Design and Fabrication of a 50,000 GPD Portable Reverse Osmosis Pilot Plant

United States Department of the Interior
Design and Fabrication of a 50,000 GPD Portable Reverse Osmosis Pilot Plant

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**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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**Appendix A** - Water Production Cost Summary

**Appendix B** - Procedures P-13, P-14, P-15 and P-16
I. INTRODUCTION

This report covers the first year of work under Contract 14-01-0001-930 which provided for the design and construction of a 50,000 gpd portable reverse osmosis pilot plant for brackish water conversion. This unit would provide the basis for design of brackish water desalination plants of large capacity, one million gallons per day, for example. The contract was started on 23 March 1966, and the system was completed on 23 April 1967, with all work conducted at the contractor's facilities at Azusa, California. The initial phase of the contract provided only for the design and construction of the unit. The testing of the unit at a brackish water test site and the pretreating equipment that might be needed to condition the feed water was to be provided in a subsequent phase of the program. As a result, at this writing, a well site for the test operation of the unit on brackish well water has been selected at South Laguna, California; a pretreatment trailer has been fabricated and field testing of the unit is underway. This report will be confined to a description of the design and final details of the unit, as built. Subsequent reports will cover the results of the field testing.

II. PILOT PLANT OBJECTIVES AND GUIDELINES

A. SPECIFIC OBJECTIVES

The primary purpose of this pilot plant is to prove a support plate design and a module assembly which will be the standard units in the future large scale desalination plants based upon the reverse osmosis process. The complete pilot plant is mounted onto a trailer so that it may be transported to various areas for evaluation of operation with different feed waters and conditions.

The experience gained during the operation of three 1000 gpd pre-pilot plants using 18-in. diameter membrane support plates and subsequently two 10,000 and one 20,000 gpd pilot plants using 24-in. plates has been used extensively in the design of this unit. This experience has resulted in revised design concepts which will result in a basis for the extrapolation of data to larger-scale operations.

In amplification of the above general remarks, the specific objectives of this pilot plant are as follows.

1. Verification of Design Concepts

The first and most important function of this pilot plant is to verify the workability of the design concepts proposed for a production plant. The basic principles of operation in this unit are the same as those in the pre-pilot plant, however, the geometry and plate details are essentially upgraded from those of the 10,000 and 20,000 gpd pilot plants which were developed after the proposal.
II Pilot Plant Objectives and Guidelines, A (cont.)

2. **Economic Relationships**

Operation of the pilot plant will still be on too small a scale to provide exact economic data directly on the ultimate cost of producing potable water by the reverse osmosis process in large plants, one million gallons per day, for example. Nevertheless, it will supply some preliminary economic data relating to capital and operating costs, energy requirements, and membrane replacement costs on an intermediate scale, and thus furnish the basis for more reliable estimates for water production on a larger scale. The value of the economic projections will be enhanced, however, because the criteria for the design are based on potential scale-up of the process.

3. **Miscellaneous Pilot Plant Objectives**

   Extended operation of the pilot plant will provide other helpful information which will be of value in planning any future production plant.

   a. Reliability factors can be established for mechanical components such as pumps, O-ring seals, and membrane bonds.

   b. Membrane characteristics can be statistically evaluated and improved - that is, characteristics such as initial salt-rejection and flux rates, freedom from flaws, useful economic life, membrane storage characteristics, and membrane cost.

   c. The effectiveness of the chosen corrosion-control program can be evaluated in saline-water service, and any indicated modifications put into effect.

   d. Maintenance needs can be established with respect to in-service operations. Such statistical criteria of operating reliability as contribute to down time of individual modules, of individual cells, or of the entire plant will be determined.

   Each of these objectives was considered in aiming at an optimum design for this pilot plant.

B. **DESIGN GUIDELINES**

1. The pilot plant was designed primarily to use a brackish water feed. However, the plant has been so fabricated that it may be used to pilot sea water operations.

2. With a feed of brackish water containing 3000 to 6000 ppm dissolved solids, the pilot plant will have a nominal target output of 50,000 gpd of product water. Any significant variation in composition from the above will result in a corresponding change in the volume of product and in the percentage of recovery.
II Pilot Plant Objectives and Guidelines, B (cont.)

3. The target for product water composition is 500 ppm or less.

4. No attempt has been made to recover power from the waste stream.

III. OPERATING CHARACTERISTICS

A. WATER RECOVERY

The following table lists the costs for various recovery percentages at various feed pressures as determined by the operations of the pre-pilot plants. Supporting calculations are presented in Appendix A.

COST SUMMATION

Summation of Energy, Amortized Membrane Support Plate, and Membrane Replacement Costs, $/1000 gal

<table>
<thead>
<tr>
<th>% Recovery</th>
<th>500</th>
<th>625</th>
<th>750</th>
<th>1000</th>
<th>1500</th>
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<tr>
<td>80</td>
<td>28.62</td>
<td>24.93</td>
<td>22.87</td>
<td>21.10</td>
<td>21.66</td>
</tr>
<tr>
<td>65</td>
<td>30.64</td>
<td>26.33</td>
<td>24.38</td>
<td>23.16</td>
<td>24.65</td>
</tr>
<tr>
<td>50</td>
<td>31.30</td>
<td>28.28</td>
<td>26.86</td>
<td>26.49</td>
<td>29.63</td>
</tr>
<tr>
<td>40</td>
<td>33.12</td>
<td>30.53</td>
<td>29.63</td>
<td>30.13</td>
<td>35.15</td>
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<tr>
<td>33</td>
<td>34.90</td>
<td>32.83</td>
<td>32.68</td>
<td>33.65</td>
<td>40.53</td>
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</table>

Based on the economics as shown in the above table, the 50,000 gpd pilot plant has been designed to recover as much as 80% of the feed water as product. However, sufficient flexibility has been incorporated into the plant design to permit the recovery of as low as 30% of the feed water. This flexibility will permit for operation on a variety of brackish waters, as well as on sea water.

