in error. This questionable region is for heat treat temperatures less than approximately 65° Centigrade.

To give some insight into how the total plant area is influenced by the individual stage area, Figure 25 was prepared. For the given set of individual stage recoveries (when combined they yield a plant recovery of 90%) the first stage area increases and second stage area decreases as $C_{p2}$ increases. Similar results would be obtained if other sets of stage recoveries were plotted. The minimum total area is reached at a particular value of $C_{p2}$; this is because the rate of change (slope) of first stage area is initially less than the rate of change of second stage area; however, as $C_{p2}$ is increased, a point is reached where the first stage area increases more rapidly than the second stage area decreases.

(1) Conclusions

The results that have been obtained and presented in the previous paragraphs have been used to arrive at the following observations and conclusions.

(1) Based on area and power considerations it appears that the 0.125-in. diameter tubes must be fabricated at significantly lower cost per unit area than the other diameters to make a 0.125-in. diameter design economical. Sufficient performance data are available to select an
10^6 GPD PRODUCT
0.5" DIAMETER TUBE
TWO STAGE PLANT

SECOND STAGE PRODUCT COMPOSITION C_{P2}

FIRST AND SECOND STAGE AREA VARIATION VS SECOND STAGE PRODUCT COMPOSITION C_{P2}
optimum tube size from the 0.125, 0.25, 0.50 and 1.0-in. sizes when cost information is utilized.

(2) Variations in feed pressure can cause either higher or lower power demand depending on the Reynolds number, however, membrane area requirements are always less at higher feed pressures. Therefore, it is necessary to conduct optimization studies based on the relative costs of power, membrane area and life, and plant hardware to determine the optimum feed pressure.

(3) Performance data are available showing how membrane area and power are influenced by the number of sections for a given plant recovery (75%). These data can be combined with cost information to select the optimum number of sections for the overall recovery of 75%. Additional investigation is needed to establish the effects of different overall recovery on the optimum number of sections.

(4) It was found that as overall recovery becomes large it is desirable to have more than one stage. Additional investigation is needed to establish the optimum number of stages for a given plant recovery. Problems will have to run for both 2 and 3 stage designs and the effects of varying the stage feed pressure and feed composition on staging needs to be studied.

(5) All of the problems that have been run used inlet pumps in each section. The effects of varying the number of inlet pumps that are used should be investigated.

(6) At present, design plan two (same product composition from each section) does not appear to provide as efficient a design as does design plan one (same heat treat temperature in each section). Since the membrane constants influence the relative performance of design plans one and two, additional studies should be made using design plan two if different membrane constants are obtained.

(7) An average inlet Reynolds number ($R_0$) of 15,000 can be selected to provide single point comparisons of membrane area and plant power versus overall recovery and of membrane area versus feed pressure. Total power versus feed pressure is strongly effected by $R_0$ and, therefore, single point comparisons cannot be made of this parameter.

(8) The plant performance predictions that have been generated are all based on a feed composition of 5000 ppm of NaCl. A complete evaluation must include other salts and a range of compositions to include brackish water and sea water. This entails not only additional problem solving but membrane constants must be evaluated for the different salts found in natural waters.
The work reported herein on optimization is preliminary, as it is entitled. Under Contract DI 14-01-0001-1835 a multisalt program has been prepared using design plan one which allows treatment of waters more closely representing those occurring naturally. In addition a multistage program which uses the multisalt program to simulate each stage has been devised, and these have been combined into an optimization program which uses costs to find the plant design yielding the lowest cost water for a given situation and set of assumptions.

2. **Header Development and Design**

   a. The plan followed in developing the header design consisted of the following steps:

   (1) Establishment of design criteria.

   (2) Preparation of applicable design concepts.

   (3) Evaluation of design concepts with respect to design criteria.

   (4) Selection of a design for functional testing.

   (5) Evaluation of test results and revision of the design as necessary.

   b. The criteria were divided into a group of general standards and a set of supplemental considerations for judging the acceptability of various designs. These criteria are listed below.

   (1) **General Criteria**

      (a) **Low** cost per unit of product.

      (b) Suitability for a working pressure of 800 psig.

      (c) Easy assembly and disassembly.

      (d) Easy detection of defective tubes.

      (e) Easy replacement of defective tubes.

      (f) Minimum leakage of feed water into product.
(g) Suitable distribution of water to tubes.

(h) Characteristics conducive to low costs for maintenance and cleaning.

(i) Easy collection of product from individual tube bundles.

(j) Good handleability.

(k) Maximum practicable utilization of space.

(2) Supplemental Criteria

(a) Susceptibility to manufacture by standard low-cost methods and equipment and automated or continuous processes.

(b) Potentiality for automated assembly.

(c) Unacceptability of aluminum, magnesium, and zinc or their alloys.

(d) Inherent resistance to handling damage during assembly and subsequent use.

(e) Ultimate strength equivalent to a factor of safety of 6 if constructed of plastic, or 4 if made of metal, based on the working pressure of 800 psi.

(f) Ambient temperature conditions for assembly to avoid damage to tube membranes.

(g) Avoidance of solvents or other materials which might affect performance of membrane significantly.

(h) Single design if practicable to be used for either end of tubes.
c. Several header designs were considered of which the following five may be considered to be typical.

1. Three-piece, thirty-tube stainless steel circular design capable of being used as a 5-pass assembly, or as a single-pass header if a flow deflector were omitted, with tubes bonded in place.

2. Two-piece, forty-four-tube, multirow, 11-pass, U-bend, molded plastic header with a rectangular configuration and with tubes bonded in place.

3. Fifty-tube, two-row, U-bend, molded plastic header with tubes bonded in place and U-shaped caps bolted in place over pairs of tubes.


5. Three-piece, fifty-two-tube, two-row, single-pass, extruded plastic header with tubes connected by quick-disconnect fittings. In this design, sections of extrusion would be closed with caps bolted to each end, and holes for tubes would be machined rather than being molded.

d. After reviewing carefully the various designs, number (4) was chosen for refinement and development. This choice was based on the facts that the estimated first cost of this header was only about 60% of that of the next least expensive and that it most nearly fulfilled the other established criteria.

e. Structoform S-6400, manufactured by the Fiberite Corporation, Winona, Minnesota, was chosen as the material to be used in manufacturing these headers because of its very high physical properties and its excellent molding characteristics. It is a low-cost random glass-filled, polyester sheet molding compound which can be compression molded into narrow cavities and which will cure in heavy sections in short times with very good reproducibility. The properties of this material are listed in Table 1.
## TABLE 1
PROPERTIES OF FIBERITE SHEET MOLDING MATERIAL
STRUCTOFORM S-6400

<table>
<thead>
<tr>
<th>Property</th>
<th>Data from Supplier</th>
<th>Data from Aerojet Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, psi</td>
<td>20,100</td>
<td>18,155</td>
</tr>
<tr>
<td>Tensile modulus, ksi</td>
<td>(1)</td>
<td>2,220</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>(1)</td>
<td>1.65</td>
</tr>
<tr>
<td>Flexural strength, psi (2)</td>
<td>31,500</td>
<td>22,300</td>
</tr>
<tr>
<td>Flexural modulus, ksi</td>
<td>1,990</td>
<td>2,760</td>
</tr>
<tr>
<td>Compressive strength, psi</td>
<td>25,550</td>
<td>(1)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.94</td>
<td>2.00</td>
</tr>
<tr>
<td>Barcol hardness</td>
<td>(1)</td>
<td>62 (3)</td>
</tr>
</tbody>
</table>

(1) Data not available
(2) Span length 4.0-in. All specimens failed in tension.
(3) Average of 8 specimens; other Aerojet data averages of 4 specimens.
f. Conventional analytical procedures were employed to establish the thicknesses of the various parts of the header, and preliminary drawings were prepared to be used for fabricating a prototype part. The prototype was machined from a billet of cotton phenolic material, since it was to be used only as a pattern from which transparent copies could be cast in an RTV mold for photoelastic studies and tests of flow distribution. This prototype is shown in Figures 26, 27, and 28.

g. The transparent copy for photoelastic studies was cast using an epoxy resin mixture composed of 100 parts of ERL 2774 and 23 parts of ZZL 0803 hardener, manufactured by the Union Carbide Company. This model was assembled and subjected to a low internal pressure while at 100°C and while cooling slowly to room temperature. This operation "froze" the model in the deformed state, thereby "locking in" the stresses so that sections could be cut for analysis by photoelastic techniques. The study showed that the design was generally satisfactory but that certain details could be improved to reduce stress concentrations. A more complete discussion of this investigation is contained in Appendix C. The results may be employed as a basis for designing headers for larger tubes.

h. Another transparent copy of the prototype header was fitted with clear plastic tubes in which orifices had been placed to control the flow, and the assembly was flow tested to determine the hydraulic characteristics. Data were taken at flow rates through the header of 10, 25, 32, 40 and 60 gallons per minute, corresponding to Reynolds numbers of 1963, 4840, 6195, 7744 and 11,616. The variation in flow among the tubes was less than 1-1/2 percent from the mean. More complete information is given in Appendix D.

i. From the studies which have been conducted to date revised designs have been prepared for the headers for 1/4-in. and 1/2-in. tubes. These designs are shown in drawings which are included as Appendix E. It will be observed that tubes can be inserted or removed easily and that the header may be disassembled for complete cleaning. The O-ring which seals the joint between the two sections is probably the only part that would have to be replaced after disassembly; hence replacement costs should be low. Design of such headers for other sizes of tubes is a straightforward operation, but care must be taken to minimize stress concentrations and to provide satisfactory serrations into which the end-fittings on the tubes will mate. This latter point is discussed more fully in the following section regarding the end-fittings.

3. End Fitting Development and Design

a. Design and development of end-fittings which will provide leakproof hydraulic connections between the tubes and the headers and which will have adequate strength to preclude structural failure has been one of the most important tasks on this program. It has been attacked by two
Figure 26. Tube Header - Cap and Tube Plate
Figure 28. Inside of Header Tube Plate
entirely different methods - one mechanical and one chemical - as well as a combination of the two. The major mechanical approach involved the installation of a plastic fitting on each end of each tube, the two components being squeezed closely together by a hemitoroid metal eyelet. Another mechanical approach was employed for laboratory use only and incorporated re-usable metal fittings. The chemical approach was to coat the ends of the tubes with a material that would seal the surface and which could be used to bond the tube to end-fittings or headers.

b. Because of the desirability of having an arrangement in which tubes can be removed from the headers and replaced quickly, it is essential that they not be bonded permanently to the headers. The design shown in Figure 29 was considered to be the most practical of the various ones considered for production tubing. The molded polycarbonate ferrules are comparatively low in cost and are attached permanently to the ends of the tubes. The attachment has been accomplished by expanding the metal eyelet to force the tube out against the ferrule and to flare the fiber-glass composite to fit the conical shape in the plastic fitting. This step in the fabrication process has been found to be susceptible to unreliability, since although many fittings have withstood tube pressures of over 3000 psi some ferrules have pulled off the tubes at working pressure. The variability is considered to be the result of variation in the outer diameter of the tubes and the consequent tightness of the fit of the ferrule upon the tube. When the fit is a close one the ferrule remains in its proper position on the tube during expansion of the eyelet, and the tube is expanded tightly against the plastic component, thereby providing good frictional resistance to separation of the parts. Also under these conditions the ends of the glass rovings in the tube are flared out into the conical portion of the ferrule and are held tightly in place by the eyelet. However, if the fit between the outside of the tube and the inside of the ferrule is not a close one, it is possible for the latter part to slip from its proper position on the tube during assembly, there is less frictional resistance to separation of these parts, and the tube end does not fill the conical flare in the ferrule. To provide end-fittings which are less sensitive to minor variations in tube outer diameters a preliminary design has been prepared for a modified ferrule in which a wedge will be incorporated to compensate for such differences. This design will be substantiated and refined on the follow-on work.

c. The other mechanical fitting previously referred to for laboratory work is shown in Figure 30. It is a re-usable compression type device which can be produced from standard AN fittings, and it can be installed quickly.

d. The chemical approach to the connection of tubes to fittings or headers has not been successful because no adhesive has been
found which will bond tightly and reliably to wet tubes. Epoxy resins which harden as a mass under water have been tried, but the surface layer of such a mass (which was in contact with the water) remained soft. Consequently, since the planned process for making these tubes includes running them into water as the membrane is placed and keeping them wet thereafter, it has been concluded that further work along this line should be discontinued.
II Technical Discussion (cont.)

B. COMPONENT DEVELOPMENT

1. Tube Manufacturing Techniques
   a. Paper Forming

Many membrane support materials have been investigated at Aerojet-General during the past several years, and forming of substrates for tubular reverse osmosis units has been the subject of independent research and development since 1967. Consequently several concepts had been considered and the process which was believed to be most likely to succeed was adapted for this program.

(1) Paper Machine Design and Development

A machine to cut paper substrate to precise width, scarf both edges, apply adhesive to one edge, and form the material into a circular tube had been under development since September 1967, and was ready for operation. The first combined-action runs were made during the first month of performance on this contract. This machine is shown in Figure 31. Cutting of the paper to the desired width was performed very reliably and precisely. Also, scarfing of the edges to the desired 15° angle appeared to be satisfactory, although reliability of this operation had not been established. Early in the program it was determined that modification of the hot-melt glue applicator was necessary in order to permit easier cleaning and insure more uniform operation. Forming of the paper into the desired cylinder was also an operation which required improvement. The following discussion is confined to the more significant improvements. However, minor changes such as addition of vacuum lines to remove paper dust and cuttings, and trial of various contours of scarfing knives were also accomplished. The object of each change was to improve a specific step in the process so as to achieve a precisely round paper tube with a scarfed joint on which the braided fiberglass would be placed.

(a) Paper Tension Control

Slight jerking and rapid unrolling of the paper from the spool had occurred during starting of the machine because the entire mechanism is driven by a torque motor to reduce friction and because a sudden release in tension could cause the unit to "run away". Consequently, a dancer roller was placed between the paper spool and the first tension roller, and this idler was coupled mechanically to a brake on the shaft which carries the paper. This device resulted in good control of tension.

(b) Control of Width of Scarf

Each rotary scarfing knife was equipped with a micrometer screw adjustment so that the width of the scarfed edges could be controlled precisely.
Figure 31. Paper Cutting and Forming Machine
II  Technical Discussion, B (cont.)

(c) Control of Angle of Scarf

Intermittant lifting of the paper from the scarfing rollers, because of the action of the knives, and consequent irregular edges of the substrate occurred and was overcome by the addition of adjustable leaf springs to hold the paper close against the rollers.

(d) Paper Forming

Operating of the paper machine showed that more gradual forming of the substrate was necessary. Consequently, a four-roller system was installed. Three of them curved the paper by increasing amounts until a fourth roller, in the same plane but diametrically opposite the others, brought the edges close to the final position. After the last roller a split forming or ironing block was employed to hold the paper in its final shape up to the point at which the first braiding was applied.

(e) Protection of Scarfed Edges

In approaching the forming block and assuming their final positions, the two scarfed edges of the paper did not slide together easily and occasionally one edge would become rolled over, leaving an unsatisfactory joint. To prevent this occurrence, a steel shim 0.001-in. thick was formed to the proper radius and placed between the mating edges. The shim was allowed to protrude into a local conical relief in the form block so that the edges of the paper could slide into position over the smooth surfaces of the metal.

(2) Substrate Paper Selection

Certain criteria were established for selection of substrates papers, and improved material was obtained.

(a) Criteria for Selection of Substrate

The criteria for selection of the substrate paper that evolved during the period of this development are the following:

- High tensile strength, to permit transport through the paper forming machine with minimum breakage.
- High compressive modulus in the dry condition to prevent excessive pressure on the mandrel, and consequent drag from the tension in the braid.
- Sufficient resin loading to result in a clean scarf free of loose fibers.
- At least one surface free of loose protruding fibers.
- Good formability to insure a properly shaped tube.
- High wet strength, both tensile and compressive. These properties are required for proper reverse osmosis operation.

(b) Evaluation of Substrates

Several commercially manufactured filter papers were evaluated for compliance with the proceeding criteria. Specifications of each of these are shown.

- **Paterson Custom Made 532 40# Filter Paper**

**Properties**

Paterson Custom Made 532 is a flat, non-creped high wet strength, fast filtering, strong, porous paper. It has a medium fast filter rate. It is not for use as a qualitative or quantitative type filter paper. It is designed as an industrial type filter paper.

**COLOR** - White

**Basis Weight** - 24 x 36" - 500 sheets - 40#

**Caliber** - Approximately .0073-in.

**Dry Mullen** (Dry bursting strength) - Approx. 35 lb/sq in.

**Wet Mullen** (Wet bursting strength) - Approx. 15 lb/sq in.

**Eimendorf Tear** (Edge tearing resistance)

Approx. machine direction - 100 grams

Cross direction - 100 grams

**Gurley** (Porosity) - 0.65 to 0.75 seconds/100 cc
II Technical Discussion, B (cont.)

**ABSORBENCY** (Klemm)

Approximate inches per 2 minutes M.D. 42/16ths

**TENSILE STRENGTH**

Approximate machine direction 22.0 lb/in.
Cross direction - 14.0 lb/in.

**WET TENSILE STRENGTH** - Approx. machine direction 6.0 lb/in.

**TAPPI FILTER RATE** - Approximately 10 seconds per 10 cc

**SIZES**

Sheets and rolls up to 86 inches in width
Available in 2,000# quantities and up

**SUGGESTED USES**

Wine filtration
Industrial filtration

Tubes made with this paper showed that it was lacking in both tensile strength and surface finish.

- **C. H. DEXTER, GRADE X-1140 FILTER MEDIA**

**MATERIAL DESCRIPTION**

A high quality viscose treated manila hemp paper with exceptional dry and wet strength properties. All materials are FDA approved for filtration of foods and beverages.

**BASIS WEIGHT** - 50#/ ± 5#/ (24 x 36 - 480)

Tappi Standard T-410-os-61

**THICKNESS** - 9.5 ± 1.0 mils

**POROSITY** - 15 cfm/ft² 1/2" H₂O ΔP (Gurley Permeometer - Model 4300)
10 minimum
20 maximum

ASTM Standard D-737-46 (Average of 5 specimens)
BURSTING STRENGTH (mullen)

<table>
<thead>
<tr>
<th>Dry</th>
<th>Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 psi average</td>
<td>62 psi average</td>
</tr>
<tr>
<td>75 psi minimum</td>
<td>50 psi minimum</td>
</tr>
</tbody>
</table>

Tappi Standard T-403-ts-63 (Avg. of 10 specimens)

DRY TENSILE STRENGTH (#/inch strip)

| Machine direction or length | 55#/in. Avg. |
| Cross direction             | 50#/in. Avg. |

Tappi Standard T-404-os-61 (Avg. of 10 specimens in each direction)

WET TENSILE STRENGTH (#/inch strip)

| Machine direction or length | 16#/in. Avg. | 12#/in. Minimum |
| Cross direction             | 15#/in. Avg. | 11#/in. Minimum |

Tappi Standard T-456-in-49 (Avg. of 10 specimens in each direction)

COLOR - Natural white

SUGGESTED USES - A high wet strength filter media for use as a core support in filter cartridges. Suitable for filtration of photo processing chemicals.

While this material offered nearly all the properties necessary for tube manufacturing, its surface presented a large number of loose fibers, most of which were protruding to heights much greater than the thickness of the membrane. These fibers perforated the membrane and provided leakage paths.

