PB83-108605

Development and Demonstration of a Reverse-Osmosis Energy-Recovery Device

SRI International
Menlo Park, CA

Prepared for

Office of Water Research and Technology
Washington, DC

Jun 82

BIBLIOGRAPHIC INFORMATION

PB83-108605

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Gerry B. Andeen, and Jeffrey C. Eid.

PERFORMER: SRI International, Menlo Park, CA.
Contract DI-14-34-0001-1403

SPONSOR: Office of Water Research and Technology, Washington, DC.
W8300256 OWRTC-00146-D(1403)(1)
Final rept.

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KEYWORDS: *Desalting, *Reverse osmosis desalination, *Energy consumption.

Available from the National Technical Information Service, Springfield, Va. 22161

PRICE CODE: PC A03/MF A01

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DEVELOPMENT AND DEMONSTRATION OF A REVERSE-OSMOSIS ENERGY-RECOVERY DEVICE

Final Report

June 1982

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Membrane Separation Program
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Prepared for:

U.S. Department of the Interior
Office of Water Research and Technology
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Contract 14-34-0001-1403
Account 1-591-210

SRI Project 2669

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Selected Water Resources Abstracts
Input Transaction Form

W 286565

1. Report No. | 2. | 3. Accession No. W 83-00256

4. Title DEVELOPMENT AND DEMONSTRATION OF A REVERSE-OSMOSIS ENERGY-RECOVERY DEVICE,

5. Report Date

6.

8. Performing Organization Report No.

7. Author(s)
Andeen, G.B., and Eid, J.C.

10. Project No. OWRT C-00146-D(#1403) (1)

9. Organization
SRI International, Menlo Park, California, ~~Membrane Separation Program~~

11. Contract/Grant No.
14-34-0001-1403

13. Type of Report and Period Covered

12. Sponsoring Organization

15. Supplementary Notes
~~Completion~~ Final Report, ~~SRI Project 2669,~~ June, 1982. 37 p, 16 fig, 2 tab, 4 ref, 1 append.

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17a. Descriptors *Reverse osmosis, *Desalination, *Desalination apparatus, *Energy recovery, *Mechnical equipment, Seawater, Desalination plants, Demineralization, Membranes, Membrane processes, Energy, Mechnical engineering, Pumps, Pressure head, Industrial plants.

17c. COWRR Field & Group

03A

18. Availability
Available from the National Technical Information Service as PB83 108605

Send to:
Water Resources Scientific Information Center
OFFICE OF WATER RESEARCH AND TECHNOLOGY
U.S. DEPARTMENT OF THE INTERIOR
Washington, D.C. 20240

Abstractor W.L. Zielinski | Institution The MAXIMA Corporation

WRSIC 102 (REV. OCTOBER 1979)

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I SUMMARY

An energy-recovery device for seawater reverse-osmosis systems has been designed, fabricated, and tested by SRI International (SRI). The device uses waste streams from a reverse-osmosis system to drive a pump which, in turn, sends additional feed flows to the reverse-osmosis elements. Test results show that efficiencies in excess of 95 percent can be expected, and thus energy consumption in a seawater reverse-osmosis desalination system can be decreased by 50 percent. Also, the conversion may be decreased from 30 percent so that membrane life is extended. The size of the main pump and prime mover can likewise be halved.

Nearly 1000 hours (175,000 cycles) of testing have been conducted. The device underwent testing as if it were functioning in a 4800-gal/day seawater system and produced an outlet pressure of more than 850 psi for an inlet pressure of 750 psi. In system simulation, the energy-recovery device demonstrated the ability to self-start and to be controlled. A duplicate device has been delivered to the Office of Water Research and Technology (OWRT).

An analysis of value and costs suggests that energy-recovery device will be applicable to systems as small as 10,000 gal/day.

II BACKGROUND

Reverse-osmosis desalination is recognized as a technique that is an order of magnitude more efficient in use of energy for seawater desalination than is distillation, especially for small systems where multiple-stage use of heat is not justified as a capital investment. This considerable energy saving has been one of the driving forces in application of reverse osmosis. Even with greatly improved efficiency, however, the discharge of high-pressure waste brine carrying off the separated salts has been a conspicuous energy loss in reverse osmosis and has attracted attention. One approach to recover this energy is to use a turbine, or some kind of backward-running pump. Unfortunately, such devices have low efficiency in the size range of nearly all reverse-osmosis plants, and their cost is high. Turbines and similar devices may play a significant role in the future on very large systems, but they are not likely to be used on systems of moderate size (plants producing a million gallons per day from seawater).

Another alternative to energy recovery is the flow work device. In the flow work concept, the waste stream is used to displace the fluid to be pumped from a vessel. The flow of the waste stream and its pressure are transferred to the pumped stream. The process is necessarily intermittant, because the pressure vessel volume is displaced and must be recharged. The flow work device offers high efficiency at all flow rates. The simplicity of the flow work device, and the fact that the device acts as a pump itself, rather than merely transferring energy to a pump, suggests that costs might be reasonable, even for small desalination systems.

OWRT and its predecessor, Office of Saline Water (OSW), have sponsored development projects on flow work energy-recovery devices for two decades (Cheng and Fan, 1968; Cheng et al., 1967; Gilbert and Rose, 1973; Polymetrics, Inc., 1981). The devices developed have used bladders or free pistons to separate the waste brine from the pumped brine while transferring the pressure. Much of the development work has been concerned with appropriate valving and materials and has been particularly useful in the present development.

SRI conceived of an improved flow work device, differing from other flow work exchangers in that it augments the pressure, so that the pumped brine is at a higher pressure than the waste brine doing the pumping. This augmentation eliminates the need for a booster pump, which, in this application, requires a high-pressure housing and seals. The usual way to augment hydraulic pressure is to have a large piston connected to a small piston; large pressure amplifications can thus be achieved. In our case, the pressure difference required is small and can be provided by the effective piston area difference due to a shaft on one side of the piston. Figure 1 shows a schematic of the device and one system application.

OWRT undertook sponsorship of the current work in order to develop and evaluate the potential of this new concept. The objectives of the work were not only to demonstrate the concept, but to design, fabricate, test, and evaluate a device that would be useful in real seawater desalination systems.