B. PRESSURE

It is also shown in the table that, for 80% recovery, the optimum pressure, which yields minimum cost, is 750 psig. Accordingly, the plant has been designed to operate at that pressure. To ensure maximum flexibility, all elements of the plant which experience pressure are designed for 1500 psig service, and the high-pressure pump chosen is capable of operation at pressures up to 1500 psig. This will also enable sea water operation.
III Operating Characteristics, (cont.)

C. FLUX

The membrane performance varies with pressure, feed water composition, and product water composition. For example, a membrane heat-treated at 82°C will operate at 750 psig with the following performance: For a feed of 5000 ppm - flux 33, 400 ppm; for a feed of 10,000 ppm - flux 28, 900 ppm; for a feed of 20,000 ppm - flux 19, 2700 ppm. Thus, as the feed passes along the membrane surface becoming continually more concentrated, the flux and the quality of the instantaneous product will decrease. The actual flux and product quality from the plant will be integrated sums of the instantaneous values over the surface of the membrane.

For a product of 450 ppm, feed containing 5000 ppm, 80% recovery of feed (reject waste at 25,000 ppm), operation at 750 psig can be achieved with an average flux of 20 gfd, using "T" type membranes heat-treated to 74°C. This, then, is the design flux for the plant, which will require 2500 sq ft of membrane.

The design parameters of the plant to achieve this performance are summarized in the following table, in which is also given the expected performance on sea water, assuming 33% recovery.

The operating parameters based on the above are listed in the following table.

<table>
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<th>Brackish Water (5000 ppm)</th>
<th>Sea Water* (35,000 ppm)</th>
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<tr>
<td>Design feed rate, gpd</td>
<td>62,500</td>
<td>75,000</td>
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<tr>
<td>Operating pressure, psi</td>
<td>750</td>
<td>1,500</td>
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<tr>
<td>Feed composition, ppm TDS</td>
<td>3000-6000</td>
<td>35,000</td>
</tr>
<tr>
<td>Feed temperature, °C</td>
<td>20 ± 5</td>
<td>15 ± 10</td>
</tr>
<tr>
<td>Brine velocity, ft/sec</td>
<td>0.2-1.0</td>
<td>0.24-1.2</td>
</tr>
<tr>
<td>Flux, average gfd</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Recovery, %</td>
<td>80</td>
<td>33</td>
</tr>
<tr>
<td>Design pump horsepower</td>
<td>27.5</td>
<td>65.5</td>
</tr>
<tr>
<td>Product rate, gpd</td>
<td>50,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Product composition, ppm TDS</td>
<td>450</td>
<td>500</td>
</tr>
</tbody>
</table>

*It is assumed that current membrane development will provide suitable membranes to achieve these parameters.
III Operating Characteristics, (cont.)

D. PRODUCT QUALITY

Membrane performance will be adjusted to yield product quality of 450 ppm total dissolved solids. For given membranes, this gross quality will vary with feed water composition, because of the different permeabilities of Na⁺, Cl⁻, compared with Ca²⁺, Mg²⁺, and SO₄⁻⁻.

E. PRETREATMENT

Aeration and diatomaceous earth filtration will be the only pretreatment required of the water. This minimum requirement was proposed, based on experience in the pre-pilot plant at the Laguna site. The pretreatment facilities are being installed on a second trailer and are included in Phase II of this contract which covers the site preparations.

IV. HOUSING OF EQUIPMENT

The contract specified suggested that the 50,000 gpd plant be so constructed as to be transportable. Figures 1 and 2 show the overall unit ready for transport.

The trailer selected is a 40 ft long, 25 ton gross capacity unit built by Freuhauf. The longitudinal structural frame members are located to the sides of the trailer which permits placing of the pressure vessel down through the bed of the trailer. The front half of the trailer has an 18 ft long van body in which is housed the control console, instrumentation, power supply, and the motor starters. Also in the front is an area which includes a work bench, a sink, and some cabinets for laboratory analysis. The main circuit breaker and meter unit have been mounted on the forward external wall of the trailer facing the prime mover. Air compressor, feed pump, and compressed air tank have all been mounted on the underside of the trailer.

The back half of the trailer (Figure 3) is open and contains the pressure vessel, the pumps, and the filters. Over the back half of the trailer is a 26 ft long 12-in. I-beam that extends 6 ft beyond the end of the trailer and which is supported on four telescoping legs (Figure 4). A 5 ton capacity electric hoist on a geared trolley is mounted on this beam. When the trailer is brought to a new location it will be necessary to rent a crane to lift the rail to its maximum height of 23 ft. The telescoping legs will be pinned and the rail will remain at this height while at the location. When the gantry is raised, it will be possible to lift off the vessel head, raise the desalination plate stack out of the vessel, transport it over the end of the trailer and lower it onto a truck. The rail will be lowered only when the trailer is to be moved to a new location.

*Figure 24 - 50K Preliminary Equipment Layout
V. DESCRIPTION OF EQUIPMENT

A mechanical flow diagram is shown in Figure 5. With the exception of the desalination cell, all items of equipment and instrumentation are standard products of recognized equipment manufacturers. The feed water to the pilot plant will have been processed through the pretreatment trailer where it is aerated, filtered to remove precipitated iron and particulate suspended matter, and chemically treated if such is necessary.

A. FEED PUMP

The feed pump (Figure 6) is a 7.5 horsepower centrifugal unit which will take water from the source of supply or the pretreatment facilities and drive it through filters to the high-pressure pump. Capacity of the pump is 100 gpm @ 75 psi, 150 gpm @ 45 psi.

B. FILTERS

The feed water will pass through four filters (Figure 7) mounted in parallel, each of which will contain 18 replaceable 5-micron cartridges. Each of the filters will have a flow rate capacity of 108 gpm based on 2 psi initial pressure drop. However, these filters will also be used in lieu of the diatomaceous earth filters of the pretreatment facilities during regeneration. During these times it may be necessary to use all four filters. They will be used primarily for polishing the feed water that will have undergone pretreatment.