- C.H. DEXTER X-1610 AND X-1611 FILTER MEDIA

C. H. Dexter X-1610 was developed taking the C-1140 as a starting point and flame treating one face of the paper during manufacture. However, the improvement in surface quality was not consistent enough and a further step of quality improvement was necessary. The properties of this paper are shown along with those of X-1611 in the next paragraph.
C. H. Dexter X-1611 - This material was an improvement on X-1610 which was achieved by adding additional resin (xanthate) and burning the fibers on the second surface also. This additional resin keeps the remaining surface fibers adhered to each other, preventing the previously encountered problems, however, the increased stiffness of this paper made the forming operation somewhat more critical. Steps to overcome this problem mechanically are currently being taken.

<table>
<thead>
<tr>
<th></th>
<th>X-1610</th>
<th>X-1611</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis weight (#/2880 ft²)</td>
<td>51.9</td>
<td>54.3</td>
</tr>
<tr>
<td>Gauge (inches)</td>
<td>0.0094</td>
<td>0.0089</td>
</tr>
<tr>
<td>Permeability (cfm/sq ft 1/2&quot; P)</td>
<td>15.2</td>
<td>11.8</td>
</tr>
<tr>
<td>Wet Mullen burst (psi)</td>
<td>59</td>
<td>74</td>
</tr>
<tr>
<td>Tensile strength (wet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine direction (lb/in.)</td>
<td>17.4</td>
<td>21.3</td>
</tr>
<tr>
<td>Cross direction (lb/in.)</td>
<td>11.0</td>
<td>14.1</td>
</tr>
</tbody>
</table>

b. Braiding

(1) Braiding Machine Design

Fabrication of the structural tube is performed on the prototype line (Figure 32) by a pair of braiders manufactured by the New England Butt Company. The braiders are operated by "cog-tooth" belts connected to a common drive. Basically, the braiding machine is a train of gears mounted and operated between two accurately ground flat plates. These gears have flanges or horns at the top which engage the bottom end of the bobbin carriers on which the glass roving is held. The upper of the two plates is formed with serpentine paths to guide the carriers. The paths or grooves are profile milled to facilitate interchangeability of carriers. Braiding machines of this kind are built in two sizes, No. 1 and No. 2. The machines on the prototype line are the smaller, No. 1 braidors and accommodate 16 carriers and bobbins.

The braidor carrier, manufactured by the Mossberg Pressed Steel Corp., is milled to such a shape that it fits into the groove in the top plate. The lower end has a lug which engages the horns of the gears by which it is carried around the groove of the machine during operation. In addition to accommodating the bobbin and dispensing the roving evenly, the carriers utilize a spiral compression spring to maintain tension on the roving irrespective of the carrier position.
Figure 32. Laboratory Structural Tube Fabricating Line
Braiding tension may be modified by replacement of the compression spring on each carrier. Selection of the springs is a critical phase of the braiding operation. A light-tension spring produces a tube with loose braid and poor structural properties while a spring requiring high tension to dispense the glass will form the paper substrate around the mandrel too tightly, thus preventing line travel. Current braiding operations are performed with 0.012-in. size springs designated by the manufacturer as 2 oz.

Larger, No. 2 Butt braiders are being installed on the pilot production line. These units appear much more satisfactory from a rigidity standpoint and utilize larger and additional bobbins (24 rather than 16). Further, the carriers are more sophisticated and also have replaceable tension springs with a wider range of available tensions. The carriers also utilize rollers instead of bent wires to guide the rovings, thereby reducing friction and damage to the fibers due to wear on sharp corners.

(2) Braiding Pattern and Operation

The unidirectional glass filaments of the cylindrical tubes are the primary structural material and must be oriented to meet the biaxial force field from internal pressure and axial loads from the weight of the header assembly. Various winding patterns are available to obtain this orientation. A more dense and efficient structure would be produced by placing two independent sets of fibers in the principal force directions (hoop and longitudinal), primarily because the reduction of filament crossovers minimizes stress concentrations in the fibers. But a more dense structure is not a requirement for these tubes, since structural integrity with sufficient porosity is more desirable in order to facilitate obtaining the required product flux under pressure loads. For this reason, and because winding equipment is readily available from the textile industry, an open-weave or braiding pattern was selected for the tubes.

The braid for the tubular reverse osmosis tubes is formed around a center mandrel by passing each strand alternately over and under two of the opposite strands thus producing two complete double ribs or lines of herring-bone shape. Axially-oriented fibers are also utilized to prevent occurrence of a "Chinese Finger" effect and consequent resistance to movement lengthwise in the mandrel during winding. These longitudinal fibers were first applied in a resin-preimpregnated form between the paper substrate and the braided layer but were found to form nodes which contributed to membrane fracture. This condition was resolved by applying each strand of longitudinal fiber between each pair of braiding strands. Thus, 8 bobbins of longitudinal fibers and 16 bobbins of braiding glass roving are used in each of the two layers on the glass tubular structure fabricated on the prototype line. The angle of braiding was adjusted so that the tangential component of the fiber
stress would resist all hoop force in the tubing, and the longitudinal component together with the stress in the longitudinal filaments would resist the axial force.

A manufacturing plan for the fabrication of the 1/4-in. diameter glass-reinforced tubes is presented in Appendix F. The more pertinent details of the tube fabrication, including the braiding operation, are outlined and serve as a guide in order to ensure that reliable, reproducible units are obtained and that deviations in parts, materials, or processes are recorded.

As previously indicated, the braiding is performed around a tapered, stainless steel mandrel. Several variations of the winding mandrel were initially evaluated, starting with a straight tube of uniform diameter progressing to a machined tube with full diameter only where pressure is applied (at the drive rollers and braidies), and finally to the present mandrel which tapers approximately 0.0001-in. per foot of length. Initial mandrels had a silicone release agent applied to the outer surface to facilitate travel of the formed tube, but more recent mandrels are coated with Teflon (approximately 0.0005-in. thick). The Teflon-coated units are preferred since they imposed less resistance to tube travel and avoided the uncertainty of possible detrimental effects of the silicone release agent to the subsequently applied membrane. Both tubular and solid tapered mandrels have been utilized with equal success.

(3) Fiber Selection

A major consideration in the selection of materials utilized for the tubular reverse osmosis components was minimum cost. Consequently "E" glass fiber was considered to be the most logical choice because it is readily available in continuous filaments of acceptable cost, whereas "C" glass is almost always made into staple fibers only. The glass roving initially chosen for evaluation as the load-carrying portion of the tubular structure was Aerorove 2, which is a single-end (each end consists of 204 individual filaments), E-glass roving with a 721 finish. This material is roughly equivalent to Owens-Corning ECK with an 801 finish. The material was formerly produced by Aerojet's Structural Products Division (personnel involved in the glass manufacture have since formed Glass Fiber Products, Inc.). Thus, at the time, the material was selected not only for its low cost but because of its ready availability, quick delivery, and the willingness of glass plant management to produce glass with modified finishes if required.

Unfortunately, preliminary material samples exhibited excessive fuzzing and breakage, and additional samples of single-end type E-glass fiber with an epoxy-compatible finish were obtained from Glass Fiber Products and other commercial sources including the following:
(a) Owens-Corning  
(b) Pittsburgh Plate Glass  
(c) Ferro Corporation

The sample materials were evaluated on the prototype tube line with fiber breakage and fuzzing during the braiding process being the basic criteria. While all the materials produced acceptable tubing, the FRG glass fiber appeared to be best and became the standard for subsequent operations. Initially, the E-glass roving was obtained in four single ends which were subsequently combined into 4-end form on nylon bobbins with one twist per inch for the braiding operation. Currently, the material is supplied in 4-end form and wound by Aerojet onto the braider bobbins. The material is designated as ECG 150 4/0 with L-131 finish. Preliminary Aerojet material specifications on the fiber glass roving are presented in Appendix G.

With the 4-end glass roving, as described above, highly successful tube production runs of several hundred feet have been accomplished during a normal working shift. Current production runs are performed at tube speeds of 18 to 24-in./min, although higher manufacturing rates are limited only by the mechanics of the prototype system; thus, indicating that rates of 5 ft/min or more could be obtained with more sophisticated equipment. Figure 33 presents typical 16-ft tubes produced during the manufacturing operations.

c. Resin Application

In constructing components which depend upon fiber glass for their strength, a resin matrix is employed to bind the filaments together in the desired shape and to protect the fibers from abrasion and from the environment. For fabricating reverse osmosis tubing at an economical rate by the desired continuous process two other requirements are necessary, assuming the resin is sufficiently soft to allow the filaments to form into a compact structure during the braiding operation. First, the matrix must result in a tube which is porous to allow flow of water, and second, the resin must harden rapidly so that rigid tubing can be produced in a reasonable length of manufacturing line.

(1) Resin Selection

The most significant characteristics upon which the choice of matrix was based are as follows:

(a) Freedom from ingredients which may be injurious to health.

62
Figure 33. Sixteen-foot Lengths of Fiber Glass-Paper Tubing
(b) Good mechanical properties - strength and elongation.

(c) Ease of processing.

A plastic which is considered to fulfill these requirements is Bakelite® Brand Phenoxy Resin PKHS-1 produced by Union Carbide Corporation. This is an MEK solution containing 40% phenoxy PKHC, a high molecular weight thermoplastic resin made from bisphenol-A and epichlorohydrin without terminal, highly reactive epoxy groups; consequently it has an infinite shelf life. However, it does contain 6% by weight of secondary hydroxyl groups which allows crosslinking with other materials to achieve improved solvent and temperature resistance. Properties of the resin are listed in Table 2.

(2) Application Methods

In the original tube forming concept, the glass roving was to be preimpregnated with the phenoxy resin to approximately the 20% level by weight. A good deal of effort was directed in preparing a single-end roving with this resin, the objective being to individually coat each of the 204 monofilaments of the single-end roving. Several dip tank variations were evaluated, all with some success, but not with the desired uniformity of results. The filaments were mechanically separated and impregnated through several rollers in the 25% resin bath, then drawn between steel metering bars. The solvent was evaporated through counter current warm air in a 15-ft horizontal tube heater, followed by a 10-pass vertical oven operating at 250°F. Roving was prepared at approximately 200 linear feet with a resin content of 18%. The equipment is shown in Figure 34.

In order to determine the strength of glass-resin composite, N.O.L. rings were prepared and tested, and this investigation showed that two characteristics of the preimpregnated roving were not satisfactory. First, in the initial fabrication of the rings, heating above 400°F was necessary to soften the resin and fuse the composite. Consequently a melting point depressant (EDBC) was added. Second, despite the use of mechanical separation of the fibers while in the resin bath, the glass was not coated completely and uniformly. Wetting and coupling agents were therefore also included. PKHC phenoxy, supplied as 40% solids in MEK/water 98/2 solution (designated as PKHS-1) was the basic resin which was employed as a control and in which the various additives were incorporated. The matrix formulations are listed in Table 3.

Although minor differences were noted in using the various matrix formulations, no clear advantages were evident, and the preimpregnated roving containing approximately 18% resin did not bond
TABLE 2

PHYSICAL PROPERTIES OF PHENOXY RESIN

Molecular Structure

\[
\begin{array}{c}
\text{CH}_3 \\
O-\text{CH}_2-\text{C} \quad \text{CH}_3 \\
| \quad | \\
| \quad | \\
H \quad H \quad H \\
\mid \quad \mid \quad \mid \\
H \quad \text{OH} \quad H \\
\end{array}
\]

N \approx 100

Approximate molecular weight  20,000-30,000
Specific gravity  1.18
Melt flow (g/10 min @ 220°C)  2.5-10
Ultimate tensile strength (psi)  9000-9500
Ultimate tensile elongation (%)  50-100
Tensile modulus, 10^5 (psi)  3.5-3.9
Compressive strength (psi)  10,400-12,000
Flexural yield strength (psi)  12,000-13,000
Impact strength, ft-lb per inch of notch Izod Test  1.5-2.0
Water absorption, 24 hr 1/8-in. thick, (%)  0.13
Figure 34. Equipment for Impregnating Glass Roving with Resin
# TABLE 3

**MATRIX FORMULATIONS EMPLOYED IN PREIMPREGNATING ROVING**

<table>
<thead>
<tr>
<th>Designation No.</th>
<th>Formulation, Parts by Weight of Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>JC-1</td>
<td>PKHC only</td>
</tr>
<tr>
<td>JC-2</td>
<td>PKHC-100, Dow Corning Co. Silane Coupling Agent (Z-6040)-2</td>
</tr>
<tr>
<td>JC-3</td>
<td>PKHC-100, DuPont Wetting Agent (Zonyl A)-1</td>
</tr>
<tr>
<td>JC-4</td>
<td>PKHC-100, Bakelite Vinyl Ether Ether Resin (EDBCr)-5</td>
</tr>
<tr>
<td>JC-5</td>
<td>PKHC-100, EDBC-5, ZONYL A-1</td>
</tr>
<tr>
<td>JC-6</td>
<td>PKHC-100, EDBC-5, Z-6040-2</td>
</tr>
<tr>
<td>JC-7</td>
<td>PKHC-100, EDBC-5, Z-6040-2, Zonyl A-1</td>
</tr>
</tbody>
</table>
satisfactorily during the fabrication process. Consequently formulations were modified further by the addition of wetting agents, coupling agents, and plasticizers, and the resin content of the roving was increased to 30% ± 5%. However, even these changes did not result in well compacted tubes, and failures of the membranes in the region of the joint in the paper substrate were experienced, apparently from lack of adequate support from the fiber glass structure. Moreover, the impregnated roving was in some cases unacceptably stiff for the braiding operation. Additional heaters were installed on the tube fabricating line, and filament tensions were adjusted in an effort to avoid the failures in the membranes. Better tubes were produced, but since failures continued to occur, it was decided to change the process to incorporate in-process impregnation to produce a much tighter and more uniform tube.

The success of in-process impregnation depends on the proper balance of resin properties to obtain a tube of sufficient structural strength, yet with the right amount of porosity. Resin application tanks were built and installed after each braiding station. A resin solution containing 35% of solid PKHC was prepared with and without Cab-O-Sil which provided viscosities of 2200 cps and 950 cps, respectively. Initial tube fabrication with the Cab-O-Sil-filled solution appeared to be resin starved. Use of the lower viscosity material improved tube appearance, but the tube resin content was only 13%. In order to establish the relationship between resin solids contents of the impregnating baths and of the fabricated tube, the machine was run using different resin solutions. The relationship is shown in Figure 35 indicating that 40 to 45% resin solids will provide a tube resin content of 17-18%. It is felt that tube resin content should be in the range of 18 to 20% to meet the structural and porosity requirements.

While the viscosity and resin solids of the impregnating solution had been fairly well defined, it was observed that the infrared heating unit used to remove solvent from the impregnated tube burned the internal membrane support paper. Carbon black was initially used as a screening agent, but it was subsequently replaced with 1.0 part of TiO₂ per 100 parts of solid PKHC resin. The resin formulation consisted of PKHS-1 to which was added 1.0 part of TiO₂ screening agent and 1.0 part Cab-O-Sil viscosity control agent. This formulation has produced tubes with resin contents of 16.0%. More recently the Cab-O-Sil has been deleted, and 45% PKHC resin containing 1.0 part TiO₂ has been used resulting in a tube resin content of 19.0%. This is more in line with our original estimates and also is sufficient to provide adequate bond of the paper to the fiberglass.

d. Membrane Application

(1) Membrane Formulation

A previously developed membrane formulation was available for use in the tubular membrane system. It does not require an
Figure 35. The Effect of Impregnating Resin Solids on Resin Content of Braided Tube
extended drying time between casting and gelation and, therefore, can be used in the restricted air space inside of a small diameter support tube. The resulting membrane is quite tough and has acceptable reverse osmosis properties.

A series of membranes was cast at various speeds on an aluminized Mylar belt to determine the effect of casting speed and drying time on the osmotic properties of the membrane, the finished membranes were approximately 3 mils thick throughout the series. As shown in Table 4, the flux was found to increase as the casting speed was increased and the drying time was reduced, which indicates that the maximum flux would be achieved if there were no evaporation at all prior to gelation. This condition is realized when a membrane is cast in a small diameter tubular support, since the air space becomes saturated before any appreciable amount of solvent has been lost from the casting solution.

A second series of membranes was cast from the same solution on several types of support paper as well as Mylar\textsuperscript{R} to determine the effect of the various supports on the osmotic properties of membrane. A sheet extruder was used to apply the casting solution to the papers, which were taped to the Mylar belt in the production sheet machine. The results of this series, shown in Table 5 show that the flux of the membrane is somewhat lower when cast on paper than when cast on Mylar.

The flux of the control membrane cast on Mylar is abnormally high, however, and the more commonly found flux approximately 30 gfd should be used in making this comparison. A series of flat sheet membranes was hand cast with a doctor blade on both aluminized Mylar\textsuperscript{R} and Dexter C-1140 from casting solutions containing from 10 to 30 parts of acetone to determine the optimum amount of acetone in the formulation:

| Parts by Weight |
|-----------------|-----------------|
| Cellulose acetate, E 400-25 | 10 |
| Acetone | See following table |
| Water | 3 |
| Propionamide | 6 |

All of the membranes were cast at 10 mils wet thickness, dried for 1.6 seconds and gelled in ice-water, they were heat-treated for 3 minutes at 76\textdegree C and tested with 1% sodium chloride at 800 psi for the standard two-hour period (all values are the average of 3 tests):
<table>
<thead>
<tr>
<th>Casting Speed, ft/min</th>
<th>Drying Time, sec.</th>
<th>Sample Code</th>
<th>Number of Samples</th>
<th>Flux (J), gfd</th>
<th>Product Salt Concentration, ppm</th>
<th>Salt Rejection, Avg %</th>
<th>NaCl Feed, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>4.8</td>
<td>HK-OSS-3</td>
<td>3</td>
<td>19</td>
<td>298 ± 54</td>
<td>97.2</td>
<td>10,820</td>
</tr>
<tr>
<td>2.6</td>
<td>3.8</td>
<td>HK-OSS-2</td>
<td>1</td>
<td>24</td>
<td>272</td>
<td>97.5</td>
<td>11,040</td>
</tr>
<tr>
<td>3.9</td>
<td>2.6</td>
<td>HK-OSS-1</td>
<td>2</td>
<td>25.5</td>
<td>275 ± 15</td>
<td>97.5</td>
<td>11,040</td>
</tr>
<tr>
<td>6.3</td>
<td>1.57</td>
<td>HK-OSS-5</td>
<td>2</td>
<td>25.5</td>
<td>257 ± 3</td>
<td>97.7</td>
<td>11,040</td>
</tr>
<tr>
<td>8.9</td>
<td>1.10</td>
<td>HK-OSS-4</td>
<td>3</td>
<td>30</td>
<td>352 ± 16</td>
<td>96.7</td>
<td>10,820</td>
</tr>
</tbody>
</table>

(1) Casting Formulation

<table>
<thead>
<tr>
<th>Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose acetate E 400-25</td>
</tr>
<tr>
<td>Acetone</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Propionamide</td>
</tr>
</tbody>
</table>

Viscosity (Brookfield) 83,000 cps @ 24°C

Membranes doctor blade cast on aluminized Mylar belt, gelled in ice-water. Membrane samples annealed 3 min at 75°C.
<table>
<thead>
<tr>
<th>Paper</th>
<th>Type</th>
<th>Flux, gfd</th>
<th>Rejection, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td></td>
<td>43.3</td>
<td>86.6</td>
</tr>
<tr>
<td>4229</td>
<td>Phenolic impregnated - used for flat membrane support</td>
<td>26.2 ± 0.8</td>
<td>94.7 ± 0.5</td>
</tr>
<tr>
<td>4229</td>
<td>Lightly sanded</td>
<td>25.2 ± 0.1</td>
<td>94.0 ± 0.3</td>
</tr>
<tr>
<td>Paterson //532</td>
<td>Industrial filter paper (used in tubular unit to date)</td>
<td>24.8 ± 0.5</td>
<td>91.4 ± 0.2</td>
</tr>
<tr>
<td>Whatman //50</td>
<td>Laboratory filter paper</td>
<td>21.0 ± 0.3</td>
<td>89.4 ± 0.3</td>
</tr>
<tr>
<td>Mead //936J</td>
<td>Glass paper</td>
<td>35 ± 2</td>
<td>83.4 ± 1.7</td>
</tr>
<tr>
<td>Mead //936A</td>
<td>Glass paper</td>
<td>36.5 ± 2.5</td>
<td>79.5 ± 4.3</td>
</tr>
</tbody>
</table>

*Osmotic conditions were 800 psi with an input of 10,000 ppm NaCl. The drying time was 2 seconds.*
II Technical Discussion, B (cont.)