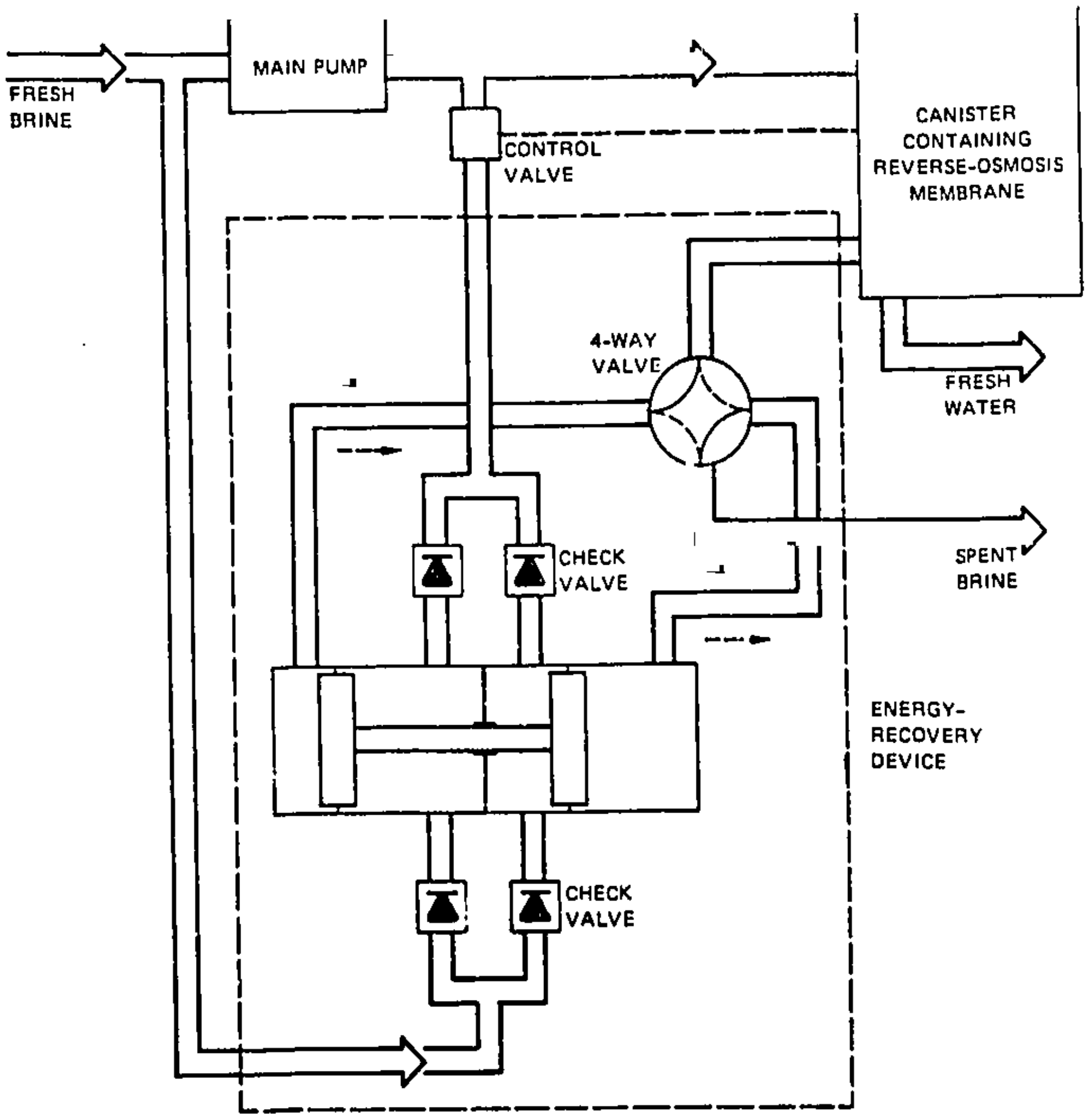


FIGURE 1 ENERGY-RECOVERY DEVICE IN SYSTEM

III DEVELOPMENT AND TESTING

SRI fabricated two different energy-recovery devices. The first-generation device, Mark I, was a "breadboard" device used to demonstrate the concept of energy recovery and to provide engineers with necessary operating experience in a typical energy-recovery system. The second-generation device, Mark II, was designed with great attention to selection of appropriate valves, seals, and materials that would withstand the harsh saline environment. Flow geometry was greatly improved in the Mark II device. To increase the flow capacity and performance and reduce fabrication cost, other minor modifications were also made.

A. The Mark I Energy-Recovery Device

1. Design

Initially, SRI's strategy was to "breadboard" a device that would provide operating experience as soon as possible, because many problems of such devices can be uncovered only by experience.

The main components of the Mark I breadboard device are two commercially available hydraulic cylinders fitted with limit switches. The cylinders are Parker Fluidpower, 3.25 inches in diameter with a 1-inch diameter shaft and an 18-inch stroke, of tie rod construction. The use of two separate cylinders means that two shaft seals are used instead of one, which decreases performance, and the off-the-shelf hydraulic cylinders are designed for high-pressure drops across the pistons. The high-pressure piston seals also decrease performance. The area ratio of the piston to shaft is 10:1.

The main valve is a solenoid-operated spool valve manufactured by the Hunt Valve Company. The advantage of a spool valve is that it is balanced; there are no pressure-induced forces causing the parts to wear. Use of a spool valve should eliminate the short valve life experienced in some other flow work devices. The disadvantage of the spool valve is that a small leakage rate is inherent in the design. The valve must be sized for the particular application so that the energy loss is limited. There may be ways to modify spool valves to regain their advantage without leakage, but there is no need to attempt this unless leakage proves to be a problem.

Circle Seal check valves are used in the Mark I system to admit and exit the brine to and from the cylinders to the reverse-osmosis system.

The two pistons and valves are bolted onto a mounting. The two piston shafts are connected by bumpers, one of which has been fitted with strain gauges to measure the force required during operation.

The pistons and solenoid valve have been designed to function in a seawater reverse-osmosis plant of up to 50,000-gal/day capacity. The interconnecting piping, however, has been designed for a 5,000-gal/day seawater reverse-osmosis plant, as that is the capacity of the pump for initial testing.

The device is designed to switch the solenoid valve when the piston reaches the end of a stroke. In addition, we provided a direction-control switch on the breadboard device so that we can study the effects of more rapid switching.

The assembled Mark I device is shown in Figure 2.

2. Test Circuits

Two different test circuits were designed. Figure 3 shows the performance test loop to measure pressure amplification, flow ratios, energy loss, and leakage. The test setup is also suitable for extended testing, because it has a minimum of external components to fail and interfere with test operation.

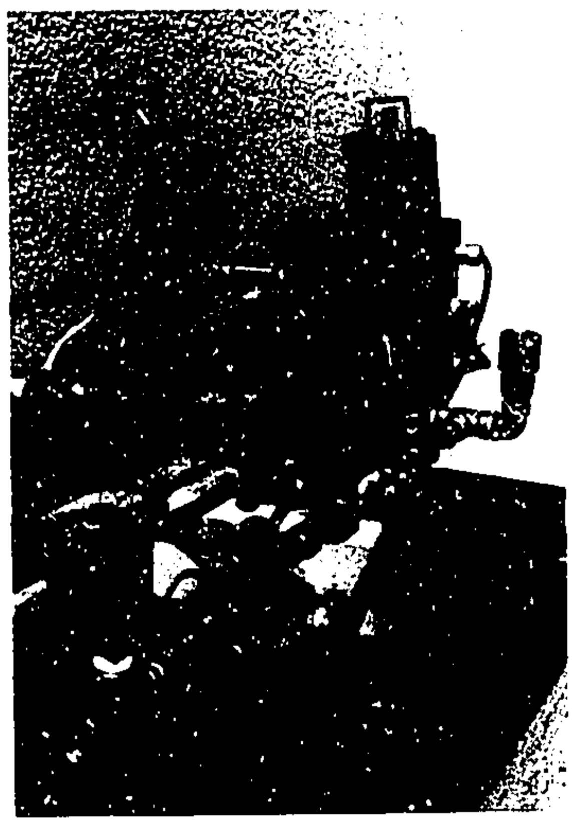
Figure 4 shows the second setup, referred to as the demonstration setup because the system is piped as it would be for an operation in which the reverse-osmosis-element pressure drop is simulated by a valve. The purpose of this setup is to evaluate how the energy-recovery device would operate in a system. Particular points to be examined are how the system starts up, particularly if there is air in the cylinders, and how the proposed pressure control system will operate.

3. Testing and Test Results

Both performance and demonstration tests were conducted on the Mark I device. The tests were run on the setup shown schematically in Figure 5. Because some of the Mark I components were not designed to tolerate salt water, only fresh water was used.

In the performance tests, valve A was closed and valves B and C were fully open. Pressures and flows in and out were measured under various conditions. The setup was operated to simulate a system in the demonstration tests. Valve A was opened to permit water pumped by the energy-recovery device to join water from the primary pump. Valve C was partially closed to simulate the water passing through the membrane in a real system. Valve B was used to demonstrate control aspects of the system.