C. HIGH-PRESSURE PUMP

The high-pressure pump (Figure 8) is a horizontal single acting reciprocating quintuplex plunger pump having a capacity of 70 gpm at 1500 psi discharge when operating at 385 rpm. This pump has been used extensively in steam flooding service in oil fields. It is driven by a 75 horsepower electric motor.

D. FEED WATER FLOW CONTROL VALVE

Feed rate to the cell will be regulated by a bypass line with a control valve that recycles water back to the inlet of the pump. Control of the feed rate will be from the console in the front of the trailer. The flow control valve is 1-in., 1500 psi pressure drop, pneumatically operated valve with a maximum flow rate of 70 gpm.

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E. DESALINATION CELL

1. General Description

The desalination cell concept was originally conceived as a horizontal cell containing two single-pass modules. In order to obtain the best membrane performance, several modules, operating in series, are needed. In addition, it is desirable to be able to vary the number of modules and the number of membrane support plates per module to provide for operation on varying feed waters.

Accordingly, the cell concept has been modified to provide for a plate stack containing multiple passes (modules). The plate stack will be in a series-parallel flow arrangement. The modules will be in series and the plates within a given module will be in parallel. Separating each of the modules will be divider plates. Alternate divider plates will have peripheral seals against the side of the pressure vessel and will have ports near the center through which the feed water will flow. The balance of the plates will not have flow ports and will be smaller in diameter than the inside of the vessel leaving an annular space through which the water will flow.

The new cell concept has decreased the overall height of the vessel so that it may now be mounted in the vertical position permanently.

This unit contains approximately 2500 sq ft area of working membrane mounted on both sides of the membrane support plates.

Figure 9 shows the completed stack. It will have nine passes. The feed water enters through the open centered top plate, down through the openings of the plates in the first pass and is stopped by the closed center plate. The water is forced to flow between the membranes mounted on the plates and is directed to the outer periphery of the plate. At this point it flows down around the closed center divider plate and enters the second pass from the outer edges of the plates where it again flows between membranes toward the center of the plates.

As the feed water containing salts flows across the membrane under pressure, purified water passes through the membrane. This purified water then flows through the grooves of the plates, into the collecting channels which converge to the slotted product shaft. Between each of the plates are O-rings which prevent the feed stream from flowing into the product shaft.

2. Pressure Vessel

The first major change was the decision to place the vessel in a vertical position on the trailer. The problems associated with the loading of the membrane support plates stack into a horizontal vessel became insurmountable because of the necessary peripheral seals.
V Description of Equipment, E (cont.)

The 50,000 gpd pressure vessel (Figure 10) is built in compliance to the ASME Unfired Pressure Vessel Code with an allowable working pressure rating of 1500 psig. It is 44-in. O.D., 10-1/2 ft overall length and the wall thickness is 1.91-in. The entire pressure vessel is constructed of A212B carbon steel protected internally with an organic coating. Figure 11 shows the vessel before being lowered into position on the trailer.

The vessel is mounted on the trailer with a phenolic isolation gasket between the vessel support ring and the deck of the trailer. All piping to the vessel have isolation gaskets at the flanges. Isolation of the vessel minimized corrosion due to galvanic potential through the process lines. When connecting piping is removed, the road clearance of the bottom of the vessel will be approximately 14-in. The flange height above the deck is 5-1/2 ft. The top of the vessel including the blind flange is 12 ft above ground. When the gantry assembly is resting on the flange it will be in the "travel" position and the overall height will be 13 ft 6-in. which is the maximum allowable in most states.

There have been cases in the 10,000 gallon per day pilot plants in which the plate stack as an assembly has lifted off of the support pedestal in the vessel. This is apparently caused by a rapid lowering of pressure at the inlet of the vessel causing a differential pressure across the plate stack in a reverse direction. This results in a displacement of the O-rings at the base of the stack. To prevent this occurrence in the new pilot plant, a jackscrew (Figure 12) has been placed into the head of the vessel to hold down the stack. This jackscrew is also necessary to hold down the stack when the trailer is in transport.

3. **Membrane Support Plates (Figures 13 & 14)**

The membrane support plates are made of bonded half plates similar to the 24-in. plates currently used in the 10,000 gpd plants. The basic design of the half plates is an upgrading of those used for the 24-in. units. Plate Support 36-in. Gap Half and Flat Half are shown in Figures 25 & 26.

The plates are fabricated from a filled phenolic thermo-setting material. The mold for the membrane support plate is a transfer-compression type weighing approximately 8000 pounds and was the highest cost item of the unit.

The method of attaching the membrane to the support plate is described in detail in Appendix B.

4. **Baffles (Figure 15)**

The spiral flow baffles will be vacuum formed out of polystyrene sheet and are designed to create turbulent flow across the membranes.
5. Stainless Steel Internals

Parts referred to as stainless internals are:

1 - Top pressure plate (Figure 16 & 17)
4 - Open center divider plates (Figure 18)
4 - Closed center divider plates (Figure 19)
1 - Bottom plate (Figure 20)
1 - Product shaft (Figure 21)

Before making the decision to fabricate the divider and end plates of stainless steel other materials were investigated. The use of stainless is not only expensive because of the material cost, but because of the higher costs involved in the machining of this material.

Methods that were checked were:

a. Plates made out of fiberglass and epoxy laminates. These plates would have been approximately three times thicker than the steel plates because of the lower modulus of elasticity.

b. Carbon steel plates with a vulcanized neoprene coating to which would be bonded membrane support half-plates. (The support plate halves would eliminate the need for machining the grooves, etc., into the carbon steel plate.) The neoprene coating is designed to allow sufficient movement to relieve the lap shear force between the half plates and the carbon steel plate when the plate is undergoing deflection. The neoprene would also protect the carbon steel material from corrosion.

c. The same as (b) except the base plate would be stainless. This would require the upper half of the membrane support plate to be bonded.

d. Modifications being made to the existing stainless steel plate design to reduce the cost of machining.