<table>
<thead>
<tr>
<th>Acetone</th>
<th>Aluminized Mylar</th>
<th></th>
<th></th>
<th>Dexter C-1140</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flux, gfd</td>
<td>Rejection, %</td>
<td></td>
<td>Flux, gfd</td>
<td>Rejection, %</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>29.7</td>
<td>96.1</td>
<td></td>
<td>Did not prepare</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>30.2</td>
<td>96.8</td>
<td></td>
<td>19.7</td>
<td>91.2</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>30.5</td>
<td>96.9</td>
<td></td>
<td>20.8</td>
<td>90.7</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>18.3</td>
<td>97.7</td>
<td></td>
<td>19.1</td>
<td>93.5</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>19.7</td>
<td>97.2</td>
<td></td>
<td>15.4</td>
<td>95.4</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>10.3</td>
<td>96.6</td>
<td></td>
<td>9.7</td>
<td>98.0</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>10.0</td>
<td>97.4</td>
<td></td>
<td>6.2</td>
<td>95.9</td>
<td></td>
</tr>
</tbody>
</table>

As expected, the membranes prepared from the more concentrated solutions had the best performance even though the solution containing only 18 parts of acetone was not entirely soluble. The flux of the membranes cast on Dexter C-1140 initially followed the pattern established by those cast on aluminized Mylar®, their maximum flux, however, tends to be somewhat lower than the maximum flux of those cast on Mylar®. Whether this is due to resistance to flow through the membrane support region or to a less permeable active layer will have to be determined. The thickness of the membranes cast on Mylar® from the solution containing various amounts of acetone did not exceed 4 mils. The thickness of those cast on paper is unknown since the depth of penetration of the substrate into the paper was not determined.

To determine the optimum membrane thickness, a series of membranes was cast with an adjustable "doctor" blade onto a Mylar® belt from the following formulation:

```
Parts by Weight

Cellulose acetate, E 400-25 10
Acetone 22
Water 3
Propionamide 6
```

All of the membranes were dried for 1.6 seconds, then gelled in ice-water. After heat treatment for 3 minutes at 76°C, they were tested with a 10,000 ppm sodium chloride solution at 800 psi (all values are the average of 3 tests).
As seen from the above data, the 4-mil membrane has a distinct advantage over its thicker counterparts. In addition to the membranes cast on the aluminized Mylar® belt, a 4-mil membrane was prepared in a similar manner on Dexter C-1140. It had an average flux of 20.5 gfd at 93.7% rejection, compared to 33 gfd for the 4-mil membranes cast on Mylar®.

(2) Membrane Support Criteria

(a) Tube Configuration

A series of membranes was extruded into 0.25-in. diameter tubes from the following casting formulation:

Parts by Weight

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose acetate, E 400-25</td>
<td>10</td>
</tr>
<tr>
<td>Acetone</td>
<td>20</td>
</tr>
<tr>
<td>Water</td>
<td>3</td>
</tr>
<tr>
<td>Propionamide</td>
<td>6</td>
</tr>
</tbody>
</table>

The membranes were cast into the previously prepared tubes at 1.5 ft/min and gelled in ice-water within 30 seconds after the end of the 2-ft section left the extrusion nozzle. Thus, the first part of the membrane had been on the paper for over 3 minutes before gelation, while the last section was gelled within 30 seconds. The membranes were heat treated with hot water (76°F) for 5 minutes under 3 to 4 psi. Most of the tubes leaked during gelation or heat treatment and were not tested under reverse osmosis. One tube was tested with 1% sodium chloride at 800 psi. It had a flux of 19.6 gfd, but a salt rejection of only 63%. Nearly all of the gross leaks were on the same side of the tube as the seam in the Dexter C-1140 support paper. Microscopic examination revealed thin areas and holes in the membrane immediately over the 80- to 100-mil overlap at the seam. It appeared that the additional wall thickness (18 mils vs 9 mils) due to the overlap was creating a ridge on the inside of the tube which pressed against the extrusion.
nozzle, thus wiping the high spots free of membrane. Therefore, the paper machine was modified to reduce the width of the paper and both edges were scarfed at an angle instead of just the inner one. The proper width of the support paper was determined by sectioning the finished tube and marking the seam with a pen. After removing the overlapping part of the seam, the mark on the outer section was observed under the microscope. The excessive overlap in Figure 36a is shown by the ink mark to the right of the scarfed edge. (In this and the succeeding photographs, 1-in. equals 20 mils.) By further reduction in the width of the paper, the overlap was limited to the 10-mil scarf as shown in Figure 36b. The inner edge of the overlap has a tendency to roll under when the tube is formed as shown in Figure 37a, but the addition of a thin metal guide in the paper machine at the point where the tube is rolled together results in a nearly perfect joint as shown in Figure 37b.

(b) Paper Finish

The membrane support paper, Dexter C-1140, has many fibers which tend to protrude through the membrane. These as well as the paper support were heavily stained when a water soluble dye, Niagara Sky Blue, was added to the reverse osmosis test solution (Figure 38). Since some of the dye was absorbed by the paper support, the amount of dye in the product could not be used to determine the actual leakage through the fibers. Therefore, a second reverse osmosis test was made with sodium sulfate, which is much less permeable than sodium chloride. Past experience with similar membrane systems has shown that a membrane which has a sodium chloride rejection of 90% will reject 99% or more of sodium sulfate. Conversely, a 70% membrane would have a sodium sulfate rejection of 97% or better. A sodium sulfate-sodium chloride permeation ratio of greater than one to ten would indicate that leaks were contributing to the high salt permeation of the membrane. Several membranes were cast into previously prepared tubes at 1.5 ft/min and pulled by forcing ice-water through the tube within 30 seconds after the end of the 2-ft tube left the extrusion nozzle. After heat treatment for 3 minutes at 160°F under 3 psi applied pressure, the tubes were tested under reverse osmosis with both sodium chloride and sodium sulfate in separate tests. As shown below, all of the tubes exhibited over 97% sodium sulfate rejection, which indicated that leakage through fibers in the membrane was not a significant factor, and that the low sodium chloride rejection was due to diffusion through the membrane itself (test conditions: 80 psi, 10,000 ppm).

<table>
<thead>
<tr>
<th>Tube No.</th>
<th>Sodium Chloride</th>
<th></th>
<th>Sodium Sulfate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flux, gfd</td>
<td>Rejection, %</td>
<td>Flux, gfd</td>
</tr>
<tr>
<td>457</td>
<td>3.9</td>
<td>77</td>
<td>4.8</td>
</tr>
<tr>
<td>459</td>
<td>5.0</td>
<td>65</td>
<td>5.1</td>
</tr>
<tr>
<td>460</td>
<td>11.0</td>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>462</td>
<td>6.8</td>
<td>80</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Figure 36. Scarfed Edge of Support Paper Showing Amount of Overlap
Figure 38. Paper Fiber Protruding Through Membrane
The sodium chloride rejection was improved by changes in the membrane gelation procedure as shown in the section on gelation techniques.

(3) Application Operating Parameters

A small transparent reservoir, as shown in Figure 39, was found to be the most suitable system for supplying the casting solution to the feed pump. The filtered solution is placed in the reservoir approximately 48 hours prior to use to allow time for all air bubbles to rise out of the solution. This simple arrangement facilitates cleaning of the system and permits replacement of the casting solution with a minimum amount of material.

Due to the low flow rates, it is necessary to operate the casting solution metering pump below its designed speed. At first, this was felt to be unsatisfactory and the differential output of two pumps was used to supply casting solution to the extrusion nozzle with most of the output of the pumps being returned to the reservoir. Bubbles in the casting solution returned to the reservoir were soon picked up by the pump intake, thus making it nearly impossible to purge the system of air. The metering pumps were found to be capable of delivering smooth reproducible flow rates when operated below their design speed, and the system was changed back to the once-through single-pump-system.

Only minor modifications have been made in the design of the extrusion nozzle. The angle of the extruder lip (45, 30 and 15°) was made steeper to obtain a more nearly vertical (from the tube axis) extrusion. This together with a reduction from 10 to 5 mils in the distance the extruded membrane had to travel from extruder lip to tube wall eliminated the need for a differential pressure across the extruded membrane to keep it in a bubble. It was found, however, that a slight ridge on the inside of the tube, caused by the overlap of the paper at the seam, tended to press against the extruder lip, wiping off the casting solution and leaving little or no membrane at all on the seam. Therefore, the step on the nozzle was increased to 15 mils to allow casting over irregularities in the paper and an air differential was used to maintain the bubble form. This can be provided by drawing a vacuum around the outside of the tube, but it is more convenient to supply a slight positive pressure to the inside of the bubble. Three methods were considered: A capillary tube could be inserted through the face of the nozzle. This is the most general method and will be used as soon as a nozzle with a suitable hole in it can be obtained. Positive air pressure can be supplied through a flexible line attached to the lower end of the tube to be membraned. When this method is used, the gelation step must wait until the membrane has been applied to the entire tube, which is undesirable. In the third method, the tube passes directly into the gel bath after leaving the extrusion nozzle. The pressure inside the bubble space can be regulated to a limited extent by raising the
Figure 39. Transparent Reservoir on Membrane Casting Equipment
level of the gelation bath after the membrane has formed a seal with the tube wall. This technique is not as flexible as the internal capillary approach since it is difficult to establish the proper initial pressure and there is no way to maintain a given pressure throughout the length of the tube. As seen in the next section, however, short tubes with acceptable performance can be made by this technique.

(4) Membrane Gelation

In developing the original casting formulation for this program, it was assumed that little acetone would be lost from the casting solution in the interval between casting and gelation since gelation would take place immediately after the membrane was applied to the support. Furthermore, the amount of acetone required to saturate the air space inside the tube could not materially effect the composition of the casting solution even if the liquid film were applied to the tube several minutes prior to gelation.

While it is planned that the membrane will be applied at the same rate and at the same time as the tube is manufactured, the present membranes are applied to short (2 to 4 ft) tube sections in a separate operation. The nozzle for the 0.25-in. tube was not designed for simultaneous gelation and the ice-water for gelation cannot be pumped through it as is planned for future systems. Therefore, the membranes shown below were applied to the entire tube prior to gelation. As a result, the time between casting and gelation varied from 15 seconds at one end of the tube to over 3 minutes at the other end, which may account for their generally low flux.

<table>
<thead>
<tr>
<th>Tube No.</th>
<th>Pressure</th>
<th>Flux, gfd</th>
<th>Salt Rejection, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>400</td>
<td>6.3</td>
<td>81</td>
</tr>
<tr>
<td>95</td>
<td>600</td>
<td>11.4</td>
<td>81</td>
</tr>
<tr>
<td>95</td>
<td>800</td>
<td>14.9</td>
<td>81</td>
</tr>
<tr>
<td>95</td>
<td>1000</td>
<td>18.3</td>
<td>82</td>
</tr>
<tr>
<td>93</td>
<td>400</td>
<td>2.6</td>
<td>77</td>
</tr>
<tr>
<td>93</td>
<td>600</td>
<td>5.5</td>
<td>85</td>
</tr>
<tr>
<td>93</td>
<td>800</td>
<td>7.8</td>
<td>80</td>
</tr>
<tr>
<td>93</td>
<td>1000</td>
<td>9.1</td>
<td>75</td>
</tr>
</tbody>
</table>

Laboratory experiments have shown that the paper support absorbs nearly 50% of the acetone from the casting solution during
the three minutes between casting and gelation. It is not practicable to compensate for this loss by adding more acetone to the casting solution since the residence time varies from one end of the tube to another.

The loss of acetone between casting and gelation was believed to be one of the major factors responsible for the rather low flux obtained from tubes prepared in this manner. Therefore, the procedure was modified to permit gelation within one to two seconds after the membrane was extruded into the tube. In this method, the gelation tank is located directly below the extrusion nozzle. Initially, the water level is 1.5 to 2.0-in. below the bottom of the extrusion nozzle. As soon as the membranated tube enters the water, the water level is raised to within 0.5-in. of the nozzle, thus slightly compressing the air within the bubble and forcing the bubble wall into intimate contact with the wall of the support tube.

(5) Heat Treatment

The osmotic properties of a series of tubular membranes which had been heated for 3 minutes at various temperatures, were measured to determine the effect of heat treatment on their flux and salt permeability. The membranes were cast from the following formulation at 3 ft per min (5 mil membrane) into a previously prepared 0.25-in. tubular support, which passed directly into an ice-water gelation bath located 0.5-in. below the extrusion nozzle:

<table>
<thead>
<tr>
<th>Parts in Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose acetate, E 400-25</td>
</tr>
<tr>
<td>Acetone</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Propionamide</td>
</tr>
</tbody>
</table>

The propionamide was increased from 6 to 7 parts to increase the flux of the membrane. This change was indicated by the low flux (10-17 gfd) and the opaque appearance of the membranes prepared from solutions containing 6 parts of propionamide. After heat treatment under an applied pressure of 3 psi, they were tested for 2 hours with 1% sodium chloride at 800 psi, followed by a one hour test with 1% sodium sulfate at the same pressure. As shown below, the flux and the sodium sulfate rejection remained constant while the sodium chloride rejection increased with heat treatment temperature:
<table>
<thead>
<tr>
<th>Tube No.</th>
<th>Temp.</th>
<th>Sodium Chloride</th>
<th>Sodium Sulfate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Flux, gfd</td>
<td>Rejection, %</td>
</tr>
<tr>
<td>616A</td>
<td>65</td>
<td>21.5</td>
<td>36.0*</td>
</tr>
<tr>
<td>616B</td>
<td>--</td>
<td>---</td>
<td>Tube leaked</td>
</tr>
<tr>
<td>616C</td>
<td>65</td>
<td>18.5</td>
<td>51.0</td>
</tr>
<tr>
<td>617A</td>
<td>65</td>
<td>16.5</td>
<td>51.0</td>
</tr>
<tr>
<td>617B</td>
<td>65</td>
<td>17.5</td>
<td>46.0</td>
</tr>
<tr>
<td>618</td>
<td>--</td>
<td>---</td>
<td>Tube leaked</td>
</tr>
<tr>
<td>618A</td>
<td>70</td>
<td>18.0</td>
<td>70</td>
</tr>
<tr>
<td>618B</td>
<td>70</td>
<td>17.0</td>
<td>70</td>
</tr>
<tr>
<td>618C</td>
<td>70</td>
<td>17.5</td>
<td>70</td>
</tr>
<tr>
<td>614</td>
<td>70</td>
<td>17.0</td>
<td>66</td>
</tr>
<tr>
<td>620A</td>
<td>75</td>
<td>20.0</td>
<td>80</td>
</tr>
<tr>
<td>620B</td>
<td>75</td>
<td>24.0</td>
<td>77</td>
</tr>
<tr>
<td>622A</td>
<td>75</td>
<td>20.0</td>
<td>72</td>
</tr>
<tr>
<td>623</td>
<td>75</td>
<td>21.0</td>
<td>76</td>
</tr>
<tr>
<td>622B</td>
<td>75</td>
<td>22.0</td>
<td>76</td>
</tr>
<tr>
<td>622C</td>
<td>75</td>
<td>19.0</td>
<td>73</td>
</tr>
<tr>
<td>608A</td>
<td>80</td>
<td>26.0</td>
<td>62*</td>
</tr>
<tr>
<td>608B</td>
<td>80</td>
<td>27.0</td>
<td>70*</td>
</tr>
<tr>
<td>608C</td>
<td>80</td>
<td>29.0</td>
<td>59*</td>
</tr>
<tr>
<td>609A</td>
<td>80</td>
<td>23.5</td>
<td>83</td>
</tr>
<tr>
<td>609B</td>
<td>80</td>
<td>21.0</td>
<td>82</td>
</tr>
<tr>
<td>610A</td>
<td>80</td>
<td>22.0</td>
<td>84</td>
</tr>
</tbody>
</table>

*These tubes leaked at some point along the seam. They were cut off and remounted before testing with sodium sulfate.

A series of tubes were heat treated at 80°C for 3 minutes at 0, 20, 40 and 60 psi to determine the effect of heat-treatment pressure on their osmotic properties. They were given the standard two-hour test with 1% sodium chloride at 800 psi.
While the results of this series of tests are inconclusive, higher pressures were found to have one important advantage. Minor leaks, which go undetected at the lowest pressure, are readily apparent at 20 psi or more. Thus the heat treatment step becomes the first stage of the quality control procedure and tubes with gross leaks can be eliminated at that point. Seventeen tubes were membraned and gelled by direct immersion in ice-water. One tube had a poor membrane due to loss of bubble pressure. Eight others had gross leaks which were detected by visual observation during heat treatment at 15 psi (3 min at 80°C). The leaks were shown to be a break in the membrane due to foreign material in the casting nozzle. The remaining nine tubes were given a two-hour reverse osmosis test with 1% sodium chloride at 800 psi:
From the above data, it appears that a flux of 16 to 20 gfd at 88 to 90% rejection can be expected of this particular membrane-support system.

While the experiments are not complete, preliminary evaluation of the flux stability of similar membranes cast on flat sheets of the Dexter support paper indicates that the slope of the log of their flux vs log time is approximately 0.04, which is normal for a brackish water membrane at 800 psi.

e. Tube Cut-off

(1) Equipment Design and Testing

It is necessary to cut the continuously fabricated and membranded reverse osmosis tube as it emerges from the machine into discrete lengths for end-fitting attachment, membrane heat treatment and ultimate assembly into the headers. Automatic, traveling cut-off technique (a cut-off saw that travels with the moving tube as it cuts off) was selected as the best method for separating the tube lengths.

The first attempt at a flying cut-off was a failure because the cut-off unit was too heavy and stiff to operate under the delicate force available from the moving tube. The redesigned unit, shown in Figure 40, operates on a new principle and is much lighter and more accurate than the previous model. In this unit the mass of the cut-off saw mechanism is started into motion by means of an air clutch for the actual cut-off. Actuation of the cut-off operation is cam operated from the downward travel of the tube as shown in Figure 41.

Several saw blade materials have been investigated including abrasive cut-off, a hardened steel fine-toothed saw, a carbide toothed saw blade and a diamond impregnated blade. The best performance was achieved with a 20,000 rpm air-driven saw using a 5-mil thick diamond cut-off blade.