(a) FRONT VIEW



(b) VIEW SHOWING VALVES

FIGURE 2 MARK I ENERGY–RECOVERY DEVICE

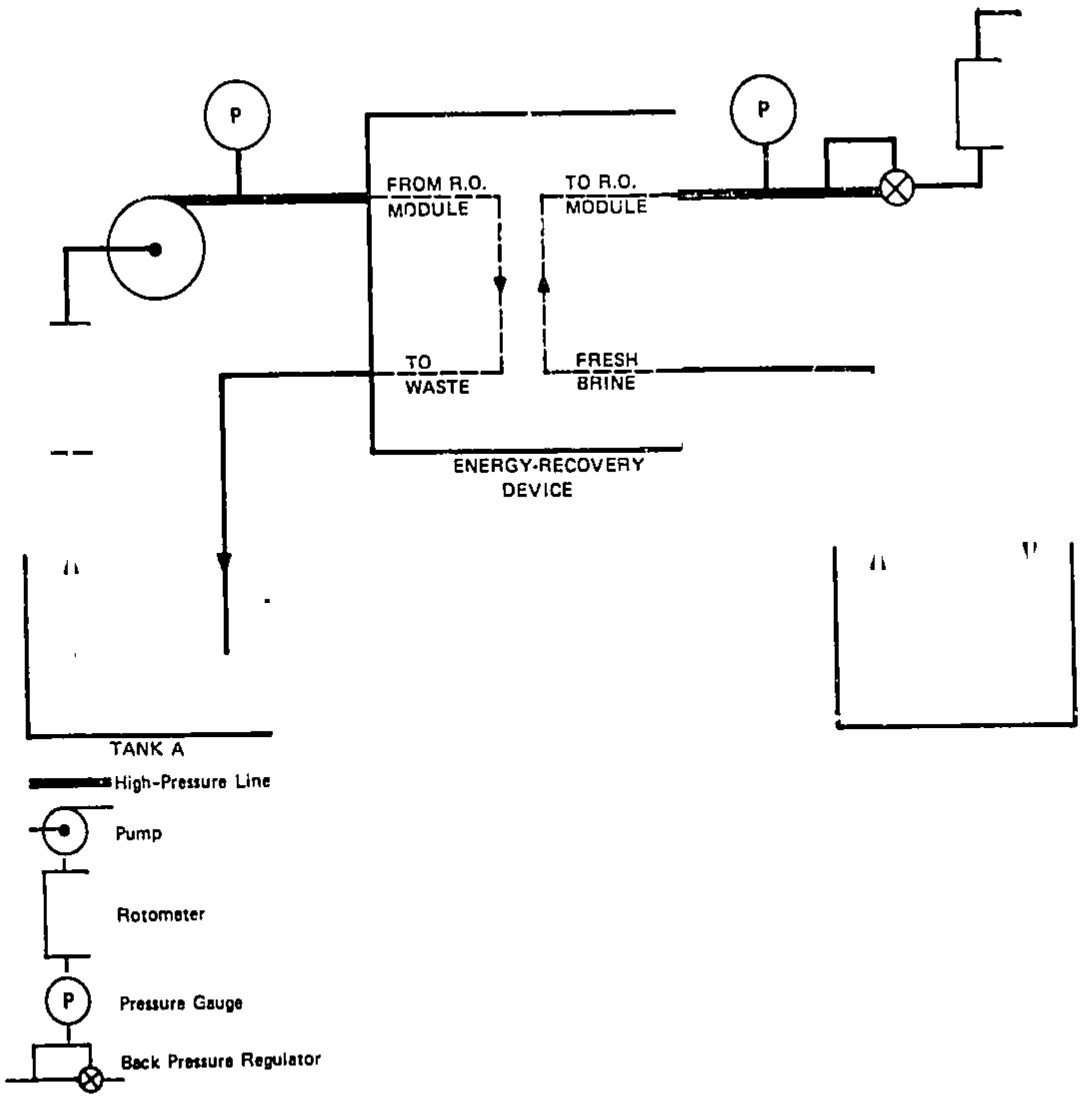


FIGURE 3 PERFORMANCE TEST SETUP

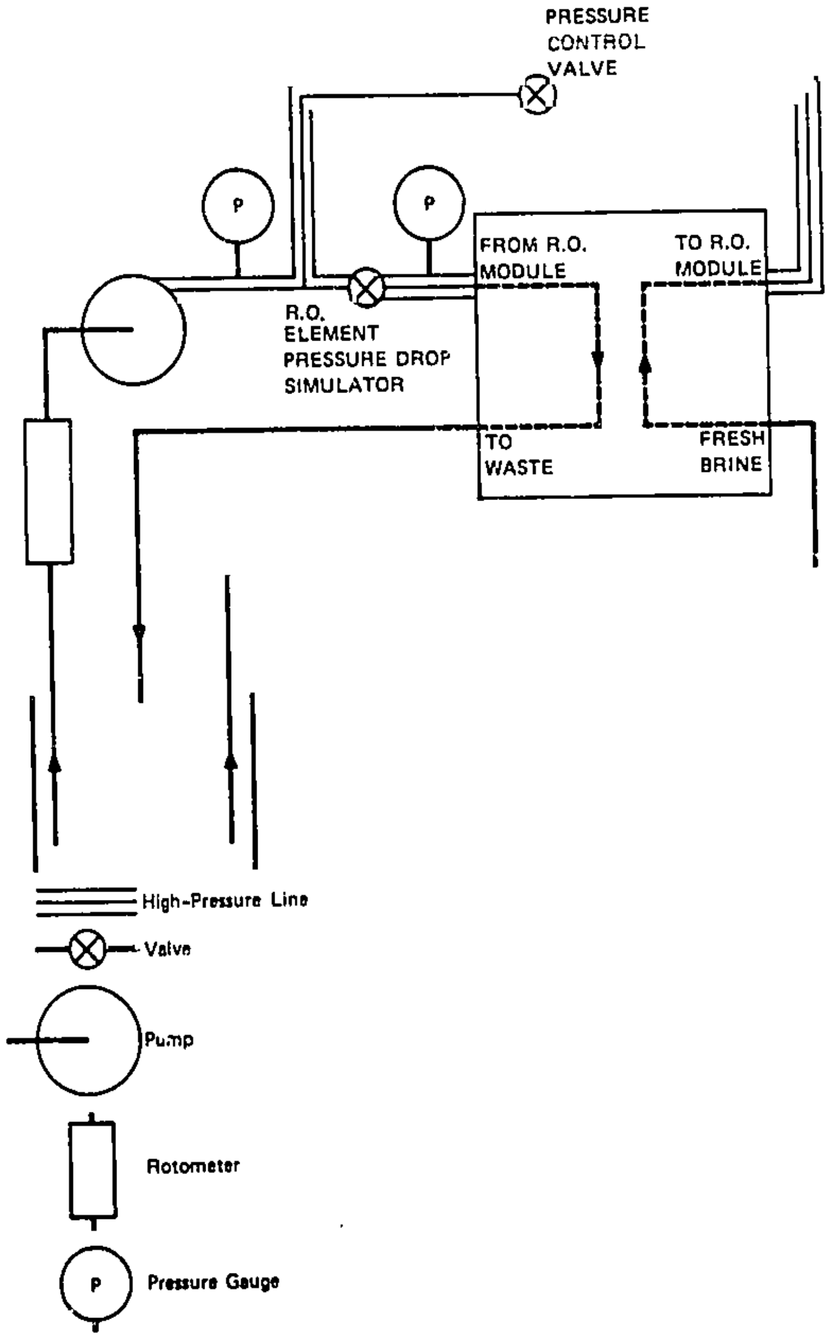


FIGURE 4 DEMONSTRATION SETUP

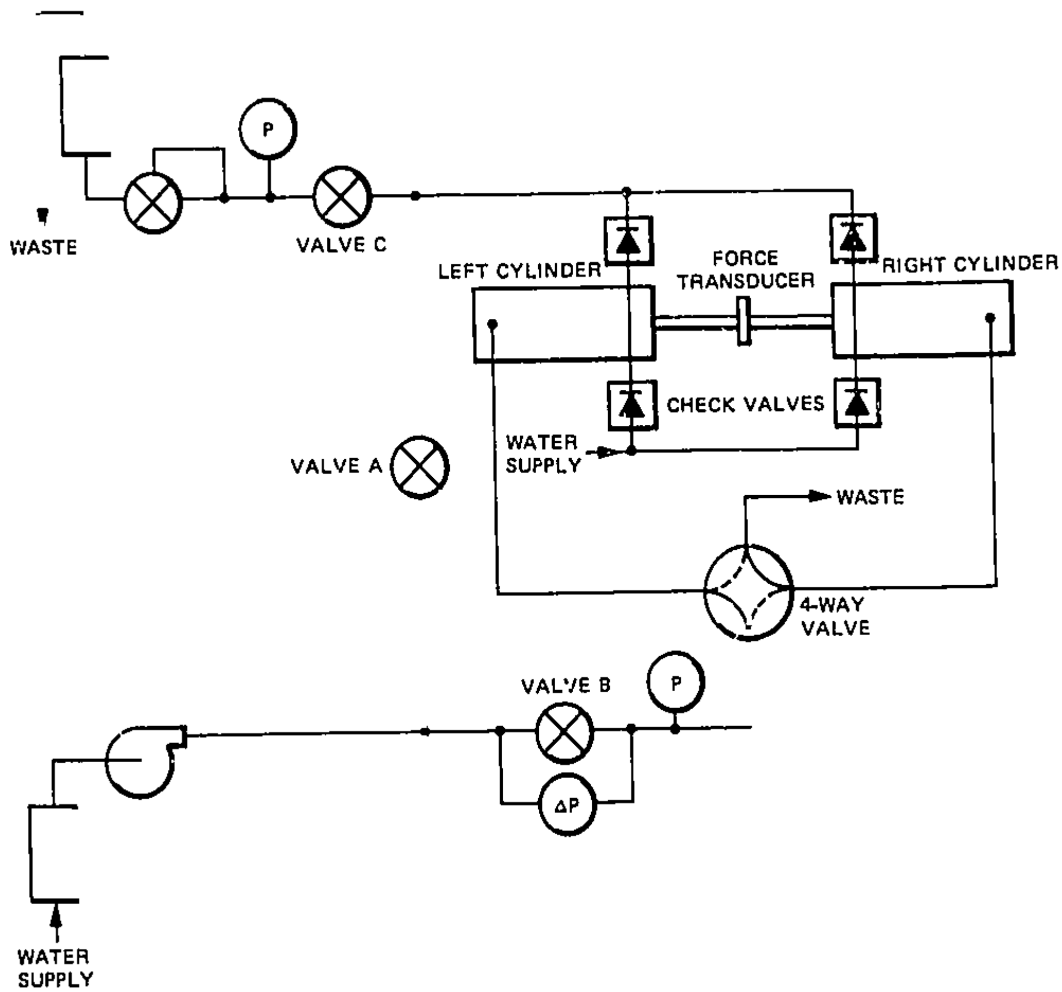


FIGURE 5 SCHEMATIC OF MARK I TEST SETUP

The total run time on Mark I is about 160 hours. At the end of that time, one shaft seal was giving a high friction loss and wear was visible on one side of the shaft. We believe the excessive friction and wear resulted from a misaligned shaft seal bushing. No corrosion was observed, but none was expected, because the test fluid was fresh water.

a. Performance Tests

Figure 6 shows efficiency as a function of outlet pressure for a typical test at 1.12 gal/min. The test flow rates are limited by the capacity of our high-pressure pump: They are satisfactory for the low range of demonstration tests, but lower than desired for the performance testing for the desired capacity. It should be noted that the data show different performances when the pistons are traveling one way than when traveling the other. This is caused by different valve leakage rates and seal frictions for the two directions.