Because of the necessity to pin down the final length of the pressure vessel which was dependent upon the length of the stack, the decision was made to eliminate the fiberglass plate design for this unit. It was felt that the pressure vessel construction would have been delayed too long awaiting the necessary tests to prove this material. The tests, however, will continue to prove the feasibility of the design in future units.
Ultimately it was felt that additional tests would be required to prove the other methods and that the 50X gpd should not be used for this type of testing. On this basis the decision was made to use the stainless steel material.

The product shaft is fabricated from stainless tubing.

6. **Peripheral Seal**

The original peripheral seal design has been eliminated because of the inability to obtain inflatable seals that will hold up under the design conditions. The new design incorporates a rubber sleeve or boot which will capsule the entire stack. At the location of each of the open center divider plates the sleeve will be clamped to the outside diameter of the plate. This will allow the water to flow through the stack and yet not bypass the open center plates.

F. **Feed Pressure Control Valve**

Control of the feed water pressure to the desalination cell will be by a pneumatically operated valve same as the flow control valve. This valve is on the reject line of the cell but is controlled by the inlet pressure to the cell.

G. **Cell Bypass Valve**

There is an additional manually operated valve that is on a bypass line from the feed line to the cell to the reject line. This line will be used during start-up as well as times when low flow rates are required through the cell.

H. **Instrumentation**

The instrumentation which includes the control console (Figure 22) will be mounted in the front half of the trailer. All of the major items will be recorded for a permanent record. These items are:

1. Feed and product flow
2. Feed temperature
3. Desalination cell inlet pressure and the differential pressure across the cell
4. Conductivity of the feed, product, and reject streams for determination of total dissolved solids concentration.
The feed flow and the desalination cell inlet pressure will be controlled automatically. Major instrument components are listed below.

**Conductivity Instrumentation**
- Feed Conductivity Cell, 0-10,000 μmhos - Beckman CEL-VK2-T
- Feed Conductivity Measuring Circuit - Beckman RA-5 SoluMeter
- Waste Conductivity Cell, 0-100,000 μmhos - Beckman CEL-VH40-T
- Waste Conductivity Measuring Circuit - Beckman RA-5 SoluMeter
- Product Conductivity Cell, 0-2000 μmhos - Beckman CEL-VK4-T
- Product Conductivity Meas. Circuit - Beckman RA-5 SoluMeter
- Conductivity Recorder (3 pen) - Foxboro 6430HF

**Pressure-Temperature Instrumentation**
- Cell Inlet Pressure Transmitter (0-2000 psig) - Foxboro 44BP
- Cell Differential Press. Trans. (0-200 psid) - Foxboro 11DM
- Feed Temperature Trans. (0-200°F) - Foxboro 44BT/TA-1B
- Pressure-Temperature Recorder (3 pen) - Foxboro 5330-FE
- Feed Inlet Press. Controller (0-1750 psig) - Foxboro 52A-SM4F
- Back Pressure Control Valve (0-1500 psig) - Fisher 512B

**Flow Instrumentation**
- Cell Inlet Flow Transmitter (0-100 gpm) - Foxboro 13A
- Product Flow Transmitter (0-100 gpm) - Foxboro 13A
- Flow Recorder (3 pen - one open) - Foxboro 5330-FE
- Inlet Flow Controller (0-100 gpm) - Foxboro 52A-SM4F
- Flow Control Valve (0-100 gpm) - Fisher 512B

The balance of the instrumentation is composed of local and panel mounted gages, lights, and switches, most of which are mounted on the control console.

I. SUPPORT EQUIPMENT

1. **Stack Compression Press**

   The 50-ton capacity stack compression press (Figure 23) is complete. This unit stands 11-1/2 ft high and will accommodate a full stack of 36-in. plates having nine modules including the product shaft. After the assembled stack is placed in the press, two hydraulic rams will bear down on
the top pressure plate compressing the stack with a force of approximately 30 tons to squeeze down the baffles, membrane, and plates to the point that the O-rings are sealed.

Additional major support equipment that has been built includes:

a. Modification to the membrane heat sealing press to handle the 36-in. plate.

b. A special skid to hold the full desalination stack when in transit to or from the trailer and for vacuum testing.

c. Fixture for lifting each module when making up the stack.
Figure 2  Overall View of Portable 50,000 gpd Pilot Plant
Figure 3  Arrangement of Filters, Feed Pump and Desalination Cell
7-1/2 H.P. Feed Pump, Under Trailer

Figure 6
75 H.P. High-Pressure Pump

Figure 8
Pressure Vessel Being Lowered

Figure 11
APPENDIX A

WATER PRODUCTION COST SUMMARY

The cost elements of a reverse osmosis operation most subject to variations resulting from variations in pressure and recovery rate are energy, membrane support plate, and membrane replacement. Calculation of the relationships between these various parameters is useful in designing optimum operating conditions for the plant. The calculations have been made as shown below for a 1,000,000 gpd plant on brackish water:

I. ENERGY COST
A. PUMPING RATES

<table>
<thead>
<tr>
<th>Stream</th>
<th>80%</th>
<th>65%</th>
<th>50%</th>
<th>40%</th>
<th>33%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>870</td>
<td>1,070</td>
<td>1,390</td>
<td>1,740</td>
<td>2,085</td>
</tr>
<tr>
<td>Product</td>
<td>695</td>
<td>695</td>
<td>695</td>
<td>695</td>
<td>695</td>
</tr>
<tr>
<td>Waste</td>
<td>175</td>
<td>375</td>
<td>695</td>
<td>1,045</td>
<td>1,390</td>
</tr>
</tbody>
</table>