The cut-off unit has been functionally tested separately from the continuous tube fabrication line and performs the cut-off operation satisfactorily. The unit has not been tested integrally with the line because the available laboratory equipment membranding of the tube is done on a separate line using precut tubes.

C. PILOT PLANT CONSTRUCTION AND START-UP

1. The final design for the 1000 gpd tubular reverse osmosis pilot plant was developed during the course of Contract No. DI 14-01-0001-1764.
Figure 40. Tube Cut-Off Equipment
Figure 41. Cam Operation on Cut-Off Machine
The significant aspects of the highly versatile design are described by the following photographs and drawings which are included as Appendix H.

Photograph 1213/033 - Small Scale Model of Pilot Plant
Photograph 1213/034 - Small Scale Model of Pilot Plant
Drawing No. 1360082, Sheet 1 - Equipment Skid
Drawing No. 1360082, Sheet 2 - Equipment Layout
Drawing No. 1360082, Sheet 3 - Piping - Section 1
Drawing No. 1360082, Sheet 4 - Piping - Section 2
Drawing No. 1360082, Sheet 5 - Piping Details
Drawing No. 1360082, Sheet 6 - Miscellaneous Details
Drawing No. 1360082, Sheet 7 - Flow Diagram
Drawing No. 1360082, Sheet 8 - Valve Schedule
Drawing No. 1360082, Sheet 9 - Instrument Panel
Drawing No. 1360082, Sheet 10 - Electrical Plan & Details
Drawing No. 1360082, Sheet 11 - Instrument Panel Electrical Details
Drawing No. 1360082, Sheet 12 - Isometric Piping Diagram

2. The pilot plant design was based upon three modules each having 52 tubes, 1/4-in. inside diameter and 10 ft long. Any other combination of tubes and headers having approximately the same cross-sectional flow characteristics would also be suitable. The product capacity was based upon approximately 100 sq ft of membrane area at a flux of 10 gfd yielding 1000 gal product per day. Thus 15 lineal feet of 1/4-in. tube approximately equals one square foot of membrane area. The flow capacity of the pilot plant is 20 gpm limited by the capacity of the Triplex plunger pump which delivers the required feed pressure. The limiting pressure is 1000 psi since the design is for brackish water. Each module included the capability to recycle up to 80 gpm of water. Lesser flows and pressure can of course be used in pilot plant operation.

3. The flow arrangements available in the design are (a) series flow through Modules 1, 2, and 3 or through Modules 1 and 2 or through Module 1 only, (b) parallel flow through Modules 1 and 2, and (c) parallel-series flow through Modules 1 and 2 and then through Module 3.

4. Construction of the pilot plant was delayed pending delivery of the skid structure to make the system portable, and because of overdue delivery of many of the system instrument components and of the module
recycle pumps. Construction was begun on 9 October 1968, and consisted of beginning the assembly of welded piping components, many of which could not be completed until delivery of critical components such as flanged flow transmitting rotometers, recycle pumps, control valves, etc. Piping construction was entirely of stainless steel.

5. Because of difficulties experienced in fabricating tubes with smooth, round interior surfaces on the substrate, a decision was made to expedite the obtaining of operating data by assembling only the first module at the El Monte plant site, with assembly of the remaining two modules to be accomplished at the test site. Also, because 10-ft long tubes cannot be manufactured and membrane with the laboratory equipment, it was decided to limit the length of tubes in the first module to 3- to 5-ft which could be made. Therefore, a 2-in. pipe spool piece flanged at each end and a 2-in. to 1-1/4-in. flanged spool were fabricated to "fill-in" for the space left by the short tubes.

6. Two stainless steel tube headers were fabricated for the initial test runs since expenditure of funds for molds for plastic parts was not considered justifiable until a larger number of parts is required.

7. The initial assembly of the single short length module was completed on 15 November 1968. A 10-ft long spool piece was substituted for the tube headers and tubes, and the unit was hydraulically checked for leaks. Following the leak corrections, a water solution of commercial cleaner was recirculated throughout the system to degrease and flush debris from the pipe lines.

8. On 19-20 November 1968, the skid-mounted pilot plant was partially disassembled, loaded, and trucked to the Laguna Beach site. The unit was set in place on a pre-prepared concrete pad with the use of a 5-ton mobile crane. Re-assembly of the pilot plant, using the spool piece in place of the tubes and headers, was completed on 23 November 1968. Temporary 440-volt power was connected to the skid as permanent hook-up was not scheduled until 27 November 1968.

9. In the few remaining days of the contract period, the pilot plant components were operated functionally but without benefit of calibration of flow and pressure control instrumentation. Simulated operation was possible after several critical instruments were readjusted by instrument technicians. Thus operation with tubes was planned to begin 25 November 1968.

10. The initial and succeeding installation of tubes was plagued by tube end-fittings being forced from the tube headers at pressures approaching 300 psig. Since these same tubes and fittings had been tested previously to the full 800 psi in a single-tube test fixture, and since similar
tubes and fittings had been tested to over 3000 psi, it was suspected, and confirmed, that some of the serrations had not been machined sufficiently deep in the headers. The headers were therefore reworked, and each tube opening was checked with a special gage to insure adequate depth of serration.
III. CONCLUSIONS

A. PROCESS FEASIBILITY

As stated in the introduction to this report, in meeting the objective of developing an economical tubular reverse osmosis system emphases was to be placed upon three major tasks: Engineering and parametric studies, design and development of tube headers and manifold systems, and development of a low-cost manufacturing method to produce the tubular elements. The accomplishments have been discussed in detail in the preceding sections. The feasibility of the process has been demonstrated as summarized in the following paragraphs.

1. The analytical studies have shown that tube areas and power requirements would be within acceptable limits. However, because of the uncertainty regarding the equations for predicting performance at Reynolds numbers less than 8000, the most desirable tube size for minimum power, area, and cost cannot be stated exactly, although indications are that 1/2-in. tubing is near optimum. Empirical information to be obtained from continued operation of the pilot plant will be necessary to eliminate this uncertainty.

2. A design has been prepared for a molded plastic header or manifold which is considered to be the least costly of the designs considered, and tube end-fittings suitable for easy insertion or removal from the header have been fabricated and demonstrated. Minor refinements were found necessary to improve reliability of the attachment of the fittings to the tubes, but the solution to this problem is available. Two headers having essentially the same configuration were machined from stainless steel in order to avoid the cost of molds, and used on the pilot plant.

3. Many hundreds of feet of 1/4-in. tube have been fabricated on the laboratory equipment in which the following steps of the process are accomplished as a continuous operation.

   a. Trimming, scarfing, and forming of the paper substrate.

   b. Braiding the fiber glass structure over the substrate, impregnating the glass with a solution of phenoxy resin, and removing the solvent to result in a rigid tube.

4. Membranes have been extruded and gelled continuously in 40-in. lengths of tubing on a separate processing line and have been heat-treated in a routine reliable manner using a pressurized temperature-controlled heating and cooling system.
5. Also as a separate operation a flying cut-off device has been successfully tested to separate the continuously manufactured tube into the desired lengths for modules.

6. Incorporation of all of these steps in tube manufacture into a continuous operation does not present any insurmountable problems, and the design of the pilot production line, which is now being fabricated and installed, will accomplish this.

7. Membraned tubes produced by the laboratory equipment have produced up to 20 gallons of product per square foot per day with rejection rates of about 80% of sodium chloride and 97% of sodium sulfate when operating at 800 psi.

8. From the foregoing list of accomplishments, it is considered that a completely feasible process to produce tubular reverse osmotic modules has been demonstrated on a semi-automatic basis.

\section*{FUTURE WORK}

The work to be accomplished will follow closely that described in the program plan of Aerojet-General Proposal No. PP-08-1213, minor modifications being made as dictated by the results of work which has been done during recent months. From present knowledge these changes are considered to be as outlined in the following paragraphs.

1. Task IA - Paper Substrate Tube Manufacture

In designing new equipment for cutting and feeding substrate for the pilot production line, more accurate tension control on the paper, more positive holding of the edges in position for scarfing, and an improved arrangement of micrometer adjustment of the scarfing knife wheels will be incorporated. Also additional rollers will be added to curve the paper more gradually and more positively to insure that the substrate will conform closely to the radius of the mandrel, particularly at the joint. This will produce a tubular substrate which will not be dependent upon the fiber glass braiding to hold the truly circular shape, which is necessary to insure a uniform thickness of membrane.

2. Task IB - Structural Tube Manufacture

Although it was proposed to install a Wardwell braiding machine on the pilot production line because of its greater speed, it has not yet been possible to devise an arrangement for incorporating longitudinal fibers as part of the braided construction. It may therefore be necessary to continue to use the Butts braiders, since the longitudinal fibers are necessary for transporting the braided tube through the manufacturing line.
APPENDIX A

COMPOSITION AND FLOW RELATIONSHIPS FOR TUBULAR REVERSE OSMOSIS UNITS OPERATING UNDER TURBULENT FLOW CONDITIONS
This technical memorandum shows the derivations of the principal equations needed to design and to predict the performance of tubular reverse osmosis units consisting of several sections placed in series. A section, as the term is used herein, consists of a number of tubes which are operated in parallel, and each tube may consist of several portions connected in series to give a tube of series length $L$. Succeeding sections generally will have a smaller number of tubes in parallel in order to maintain the Reynolds number at an acceptable level.

The material balances and the equations giving compositions in a single section are found in Part I of this memorandum. In Part II these are extended to a complete unit consisting of $n$ sections. Part III gives pressure drops, lengths, and performance parameters, while Part IV describes one way of correlating membrane properties in a quantitative fashion so that they can be used for design purposes.

At the present time the uncertainty in membrane properties, particularly with regard to deterioration with time, is probably the weakest point in our ability to design units to yield a specified performance. However, it is hoped that this situation can be improved sufficiently with actual performance data that the refinements in the performance equations shown herein are truly useful.

The nomenclature used is described fully at the end of the text.

I. MATERIAL BALANCES AND COMPOSITIONS, SINGLE SECTION

The $(j)^{th}$ section of a reverse osmosis unit is shown in Figure 1. The weight rates of flow of the various streams are indicated by $F_j$, $I_j$, $P_j$, $D_j$, and $\beta_j F_j$, where $\beta_j$ is the ratio of recirculation to feed. The compositions of the various streams are also on a weight basis (i.e., ppm) and are indicated by subscripted $C$'s.
The section recovery, designated by $\gamma_j'$, is defined as:
\[
\gamma_j' = \frac{P_j}{F_j} \tag{1}
\]

and flow rates in the section are, therefore,
\[
P_j = \gamma_j' F_j \tag{2}
\]
\[
I_j = (1 - \beta_j') F_j \tag{3}
\]
\[
D_j = (1 - \gamma_j') F_j \tag{4}
\]

Overall section material balances on salt can be written as:
\[
F_{j,i} C_{i,j} = P_{j,i} C_{P_j,i} + D_{j,i} C_{D_j,i} \tag{5}
\]
\[
I_{j,i} C_{I_{j,i}} = F_{j,i} C_{I_{j,i}} + \beta_j' F_j C_{D_j,i} \tag{6}
\]

It is necessary to consider the process inside one section in order to relate compositions to membrane properties and concentration polarization effects.

Consider the portion of the section from the inlet, where section recovery is zero, to a point where the section recovery is $\delta$, with $\delta$ varying from zero to $\gamma_j'$ in the complete section. Figure 2 shows this portion. Subscript j's are omitted in the figure and will be omitted in the derivation until needed.

The salt permeability $(1 - \lambda)$ of a membrane is defined as the ratio of composition of the product passing through the membrane to the composition $C_w$ of the saline water at the membrane surface, and is often a function of flux as well as other parameters. The composition of the product passing locally through a membrane is therefore $(1 - \lambda) C_w$. For the streams emerging in Figure 2:

Weight of product $= \delta F \tag{7}$

Weight of salt in product $= \int_0^\delta (1 - \lambda) C_w (F \, d\delta) \tag{8}$

A-3
Concentration of product \[ \frac{1}{\delta} \int_0^\delta (1 - \lambda) C_0 \, d\delta \] (9)

and for the saline stream:

Weight of stream \[ (1 + \beta - \delta) F \] (10)

Weight of salt \[ (1 + \beta) F C_i - \int_0^\delta (1 - \lambda) C_w \, d\delta \] (11)

Concentration \[ \bar{C} = \frac{1}{(1 + \beta - \delta)} \left[ (1 + \beta) C_i - \int_0^\delta (1 - \lambda) C_w \, d\delta \right] \] (12)

Since \[ \frac{C_w}{C} \] , and taking

\[ \lambda = (1 - \lambda) \left( \frac{C_w}{C} \right) \] (13)

Equation (12) can be written as

\[ \bar{C} = \frac{1}{1 + \beta - \delta} \left[ (1 + \beta) C_i - \int_0^\delta \bar{C} \, d\delta \right] \] (14)

which is an integral equation in \( \bar{C} \). Differentiation of Equation (14) with respect to \( \delta \) gives

\[ \frac{d\bar{C}}{C} = \frac{(1 - \lambda) \, d\delta}{1 + \beta - \delta} \] (15)

Taking \( s \) constant, since \( (C_w / \bar{C}) \) will vary little in a section for turbulent flow, and integrating Equation (15) from 0 to \( \delta \):

\[ \ln \frac{\bar{C}}{C_i} = (1 - \lambda) \ln \frac{1 + \beta}{1 + \beta - \delta} \] (16)

or

\[ \bar{C} = C_i \left( \frac{1 - \delta}{1 + \beta} \right)^{\lambda - 1} \] (17)

The discharge concentration is obtained from Equation (17) by setting \( \delta = \gamma \)' to give
Appendix A (cont.)

\[ C_D = C_I \left(1 - \frac{\gamma'}{1+\beta}\right)^{A-1} \]  
\[ \text{(18)} \]

or, letting

\[ A = 1 - \frac{\gamma'}{1+\beta} \]  
\[ \text{(19)} \]

\[ C_D = C_I A^{A-1} \]  
\[ \text{(20)} \]

Using Equations (3) and (20) in Equation (6)

\[ (1+\beta)FC_I = FC_F + \beta FC_I A^{A-1} \]  
\[ \text{(21)} \]

giving

\[ C_I = \frac{C_F}{1+\beta - \beta A^{A-1}} = C_F \frac{A}{(1-\gamma')(1 + \frac{\beta}{1-\gamma'}(1-A^A))} \]  
\[ \text{(22)} \]

or

\[ C_I = C_F \frac{A}{(1-\gamma')E} \]  
\[ \text{(23)} \]

with

\[ E = 1 + \frac{\beta}{1-\gamma'}(1-A^A) \]  
\[ \text{(24)} \]

So, using Equations (2) and (23)

\[ C_D = C_F \frac{A^A}{(1-\gamma')E} \]  
\[ \text{(25)} \]

and, using Equations (2), (4), (5), and (25),

\[ C_P = \frac{C_F}{\gamma'} \left[1 - \frac{A^A}{E}\right] = C_F \frac{(1+\beta)A(1-A^A)}{\gamma'(1-\gamma')E} \]  
\[ \text{(26)} \]
Subscripts \( j \) can now be appended and the concentrations for section \( j \), as shown in Figure 1, summarized:

\[
C_{I,j} = C_{F,j} \frac{A_j}{(1 - \gamma_j')} E_j \tag{27}
\]
\[
C_{D,j} = C_{F,j} \frac{(A_j)^{\alpha_j}}{(1 - \gamma_j')} E_j \tag{28}
\]
\[
C_{P,j} = C_{F,j} \frac{(1 + \beta_j)A_j \left[ 1 - (A_j)^{\alpha_j} \right]}{\gamma_j' \left( 1 - \gamma_j' \right) E_j} \tag{29}
\]

with

\[
A_j = 1 - \frac{\gamma_j'}{1 + \beta_j} \tag{30}
\]

and

\[
E_j = 1 + \frac{\beta_j}{1 - \gamma_j'} \left[ 1 - (A_j)^{\alpha_j} \right] \tag{31}
\]

If there is no recirculation, \( \beta_j = 0 \) and Equations (27) through (29) become:

\[
\begin{align*}
C_{I,j} &= C_{F,j} \quad \beta_j = 0 \tag{32} \\
C_{D,j} &= C_{F,j} \left( 1 - \gamma_j' \right)^{\alpha_j - 1} \tag{33} \\
C_{P,j} &= C_{F,j} \frac{1}{\gamma_j'} \left[ 1 - \left( 1 - \gamma_j' \right)^{\alpha_j} \right] \tag{34}
\end{align*}
\]
Appendix A (cont.)

On the other hand, for $\beta_j$ very large,

$$ A_j \rightarrow 1 \quad (35) $$

$$ 1 - (A_j)^{A_j} \rightarrow \frac{A_j \cdot \gamma_j}{1 + \beta_j} \quad (36) $$

$$ E_j \rightarrow 1 + \frac{A_j \cdot \gamma_j}{1 - \gamma_j} \quad (37) $$

so Equations (27) through (29) become

$$ \beta_j \text{ large} \begin{cases} 
C_{I, j} = C_{F, j} \frac{1}{(1 - \gamma_j)(1 + \frac{A_j \cdot \gamma_j}{1 - \gamma_j})} \\
C_{D, j} \approx C_{I, j} \\
C_{P, j} \approx C_{F, j} \frac{A_j}{(1 - \gamma_j)(1 + \frac{A_j \cdot \gamma_j}{1 - \gamma_j})} 
\end{cases} \quad (38, 39, 40) $$

2. Material Balances and Compositions, Multisection Unit

Figure 3 shows a unit consisting of $n$ sections arranged in series, with the discharge from one section being the feed to the next, and the product all collected together.

Section $j$ is related to the proceeding one by

$$ F_{j} = D_{j-1} \quad (41) $$

$$ C_{F, j} = C_{D, j-1} \quad (42) $$
Appendix A (cont.)