More detail can be seen in Figure 7, which shows the ratios of output to input flows and pressures. The output flow is expected to reach the area ratio (about 0.9) from one side of the piston to the other (which is different because of the shaft). Deviation from that value indicates leakage in the system; the leakage that occurred was traced to the spool valve. The pressure ratio is expected to approach 1.1. Deviation indicates a loss due to seal friction and flow losses. The type of loss can be determined by inference from results at different pumping rates. Figure 7 shows that both the valve leakage and friction losses were less when the pistons were moving to the right.

Leakage in the four-way valve was measured to be 320 ml/min (0.085 gal/min) and 560 ml/min (0.148 gal/min) at 800 psi depending on flow direction. This leakage was well above that specified by the manufacturer (80 ml/min at 1000 psi). At lower test pumping rates, leakage is a greater proportion of the total, and lowers the measured efficiency. Although one would always like to have less leakage, the amount observed is not distressing because it is a small percentage of system rates.

The low pressure ratio in the leftward travel direction was traced to a seal binding on a shaft, which led to a visible wear pattern on the shaft. This is believed to be an anomalous result that is unlikely to occur again.

The higher-pressure-ratio data reflect that efficiencies above 90 percent can easily be expected at reasonable flow rates. This performance is more than sufficient to cut power by a factor of two, while simultaneously decreasing the conversion from 30 percent so that energy consumption is reduced and membrane life is extended.

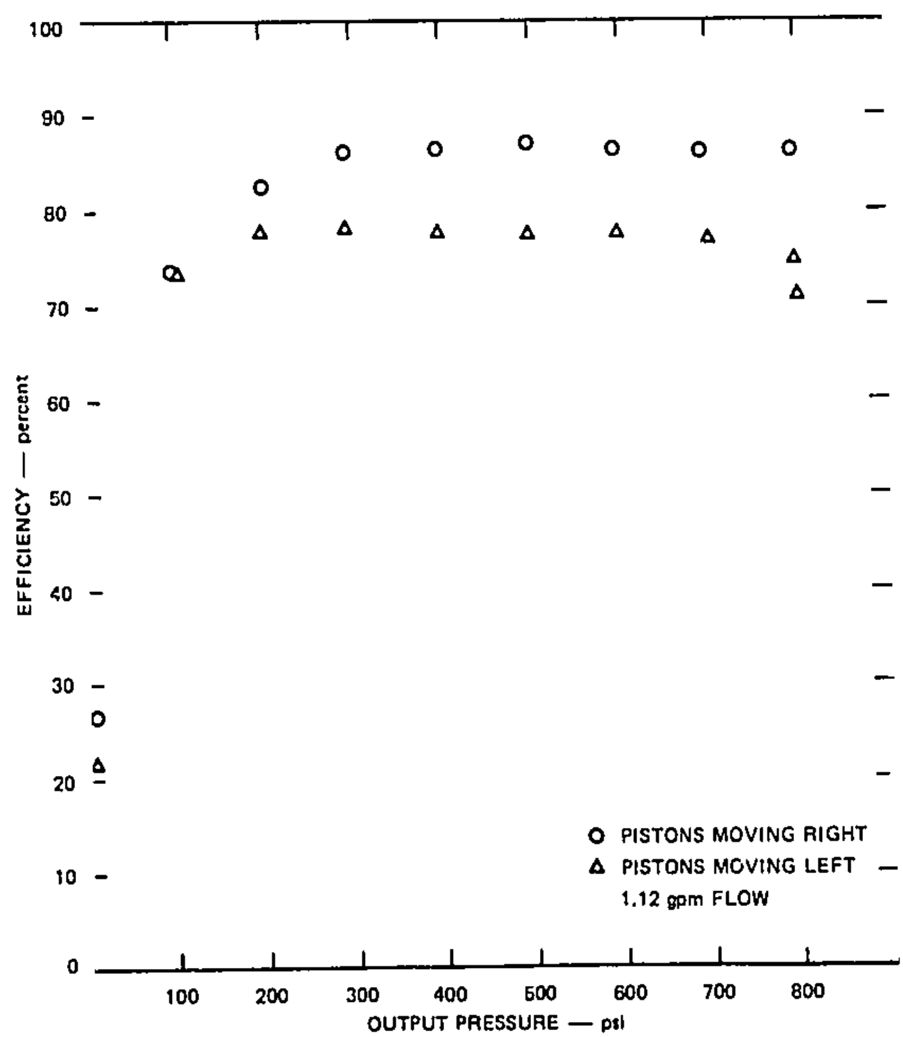


FIGURE 6 MARK I DEVICE PERFORMANCE EFFICIENCY AS A FUNCTION OF OUTPUT PRESSURE

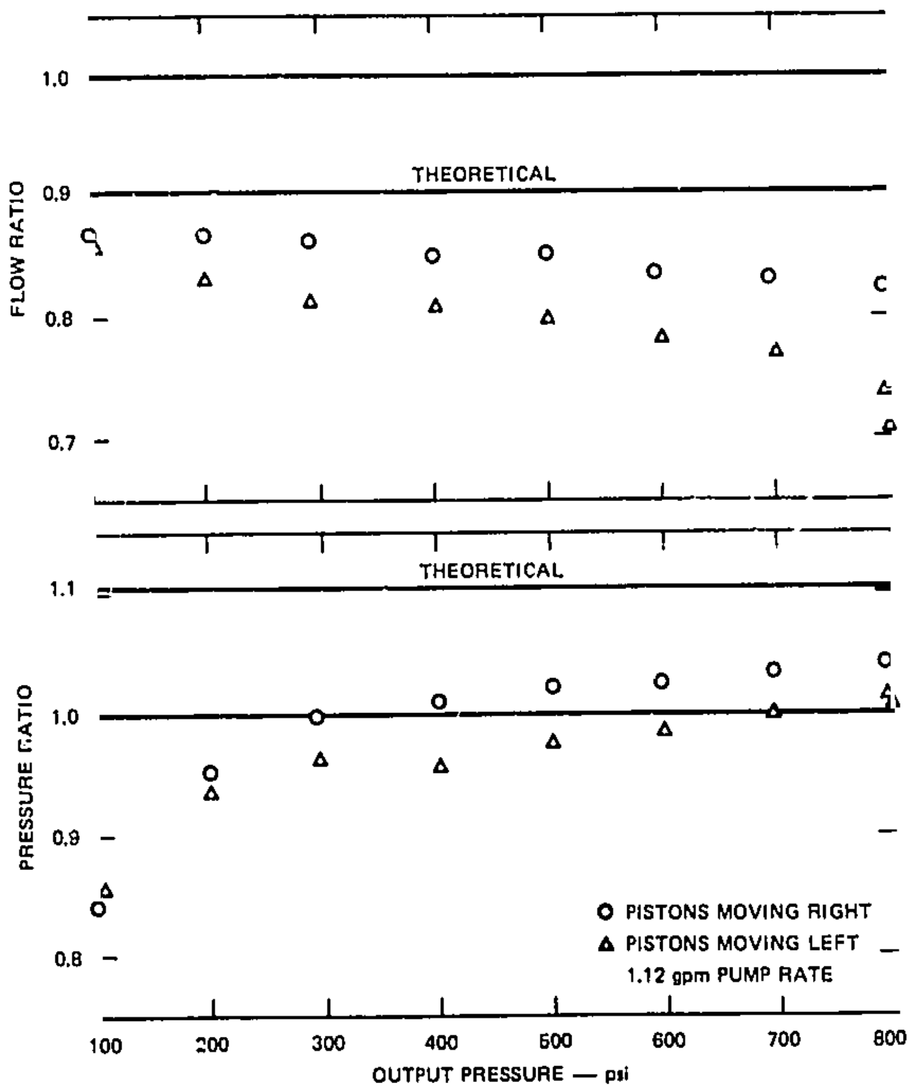


FIGURE 7 MARK I DEVICE PERFORMANCE FACTORS

b. Demonstration Tests

Demonstration tests were run by opening valve A and throttling valve C (refer to Figure 5) so that the ratio of flows exiting through valve C and the four-way valve were in the ratio 30:70 (20:80 for 20 percent conversion). This mode demonstrated that the device can start with a 50 percent capacity pump. The energy-recovery device then begins to function and picks up half of the pumping load (actually more than half with the piston ratios of the present design). The flow through valve A exceeds that delivered by the pump.