Sample Calculation for 65% Recovery

Product Flow Rate

\[
\frac{1,000,000 \text{ gal/day}}{1440 \text{ min/day}} \quad \text{(definition)} = 695 \text{ gal/min}
\]

Feed Flow Rate

\[
\frac{695 \text{ gal/min}}{0.65} = 1,070 \text{ gal/min}
\]

Waste Flow Rate

\[
1,070 \text{ gpm} - 695 \text{ gpm} = 375 \text{ gpm}
\]
B. HORSEPOWER REQUIREMENT

<table>
<thead>
<tr>
<th>Operating Pressure</th>
<th>80%</th>
<th>65%</th>
<th>50%</th>
<th>40%</th>
<th>33%</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>362</td>
<td>445</td>
<td>578</td>
<td>723</td>
<td>866</td>
</tr>
<tr>
<td>625</td>
<td>454</td>
<td>568</td>
<td>724</td>
<td>905</td>
<td>1,088</td>
</tr>
<tr>
<td>750</td>
<td>545</td>
<td>665</td>
<td>865</td>
<td>1,085</td>
<td>1,300</td>
</tr>
<tr>
<td>1,000</td>
<td>725</td>
<td>890</td>
<td>1,155</td>
<td>1,445</td>
<td>1,730</td>
</tr>
<tr>
<td>1,500</td>
<td>1,090</td>
<td>1,330</td>
<td>1,730</td>
<td>2,170</td>
<td>2,600</td>
</tr>
</tbody>
</table>

Sample Calculation for 65% Recovery at 750 psi

Using the following equation (1):

\[
\text{Work (hp)} = \frac{(P_D - P_S)(G_a)}{1715 \times E}
\]

where:
- \( P_D \) = discharge pressure, psia
- \( P_S \) = suction pressure, psia
- \( W \) = work, hp
- \( G_a \) = actual gal/min pumped
- \( E \) = overall mechanical and electrical efficiency

\[
hp \text{ (65% recovery, 750 psi)} = \frac{750 \times 1070}{1715 \times 0.7} = 665 \text{ hp}
\]

C. ELECTRICAL ENERGY COST - cents/1000 gal product

<table>
<thead>
<tr>
<th>Pressure</th>
<th>80%</th>
<th>65%</th>
<th>50%</th>
<th>40%</th>
<th>33%</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>4.53</td>
<td>5.55</td>
<td>7.21</td>
<td>9.03</td>
<td>10.81</td>
</tr>
<tr>
<td>625</td>
<td>5.70</td>
<td>7.10</td>
<td>9.05</td>
<td>11.30</td>
<td>13.60</td>
</tr>
<tr>
<td>750</td>
<td>6.81</td>
<td>8.32</td>
<td>10.80</td>
<td>13.57</td>
<td>16.62</td>
</tr>
<tr>
<td>1,000</td>
<td>9.05</td>
<td>11.11</td>
<td>14.44</td>
<td>18.08</td>
<td>21.60</td>
</tr>
<tr>
<td>1,500</td>
<td>13.63</td>
<td>16.62</td>
<td>21.60</td>
<td>27.15</td>
<td>32.50</td>
</tr>
</tbody>
</table>

Sample Calculation for 65% Recovery at 750 psi

Cost per kWh = 0.7¢ (assumed)

\[
\frac{\text{cents}}{\text{1000 gal}} = \frac{\text{hp}}{1.341 \text{ hp/kw}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{1 \text{ day}}{\text{1000 (1000 gal)}} \times \frac{0.7 \text{ cents}}{\text{kWh}} = \text{hp} \times 0.0125
\]

665 hp (65% recovery at 750 psi) \times 0.0125 = 8.32 ¢/1000 gal

II. **MEMBRANE SUPPORT PLATE COST**

The membrane support plate cost is a function of its amortized cost and the productivity of the membrane which it supports. Cost is essentially a constant but membrane productivity varies with pressure. Based on assumptions that flux at 750 psi is 20 gfd, flux is directly proportional to pressure, and the unit cost of support plates in sufficient quantity for a 1,000,000 gpd plant will be 77 ¢/ft² (11.55 ft²/plate \times $0.77/ft² = $8.90/plate), the following table shows membrane support plate cost vs pressure.

<table>
<thead>
<tr>
<th>Pressure, psi</th>
<th>Flux, gfd</th>
<th>Membrane Area, ft²</th>
<th>Support Plate Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>13.3</td>
<td>75,000</td>
<td>57,750</td>
</tr>
<tr>
<td>625</td>
<td>16.7</td>
<td>60,000</td>
<td>46,200</td>
</tr>
<tr>
<td>750</td>
<td>20.0</td>
<td>50,000</td>
<td>38,500</td>
</tr>
<tr>
<td>1,000</td>
<td>26.6</td>
<td>37,500</td>
<td>28,875</td>
</tr>
<tr>
<td>1,500</td>
<td>40.0</td>
<td>25,000</td>
<td>19,250</td>
</tr>
</tbody>
</table>

Sample Calculation for 625 psi Operating Pressure

\[
\text{Flux} = \frac{625}{750} \times 20 = 16.7
\]

Membrane Area

\[
\frac{1,000,000 \text{ gal/day}}{16.7 \text{ gal/ft²/day}} = 60,000 \text{ ft}²
\]

Support Plate Cost

\[
\text{Total} = 60,000 \text{ ft}² \times $0.77/\text{ft}² = $46,200
\]
\[ \frac{\$}{1000 \text{ gal}} \]

\[
\frac{0.074}{\text{year}} \times \frac{\text{plate cost}, \$}{1000 \text{ gal/year}} \times \frac{100\$}{\$} = \frac{0.074 \times \$46,200}{330,000 - 1000 \text{ gal}} = 1.03 \frac{\$}{1000 \text{ gal}}
\]

*20-year amortization of capital cost and 4% interest on unamortized balance is equivalent to an annual charge of 7.4% of the capital investment. Annual production is based on 330 operating days per year.