From these relations, and Equations (2) through (4) and (27) through (29), the flow rates and compositions in section \( j \) can be related to those for the feed to section \( 1 \) as follows:

\[
F_j = F_1 \frac{j-1}{\sum_{i=1}^{j-1} (1 - \gamma^i)}
\]

(43)

\[
P_j = F_1 \gamma_j \frac{j-1}{\sum_{i=1}^{j-1} (1 - \gamma^i)}
\]

(44)

\[
I_j = F_1 \left(1 + \beta_j \right) \frac{j-1}{\sum_{i=1}^{j-1} (1 - \gamma^i)}
\]

(45)

\[
D_j = F_1 \frac{j}{\sum_{i=1}^{j} (1 - \gamma^i)}
\]

(46)

\[
C_{F,j} = C_{F,1} \frac{\prod_{i=1}^{j-1} (A_i)^{A_i}}{\prod_{i=1}^{j-1} (1 - \gamma^i)} \prod_{i=1}^{j-1} E_i
\]

(47)

\[
C_{I,j} = C_{F,1} \frac{\prod_{i=1}^{j-1} (A_i)^{A_i}}{\prod_{i=1}^{j-1} (1 - \gamma^i)} \prod_{i=1}^{j-1} E_i
\]

(48)

\[
C_{P,j} = C_{F,1} \frac{(1 + \beta_j) A_j \left[1 - (A_j)^{A_j} \right] \prod_{i=1}^{j-1} (A_i)^{A_i}}{\gamma_j \left[\prod_{i=1}^{j-1} (1 - \gamma^i)\right] \prod_{i=1}^{j-1} E_i}
\]

(49)

\[
C_{D,j} = C_{F,1} \frac{(A_j)^{A_j}}{\prod_{i=1}^{j} (1 - \gamma^i) \prod_{i=1}^{j} E_i}
\]

(50)

The combined product of the \( n \)-section unit, \( \sum_{j=1}^{n} P_j \), is used to define the unit recovery \( \gamma \), which is on a weight basis, as
Appendix A (cont.)

\[
\gamma = \frac{\sum_{j=1}^{n} P_j}{F_i}\]  \tag{51}

and the composition of this product is given by

\[
\bar{C}_p = \frac{1}{F_i \gamma} \sum_{j=1}^{n} C_{p,j} P_j \]  \tag{52}

or

\[
\bar{C}_p = \frac{C_{F_{i,j}}}{\gamma} \sum_{j=1}^{n} \frac{(1 + \beta_j) A_j \left[1 - (A_j)^{A_j} \right]^{j-1} (A_{\gamma})^{A_j}}{(1 - \gamma_j^i) \prod_{\lambda=1}^{j-1} E_{\lambda}} \tag{53}

For no recirculation, where \( \beta_j \) equals zero,

\[
A_j = 1 - \gamma_j^i \]  \tag{54}

\[
E_j = 1 \]  \tag{55}

and compositions are, from Equations (47) through (50) and (53),

\[
\beta = 0
\]

\[
\begin{align*}
C_{F_{i,j}} &= C_{F_{i,1}} \left(1 - \gamma_j^i\right)^{A_j - 1} \\
C_{T_{i,j}} &= C_{F_{i,1}} \left(1 - \gamma_j^i\right)^{A_j - 1} = C_{F_{i,j}} \\
C_{P_{i,j}} &= C_{F_{i,1}} \frac{1}{\gamma_j^i} \left[1 - (1 - \gamma_j^i)^{A_j}\right] \prod_{\lambda=1}^{j-1} (1 - \gamma_j^i)^{A_j - 1} \\
C_{D_{i,j}} &= C_{F_{i,1}} \prod_{\lambda=1}^{j-1} (1 - \gamma_j^i)^{A_j - 1}
\end{align*} \tag{56-59}
\]
\[
C_p = \frac{C_{F_i}}{\gamma} \left[ 1 - \frac{1}{\prod_{j=1}^{n} (1 - \gamma_j) \gamma_j' \prod_{i=1}^{m} (1 - \delta_i \gamma_i')} \right] \quad (60)
\]

For very large recirculation, that is all \( \beta_j \gg 1 \),

\[
C_{F_{j,i}} \approx C_{F_{i}}, \quad \frac{1}{\prod_{i=1}^{n} (1 - (1 - \delta_i) \gamma_i')} \quad (61)
\]

\[
C_{I_{j,i}} \approx C_{F_{i}}, \quad \frac{1}{\prod_{i=1}^{n} (1 - (1 - \delta_i) \gamma_i')} \quad (62)
\]

\[
C_{P_{j,i}} \approx C_{F_{i}}, \quad \frac{1}{\prod_{i=1}^{n} (1 - (1 - \delta_i) \gamma_i')} \quad (63)
\]

\[
C_{D_{j,i}} \approx C_{I_{j,i}} \approx C_{F_{j,i}}, \quad \frac{1}{\prod_{i=1}^{n} (1 - (1 - \delta_i) \gamma_i')} \quad (64)
\]

\[
C_p \approx \frac{C_{F_{i}}}{\gamma} \sum_{j=1}^{n} \frac{\delta_j \gamma_j'}{\prod_{i=1}^{m} (1 - \delta_i \gamma_i')} \quad (65)
\]

Material balances over the whole \( n \)-section unit show that

\[
F_i = \sum_{j=1}^{n} P_j + D_n \quad (66)
\]

and using the definition of Equation (51),

A-10
Appendix A (cont.)

\[ \sum_{j=1}^{n} P_j = \gamma F_i \]  \hspace{1cm} (67)

so that

\[ D_n = (1 - \gamma) F_i \]  \hspace{1cm} (68)

If Equation (46) is applied for \( j = n \), there is obtained

\[ 1 - \gamma = \prod_{j=1}^{n} (1 - \gamma_j) \]  \hspace{1cm} (69)

which relates the overall recovery to the section recoveries.

There is logic for designing a unit having all section recoveries equal. For all \( \gamma_j' = \gamma' \)

\[ 1 - \gamma = (1 - \gamma')^n \]  \hspace{1cm} (70)

so

\[ \gamma' = 1 - (1 - \gamma)^\frac{1}{n} \]  \hspace{1cm} (71)

Substitution of equal \( \gamma' \) in Equations (43) through (50) gives

\[ \int F_j = F_i (1 - \gamma')^{j-1} \]  \hspace{1cm} (72)

A-11
\[ P_j = \frac{F_j \gamma'(1 - \gamma')^{j-1}}{} \]
\[ I_j = \frac{F_j (1 + \beta_j) (1 - \gamma')^{j-1}}{} \]
\[ D_j = \frac{F_j (1 - \gamma')^j}{\prod_{\lambda=1}^{j-1} (A_{\lambda})^{\Delta_{\lambda} / \lambda}} \]
\[ C_{F,j} = \frac{C_{F,1}}{\prod_{\lambda=1}^{j-1} E_{\lambda}} \]
\[ C_{T,j} = \frac{A_j \prod_{\lambda=1}^{j-1} (A_{\lambda})^{\Delta_{\lambda} / \lambda}}{\prod_{\lambda=1}^{j-1} E_{\lambda}} \]
\[ C_{P,j} = \frac{(1 + \beta_j) A_j \left[ 1 - (A_j)^{\Delta_j / j} \right] \prod_{\lambda=1}^{j-1} (A_{\lambda})^{\Delta_{\lambda} / \lambda}}{\gamma'(1 - \gamma')^j \prod_{\lambda=1}^{j-1} E_{\lambda}} \]
\[ C_{D,j} = \frac{\prod_{\lambda=1}^{j-1} (A_{\lambda})^{\Delta_{\lambda} / \lambda}}{(1 - \gamma')^j \prod_{\lambda=1}^{j-1} E_{\lambda}} \]

Equation (53) for the product composition is essentially unchanged.

For the case of no recirculation and constant section recovery, Equations (56) through (60) become:

\[ \sum_{\lambda=1}^{j-1} \Delta_{\lambda} = -(j-1) \]

\[ C_{F,j} = C_{F,1} \left( 1 - \gamma' \right)^{(j-1)} \]
The relationships for large $\beta$, Equations (61) through (65), are not much simplified by a constant $\gamma'$. 

3. Tubular Sections: Pressure Drop, Size and Performance Parameters

The pressure gradient in a tube of circular cross section is given by

$$ -\frac{dP}{dx} = \frac{4 \sigma u^2}{D g} \left( \frac{f}{2} \right) $$

(85)

in which the Fanning friction factor is used. For smooth tubes in the range of Reynolds number of $10^4$ to $10^5$ the friction factor is well fit by the equation

$$ \frac{f}{2} = 0.032 \, R^{-0.13} $$

(86)

in which the customary definition of Reynolds number is used.
Appendix A (cont.)

\[ R = \frac{D u}{v} \]  \hspace{1cm} (87)

The pressure drop due to tube friction in a recirculated section having a section recovery of \( \delta' \) will be calculated. The water flux \( v_w \) will be taken as constant at an average value, as will the viscosity and the specific weight of the solution. At a point \( x \) from the section entrance the section recovery is taken as \( \delta \), and for \( x = L \), \( \delta = \delta' \). With subscript zero designating values at the entrance to the section,

\[ u = u_0 \left( 1 - \frac{\delta}{1 + \beta} \right) \]  \hspace{1cm} (88)

\[ R = R_0 \left( 1 - \frac{\delta}{1 + \beta} \right) \]  \hspace{1cm} (89)

so

\[ u = \frac{v R}{D} = \frac{v R_0}{D} \left( 1 - \frac{\delta}{1 + \beta} \right) \]  \hspace{1cm} (90)

Substituting Equation (86) and (90) in Equation (85) gives

\[ -\frac{dP}{dx} = \frac{4(0.032)\sigma v^2 (R_0)^{1.77}}{D^3 q} \left( 1 - \frac{\delta}{1 + \beta} \right)^{1.77} \]  \hspace{1cm} (91)

However, to integrate this equation, a relationship between \( x \) and \( \delta \) is needed. The product weight is
\[
\delta F' = \pi D \times v_w \sigma p
\]  
(92)

and the inlet stream weight is

\[
I' = \frac{\pi}{4} D^2 u_0 \sigma = (1+\beta) F'
\]  
(93)

Elimination of \( F' \) between Equations (92) and (93) gives

\[
\chi = \frac{D u_0}{4 v_w} \sigma \left( \frac{\delta}{1+\beta} \right) = \frac{v^3 R_0}{4 v_w} \sigma \left( \frac{\delta}{1+\beta} \right)
\]  
(94)

which can be differentiated and used in Equation (91) to give

\[
-\Delta p = \frac{0.032 \sigma^2 v^3 (R_0)^{2.77}}{v_w D^3 g \sigma p} \left( 1 - \frac{\delta}{1+\beta} \right)^{1.77} d \left( \frac{\delta}{1+\beta} \right)
\]  
(95)

This integrates, for a section recovery of \( \chi' \), to give

\[
-\Delta p = \frac{0.032}{2.77} \frac{v^3 \sigma^2 (R_0)^{2.77}}{D^3 g v_w \sigma p} \left[ 1 - \left( 1 - \frac{\chi}{1+\beta} \right)^{2.77} \right]
\]  
(96)

for the pressure drop due to skin friction in a section. Entrance and exit losses, and other manifolding losses, are not included in Equation (96), but
can be included by multiplying by an appropriate factor \( k_p \).

The length of tube in series in a section is obtained from Equation (94) by letting \( \delta = \gamma' \) at \( x = L \), to give

\[
L = \frac{\nu R_o \sigma}{4 \sqrt{\nu w \sigma_p}} \left( \frac{\gamma'}{1 + (1/3)} \right)
\]  

(97)

It is noteworthy that the diameter does not appear explicitly in Equation (97). However the pressure drop is a very strong function of diameter if Reynolds number is held constant.

Reynolds number must be regarded as a very important parameter because of its influence on concentration polarization. For the fully turbulent regime

\[
\frac{C_n}{C} = \frac{\exp(\Theta)}{1 + (1 - \lambda)[\exp(\Theta) - 1]} = \frac{\exp(\Theta)}{\lambda + (1 - \lambda)\exp(\Theta)}
\]  

(98)

where:

\[
\Theta = \frac{2}{f} \frac{\sqrt{w}}{U} (N_s)^{2/3}
\]  

(99)

Substituting Equations (86) and (90) for a point in the middle of the section, where \( \delta = \gamma'/2 \), gives

\[
\Theta = \frac{\nu w D (N_s)^{2/3}}{0.032 \nu R^{0.77}} = \frac{\nu w D (N_s)^{2/3}}{0.032 \nu (R_o)^{0.77}} \left[ 1 - \frac{1}{2} \left( \frac{\gamma'}{1 + (1/3)} \right) \right]^{0.77}
\]  

(100)

The value of \( \frac{C_n}{C} \) therefore can be calculated from Equations (98) and (100)
Appendix A (cont.)

provided that the Reynolds number is sufficiently high for the flow to be fully turbulent. The smallest Reynolds number will be at the exit, where

$$(\bar{R})_{\min} = R_c \left(1 - \frac{8^'}{1+\beta}\right)$$

(101)

It is not certain how large $(\bar{R})_{\min}$ must be, but a value of perhaps 8000 should be adequate.

In case a specific value of $\frac{C_w}{C}$ is wanted, Equations (98) and (100) can be solved for $R_c$, to give

$$R_c = \frac{1}{1 - \frac{1}{2} \left(\frac{8^'}{1+\beta}\right)} \left\{ \frac{\nu_w D (N_s)^{2/3}}{0.032 \nu \left[ \ln \frac{C_w}{C} + \ln \left(\frac{\lambda}{1-(1-\lambda) \frac{C_w}{C}}\right) \right]} \right\}^{1/0.97}$$

(102)

The equations shown so far in this section are in consistent units, with velocity $u$ and water flux $\nu_w$ expressed in ft/sec, lengths and diameter $D$ in feet, pressure in lb/ft$^2$, and so forth. However, for calculation purposes it is advantageous to have water fluxes expressed in gal/(day)(ft$^2$), and diameters in inches. The following substitutions will be used:

$$\nu_w \text{ ft/sec} = 1.547 \times 10^{-6} \bar{J} \quad J \text{ gal/(ft}^2\text{)(day)}$$

(103)

$$D \text{ ft} = \frac{d}{12} \quad d \text{ in}$$

(104)

$$g = 32.174 \text{ ft/sec}^2$$

(105)

$$\sigma \text{ lb/ft}^3 = 62.4 \Phi$$

(106)
where \( \phi \) is specific gravity referred to water at 40°C.

\[
P' \text{ ft}^2 = 144 \ P'
\]

(107)

With these substitutions, and multiplying by \( k' \), Equation (96) for \( \Delta P \) becomes

\[
(-\Delta P')_{ps} = 1.735 \times 10^5 \frac{k' \nu^2}{d^3} \frac{\phi (R_0)^{2.77}}{J \phi_p} \left[ 1 - \left(1 - \frac{\delta}{1+\beta} \right)^{2.77} \right]
\]

(108)

The length of tube in series in a section, from Equation (97), becomes

\[
L' \text{ ft} = 1.613 \times 10^5 \frac{\nu R_0 \phi}{J \phi_p} \left( \frac{\delta}{1+\beta} \right)
\]

(109)

The argument \( \Theta \), of Equation (100), becomes

\[
\Theta = \frac{4.035 \times 10^{-6} \int d (N_s)^{2/3}}{\nu (R_0)^{0.77} \left[ 1 - \frac{1}{2} \left( \frac{\delta}{1+\beta} \right)^{0.77} \right]}
\]

(110)

and Reynolds number at the inlet, Equation (102), becomes

\[
R_n = \frac{1}{1 - \frac{1}{2} \left( \frac{\delta}{1+\beta} \right)} \left\{ \frac{4.035 \times 10^{-6} \int d (N_s)^{2/3}}{\nu \left[ \frac{\lambda}{1-(1-\lambda) \frac{C_w}{c}} \right] \left[ \frac{\lambda}{1-(1-\lambda) \frac{C_w}{c}} \right]} \right\}^{1.2987}
\]

(111)
Appendix A (cont.)

4. Membrane Properties

In order to design reverse osmosis plants, it is necessary to know the water flux and salt retention properties of membranes as functions of membrane formulation, heat treat temperature, applied pressure, salt concentration, operating temperature, length of time used, and so forth. This section describes relations which have been developed and used to fit available data on triple salt membranes.

The salt flux \( J_s \) can be expressed as

\[
J_s = k_1 (C_w - C_p) + k_2 C_w J
\]

\[
= k_1 \lambda C_w + k_2 JC_w
\]

in which the first term \( k_1 \lambda C_w \) is a diffusion term and the second term \( k_2 JC_w \) is a term representing interaction with the water flux.

The water flux can be expressed as

\[
J = R_3 (P' - \Pi) = R_3 (P' - R_\Pi \lambda C_w)
\]

in which \( \Pi \) is the osmotic pressure. However, the coefficient \( R_3 \) has been observed to be a function of pressure, and can be fitted by an equation of the form

\[
R_3 = \frac{R_w}{1 + R_4 P'}
\]

so

\[
J = \frac{R_w (P' - R_\Pi \lambda C_w)}{1 + R_4 P'}
\]
The product concentration is obtained from Equation (112) as

\[ C_P = \frac{J_s}{J} = \left( \frac{k_1 \lambda}{J} + R_2 \right) C_w \]  \hspace{1cm} (116)

so the salt permeability is

\[ 1 - \lambda = \frac{C_P}{C_w} = \frac{k_1 \lambda}{J} + R_2 = \frac{k_1 + R_2 J}{R_1 + J} \] \hspace{1cm} (117)

The membrane properties are influenced by many factors. Among these are the manufacturing method and formulation, thickness, imperfections, etc. The following discussion has to do with membranes made from a specific formulation of selected raw materials by a specific and well-controlled process. These membranes will be presumably of good quality and exhibit a relatively small variation in water flux and in salt flux when treated and tested in a standard manner.

The desalination properties of a membrane are strong functions of the types and relative amounts of salts comprising the saline solution. The set of properties discussed below is that set exhibited when the dissolved solids in the saline solution consist of only one specific salt (such as NaCl), or at least one specific composition of a mixture of salts. The coefficients, particularly \( k_1 \) and \( k_2 \), are strong functions of the salts and of their relative proportions.

The membrane properties are described in terms of the coefficients \( k_1 \), \( k_2 \), \( k_4 \) and \( k_w \). These are functions of the heat-treat temperature \( \Upsilon \), and are apparently fitted by equations of the form

\[ \ln k = a - b \Upsilon \] \hspace{1cm} (118)
Appendix A (cont.)

The coefficients $k_1$ and $k_w$, and possibly $k_2$ and $k_h$, are functions of the operating temperature, and it is believed on theoretical grounds that they should be fit by Arhennius-type equations

$$\ln k = a - \frac{E}{RT} \quad (119)$$

However, the temperature range of interest is so small that the theoretical form is probably not distinguishable from the form

$$\ln k = a + bt \quad (120)$$

for fitting experimental data. There is some evidence that the activation energy $E$, at least for salt diffusion, is a function of heat treat temperature.

Although not yet demonstrated, it seems likely that the coefficients $k_1$ and $k_w$, and possibly $k_2$ and $k_h$, may be functions of the concentration of the saline solution to which they are exposed. The form of this functional relationship remains to be determined.

Membrane properties are also known to change with time while they are in service. Change, which is often rapid, can be caused by precipitation on the membrane surface, and this must be avoided. However even without precipitation there is still change in properties which results in decline in the water flux and often an increase in product salinity. Not much is known quantitatively about this decline phenomenon. Qualitatively it appears that the decline is faster at higher operating pressures, and that membranes of lower heat treat temperatures which initially exhibit high water fluxes may decline much faster than do membranes heat treated at high temperatures and may actually decline to lower fluxes than those shown by the high heat treat temperature membranes after the same length of time. Scanning of limited data makes it appear plausible that $k_w$ decreases while $k_1$ stays relatively constant during flux decline for membranes of median heat treat temperature.

The remaining coefficient appearing in Equation (115), the osmotic coefficient $k_\gamma$, is a solution property. It is a weak function of concentration for dilute solutions, is a function of the relative proportions of the various
Appendix A (cont.)

salts, and their identity. It is also a function of temperature. The van't Hoff law of osmotic pressure is

\[ \Pi = -\frac{RT}{\tilde{v}_w} \ln(1 - n_s) \]  

(121)

presuming the partial volume of water \( \tilde{v}_w \) to be unaffected by the presence of salt. Neglecting change in partial volume of water with temperature, the temperature effect is

\[ \Pi = \Pi_0 \frac{T}{T_0} \]  

(122)

so

\[ R_0 \Pi = R \Pi_0 \frac{T}{T_0} \]  

(123)

The coefficients \( k_1, k_2, k_4 \) and \( k_w \) must be obtained from experimental results. Equation (115) can be written as

\[ J = \frac{k_w \Delta}{1 + k_4 P'} \]  

(124)

in which

\[ \Delta = P' - k_\Pi \lambda C_w \]  

(125)

and Equation (124) can be rearranged to give

\[ \frac{A}{J} = \frac{1}{R_w} + \frac{k_4}{R_w} P' \]  

(126)
Appendix A (cont.)