Another performance aspect demonstrated was control by means of throttling valve B (see Figure 5). Throttling introduces an extra pressure drop, the result of which is to cause the energy-recovery device to operate more slowly. Since the device removes more water from the system than it adds, slowing the device increases the system pressure. Thus, opening valve B decreases the system pressure, while closing valve B increases the system pressure.

We noted that water hammer occurs when the four-way valve is switched. The installation of an accumulator to the system reduced the magnitude of the hammers but did not prove to be a satisfactory solution to the problem.

B. The Mark II Energy-Recovery Device

1. Design

Testing the Mark I model raised several issues that were addressed in the design of the Mark II device. The major visual change is that the two separate piston-cylinders with the shafts pushing against one another were supplanted by two cylinders butted against a common header. A single shaft is used; this shaft is not externally visible. This modification, which was planned from the outset of the project, shortens the length of the apparatus by 30 percent. It also eliminates two shaft wipers (because the shaft is not exposed) and reduces the number of shaft seals from two to one (bidirectional) seal.

The cylinder and shaft diameters have been increased from 3 and 1 inches to 4 and 1.5 inches respectively in the second design, primarily to change the piston-to-shaft-area ratio and thereby the pressure amplification. A slightly higher pressure amplification, which was desired to account for uncertainties in the losses and to improve controllability, results in some performance sacrifices. A device with a different size ratio will demonstrate whether the change is beneficial overall.

The seals used in the first device for both the shaft and the piston were standard Buna-N U-ring seals. These seals had zero leak but somewhat higher than desirable friction. Lower friction units are available in Teflon® and graphite-loaded seals; however, such seals cannot be stretched for insertion and require mechanical backing to maintain a sealing surface.

Low-friction seals are available from Bal-Seal Engineering Company and from the Tomkins-Johnson Division of Aeroquip Corporation. The Bal-Seal requires a seat that has to be assembled; the Tomkins-Johnson solution seal is accordion-cut so that it can be expanded over a cylinder and set in a groove. We chose the Tomkins-Johnson solution, and thus selected Tomkins-Johnson as the piston-cylinder vendor. Figure 8 shows a low-friction Teflon® piston ring. The accordion pleat allows fitting over the piston groove where the Teflon® ring is backed up by an O-ring.

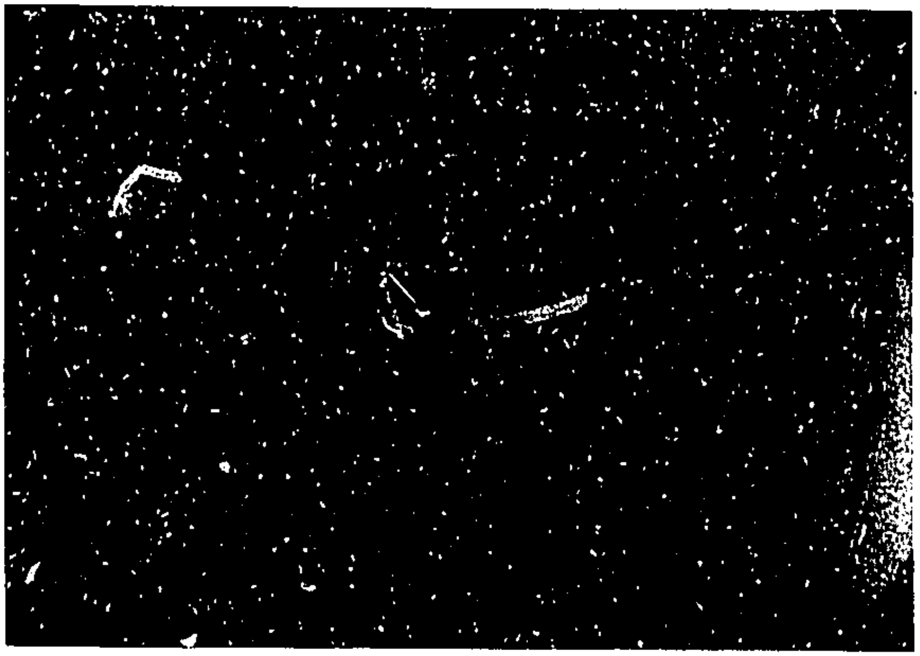


FIGURE 8 TEFLON® PISTON RING

The cylinders are of steel construction, with crack-free chrome plating for corrosion and wear resistance. Because hard chrome plating is porous to water, a soft chrome plating was deposited first to seal the steel from the cylinder contents; a standard hard chrome plating was then applied for wear resistance.

The spool valve of the Mark I device performed well, except for water hammers and large leakage rates. One major advantage of this configuration is that it can be directly solenoid operated. To reduce the leakage for a given flow coefficient, we chose to replace the spool valve in Mark I with two Sinclair Collins pneumatically actuated, axially balanced, three-way, plunger seat valves. A three-way solenoid air valve triggered by mechanical limit switches at the cylinder ends serves as a pilot for the Sinclair Collins valves.

The Mark II device is shown in Figures 9(a) and (b). For size comparison, Figure 9(a) shows a front view together with a seawater reverse-osmosis canister (DuPont B10 Model 6440), rated at 1500 gal/day. Figure 9(b) is a different perspective, giving a better view of the four check valves and two Sinclair Collins three-way valves. The device is piped with 1/2-inch stainless-steel tubing and fittings, and the three control valves (shown schematically in Figure 5) are Parker general-purpose 1/2-inch stainless shut-off valves. The switching circuit is mounted in the cast aluminum box shown in the lower-left-hand corner of Figure 9(a) and contains intermittent switches to change the direction of the piston at will. An electric counter is also included in the Mark II control system.

2. Testing and Test Results

Performance and demonstration tests were conducted on the Mark II device, similar to those on the Mark I device. Performance of the Mark II device is shown in Figures 10 and 11. Figure 10 shows efficiency as a function of outlet pressure; Figure 11 shows the pressure and flow ratios in and out. The new seals reduce the friction from the initial design; the new valves, in addition to having a lower pressure drop, also have zero leakage. The pneumatic valves switch more slowly than the solenoid-operated spool valve used before, and completely eliminate water hammer.

The total run time on the Mark II device is nearly 1000 hours (175,000 complete cycles). Of those 1000 hours, approximately 10 percent were run with a 3.5 percent weight sodium chloride solution (about the salinity of seawater). The salt solution caused galvanic corrosion of the steel cylinder end plates, center housing, and pistons. The steel cylinder walls were protected by the durable chrome plating and showed corrosion only in a single spot, where a dent in the cylinder wall caused the piston to erode the chrome plating and expose steel. The stainless-steel fittings and piping and the bronze Sinclair Collins valves withstood the harsh saline environment very well.

To combat the problems of corrosion, we plated the end plates and center housing with an electrolous nickel plating and replaced the steel pistons with 316 stainless-steel pistons. The electrolous nickel-plated components were not able to withstand 3.5 percent salt water, but the stainless pistons remained unharmed after many hours of testing. A pair of Lexan® pistons was also tested, and remained unharmed by the strong saline environment. The problems of corrosion were finally eliminated by fabricating the end plates and center housing out of 316 stainless steel. The Lexan® pistons are preferred to the stainless pistons because of their lower cost and lightness in weight.