III. MEMBRANE REPLACEMENT COST

For the purpose of this calculation, it is assumed that membrane replacement cost will be $1.000/ft^2 and that replacement must be done once a year. Replacement cost varies with membrane flux which in turn varies with pressure. The following table shows the relationship between operating pressure and membrane replacement cost per 1000 gallons of product water.

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Membrane Replacement Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>75,000 $/year</td>
</tr>
<tr>
<td>625</td>
<td>60,000 $/year</td>
</tr>
<tr>
<td>750</td>
<td>50,000 $/year</td>
</tr>
<tr>
<td>1,000</td>
<td>37,500 $/year</td>
</tr>
<tr>
<td>1,500</td>
<td>25,000 $/year</td>
</tr>
</tbody>
</table>

Sample Calculation for 625 psi Operating Pressure

\[
\frac{\$}{\text{year}} \times \frac{60,000 \text{ ft}^2}{\text{ft}^2} \times \frac{\$}{\text{ft}^2} = \frac{\$60,000}{\text{year}}
\]

\[
18.2 \frac{\$}{1000 \text{ gal}}
\]

\[
\frac{\$60,000}{\text{year}} \times \frac{100\$}{\$} \times \frac{1000-1000 \text{ gal}}{1000 \text{ gal}} \times \frac{330 \text{ day}}{\text{year}} = 18.2 \frac{\$}{1000 \text{ gal}}
\]
IV. SUMMATION OF ENERGY, MEMBRANE SUPPORT PLATE AND MEMBRANE REPLACEMENT COSTS

WATER PRODUCTION COST, $/1000 GAL

<table>
<thead>
<tr>
<th>% Recovery</th>
<th>Feed Stream Pressure, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
</tr>
<tr>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>4.53</td>
</tr>
<tr>
<td>Plate</td>
<td>1.29</td>
</tr>
<tr>
<td>Replacement</td>
<td>22.80</td>
</tr>
<tr>
<td>Total</td>
<td>28.62</td>
</tr>
<tr>
<td>65%</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>6.55</td>
</tr>
<tr>
<td>Plate</td>
<td>1.29</td>
</tr>
<tr>
<td>Replacement</td>
<td>22.80</td>
</tr>
<tr>
<td>Total</td>
<td>30.64</td>
</tr>
<tr>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>7.21</td>
</tr>
<tr>
<td>Plate</td>
<td>1.29</td>
</tr>
<tr>
<td>Replacement</td>
<td>22.80</td>
</tr>
<tr>
<td>Total</td>
<td>31.30</td>
</tr>
<tr>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>9.03</td>
</tr>
<tr>
<td>Plate</td>
<td>1.29</td>
</tr>
<tr>
<td>Replacement</td>
<td>22.80</td>
</tr>
<tr>
<td>Total</td>
<td>33.12</td>
</tr>
<tr>
<td>33%</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>10.81</td>
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<tr>
<td>Plate</td>
<td>1.29</td>
</tr>
<tr>
<td>Replacement</td>
<td>22.80</td>
</tr>
<tr>
<td>Total</td>
<td>34.90</td>
</tr>
</tbody>
</table>
APPENDIX B

This appendix presents Aerojet-General Corporation Environmental Systems Division Procedures P-13, P-14, P-15 and P-16 concerning substrate mounting, O-ring application, membrane mounting, and plate inspection. These procedures relate specifically to 24-in. reverse osmosis systems. The handling of 36-in. plates is exactly the same and, therefore, the reader may get a complete picture of the various processing steps to install membranes on 36-in. plates from these descriptions.
PROCEDURE P-13

SUBSTRATE AND NYLON MOUNTING: 2¼-IN. PLATES

1. SCOPE

1.1 This procedure establishes a method for mounting paper and nylon to 2¼-in. plates.

2. PAPER AND NYLON MOUNTING

2.1 Materials

2.1.1 Paper, U.S. Filter #4229, 13-14.5 mil thick, cut to Procedure P-12.

2.1.2 Nylon, Rice & Carelli, 3-5 mil thick, cut to Procedure P-12.


2.1.4 Support plate, 096273-1

2.1.5 Toluene, technical grade

2.1.6 Polyethylene bag, 42" x 72" x 0.004"

2.2 Equipment

2.2.1 Turntable, 096286

2.2.2 Caulking gun, Semco #550

2.2.3 Tub, Ryan Herco Corp. #RHM 3¾N, 26" I.D. x 10" deep

2.2.4 Nalpak wood platform truck, 36" x 36", 2000 lb capacity, 8" dia. wheels, 2 swivel and 2 rigid, standard push handle, center shaft, 099505.

2.2.5 Spatula, round end laboratory spatula with end ground square 1" from handle.

2.3 Procedure

2.3.1 Set support plate (2.1.4) on turntable (2.2.1).
2.3.2 Clean plate with toluene (2.1.5) and kim-wipes to remove any dirt or grease. Observe no smoking regulation when handling toluene.

2.3.3 Remove nylon (2.1.2) from formaldehyde soak tank (P-12) and place in tub (2.2.3) near turntable.

2.3.4 Repeat step 2.3.3 with paper (2.1.1).

2.3.5 Center nylon on support plate.

2.3.6 Place paper on top of nylon. There should be about 1/32" clearance between the edge of the bonding surface and the edge of the substrate on both the I.D. and O.D.

2.3.7 Insert RTV-102 cartridge (2.1.3) into caulking gun (2.2.2).

2.3.8 Start turntable. The speed of the turntable is dependent upon the person mounting the plate.

2.3.9 Extend the RTV into the outer and inner clearance between bonding edge and substrate.

2.3.10 Leave the turntable on and trowel the RTV into place using spatula (2.2.5). Remove excess from bonding step and substrate using the same spatula.