The membrane coefficients \( k_\omega \) and \( k_\delta \) are determined from the intercept and slope of a plot of \( \Delta j / j \) as a function of \( P' \) for a particular value of \( T' \), operating temperature \( t \), \( C_\omega \) (or at least \( C_\delta \)), and membrane operating age. Since some of the effects of pressurization on membranes are apparently irreversible, particular care must be taken to avoid subjecting a membrane to a pressure higher than that at which a measurement is to be made.

Equation (117) can be expressed in several ways in order to analyze data to obtain \( k_1 \) and \( k_2 \). If written without rearrangement,

\[
1 - \lambda = k_1 \frac{\lambda}{J} + k_2
\]

(1 - \( \lambda \)) is plotted against (\( \lambda / J \)). The slope is \( k_1 \) and the intercept is \( k_2 \). The data plotted should be those for a particular value of \( T' \), \( t \), \( C_\omega \), and operating age. Since \( k_2 \) is a small fraction of (1 - \( \lambda \)) for membranes having a relatively small value of (1 - \( \lambda \)), the accuracy of determination of \( k_2 \) is poor. Alternative expressions which have been used to analyze data are

\[
\frac{1}{\lambda} = \frac{1}{1 - k_2} + \frac{k_1}{1 - k_2} \left( \frac{1}{J} \right)
\]

(128)

and

\[
\frac{1 - \lambda}{\lambda} J = k_1 + k_2 \frac{J}{\lambda} = \frac{k_1}{1 - k_2} + \frac{k_2}{1 - k_2} J
\]

(129)

Equation (129) is of some interest in its final form since it is equivalent to

\[
\frac{J_3}{C_\omega - C_p} = \frac{k_1}{1 - k_2} + \frac{k_2}{1 - k_2} J
\]

(130)
and so involves plotting the normalized salt flux against the water flux. However, Equation (129) involves plotting a product involving $J$ against $J$, which is misleading in judging the extent of correlation. Equation (127) is straightforward and probably the best for use.

It is apparent that $C_w$ must be known in order to analyze the data. Therefore, measurements must be made under conditions where $C_w / \bar{C}$ is both predictable, and not much greater than unity so that errors in prediction will be small.
NOMENCLATURE

\( A \)

\( 1 - \frac{y'}{(1 + \beta)} \)

\( C \)

composition, ppm salts

\( C_D \)

composition of discharge stream, ppm

\( C_F \)

composition of feed stream, ppm

\( C_I \)

composition of inlet stream, ppm

\( C_P \)

composition of product stream, ppm

\( \bar{C} \)

composition of stream inside tube, ppm

\( \bar{C}_P \)

composition of mixed product from \( n \) sections, ppm

\( C_w \)

composition at membrane surface, ppm

\( D \)

internal diameter of tube, ft; discharge flow, lb/day

\( D_s \)

diffusivity of salt, \( ft^2/sec \)

d

internal diameter of tube, in.

\( E \)

\( 1 + \beta(1 - A^s)/(1 - y') \); activation energy, kilocal/mol

\( \exp \)

exponential function of ( ), \( = e^{( )} \)

\( F \)

feed rate, lb/day

\( F' \)

feed rate, lb/sec

\( f \)

Fanning friction factor

\( g \)

acceleration due to gravity, \( 32.174 \ ft/sec^2 \)

\( I \)

inlet rate, lb/day

\( I' \)

inlet rate, lb/sec

\( J \)

water flux, \( gal/(ft^2)(day) \)

\( J_s \)

salt flux, \( (ppm)(gal)/(ft^2)(day) \)

\( j \)

section number, varies from 1 through \( n \)

\( k_f \)

factor increasing skin friction to include other losses
Appendix A
Nomenclature (cont.)

\( k_p \) 
membrane pressure coefficient, \((\text{ft}^2)(\text{day})/\text{gal}\)

\( k_w \) 
membrane water flux coefficient, \(\text{gal}/(\text{ft}^2)(\text{day})(\text{psi})\)

\( k_1 \) 
salt flux coefficient, \(\text{gal}/(\text{ft}^2)(\text{day})\)

\( k_2 \) 
salt interaction coefficient, dimensionless

\( k_3 \) 
coefficient, \(\text{gal}/(\text{ft}^2)(\text{day})(\text{psi})\)

\( k_4 \) 
\(k_p k_w (\text{psi})^{-1}\)

\( k_\pi \) 
osmotic coefficient, \(\text{(psi)}/(\text{ppm})\)

\( L \) 
length of tubes in series in a section, ft

\( \ln \) 
natural logarithm (to base e)

\( N_s \) 
Schmidt number = \(\nu/\mathcal{D}_s\)

\( n \) 
total number of sections

\( n_s \) 
mol fraction salt ions

\( P \) 
pressure, \(\text{lb}/\text{ft}^2\); product rate, \(\text{lb}/\text{day}\)

\( P^* \) 
pressure, psi

\( R \) 
Reynolds number \(\frac{\text{uD}}{\nu}\); gas constant, \((\text{kilo})/(\text{mol})(\text{°K})\)

\( s \) 
\(\left(\frac{c_w}{\bar{c}}\right)(1 - \lambda)\)

\( T \) 
temperature, °Kelvin

\( t \) 
temperature, °F

\( u \) 
velocity, ft/sec

\( \bar{V}_w \) 
partial molal volume of water, liters/mol

\( V_w \) 
velocity perpendicular to wall, ft/sec

\( x \) 
distance along axis, ft

\( \rho \) 
recirculation ratio = \((1 - F)/F\)

\( \gamma \) 
overall recovery on weight basis = \(\sum_{j=1}^{n} P_j / F_j\)
Appendix A
Nomenclature (cont.)

\( \chi^i \)  
section recovery on weight basis = \( \frac{P'_j}{F'_j} \)

\( \Delta \)  
increment in; \((P' - k \pi \lambda C_w)\)

\( \delta \)  
section recovery to point x

\( \theta \)  
argument in Equation (110)

\( \lambda \)  
salt rejection, fraction

\( \nu \)  
kinematic viscosity of stream, \( \text{ft}^2/\text{sec} \)

\( \prod \)  
product of factors for \( i = 1, 2 - - - - j \)

\( \sum \)  
sum of factors for \( i = 1, 2 - - - - j \)

\( \sigma \)  
specific weight of stream, \( \text{lb/ft}^3 \)

\( \sigma_p \)  
specific weight of product, \( \text{lb/ft}^3 \)

\( \tau \)  
heat treat temperature, \( ^\circ \text{C} \)

\( \phi \)  
specific gravity of stream referred to water at \( 4^\circ \text{C} \)

\( \phi_p \)  
specific gravity of product referred to water at \( 4^\circ \text{C} \)

Subscripts

\( i \)  
index of summation, index of product

\( j \)  
for section \( j \)

\( n \)  
for section \( n \)

\( t \)  
temperature effect factor

\( 0 \)  
inlet value; value at reference temperature \( t_0 \)

Miscellaneous

\( \approx \)  
approximately equal to
REFERENCES


Appendix A (cont.)

Figure 1. Diagram of Section j

Figure 2. Part of a Section
APPENDIX B

CONCENTRATION BOUNDARY LAYER IN 3-IN. DIAMETER MEMBRANE TEST CELLS

In order to interpret test data to obtain membrane properties it is necessary to know the salt concentration at the membrane surface, which is larger than that in the bulk of the salt solution flowing past the membrane due to concentration polarization effects. These concentration polarization effects are particularly significant with laminar flow, such as is experienced in the Aerojet 3-in. test cells.

The results of theoretical studies to estimate the average concentration boundary layer modulus in the 3-in. test cells are shown herein, as well as the details of the analysis.
Appendix B (cont.)

The ratio of the average concentration at the surface of the membrane to the feed concentration is shown in Figure 1 as a function of flux and the percentage of bypass through the O-ring groove. The procedure for estimating this function is discussed below. It is believed that 85-90% of the total feed bypasses the membrane through the O-ring grooves. These curves are based on NaCl (for diffusivity), a channel height of 0.0077-in., a flow of 5 gal/hr, a 0.190-in. x 0.100-in. O-ring groove and a 0.139-in. diameter O-ring. As shown later, however, the boundary layer modulus changes only slightly for changes in channel heights within normal tolerances.

1. Derivation of \((C_c)_a / C_o\) Equation

The flow distribution in a cell which has no flow bypassing is shown in Figure 2. This was derived by using conformal transformations with complex variables, since it can be shown that, for laminar flow between closely spaced parallel plates, the flow per unit width is expressible as the gradient of a potential. The complex potential for this geometry is

\[
F = \frac{1}{\pi} \ln \left( \frac{C(Z^2 + i) + Z}{C(Z^2 + i) - Z} \right) 
\]

with \(C = \frac{k}{1 - k^2}\) where \(k\) is the coordinate of the entrance port as shown in Figure 2. (Please see Appendix A, pages A-25, A-26, and A-27, for a definition of nomenclature.) The stream function is equal to the imaginary part of the complex potential \(F\), as given by

\[
\psi = \frac{1}{\pi} \arctan \left( \frac{2C \gamma (1 - y^2 - x^2)}{C^2 \left[ 4x^2 + (1 - y^2 - x^2) \right] - y^2 - x^2} \right)
\]

Streamlines for each 10% increment of the flow through one-fourth of the cell are shown in Figure 2. By symmetry, flow in the rest of the cell is similar. Areas between streamlines were measured and used to calculate a recovery function \(r\), given by the relation

\[
r = \frac{1}{A_t} \frac{dA}{d\psi} \approx \frac{A_i}{A_t \Delta \psi}
\]

B-2
Appendix B

3 INCH CELL
5 GAL/HR FLOW
0.0077" CHANNEL HEIGHT

\[
\frac{(c_i)_o}{c_o}
\]

FLUX - GAL/(FT^2)(DAY)

BOUNDARY LAYER MODULUS IN 3 INCH CELLS

B-3

Figure 1-B
FLOW DISTRIBUTION IN 3 INCH CELLS
Appendix B (cont.)

so that, if there is no bypassing, the recovery from fluid following a streamline from inlet to outlet is \( Y = r Y_t \), where \( Y_t \) is the apparent overall recovery. Figure 3 shows the recovery function \( r \). If a fraction \( f \) of the fluid bypasses the cell through an O-ring groove, it is assumed that the remaining flow \((1 - f)\) is still distributed as shown in Figure 2, and the recovery becomes

\[
Y = \frac{1}{1-f} \cdot r Y_t = \frac{2.64 \times 10^{-4} J r}{1-f} \tag{4}
\]

where the last form introduces the flux \( J \) for the flow rate of 5 gal/hr.

If \( (C_n)_\text{av} / C_o \) represents the average ratio of boundary concentration to feed concentration over a streamline, the average ratio for the cell is

\[
\left( \frac{(C_n)_\text{av}}{C_o} \right)_\text{cell} = \int_0^l \frac{(C_n)_\text{av}}{C_o} r \, dy \tag{5}
\]

Earlier derivations (not yet reported) show for this case with membrane on only one plate that

\[
\frac{(C_n)_\text{av}}{C_o} = 1 + 2.18 (J S)^{3/2} \Gamma^{1/3} \left[ 1 + \left( \frac{0.14}{(J S)^{1/3}} + 0.25 \sqrt{(J S)} \right) \right] \tag{6}
\]

\[
+ \left( \frac{0.0850 + 0.1235 (J S)^{1/2} - 0.1748 (J S)^{3/2}}{0.2526 (J S)^{1/2}} \right) \Gamma^{3/2} + \cdots
\]

Equation (6) is for the entrance region and is applicable to the 3-in. cell as it is presently operated. The channel height in inches is represented by "s". Substitution of Equation (4) in Equation (6) and of the latter in turn in Equation (5) yields the results shown in Figure 1.

The final expression is of the form
RECOVERY FACTOR IN 3 INCH CELLS

STREAM FUNCTION $\psi$

B-6 Figure 3-B
\[
\left( \frac{C_w}{C_0} \right)_{cell} = 1 + b_1(1 + b_2 + b_3 + \cdots)
\]  

(7)

where

\[
b_1 = \frac{0.144 \, S^{2/3}}{(1-f)^{1/3}} \, J
\]  

(8)

and the terms \(b_2\) and \(b_3\) are small compared to one for the range of parameters involved. However, the amount of bypass \(f\) is a function of the height \(S\), and use of this function from Equation (18) gives

\[
b_1 = 2.19 \times 10^{-3} \left[ 1 + (45.7 \, S)^3 - (45.7 \, S)^6 + \cdots \right] \frac{J}{S^{7/3}}
\]  

(9)

Since \(b_1\) predominates, the lines of Figure 1 are approximately straight and the effect of bypass is roughly proportional to \((1 - f)^{-1/3}\). The curves shown are for a specific channel height of 0.0077-in., but the effect of different channel heights will be approximately inversely proportional to the \(1/3\) power of the ratio of heights if the O-ring and groove geometry remain constant. Thus, cells whose heights are different within a moderate range, but are similar otherwise, should have very similar relationships between boundary layer modulus and flux.

2. Determination of Flow in the O-ring Groove

The estimate of the flow through the O-ring groove was done as follows: Figure 4 shows the groove with the O-ring deformed by cell assembly and pushed to the outer edge by the cell pressure. The flow area is 0.004-in.\(^2\), and if the flow through this odd shaped area is taken as that through a 0.040-in. by 0.10-in. rectangle, the flow is laminar and the bulk velocity is

B-7
Appendix B

O-RING GROOVE GEOMETRY, 3 INCH CELLS

0.0695

0.190

0.100

0.0077

0.159

O-RING PRIOR TO COMPRESSION

O-RING WITH CELL CLOSED

Figure 4-B


\[ U = \frac{0.025hw}{\eta} \left( - \frac{dP}{dx} \right) \]  

(10)

where \( h \) and \( w \) are the sides of the rectangle and \( \eta \) is the viscosity. The flow across the membrane is also laminar and for flow between parallel plates without edge effects

\[ U = \frac{h^2}{12 \eta} \left( - \frac{dP}{dx} \right) \]  

(11)

The flow rates \( Q \) equal \( Uhw \) so

\[ Q_g = \frac{0.025(hw)^2}{\eta} \left( - \frac{dP}{dx} \right) = \frac{0.025(hw)^2}{\eta} \frac{\Delta P}{L_g} \]  

(12)

\[ Q_p = \frac{(h^3w)p}{12 \eta} \left( - \frac{dP}{dx} \right) = \frac{(h^3w)p}{12 \eta} \frac{\Delta P}{L_p} \]  

(13)

Flow through the groove was compared with that between the streamlines \( \psi' = 0.9 \) and \( \psi = 1.0 \) in Figure 3. The \( \Delta P \)'s were equated and average values of the length \( L_p \) and width \( W_p \) were used. The equations then became

\[ \frac{Q_p}{Q_g} = \frac{(h^3w)_p}{(hw)^2_G} \frac{L_g}{L_p} = 0.500 \]  

(14)
Appendix B (cont.)

Using the dimensions from Figure 4, and using $s$ for the channel height over the membrane

\[
\frac{Q_F}{Q_g} = \frac{s^3(0.126)}{(0.040)^2(0.10)^2} \left( -\frac{1}{0.92} \right) \frac{1}{0.30} = 2.84 \times 10^4 s^3
\]  

(15)

and with

\[
Q_g = fF
\]  

(16)

\[
Q_p = 0.1(1-f)F
\]  

(17)

\[
f = \frac{1}{1 + 2.84 \times 10^4 s^3}
\]  

(18)

Taking 0.0077-in. for the plate separation $s$ gives a value of $f$ of 0.88, so it appears that perhaps 85-90% of the flow bypasses through the O-ring grooves.
APPENDIX C

THREE-DIMENSIONAL PHOTOELASTIC ANALYSIS OF A
REVERSE OSMOSIS HEADER ASSEMBLY

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26 August 1968

Approved by:
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C-1
ABSTRACT

A full-scale photoelastic model of a ribbed header assembly was tested under simulated pressurization. "Frozen-stress" slices were removed and analyzed for determination of the location and magnitude of maximum stress. High stressed areas were noted at several locations, although no location was found with stress exceeding ultimate for the prototype material. Recommendations for design changes which will reduce locally high stresses are given.
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THREE-DIMENSIONAL PHOTOELASTIC ANALYSIS OF A
REVERSE OSMOSIS HEADER ASSEMBLY

I. INTRODUCTION

A three-dimensional photoelastic test was performed on a ribbed header assembly - Space General Drawing No. 1119228. The photoelastic model was cast to final shape, except for surfacing, utilizing a two part RTV rubber mold supplied by Space General. The header cavity was pressurized to simulate the 880 psi prototype proof pressure. The stress-frozen model was sliced on a number of different planes for the purpose of locating all critically stressed areas. The knowledge of the location and magnitude of these maximum stresses will serve to verify the present design if they are within acceptable limits. If not, redesign can be accomplished within the specified critical areas.

II. THE PHOTOELASTIC MODEL

The model was cast of an epoxy resin mixture consisting of 100 pbw ERL 2774 resin and 23 pbw ZZL 0803 hardener, Bakelite products manufactured by Union Carbide Company. The model parts and a tensile calibration specimen were cured after setting for 24 hours at room temperature by elevating their temperature to 90°C at 1°C per hour. After 72 hours at 90°C the temperature was brought to 25°C at 2°C per hour. The manifold rim and manifold block bottom surface were machined according to Drawings 1119227 and 1119226. However, due to resin shrinkage, the manifold flange had to be machined 0.01 undersize. The cover flange, Drawing No. 1118031-1, in which the pressure tap was installed was machined from a block of resin cast with the model.
Assembly of the model called for the insertion of knurled nuts in counter bored holes of the manifold block. Due to the danger of cracking the relatively weak model during the stress freezing cycle, a different method of fastening was used. Round head machine screws (#12-24) were inserted up through the manifold block and 1/2 inch washers were used between the manifold flange surface and the knurled nuts. The bolt heads rested on the recessed face of the counter bored insert holes. In order to assure a good seal without excessive clamping force, 1/8 x 1/16 inch Tygon tubing was used in place of the Buna "N" O-ring. The assembled model is shown in Figure 1.

III. MODEL LOADING

A geometrically similar model which is loaded identically to the prototype will have the same stresses as the prototype regardless of the mechanical property differences between the two*. However, since the elastic modulus of the model is approximately 2500 psi and that of the prototype 2.5 x 10^6 psi, the pressure applied to the model should be 1/1000 of design or proof pressure (880 psi) to maintain equal deformation. It was estimated that the fringe order response of model would be too low to allow accurate stress measurement at the low pressure level of 0.88 psi. A test pressure of 10 psi assured adequate response while keeping deformation within acceptable limits.

The well established three-dimensional photoelastic "stress-freezing" technique utilizes the two-phase nature of polymeric materials. There is a transition temperature well above room temperature for these materials where a secondary bond network is relaxed transforming the stiff glassy structure to a flexible rubbery one. When the model is loaded above the transition temperature

*Of course, linear elastic deformation is assumed.
Appendix C (cont.)
and cooled, this secondary bond network "freezes" the model in its deformed state. Since these bonds exist on a sub-microscopic level, the model may be sliced on planes of interest for analysis without disturbing the "locked-in" stresses.