(a) MARK II ENERGY-RECOVERY DEVICE WITH 1500-GAL/DAY REVERSE-OSMOSIS CANISTER, FOR SIZE COMPARISON

(b) VIEW SHOWING VALVES

FIGURE 9 MARK II DEVICE

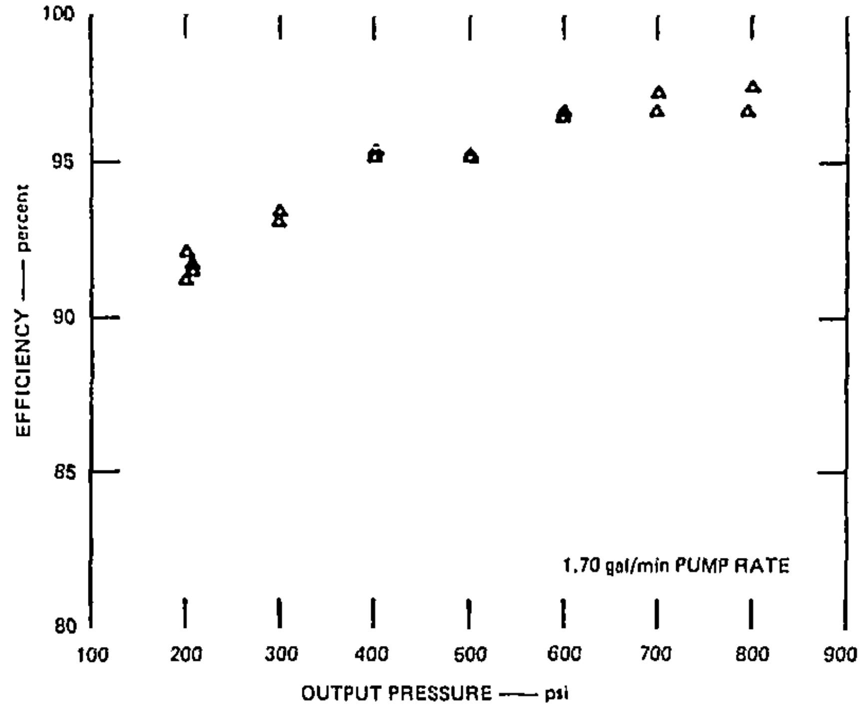


FIGURE 10 MARK II PERFORMANCE EFFICIENCY AS A FUNCTION OF OUTPUT PRESSURE

The Mark II device pumps an output of 4800 gal/day at more than 850 psi, or 1.7 fluid horsepower. An additional 3300 gal/day (1.1 fluid horsepower) would be required of the primary pump to separate 2400 gal/day of fresh water from seawater.

3. Modifications to the Mark II Device

Although substantial improvements were made in going from the Mark I device to the Mark II device, the Mark II device is not yet an optimal design. To increase performance we made two further changes in the construction of two additional Mark II devices. The first change was to increase the plumbing size on all valves, fittings, ports, and tubes from 1/2-inch to 3/4-inch, to reduce some of the fluid flow losses through the device. The second change was to eliminate valves A and B (shown in Figure 5) and replace valve C with a regulating valve appropriate for this particular application. A Dragon valve made of 316 stainless-steel with a 9/16-inch orifice was chosen as the regulating control valve. The modified Mark II devices are thus plumbed to fit directly into an existing reverse-osmosis plant. A set of operating and hook-up instructions which indicate how to connect the Mark II device to reverse-osmosis system is given in the Appendix. A list of cautions and

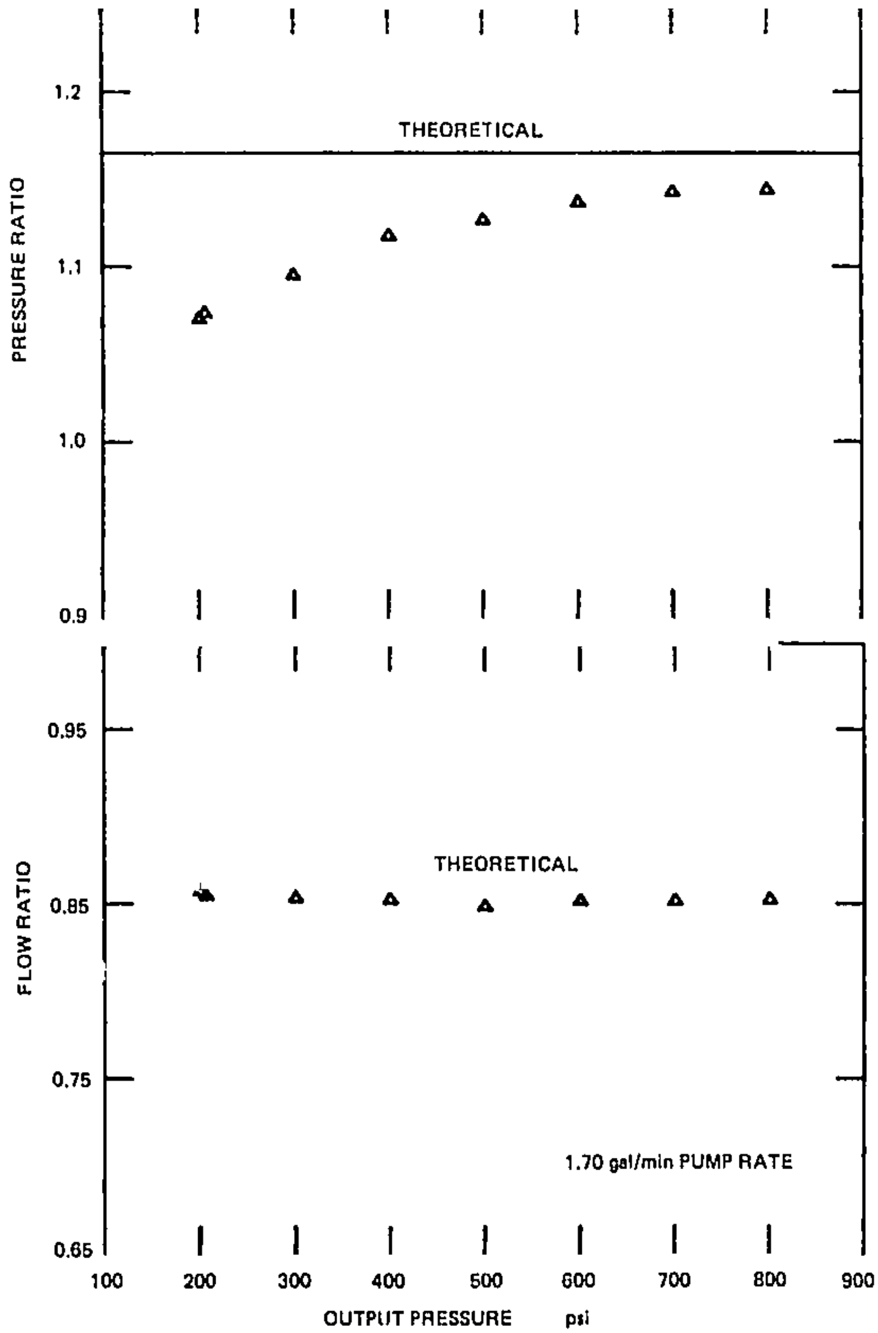


FIGURE 11 MARK II PERFORMANCE FACTORS

troubleshooting procedures, which summarize SRI's experience with the operation and installation of the energy-recovery devices, is also contained in the Appendix.

In the attempt to simplify the device and reduce its component and fabrication cost, SRI performed preliminary tests on a Barksdale shear-seal four-way valve. The seal is achieved by a metal ring pressed against a metal plate. This device is particularly attractive in small sizes because its plastic housing is resistant to seawater. It has been used with considerable success in high-pressure water applications. The Barksdale valve must be activated with a pneumatic rotary actuator. The rotary actuator, in turn, is piloted by a four-way solenoid valve which is triggered by limit switches on the cylinder ends. This entire valve system is much more compact, easier to mount, and less expensive than the currently used Sinclair Collins system. The Barksdale setup is shown in Figure 12.