2.3.11 Visually inspect plate for gaps or voids in the RTV bead and for cleanliness of the bonding surface.

2.3.12 Turn plate over.

2.3.13 Repeat 2.3.9, 2.3.10, and 2.3.11.

2.3.14 Place plate on cart (2.2.4) and go on to next plate. Capacity of cart is 120 plates.

2.3.15 When finished, pull polyethylene bag (2.1.6) down and around stack of plates to prevent drying out of the substrate and nylon.
PROCEDURE P-14

O-RING MOUNTING AND GLUE APPLICATION: 2½-IN. PLATES

1. SCOPE

1.1 This procedure establishes a method for mounting O-rings on and applying glue to 2½-in. plates.

2. O-RING MOUNTING AND GLUE APPLICATION

2.1 Materials

2.1.1 O-rings

2.1.1.1 Parco, 3.295 x 0.070, Silicone rubber, #1263939

2.1.1.2 Parco, 2.301 x 0.070, Silicone rubber, #1263939

2.1.2 Silicone resin, SR-529, G.E.

2.1.3 Toluene, technical grade

2.1.4 Polyethylene bag, ½2" x 72" x 0.004"

2.1.5 Support plate, substrated, P-13

2.2 Equipment

2.2.1 Turntable and glue assembly, 096286

2.2.2 Nalpack wood platform truck, 36" x 36", 2000 lb capacity, standard push handle, center shaft, 099505

2.2.3 Glas-pak disposable syringe, 10 cc

2.2.4 Spacers, wood blocks, 1" x 3"

2.2.5 Support plate, 096273-1

2.3 Procedure

2.3.1 Remove top from glue pot (2.2.1) and fill with resin (2.1.2)
2.3.2 Replace lid and connect air line to quick disconnect located on lid of glue pot.

2.3.3 Close line leading to pressure vessel containing toluene (2.1.3).

2.3.4 Open valve leading from glue pot to nozzle arms (2.2.1) and turn on air supply (40-80 psi).

2.3.5 Place spare plate (2.2.5) on turntable (2.2.1).

2.3.6 Adjust nozzle arms so that tip of nozzle sets about 1/16-1/8" above bonding surface.

2.3.7 Turn master switch and glue solenoid switch to "ON" position (located on left hand side of turntable). Position toggle switch, located below speed control lever, marked "normal - bypass" to "normal."

2.3.8 Start cycle by pressing button located on right side of turntable.

2.3.9 Adjust speed of turntable to give a 1/8" bead of glue on center of outside bonding surface.

2.3.10 Adjust glue bead on inner surface to 1/8" by opening or closing needle valve located at base of inner nozzle arm.

2.3.11 Allow to cycle until all air is out of system and glue flows smoothly.

2.3.12 Remove spare plate and place substrated plate (P-13), bottom side up (flat surface), on turntable.

2.3.13 Start cycle.

2.3.14 Check plate for uniform glue application.

2.3.15 Turn plate over and repeat steps 2.3.11 - 2.3.13.

2.3.16 Place toggle switch to "bypass" and shut off glue solenoid switch.

2.3.17 Fill syringe (2.2.3) with silicone resin (2.1.2).

2.3.18 Start turntable.
2.3.19 Lay a thin bead of glue (1/16") in O-ring grooves.

2.3.20 Allow glue to dry for approximately one minute.

2.3.21 Lay O-rings (2.1.1) in grooves.

2.3.22 Place bare plate, O-ring side up, in empty cart (2.2.2).

2.3.23 Place finished plate on top of bare plate, O-rings up.

2.3.24 Turn toggle switch to "normal" and turn on solenoid switch.

2.3.25 Continue operation (2.3.11 - 2.3.20). Use spacers (2.2.4) to separate glued plates when stacking plates on cart. Make sure spacers rest on substrated area and not glued surface.

2.3.26 When finished, disconnect air supply to glue pot.

2.3.27 Open valve connecting toluene vessel to nozzles.

2.3.28 Connect air supply to pressure vessel containing toluene.

2.3.29 Disconnect air supply to arm, lowering piston and lower arms by hand.

2.3.30 Place waste cans underneath nozzles and start cycle on "normal". As soon as glue solenoids open, stop turntable by lowering clutch lever to stop position. When toluene starts to flow from nozzles, turn solenoid switch to "OFF". Each nozzle can be independently shut off by disconnecting their respective plugs located in wiring going to each arm. During this operation, check to see that solenoids do not overheat.

2.3.31 During flush, slip polyethylene bag (2.1.4) over plates to prevent them from drying out.

2.3.32 After flush, release pressure on toluene vessel.

2.3.33 Allow glued plates to stand for 2 hours before proceeding to mounting operation (P-15).
PROCEDURE P-15

MEMBRANE MOUNTING: 24-IN. PLATES

1. SCOPE

1.1 This procedure establishes a method for mounting membrane on 120 support plates (24-in. in diameter).

2. MOUNTING MEMBRANE

2.1 Materials

2.1.1 Support plate, substrated and glued, Procedures P-13 and P-14

2.1.2 Membrane, 240 sheets die cut (+ 10% to allow for rejection). Procedure P-11.

2.2 Equipment

2.2.1 Steel marking table, 36" x 72" x 36" dia. casters, 600-800 lb capacity.

2.2.2 Nalpax wood platform truck 36" x 36", 2000 lb capacity, 8" dia. wheels, standard push handle, center shaft 099505.

2.2.3 Tub, Ryan Herco Corp., 26" I.D. x 10" deep, RHM 34N.

2.2.4 Heat seal press, 097573, consists of air pressure regulator, 2 mounted variacs, timer, 2 pair of energizer switches, temperature gauge, heat seal ring and locating pin 097573, and 2 carriages. On each carriage a nylon centering disk is screwed into place. Over each disk fits a teflon ring which supports the membrane support plate during bonding. Each of the two teflon plate supports are designed for a specific purpose; one (marked "P") is used when bonding the flat or bottom side of the membrane support plate, and the other (marked "T") is used when mounting the 0-ring or top side of the plate.
2.2.5 Paper, heavy woven, 30" x 30"

2.2.6 Sponge

2.2.7 Polyethylene bag, 42" x 72" x 0.004".

2.3 Procedure

2.3.1 Turn on time and variacs (2.2.4); bring air pressure to 80 psi ± 10 psi (2.2.4).

2.3.2 Set timer for 20 second bonding time.

2.3.3 Adjust variacs to maintain temperatures at 125°C ± 10°C for both the inner and outer heat seal rings.

2.3.4 Remove membrane (2.1.2) from formaldehyde solution and place in tub (2.2.3) partially filled with water.

2.3.5 Place rolling table (2.2.1) next to bonding press.

2.3.6 Using the proper teflon plate support (2.2.4) place glued plate on the carriage with the centering disk (2.2.4) fitting inside the center of the plate.