In this test, the 10 psi pressure load was held on the model while it cooled slowly from 100°C to room temperature. The transition temperature for this material is approximately 90°C.

IV. ANALYSIS

It has been shown that the "fringe" pattern resulting from viewing a planer loaded specimen in polarized light is directly proportional to the principal stress difference within the specimen:

\[ \sigma_1 - \sigma_2 = \frac{nf}{t} \]  

(1)

where: \( \sigma_1, \sigma_2 = \) principal stresses normal to the viewing direction (psi)

\( n = \) fringe order

\( f = \) material fringe value (psi-in/fringe) (calibration constant).

\( t = \) thickness in the direction of light transmission (in.)

The material fringe value, as determined with a tensile calibration specimen, was found to be 1.54 psi per fringe per inch of thickness for this material.

For the analysis of model slices more information is needed in general to determine the separate stresses \( \sigma_1 \) and \( \sigma_2 \). However, since the maximum stress occurs, typically, on the surface of the specimen where the normal stresses are known

\[ \sigma_n = -p_0 \]

\[ \tau = 0 \]

Equation (1) is sufficient to determine the stress tangent to the surface
\[ \sigma_t = \frac{nf}{t} + \sigma_n \]

or

\[ \sigma_t = \frac{nf}{t} - p_o \]

(2)

The stress at particular locations within a three-dimensional model is isolated by removing a thin slice in a plane containing the stress direction of interest. A number of such slices were removed from the manifold and manifold block, some of which are shown in Figures 2 and 3. These slices were viewed for analysis at 10X magnification in the collimated, monochromatic, polarized-light field of an optical comparator especially modified for the purpose. High stressed areas are readily locateable by viewing the overall fringe pattern and noting locations of high fringe order. Light-field fringe photographs of some of the slices are shown in Figures 4 and 5.

V. RESULTS

Analysis of the various slices revealed several high-stressed areas in the header assembly. The relative locations of the areas are indicated by the literals \( a \), \( b \), \( c \), \( d \) in Figures 2 and 3.

A. MANIFOLD STRESS

The highest stressed area in the manifold is in the fillet of the bolt flange \( a \) immediately adjacent to the bolt hole. At a prototype header pressure of 880 psi the highest recorded fillet stress was 11,500 psi in the fillet nearest the center of the manifold. The stress at this location decreases for positions further removed from the transverse centerline. The high stress at \( a \) arises due to the small radius of this fillet and its close proximity to local bolt loads. The fillet in the manifold rim \( c \) showed a maximum stress of 6430 psi at the center of the assembly.

C-8
Manifold Block Schematic

Figure 3-C
Appendix C (cont.)

FIG. 4 MANIFOLD SLICES - t=0.100, f=1.54

Figure 4-C
FIG. 5  MANIFOLD BLOCK SLICES - $t=0.100$, $f=1.54$

C-12

Figure 5-C
Appendix C (cont.)

The distribution of maximum flow-channel stress, location (b), is shown in Figure 6. A peak value of 4720 psi was noted, again near center assembly.

B. MANIFOLD BLOCK STRESSES

The manifold block showed peak stresses at locations (a), (b), (c), (d), Figure 3. The inboard O-ring fillet (b) is in compression with a maximum stress of -9880 psi and the outboard fillet (a) showed a tensile maximum stress of 6880 psi. The maximum rim fillet (c) stress was 10,300 psi. The maximum bottom surface transverse stress (d) occurs on the ligament between outlet holes, 10,000 psi. A bottom surface slice of the first two outlet holes (nearest the center) revealed a maximum tangential stress on the surface of the first hole of 10,650. The distribution of stress around this hole is shown in Figure 7.

The bottom surface longitudinal and transverse stresses on the longitudinal centerline are shown in Figure 8. The transverse stress $\sigma_y$ peaks between holes and the longitudinal stress $\sigma_x$ peaks adjacent to the holes. A light field fringe photograph of the bottom surface slice is included in this figure. The integral fringe order (light area between dark bands) n is noted at several locations. On the longitudinal centerline the principal stress directions correspond to the x and y directions so that the fringe order may be used with Equation (1) to find $\sigma_x - \sigma_y$. A subslice along this line viewed tangent to the surface was used to find $\sigma_x$ (the normal stress is known to be zero), so that both normal stresses could be evaluated.

C. DEFORMATION

The displacement of the full-scale manifold block was measured and converted to equivalent prototype values by the ratio of the elastic moduli, i.e.,

$$ U_p = \left(\frac{E_m}{E_p}\right) \left(\frac{P_p}{P_m}\right) U_m $$
FIGURE 7

Tangential Surface Stress on Outlet Hole at Bottom Surface of Manifold Block

C-15
FIGURE 8
Central Ligament Stress On
Bottom Surface of Manifold block
Appendix C (cont.)

\[ \begin{align*}
U & = \text{displacement} \\
P & = \text{applied pressure} \\
E & = \text{Young's Modulus}
\end{align*} \]

subscripts \( p \) and \( m \) refer to the prototype and model, respectively.

The ratio \( E_m/E_p = 0.001 \) and \( P_p/P_m = 85.6 \)

The bottom surface displacement is shown in Figure 9. The maximum displacement was .008 inches on the longitudinal centerline 5 inches from the transverse centerline.

VI. **DISCUSSION AND RECOMMENDATIONS**

When the assembly is pressurized, the manifold is partially restrained from expanding in the transverse direction when it contacts the rim groove of the manifold block. The resulting outward shear on the manifold block causes local deviation from a simple-supported plate condition producing a tensile stress in both the rim and outboard O-ring fillets. This surface would be in compression if contact did not occur. The effect of this shear is attenuated at the inboard O-ring fillet and all other points toward the center where a compressive stress condition exists. This behavior produces the indicated high compressive stress at the sharp corners of the tube hole counter bore (slice 2, Figure 5) a condition which should not be critical.

Present indications are that the ultimate stress for the header assembly material, Structoform, is between 15,000 and 20,000 psi. Since predicted maximum stresses as shown in Table I are rather close to ultimate and a long service life is required, modifications to the present design will probably be required. Recommended design changes are discussed below.

The proximity of the bolt holes to and radius of the flange fillet in the manifolds are contributing causes for the high stress at this location. The light bolt pre-torque should not aggravate this condition. A recommended change to the design to alleviate this problem is shown in Figure 10. The increased flange thickness allows for a larger radius fillet further removed from the bolt hole.
### MANIFOLD

<table>
<thead>
<tr>
<th>Location*</th>
<th>Max. Surface Stress (KSI)</th>
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<tbody>
<tr>
<td>a</td>
<td>11.50</td>
</tr>
<tr>
<td>b</td>
<td>4.72</td>
</tr>
<tr>
<td>c</td>
<td>6.43</td>
</tr>
</tbody>
</table>

### MANIFOLD BLOCK

<table>
<thead>
<tr>
<th>Location**</th>
<th>Max. Surface Stress (KSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>-9.88</td>
</tr>
<tr>
<td>b</td>
<td>6.88</td>
</tr>
<tr>
<td>c</td>
<td>10.30</td>
</tr>
<tr>
<td>d</td>
<td>10.00</td>
</tr>
</tbody>
</table>

*See Figure 2  
**See Figure 3

**TABLE 1. MAXIMUM STRESSES IN HEADER ASSEMBLY**
Normal Deflection on the Plane

at \( x = h.85 \)

FIGURE 9

Normal Deflection of the Manifold Block Bottom Surface at 880 psi
The large center-to-center distance of the first bolt holes across the transverse centerline is undesirable, due to the disproportionate load which results at these locations. However, the change indicated above with its thicker flange would probably reduce the stress in the region of the first hole to an acceptable level. Depending on the margin of safety required, consideration should be given to the addition of two bolts with threaded inserts on the transverse centerline as shown in Figure 11. If this is done, the first bolt off the centerline may be eliminated (total of 1 place) and the second bolt relocated as shown in Figure 11.

This change would result in an overall lessening of the stress level in the central region of the assembly as well as locally at the bolt locations by distributing the load now concentrated at the first bolt.

The stress level at all critical locations in the manifold block may be reduced by increasing the plate thickness. Since the primary contribution to the high stress in the outlet holes is transverse bending, this stress is nearly inversely proportional to the square of the plate thickness. There is some membrane tension induced by the manifold so that a 10% increase in the thickness, say, would result in a reduction of the outlet hole stress of somewhat less than 20%.

VII. CONCLUSIONS

Although all recorded stress levels were below ultimate for the material, the margin of safety could be too low (design ultimate stress and margin of safety values were not provided) for the intended application. The location and magnitude of all high stressed areas have been given and the following recommendations were indicated to relieve the critical areas

1. Increase the manifold flange thickness and fillet radius. (See Figure 10).

2. Add two more bolts with inserts and relocate existing bolts as shown in Figure 11.

3. Increase the thickness of the manifold block.

C-21
FIGURE 11

Modifications to Reduce Overall Manifold Stresses

C-22

Figure 11-C
ADDENDUM TO REPORT NO. PEL-65

During the test reported in Reference (1), the assembly bolt tension was adjusted to a level (undetermined) which would assure a positive seal for the internal pressure. Also, oversized washers were used under the bolt heads. The question has arisen - could excessive bolt pre-tension combined with added local bearing at the washer edge have contributed to producing an unrealistic bolt fillet stress? During the first test, the highest stress in the assembly was determined to be 11,500 psi and was measured in the fillet immediately adjacent to the most centrally located bolt hole of the manifold.

This addendum covers a second test on a section of the manifold in which the bolt load was controlled to a pre-determined value with dead load and the washer size was reduced to the design value. The test was designed to simulate the loading condition which should have existed in the region of an average bolt relief-fillet located away from the non-uniformly loaded bolts nearest the transverse centerline of the assembly.

In the second test, a section three inches long was removed from the half of the original model which was intact as shown in Figure 1. The manifold block with O-ring in place was used to support this manifold section while dead-load was applied to each of the six bolts in the section. The load applied to bolts was that which should have existed in the original pressure test, i.e.,

\[
L_m = \frac{P_m}{P} L_p
\]

\[
= \frac{10}{800} \times 660 = 7.5 \text{ lb/bolt}
\]

where:

\[ L = \text{bolt load (lb)} \]

\[ P = \text{pressure (psi)} \]
Appendix C (cont.)

The prototype design bolt load is 660 lb, a value approximately 10% higher than the load required to support the pressure over a typical section.

This test does not duplicate prototype conditions in that the total bolt load is reacted at the O-ring instead of by the pressure. However, it was felt that, since the bolt-fillet stress is a local condition caused primarily by the shear and moment developed by the bolt load itself, results should match closely those under true prototype conditions.

The results of this second test are contained in Figure 2 along with a comparison to the results in the initial pressure test. As can be seen, the average stresses from the second test are slightly below the average value for the first test. If bolts 4 through 8 are considered typical, the comparison is 7860 psi for the first test vs 6870 psi for the second test. If it is assumed that the difference is due to pre-torque and/or the improper washers, then the maximum stress at the center bolt locations would be reduced to approximately 10,000 psi. The considerable scatter obtained in both tests, however, would make the justification of this reduction somewhat questionable.

An examination of the model to try and explain the scatter in results produced the following observations: A magnified profile view of a typical fillet is shown in Figure 3. This fillet should have had a uniform .125 ± .010 radius. Instead, there were two regions with approximately .070 radii. The actual geometry varied somewhat from fillet-to-fillet causing variation in the maximum stress. A second cause for the scatter in the pressure test results could have been lack of uniform bolt pre-tension. However, the soft Tygon O-ring should have prevented significant variations in load. Thirdly, non-uniform bearing load distribution under the washers, due to variations in the flange bearing face flatness might have contributed to the scatter.

In conclusion, it appears that the maximum value of manifold stress reported in Reference (1) may have been influenced by bolt torque and improper seating of the washers. Furthermore, if the bolt pattern is changed in the central area to eliminate the peaking experienced in the first test, it appears that the maximum expected flange stress would not exceed 7800 psi.

Appendix C (cont.)

FIGURE 1 BOLT RELIEF-FILLET TEST SET-UP

C-25

Figure Al-C
Figure 2  DISTRIBUTION OF BOLT RELIEF FILLET STRESS

LEGEND
Pressure Test
Bolt Load Test

6870 psi Avg. of Six Values

Bolt Number From Transverse

KSI  4  5  6  7  8

12  8  4  0

C-26  Figure A2-C
APPENDIX D

HEADER ASSEMBLY FLOW TESTING
APPENDIX D

HEADER ASSEMBLY FLOW TESTING

PURPOSE

Flow tests were performed to establish flow conditions existing within the header assembly during actual operation.

TEST PLAN

The tests established steady-state flow conditions through all the openings in the header and permitted measurement of the flow rate for each tube independently. Variations in individual tube flow rates were to be determined, the cause identified, and necessary corrections recommended in the header design. The flow test unit serves to qualify the molded or machined headers during prototype production.

The individual tube flow rates were to be recorded at five separate values between Reynolds number \( R_e \) of 5000 to 12,000 (approximately 20 to 60 gpm flow). Slight back pressure to obtain steady-state conditions was to be achieved by inserting an accurately machined aluminum orifice at the outlet port of each tube. The header assembly was to be mounted to the stainless steel mounting flange provided by the project for this purpose. The necessary piping and fittings were to be assembled and mounted to the clear polyester header assembly as shown in Figures 1-D and 2-D. Photographs were to be taken of the mounted header and tubes after assembly. Provisions were to be made for dye injection in the system if required to verify areas of turbulent flow.

TEST RESULTS

Steady-state flow rates were established by testing the manifold (header assembly) in the high flow water facility. The flow rates, at which measurements were made from the individual orifices of the 52 tygon tubes, were 10, 25, 32, 40, and 60 gpm. It was intended that measurements would also be recorded at an upper limit of 80 gpm (corresponding to a Reynolds number of approximately 20,000). However, a pressure of approximately 19.8 psig was attained in the tygon tubing system during flow testing at the 60 gpm input level. Prior experience had indicated that this value represented the upper limit that the tygon assembly would tolerate before excessive leakage occurred. The gage pressure immediately upstream of each orifice was recorded at the above flow rates with the manifold pressure holding steady. Back pressure varied between 0.4 to 19.8 psig between the flow rates of 10 to 60 gpm, respectively.
Results of the tests indicated that the flow distribution was quite uniform. Deviation of flow did not vary more than 1.6% from a mean value at the highest (60 gpm) flow rate. Variations at the 60 gpm flow are presented as a function of the deviation from a mean flow for the 52 tubes in Figure D-3. Flow deviations between the 52 tubes at flow rates were even less or negligible. Results also indicated that instrumentation with greater resolution would have provided more exacting data. The highest Reynolds number attainable during the test was approximately 12,000. It appears that a value approximating 20,000 could be attained by opening the aluminum outlet orifices to maintain the pressure in the tygon tubing system within limits that could be tolerated. Examination of the clear polyester header casting during the tests did not indicate any areas of excessive turbulent flow, therefore dye injections into the stream for visual comparison were not performed. On the basis of the test results, it appears that the internal configuration of the header assembly meets the necessary requirements for prototype header assemblies which are to be compression molded from Structoform S-6400 material.
Plastic Header Assembly and Tubes Prepared for Flow Testing
Outlet Ports of Header Assembly Tubes Prepared for Flow Testing
NOTES:
1. Reference numbers correspond to outlet ports in header assembly
2. X X X odd numbered tubes
3. O O O even numbered tubes
4. The 0% base line is equal to a mean flow of 1.156 gpm
5. Flow through manifold: 60 gpm \( (R_e = 11,616) \)

VARIATIONS IN TUBE FLOW RATES FOR HEADER ASSEMBLY
APPENDIX E

Drawing TD-0351 - Header-Top 1/2-in. Tube Module

Drawing TD-0352 - Header Plate - Bottom 1/2-in. Tube

Drawing - Header Cap
APPENDIX F

MANUFACTURING PLAN
(GIASS-FILAMENT-REINFORCED TUBES)
APPENDIX F
MANUFACTURING PLAN
(Glass-Filament-Reinforced Tubes)

The following manufacturing plan describes the fabrication of glass-filament-reinforced reverse-osmosis tubes (approximately 0.25-in. inside diameter by 10-ft in length) and provides a permanent record for the data generated. Its purpose is to ensure that reliable units are obtained and that any deviations in parts, materials, handling, processes, etc., will be recorded. Currently, fabrication of the glass-reinforced tubes and the extrusion of the membrane are separate operations, although it is contemplated that these will be combined into a continuous process for larger diameter tubes. For this plan, only the tube fabrication will be covered. The individual steps in fabricating the two-layer filament-braided tubes are as follows: paper trim, scarf, and form; braid; drive; resin impregnation; vacuum; heat; cool; drive; resin impregnation; braid; resin impregnation; heat; vacuum; infrared heat; cool; drive; cut-off. The more pertinent details in fabrication are described in the following outline.

I. Fabrication Plan
   A. Preparation of Fabrication Sheet and Line Check
      1. A Fabrication Sheet, Figure 1, will be prepared prior to initiating tube manufacture.
      2. The various fabrication steps (cutting, scarfing, and forming of paper, impregnation, braiding, etc.) in the line will be critically checked to ensure ideal workability.
      3. Align the mandrel through the various processing steps (braiding, vacuum chamber, infrared heaters, etc.).

   B. Substrate Paper Forming
      1. The paper roll will be examined to ensure that sufficient length is available for a run; otherwise, a new full roll will be added.
      2. The scarfing wheels will be examined periodically and polished, if necessary, to maintain them in a sharpened condition.

F-2
Appendix F (cont.)

3. The paper roll will be threaded around the various tension and guide rollers, through the tube forming collet and onto the tapered, teflon-coated mandrel.

4. The 0.001-in. thick stainless steel separating shim will be inserted between the paper, into the forming collet, and adjusted for operation.

5. During fabrication, the paper will be checked to ensure that it is cut to a width of 0.950 ± 0.010-in. by the trimming wheels and that both edges are final scarf trimmed to a precise width of 0.857 ± .005. Adjustment to the final dimension will be made by means of the micrometer units.

6. The discarded trimmings will be fed into the vacuum inlets available for removal purposes.

C. APPLICATION OF FIRST GLASS LAYER

1. Sixteen nylon bobbins filled with 4-end glass fiber (EAG 150 4/0 with L-131 binder) will be installed on the upper braider and threaded onto the paper-covered mandrel. Glass tension will be adjusted to produce 6 ± 1 oz. static tension per 4-end material. Tension will be measured as close to the final feed on the mandrel as is practicable.

2. Eight nylon bobbins filled with 4-end glass fiber (EAG 150 4/0 with L-131 binder) will be installed on the upper longitudinal fiber mounting apparatus. Glass tension will be adjusted to produce 10 ± 1 oz. static tension per 4-end material. Tension will be measured as close to the final feed on the mandrel as is practicable.

3. The vacuum inlet will be positioned approximately at the braiding level in order to prevent any buildup of glass "fuzz" being trapped into the braiding.

D. APPLICATION OF SECOND GLASS LAYER

1. Sixteen nylon bobbins filled with 4-end glass fiber (EAG 150 4/0 with L-131 binder) will be installed on the lower braider and threaded onto the glass covered mandrel. Glass tension will be adjusted to produce 6 ± 1 oz. static tension per 4-end material. Tension will be measured as close to the final feed on the mandrel as is practicable.
2. Eight nylon bobbins filled with 4-end glass fiber (ECG 150 4/0 with L-131 binder) will be installed on the lower longitudinal fiber mounting apparatus. Glass tension will be adjusted to produce 10 ± 1 oz. static tension per 4-end material. Tension will be measured as close to the final feed on the mandrel as practicable.