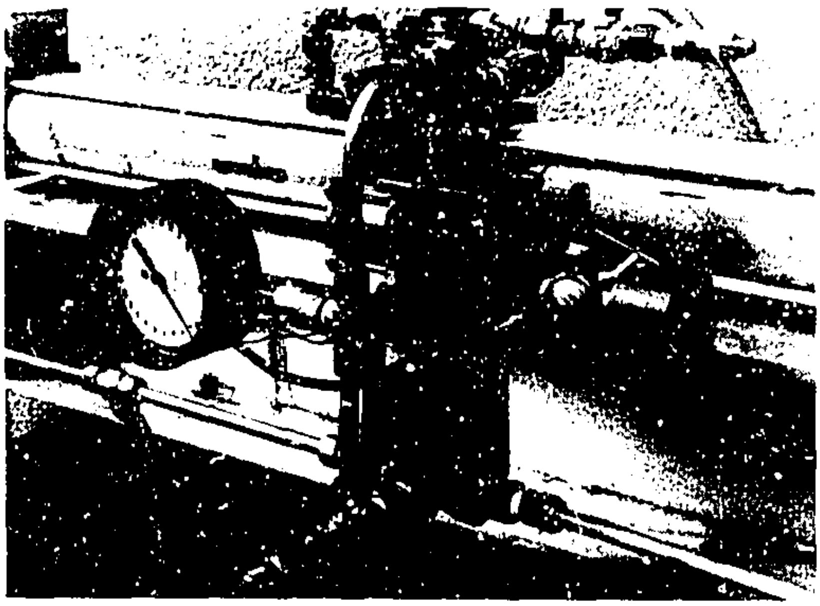


FIGURE 12 VIEW OF BARKSDALE VALVE AND ROTARY ACTUATOR ON MARK II DEVICE

Preliminary performance and demonstration tests with the Barksdale valve installed on the Mark II device indicated that efficiencies up to 97 percent can be realized with no leakage. Flow losses through the Barksdale valve are less than through the Sinclair Collins valves, enabling Mark II to pump more (~10 percent) water for a given input pressure. The Barksdale valve showed no signs of corrosion after 35 hours of testing with 3 percent sodium chloride. The pneumatic rotary actuator switched very smoothly, so that water hammer was minimal. The Barksdale valve would seem to be preferable to the Sinclair Collins system. However, no life cycle testing of any significant duration has been conducted to confirm this.

IV VALUE ANALYSIS

A. Energy-Recovery Device Value Assessment

The value of an energy-recovery device to the operators of a seawater reverse-osmosis system can be determined by comparing a system with energy recovery to a system without energy recovery. The value of the energy-recovery device is the savings realized with the use of an energy-recovery system by a reduction of system costs. System costs are to include both capital and operating costs. If the value is greater than the energy-recovery device's cost, then the energy-recovery device is useful and should be used by a cost-conscious operator.

Systems that use an energy-recovery device will differ from systems without the device in three significant ways, each of which may affect the value of the energy-recovery device. First, because the energy-recovery device is itself a pump in parallel with the high-pressure pump of the system, the size of the high-pressure pump and its prime mover can be reduced. (In a retrofit, the system size can be increased without additional high-pressure pumping capacity). The difference in cost in high-pressure pump and prime mover size is credited as value to the energy-recovery device. Second, the energy cost between comparable systems will be less with the energy-recovery device. Whatever energy is recovered is a direct reduction to the amount of energy required, and the cost of the energy saved contributes to the value of the device. Finally, because of the significant energy savings, the comparable systems may be designed differently and operated at different conditions. In particular, we believe there is incentive to design and operate the system with energy recovery at a lower recovery (percentage of desalted water to input brine). This means a smaller membrane area would be needed for similar performance, and less pretreatment would be required (possibly filtering alone in many cases). Thus, investment and chemical costs are reduced, and membrane life may be increased if energy recovery is used.

However, the energy-recovery device introduces some complexity, and some additional service needs. In particular, with the current design, main seal replacement may be required after each 1000 hours of operation. This is a negative value factor, although it may be small.

SRI's value analysis takes only the first two factors into account, the change in capital investment in the pump and prime mover, and the energy saved. That is, the analysis assumes the reverse osmosis system will operate at the same conditions of pressure and recovery. The justification for this approach is that different design and operating points have not yet been verified. Choosing the same operating conditions guarantees that the analysis will be conservative, provided equipment maintenance is a minor consideration. This appears to be the case. The basic assumptions of our analysis are listed below.

- System conditions
  - Recovery, 30 percent
  - Canister operating pressure, 800 psi
  - Plumbing pressure drop, 50 psi
  - Water production, variable
  - Pump efficiency, 85 percent
- Energy recovery device specifications
  - Area ratio, 0.85
  - Efficiency, 90 percent (greater than 95 percent demonstrated)
- Costs
  - Pump with prime mover, $100 per gal/min of pump capacity (higher at smaller sizes)
  - Power, $0.10/kWh
- Operating time, 100 days (one year in a seasonal application).

Figure 13 illustrates the energy-saving features of the recovery device. The ordinate shows the pumping capacity required to produce a unit of desalinated outflow. The abscissa shows the recovery. Figure 13 indicates that the size of the pump and prime mover, and thus the energy consumption, can be reduced by 59 percent. This number was obtained experimentally by measuring the output flow of the Mark II device during demonstration tests. Thus, the system using energy recovery has a pump and motor of less than half the size used without energy recovery, and uses less than half the energy of the system without energy recovery.

The difference in capital cost is a function of system size as shown in Figure 14. The energy cost difference for 100 days of operation is shown on the same figure, giving the total value. If the cost of the energy-recovery device is less than the value read from Figure 14, the device should be used. One hundred days is a short payback period, which makes the analysis conservative.

As an example, consider a seawater plant with a 20,000 gal/day capacity. The cost calculations, which are shown in Table 1, indicate that energy recovery is useful for a 20,000 gal/day system if the total device cost is below $5,415. Similar calculations can be made for any other system size.

The final concern of SRI's value analysis is the redesign of reverse-osmosis systems to function at another operating point. Consider Figure 13. The upper curve shows the pumping requirements with no attempt at energy recovery. For example, at the operating point for

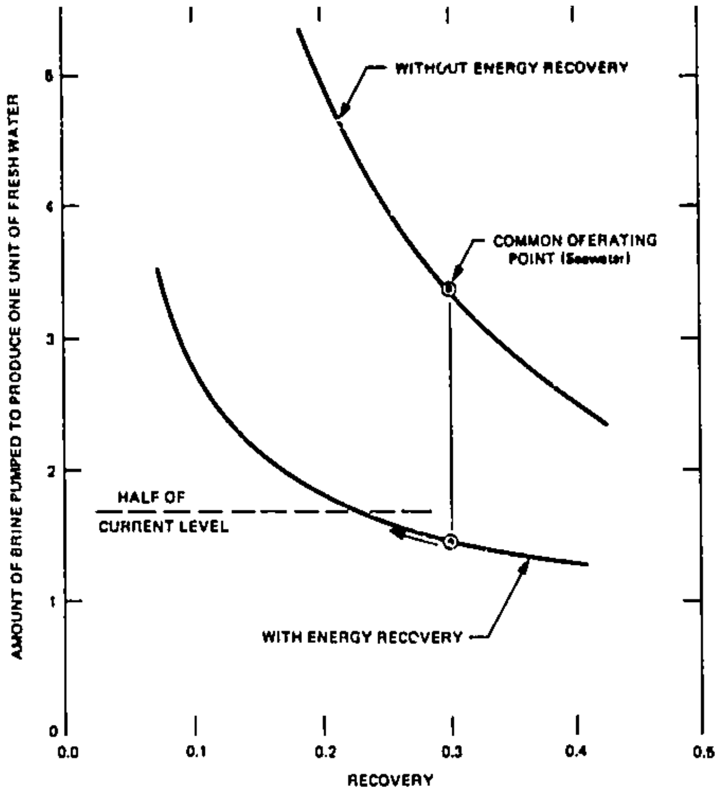


FIGURE 13 PUMPING REQUIREMENTS FOR REVERSE OSMOSIS SYSTEM

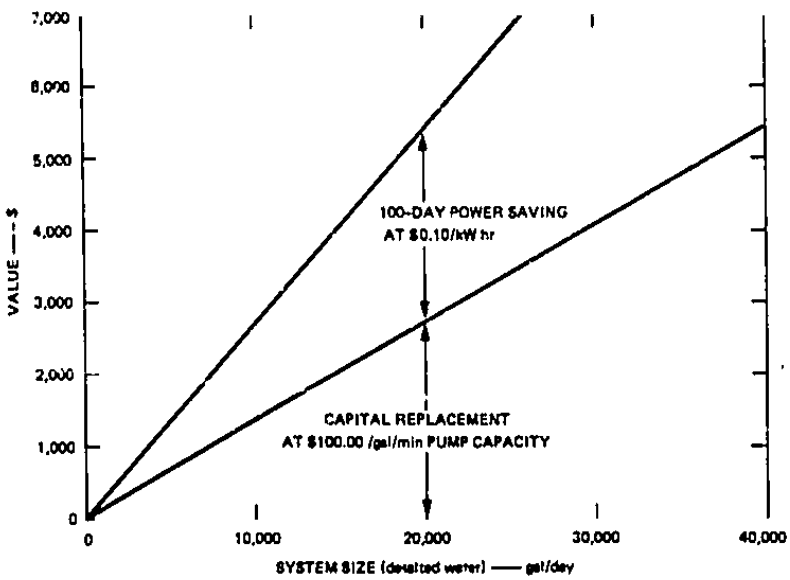


FIGURE 14 VALUE OF ENERGY-RECOVERY DEVICE IN A SEAWATER SYSTEM

Table 1

VALUE CALCULATIONS FOR A 20,000 GAL/DAY REVERSE-OSMOSIS SYSTEM

	System Without Energy Recovery	System With Energy Recovery	Energy Recovery Value
Pump size	20,000 gpd x 1/0.3 x 1 day/1440 min = 46.3 gal/min	46.3 Gal/Min (1-0.59) = 19.0 gal/min	
Pump and motor cost	$4,630	$1,900	$2,730
Motor size	19 kW	7.8 kW	
Energy cost (100 days)	19 kW x 2400 hr x $0.10 kWh = $4,550	$4,550 (1-0.59) = $1,865	$2,685
Total	$9,180	$3,765	$5,415