2.3.7 Using damp sponge (2.2.6) wipe off any dirt or material which may have fallen on plate during standing.

2.3.8 Remove membrane from tub and center on support plate active layer up.

2.3.9 Using damp sponge, smooth out membrane carefully to remove any wrinkles.

2.3.10 Place wet paper (2.2.5) over membrane; be careful not to move membrane.

2.3.11 Push in carriage. The carriage and heat seal press are marked so that the carriage can be located quickly.

2.3.12 Press energizer buttons. As the heat seal ring comes down, the centering pin (2.2.4) centers the plate exactly.
2.3.13 While the plate is being bonded, a second operator should repeat steps 2.3.6-2.3.11.

2.3.14 After bonding, pull out carriage. Second operator will push his carriage in and repeat bonding operation, 2.3.12.

2.3.15 Remove paper and place in water to keep wet.

2.3.16 Place half finished plate on one end of table. On other end of table stack plates with opposite side mounted. If for some reason there is a delay during this operation, wet the membrane and cover with polyethylene to prevent drying.

2.3.17 Continue bonding (steps 2.3.6-2.3.16) checking plates constantly for complete bonding, no voids or gaps.

2.3.18 After bonding 120 plates (60 on top side and 60 on bottom side) switch teflon plate supports. This proves easier than moving 120 plates.

2.3.19 Continue bonding operation (2.3.6-2.3.16). Place each finished plate on cart (2.2.2).

2.3.20 After bonding, slip polyethylene bag (2.2.6) over plates.

2.3.21 Turn off heaters and release air pressure.
PROCEDURE P-16

SINGLE MEMBRANE PLATE INSPECTION: 2¼-IN. PLATES

1. SCOPE

1.1 This procedure establishes a method for inspecting individual 2¼-in. diameter plates mounted with membrane.

2. INSPECTION PROCEDURE

2.1 Chemicals

2.1.1 Water

2.1.2 Niagra Sky Blue dye, J. T. Baker R753, 1% solution.

2.2 Equipment

2.2.1 Nalgene pails, 5 gal capacity

2.2.2 Tape, Temp-R-tape T, 1/2-in. wide

2.2.3 Tape, Temp-R-Tape T, 1-in. wide

2.2.4 Scissors

2.2.5 Stanley knife

2.2.6 Ultrasonic Translator Detector, Delcon 118

2.2.7 Vacuum test assembly. Assembly consists of duoseal vacuum pump, filtering flask (Pyrex 2000 ml), 4-way stop cock, vacuum gauge (0-30"), and a vacuum test fixture (SK 330416). The test fixture consists of 2 aluminum disks one of which has a 1/8" pipe tapped into it. This pipe is connected to the 4-way stop cock by heavy walled tubing. A second line runs from the stop cock to the vacuum gauge and a third to the filtering flask. Another piece of tubing connects the filtering flask to the vacuum pump.

2.2.8 Glas-pak disposable syringe, 10 cc

2.2.9 Sponge
2.3 Procedure

2.3.1 Turn on vacuum pump (2.2.7).

2.3.2 Fill syringe (2.2.8) with Niagra Sky Blue dye (2.1.2).

2.3.3 Place mounted support plate on bottom half of test fixture (2.2.7). Fixture should be visually centered over the hub area of plate.

2.3.4 Place top half of test fixture (2.2.7) on mounted plate and turn stop cock so that a vacuum is pulled on the plate.

2.3.5 Visually inspect plate for pinholes in the membrane. Normally, pinholes appear as small white areas (1/8" to 1/4" in dia.); the white appearance is due to the membrane drying out as air is pulled through the hole.

2.3.6 Place a small piece of Teflon tape (2.2.2 or 2.2.3) over pinhole. The size of patch depends upon the size of the area to be covered.

2.3.7 Turn off vacuum and remove top half of fixture.

2.3.8 Turn plate over.

2.3.9 Replace top half of test fixture and again pull vacuum on plate (2.3.4).

2.3.10 Repeat steps 2.3.5 and 2.3.6.

2.3.11 Turn stop cock so that line is sealed between gauge (2.2.7) and plate.

2.3.12 Watch gauge closely. A reading of approximately 29" ± 0.5" should be obtained and held for 15 seconds.

2.3.13 If vacuum holds, plate has passed inspection. If reading falls further, additional inspection is necessary.
2.3.13.1 Turn on sonic tester (2.2.5) and pass microphone over plate. A leak is present when sound increases sharply. Possible areas of leakage are, a) membrane-to-plate bond, b) membrane-to-membrane bond, c) small pinholes, d) crack in support plate.

2.3.13.2 When leak area is detected by sonic tester using syringe (2.2.8), place a small amount of dye (2.1.2) over area. Take sponge (2.2.7) from pail (2.2.1) filled with water (2.1.1) and wipe off dye. A blue stain is present where dye has been pulled through under vacuum. Cover leak with teflon tape. An exception is a crack in the support plate. If plate is cracked, reject it.

2.3.13.3 Repeat steps 2.3.11-2.3.13.