3. The vacuum inlet will be positioned approximately at the braiding level in order to prevent any buildup of glass "fuzz" being trapped into the braiding.

E. RESIN SYSTEM PREPARATION

1. Obtain the phenoxy (PKHS-1), titanium oxide (TiO₂), Cab-O-Sil (C-O-S), and methyl ethyl ketone (MEK) resin constituents.

2. Determine the solids content on the PKHS-1 and adjust with MEK/water (98%/2%) solution until a 40.0% solids level is obtained.

3. Measure out the following quantities of each constituent:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Quantity, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKHS-1 (adjusted)</td>
<td>1000.0</td>
</tr>
<tr>
<td>TiO₂</td>
<td>4.0</td>
</tr>
<tr>
<td>C-O-S</td>
<td>4.0</td>
</tr>
</tbody>
</table>

4. Measure out approximately 100 g of the adjusted PKHS-1 and mix thoroughly with the 4.0 g of TiO₂ until a heavy paste is obtained. Add the PKHS-1/TiO₂ mixture and C-O-S to the remaining PKHS-1 material. Thoroughly mix the constituents.

5. Place the mixture in an inert container and seal to minimize MEK evaporation.

6. Prior to use of the resin system in a fabrication run, determine the viscosity and solids level and record in the Fabrication Sheet.

7. The resin will be added to the pressurized reservoir tank and sealed with a gasket and cover prior to the fabrication run. The pressurized air supply will be maintained at 30 psig throughout the run.
Appendix F (cont.)

F. RESIN IMPREGNATION OF GLASS LAYERS

1. Assemble the three resin application fixtures in the fabrication line.

2. The two-level upper applicator will utilize 6 elastomeric wipers (3 above, 3 below) which have a 0.25-in. diameter center hole.

3. The single-level middle applicator will utilize 3 elastomeric wipers which have a 0.25-in. diameter center hole.

4. The two-level lower applicator will utilize 6 elastomeric wipers (3 above, 3 below) which have a 0.28-in. diameter center hole.

5. Prior to installing the feed lines from the reservoir to the resin applicator, the lines will be bled to ensure satisfactory operation of the system.

6. During tube fabrication, the tubular portion of each applicator will be kept continually filled with resin by adjusting the pump speed and tube orifices.

G. HARDENING OF RESIN MATRIX

1. The upper and lower vacuum chambers will be examined prior to initiating tube fabrication. End seals will be replaced if there is evidence that they might not perform satisfactorily.

2. The heat guns and infrared heater will be examined to ensure satisfactory performance prior to initiating tube fabrication. The heat guns will be set on high and the infrared heater will be positioned at a setting of 60 on the console when starting the run.

H. TUBE CUT-OFF AND STORAGE

1. The tubes will be cut to the lengths designated by the cognizant engineer.

2. Each tube will be identified by marking in pencil with consecutive numbers.

3. The glass-reinforced tubes will be stored in a tubular cardboard container in preparation for the membranizing operation.

F-5
Appendix F (cont.)

**General Notes**

1. The mandrel will be checked for center alignment in relation to each processing operation on the tube fabrication column. Adjustments will be made as necessary to correct for center alignment, particularly braiders and infrared heater.

2. Tension on the braiding and longitudinal bobbins, respectively, will be uniformly adjusted.

3. Scarfing wheels will always be started prior to any movement of the tube fabrication line.

4. Satisfactory functioning of the drivers will be checked during movement in line.

5. Cooling air to infrared heater will be started prior to turning the heater on, and left on for several minutes after turning heater off.

6. After shutdown of line and removal of resin impregnation applicators, the line will be operated 2 separate periods for approximate distances of 3-in. each.

7. Care will be exercised in handling and properly supporting long glass braided tubes.

**Required Materials and Components**

1. Glass (ECG 150 4/0 with L-131 binder)

2. Paper (Dexter X-1611)

3. Resin System
   a. Phenoxy (PKMS-1)
   b. Titanium dioxide (TiO₂)
   c. Cab-O-Sil (C-0-S)
   d. Methyl ethyl ketone (MEK)

**Required Tooling and Facilities**

1. Paper trimming, scarfing, and forming machine

2. Teflon-coated, tapered, stainless steel mandrel

3. Braiders
4. Resin application equipment

5. Vacuum equipment

6. Infrared heaters

7. Coolers

8. Tube drivers

9. Tube cutoff equipment

**Inspection Plan**

1. Glass
   (Refer to Material Specification TR-100, Glass Filament Roving, Tubular Reverse Osmosis Unit)

2. Paper
   (Refer to Material Specification TR-200, Substrate Paper, Tubular Reverse Osmosis Unit)

3. Resin System
   a. Viscosity
   b. Solids content

4. Tube (in-process)
   a. Resin content
   b. Visual examination of sample, including
      (1) Tube roundness (occurrence of tear-drop effect)
      (2) Resin penetration (adhesion between paper and tube)
   c. Microscopic examination of sample, including
      (1) Scarf angle of paper
      (2) Overlap of paper

5. Tube (final product)
   a. Length
   b. Outside diameter
   c. Inside diameter
   d. Burst strength
   e. Hoop elongation
   f. Longitudinal elongation
# REVERSE-OSMOSIS 1/2" DIA. BRAIDED TUBE

## (Fabrication Sheet)

### Tube No.: From ___ to ___ Date ___

## I. Materials:

<table>
<thead>
<tr>
<th>Glass Yarn</th>
<th>Twist</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin System</td>
<td>Resin Solids %, Viscosity Cps</td>
<td></td>
</tr>
<tr>
<td>Opacity Agent</td>
<td>PPH (Solid), Filler PPH (Solid), Others</td>
<td></td>
</tr>
<tr>
<td>Mandrel</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## II. Fabrication (Lines #)

| Paper-Tube Forming Machine: Trim | Scarf | Torque Setting |
| Drives | Gear Ratio (Braid) |
| Speed Setting | Equal to Inch | Foot Per Minute |
| Glass Yarn | Twist |
| Braiders (Mfr) | Carriers Type | Spools Longos |
| Tension Springs | Oz, T.S. Color | T.S. Size |
| Tension (Braid) Top (#1) Spools | Longos |
| Bottom (#2) Spools | 0z/Spool of Ends |
| Resin-Pot (Type) |

| Pump-Feed (Type) | Pump Feed Setting |
| Vacuum Chamber | Vacuum Level "Hg |
| Heater Settings (2) |
| Resin-Cure: a) Heater Setting (Center, Hot Air-Gun) |
| b) Infra-Red Heater Setting |
| Cooling | Cut-Off |

## III. Test Data:

| Resin Content (Tube): No | ( %); ( %); ( %); ( %) |
| Porosity (cfm/ft² 1/2" H₂O) |

## Comments:

---

**Figure 1-F**

Form No. 101 - Sept. 1968
APPENDIX G

MATERIAL SPECIFICATION
GIASS FILAMENT ROVING
TUBULAR REVERSE OSMOSIS UNIT
MATERIAL SPECIFICATION
CLASS FILAMENT ROVING
TUBULAR REVERSE OSMOSIS UNIT

1.0 SCOPE

1.1 This specification covers one type of continuous multiple end, Type E glass filament roving suitable for tube braiding applications.

2.0 APPLICABLE DOCUMENTS

2.1 Specifications and Standards - TBD
2.2 Drawings - TBD
2.3 Publications and Procedures - TBD

3.0 REQUIREMENTS

3.1 QUALIFICATION

The material furnished under this specification shall be a product which has been tested and passed the qualification tests specified herein.

3.2 PHYSICAL REQUIREMENTS

The physical requirements of the roving shall be as follows:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Ignition loss, wt-%</td>
<td>1.00</td>
<td>2.00</td>
</tr>
<tr>
<td>b. Weight/linear yard, g</td>
<td>.112</td>
<td>.129</td>
</tr>
<tr>
<td>c. Twists per inch</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>d. End count</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>e. Breaking strength, lb</td>
<td>12.5</td>
<td>17</td>
</tr>
<tr>
<td>f. Finish (epoxy compatible) wt-%</td>
<td></td>
<td>1-1/2% (Avr.)</td>
</tr>
<tr>
<td>g. Fusion resistance @ 1100°F</td>
<td>will not fuse</td>
<td></td>
</tr>
<tr>
<td>h. Filament diameter (ref), in.</td>
<td>0.00036</td>
<td>.00040</td>
</tr>
</tbody>
</table>

3.3 STRUCTURAL PROPERTIES

The glass roving shall be suitable for use in the fabrication of reverse osmosis tubes conforming to the applicable engineering drawings and associated documents. The material shall not fail or cause failure of the tube until pressurized to a minimum of 6.0 times the proof pressure value required by the applicable engineering drawings.
Appendix G (cont.)

3.6  WORKMANNISHIP

The material shall be free from any impurities and other defects which could adversely affect its performance. The material shall be uniform in quality and shall be manufactured in accordance with standard manufacturing procedures of the industry.

3.6.1  Splices

A broken end shall not be knotted. The end shall be spliced with either methyl methacrylate or cellulose acetate cement with 1-in. minimum overlap. Splices on two or more ends being spliced simultaneously shall be so spaced as to prevent any overlapping of the spliced areas.

h.0  QUALITY ASSURANCE PROVISIONS

h.1  SUPPLIER INSPECTION

Unless otherwise specified, the supplier is responsible for the performance of all inspections prior to submission for AGC inspection and acceptance. Except as otherwise specified, the supplier may utilize his own facilities or any commercial facilities acceptable to AGC. Inspection records of the examinations and tests shall be kept complete and available to AGC upon request.

h.2  SUPPLIER PROCESSING CHANGES

The supplier shall make no changes in processing techniques or other factors affecting the quality of the product without notification to AGC prior to shipment of a new lot of material.

h.3  LOT

A lot shall consist of roving processed in one continuous operation and offered for inspection at one time.

h.4  SAMPLING PLAN

Sampling shall be accomplished in accordance with Standard MIL-STD-414 for those characteristics listed in Table 1.
Appendix G (cont.)

TABLE 1

ACCEPTANCE QUALITY LEVELS AND TEST METHODS FOR CHARACTERISTIC REQUIREMENTS

<table>
<thead>
<tr>
<th>AQL and Characteristics</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>AQL 1.0%</td>
<td>4.7.4</td>
</tr>
<tr>
<td>End count</td>
<td></td>
</tr>
<tr>
<td>Tensile strength</td>
<td>4.7.6</td>
</tr>
<tr>
<td>AQL 2.5%</td>
<td></td>
</tr>
<tr>
<td>Weight per linear yard</td>
<td>4.7.2</td>
</tr>
<tr>
<td>AQL 6.5%</td>
<td>4.7.1.1</td>
</tr>
<tr>
<td>Ignition loss</td>
<td></td>
</tr>
<tr>
<td>AQL not applicable - no failures permitted</td>
<td>4.7.1.2</td>
</tr>
<tr>
<td>Weight per linear yard, lot average</td>
<td></td>
</tr>
<tr>
<td>Fusion resistance</td>
<td></td>
</tr>
</tbody>
</table>

h.1.1 Sampling Procedure

The following procedure shall be used to take samples of glass roving:

a. Remove and discard the first three waywinds of roving

b. Take a sufficient number of yards of roving for the test procedures specified in Table 1, except for tensile test. For this test take material directly from the sample ball for testing or to prepare test specimens.

c. Immediately after taking samples or making specimens rescale sample ball in container.

d. Seal each sample in a flexible, moisture-proof container. Suitably identify each sample or specimen.

h.1.2 CLASSIFICATION OF TESTS

The inspection and testing of the glass roving shall be classified as follows:

a. Qualification tests

b. Acceptance tests
4.6 QUALIFICATION TESTS

The qualification tests for this material shall consist of all the acceptance tests specified herein and the following additional tests. At the discretion of the procuring activity, these tests may be repeated subsequent to the initial qualification. Any change in processing techniques, materials or other factors affecting the quality of the product shall be immediately brought to the attention of the procuring activity for determination of the necessity for requalification.

4.6.1 Product Use Tests

Using the glass roving, reverse osmosis structural tube shall be fabricated and tested in accordance with the applicable engineering drawings.

4.7 ACCEPTANCE TESTS AND PROCEDURES

The acceptance tests and test procedures for this material shall be as specified in Table 1.

4.7.1 Ignition Loss and Fusion Resistance

The following procedure shall be used to determine ignition loss and fusion resistance:

4.7.1.1 Ignition Loss

The following procedure shall be used to determine ignition loss:

a. Cut three specimens, each 72 (plus or minus 0.1) inches long, and weigh to the nearest 0.001 gram (g).

b. Place the specimens in a muffle furnace maintained at 1100 (plus or minus 50) degrees Fahrenheit for a minimum of 15 minutes. Cool the specimens to ambient temperature and re-weigh to the nearest 0.001 g. Report average ignition loss of three specimens.

c. Calculate ignition loss as follows:

\[
\text{Ignition loss, wt-% } = \frac{W - W_1}{W} \times 100
\]

where:

\[W = \text{Original weight of specimen, g}\]

\[W_1 = \text{Weight of specimen after ignition loss, g}\]
4.7.2 Fusion Resistance

After determining ignition loss, observe the specimens for fusion. Any visible fusing of the roving is unacceptable.

4.7.2 Weight Per Linear Yard

Convert to and report as grams per linear yard the average weight of the specimens subjected to the ignition loss test (4.7.1).

4.7.3 Weight Per Linear Yard Lot Average

Calculate the lot average (3.2 ± 2) from the individual average values obtained in accordance with 4.7.2.

4.7.4 End Count

Cut a length of roving about 6-in. long from the ball. Loosen the end of the roving and make a visual count of the ends. Report the number of ends.

4.7.5 Tensile Strength

The following procedure shall be used to determine tensile strength:

4.7.5.1 Preparation of Specimen

The following procedure shall be used to prepare specimens:

a. Using slight tension, wind the glass roving on the Strand Fabrication Fixture, conforming to Drawing No. SA-2683129, or equivalent approved by the procuring activity. Securely fasten the roving at each end of the fixture.

b. Raise the bottom of the fixture to relieve roving tension, and thoroughly coat the loose roving with a vinyl solution of the following formulation:

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Parts by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exon 461 - made by</td>
<td>20 ± 1</td>
</tr>
<tr>
<td>Firestone Plastics Co.</td>
<td></td>
</tr>
<tr>
<td>P.O. Box 690, Pottstown, Pa.</td>
<td></td>
</tr>
<tr>
<td>or equivalent</td>
<td></td>
</tr>
<tr>
<td>Toluol</td>
<td>38 ± 1</td>
</tr>
<tr>
<td>Methyl Ethyl Ketone</td>
<td>38 ± 1</td>
</tr>
<tr>
<td>Cyclohexanone</td>
<td>4 ± 0.5</td>
</tr>
</tbody>
</table>
c. Immediately after coating, stress the roving by attaching a weight to the bottom yoke of the fixture. A weight of 63 (plus or minus 3) pounds is sufficient. Allow the coating to air dry for one minute.

d. Place the fixture, with the roving under stress, in an oven maintained at a temperature of 160 (plus or minus 10) degrees Fahrenheit, as determined by indicated temperature at control point, for 10 (plus or minus 1) minutes. Control point is defined as mean profile temperature of oven.

e. Remove the fixture and repeat steps b, c, and d until, as based on experience, a 1/4-in. specimen weighs a minimum of 1.00 gram. Then place the fixture with roving under stress into an oven maintained at 345 (plus or minus 10) degrees Fahrenheit as determined by indicated temperature at control point for 10 (plus or minus 0.5) minutes.

f. After cooling the oven and jig to below 125 degrees Fahrenheit, remove the fixture from the oven. Cut four specimens, each 14.0 (plus or minus 0.5) inches long from the center lengths of coated roving and discard the outer two lengths. Ensure that each specimen exceeds 1.00 g in weight.

h.7.5.2 Procedure

The following procedure shall be used to determine tensile strength:

a. Secure specimens in a suitable tensile testing apparatus having grips that provide minimum slippage or grip failure such as grips, Model No. DJ, with jaws and faces, Catalog No. A-53-5 and A-53, respectively, Instron Engineering Corp., Canton, Mass.

b. For this apparatus, fasten a specimen with a torque of 75 inch-pounds minimum, using a specimen gage length of 10 (plus or minus 0.10) inches.
Appendix G (cont.)

c. Take up the slack in the specimen with 12 (plus or minus 2) pounds of tension.

d. Using a crosshead travel rate of 0.10 (plus or minus 0.01) inches per minute, and with the recorder engaged, increase stress until the specimen fails.

NOTE: Observe the chart while running the tensile strength test. A decrease in slope, without failure, in the indicated load curve is a result of grip slippage. In this event, stop the test, inspect the condition of the specimen; if apparently satisfactory, replace in the grips, and complete the test.

e. Repeat the procedure for the three remaining specimens.

f. Calculate tensile strength, on only those specimens that do not fail in the grip area, as follows. Acceptance shall be based on an average of results from three specimens or more.

\[
\text{Tensile strength, psi} = \frac{1450 \times P}{W}
\]

Where:

\[P = \text{Average breaking force, lb}\]
\[W = \text{Average final weight after ignition loss test, g/linear yard of roving.}\]

\[1450 = \text{The factor for converting final calculation into psi.}\]

5.0 NOTES

5.1 INTENDED USE

This material is intended for use as a component of tubular reverse osmosis units.

5.2 ORDERING DATA

Procurement documents should specify, but not be limited to, the following information:
a. Title, number, and revision letter of this specification
b. Place of inspection
c. Type and size of packing container desired
d. Place of delivery
e. Request for three copies of results of acceptance tests, (if inspected by the supplier).
f. Manufacturer or supplier should be requested to certify that the material to be submitted under this procurement document, complies with Paragraph 4.6 relative to no change in processing techniques, material or formulation since qualification to this specification.

5.3 DEFINITION OF TERMS

The following definitions apply to the terms used in this specification.

a. Continuous filament - an individual rod of glass of small diameter, with flexibility, of great or indefinite length.

b. Strand or end - a given number of filaments gathered together into a single, continuous unit.

c. Roving - a number of ends of glass gathered together.

d. Roving ball - roving wound to a given outside diameter onto a cardboard tube.
APPENDIX H
DRAWINGS FOR 1000 GPD TUBULAR REVERSE OSMOSIS PILOT PLANT

Photograph - Small Scale Model of Pilot Plant
Photograph - Small Scale Model of Pilot Plant
Drawing #1360082, Sheet 1 - Equipment Skid
Drawing #1360082, Sheet 2 - Equipment Layout
Drawing #1360082, Sheet 3 - Piping - Section 1
Drawing #1360082, Sheet 4 - Piping - Section 2
Drawing #1360082, Sheet 5 - Piping Details
Drawing #1360082, Sheet 6 - Miscellaneous Details
Drawing #1360082, Sheet 7 - Flow Diagram
Drawing #1360082, Sheet 8 - Valve Schedule
Drawing #1360082, Sheet 9 - Instrument Panel
Drawing #1360082, Sheet 10 - Electrical Plan & Details
Drawing #1360082, Sheet 11 - Instrument Panel Elect. Details
Drawing #1360082, Sheet 12 - Isometric Piping Diagram
Scale Model - Pilot Plant, Rear View