30-percent recovery from seawater, 3.33 gallons of brine must be pumped for each gallon of fresh water produced. If the recovery were reduced to 20 percent, 5 gallons of brine would have to be pumped for each gallon of desalinated water. This would mean a proportional increase in both pump capacity and energy cost. The common operating point of 30-percent recovery for seawater systems has been arrived at as a tradeoff between increasing energy costs as the recovery is lowered, and increasing membrane costs, shortened life, and increasing pretreatment costs as the recovery is increased. The lower curve shows the same information as the upper curve for a system with an energy-recovery device. Not only is the energy cost less at 30-percent recovery, but the slope of the curve is less as well. This suggests that an optimization, based on energy tradeoffs against membrane area, life, and pretreatment, will have a different optimum value at a lower recovery. This tradeoff has not been worked out and is situation- and water-chemistry-dependent. The point, however, remains that the value of the energy-recovery device will be augmented by optimization of the operating point.

B. Energy Recovery Device Cost Assessment

Table 2 lists the materials and parts cost for the most recently assembled device. This estimate is approximately $1000 more than the parts costs of the device actually tested because of

- Price increases of the cylinder and three-way valves.
- Use of larger lines and check valves.

The test device was operated at 4800 gal/day (recovery device output of 6.5 gal/min). It can operate from nearly zero up to 5000 gal/day. The newer device, with larger flow ports and lines, should be capable of operation in systems up to 10,000 gal/day water production.

Table 2

PRICE LISTING OF ENERGY-RECOVERY DEVICE COMPONENTS

Material Item	Cost
Aeroequip custom cylinder	$ 1,751.50
Sinclair Collins 4000 psi three-way valve, 2 at $531.00 each	1,062.00
Three-way solenoid pneumatic valve	112.00
3/4-inch stainless check valve, 4 at $205.20 each	820.80
Dragon control valve	250.00
Plumbing fittings	945.20
Pneumatic fittings	35.00
Electrical control equipment	51.80
Miscellaneous mounting fixtures	100.00
Total	$ 5,128.30

It is clear that the cost of the parts and labor for the energy-recovery device, on a one-of basis, exceeds the value by a factor of two. The cost of the device, including assembly, must be reduced by at least a factor of four for the device to be useful. We believe this is a reasonable goal based on the difference in one-of and OEM prices for small batch production. In addition, the device has yet to undergo value engineering. The four-way Barksdale "shear-seal" valve most recently tested, together with its actuator, costs $451. This valve could replace the two Sinclair Collins three-way valves for a savings of $611. Two four-way valves with actuator would cost $605, and would replace the three-way valves and the four check valves. In this case the cost reduction on a one-of basis is $1,277.80. Potential cost savings through use of other materials have not been examined. In particular, stainless-steel has been used extensively; plastic or lined-steel substitutes may perform as well or better.

Assuming that the cost can be cut by a factor of four, a retail price of $2500 for a 0-10,000 gal/day system energy-recovery device appears to be realistic. The retail price for a much larger device, say for a 50,000 gal/day system, might be expected to be $10,000. Using these estimates as the cost of an energy-recovery device, Figure 15 shows how the cost of the device compares with its value. The figure suggests that for small systems, there are size windows where the system would be beneficial. The windows become larger as system size increases. For small systems, the sizing as well as the cost of the device are thus important considerations.

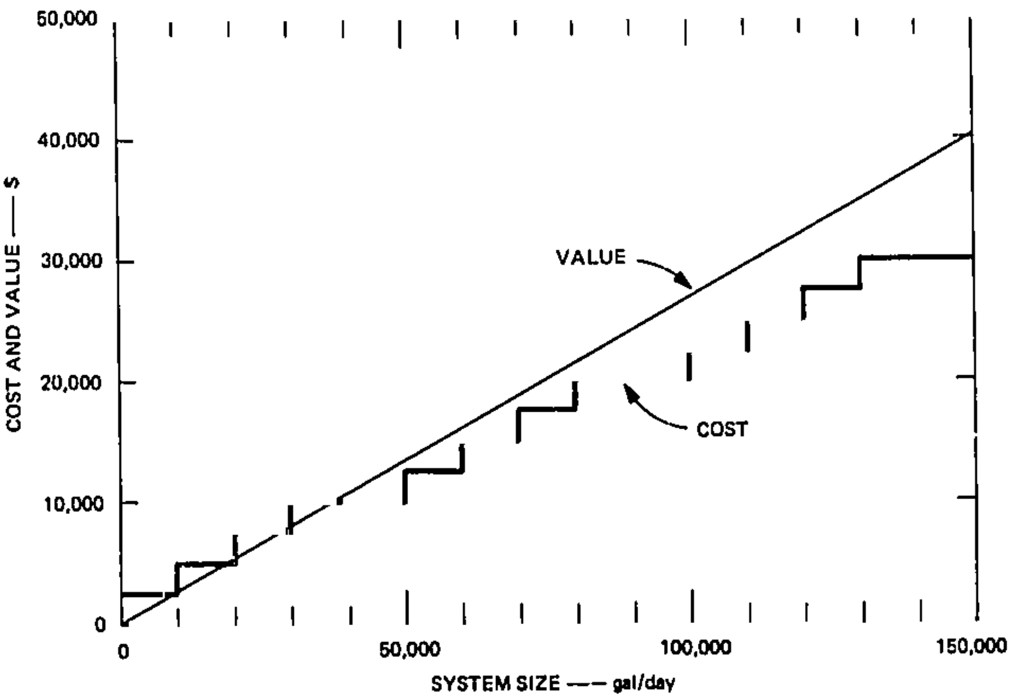


FIGURE 15 ENERGY RECOVERY VALUE/COST COMPARISON FOR VARIOUS SYSTEM SIZES

V COMMERCIALIZATION

The work on this project has reduced to practice the concept of pressure-amplified energy recovery. The principles have been clearly demonstrated and potential capital and operating savings elucidated. The energy recovery device is ready for evaluation as a commercial venture.

SRI, by its charter, is prohibited from commercial ventures. Commercialization could take place through existing companies already in reverse osmosis or by suppliers to the field such as pump manufacturers. Another alternative is an entrepreneurial venture based on the device.

We have kept many manufacturers of reverse-osmosis systems and suppliers to those manufacturers aware of the progress of this project through conversations with them and distribution of quarterly progress reports to them. This has been to determine their interest in purchasing manufacturing energy recovery devices.

Manufacturing may be especially attractive to small entrepreneurial operations. The research investment from the current device status to commercialization is small. Furthermore, the production investment can be handled with small inventories of components.

VI CONCLUSIONS

In the course of this project, the original concept (energy recovery with a flow work device) has gone through several design and test stages. The first energy-recovery device was a "breadboard" type which demonstrated pressure-augmented flow work energy recovery and provided a basis for performance and design improvements. The second energy-recovery device has been subjected to extended life testing. Further improvements have been implemented to reduce corrosion and costs. Fnally, the economic value of the device in a reverse-osmosis system has been analyzed and compared with costs.

A device has been delivered to the OWRT test facility at Roswell, New Mexico, for independent evaluation.

The results of the project confirm the original expectation that significant improvements in the energy and economic performance of seawater desalination systems can be achieved even in small systems (down to 10,000 gal/day).

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Appendix

ENERGY-RECOVERY DEVICE

Appendix

ENERGY-RECOVERY DEVICE

HOOK-UP INSTRUCTIONS

1. All hose connections should be 3/4-inch high pressure (HP) lines with 316 stainless-steel fittings. Hose connections should be as short as possible. Hoses larger than 3/4-inch may be used with no degradation of performance of the energy recovery (ER) device. Smaller hoses may degrade the ER device performance, and, if on the suction inlet line to port D (see Figure A-1), may cause cavitation in the cylinder.

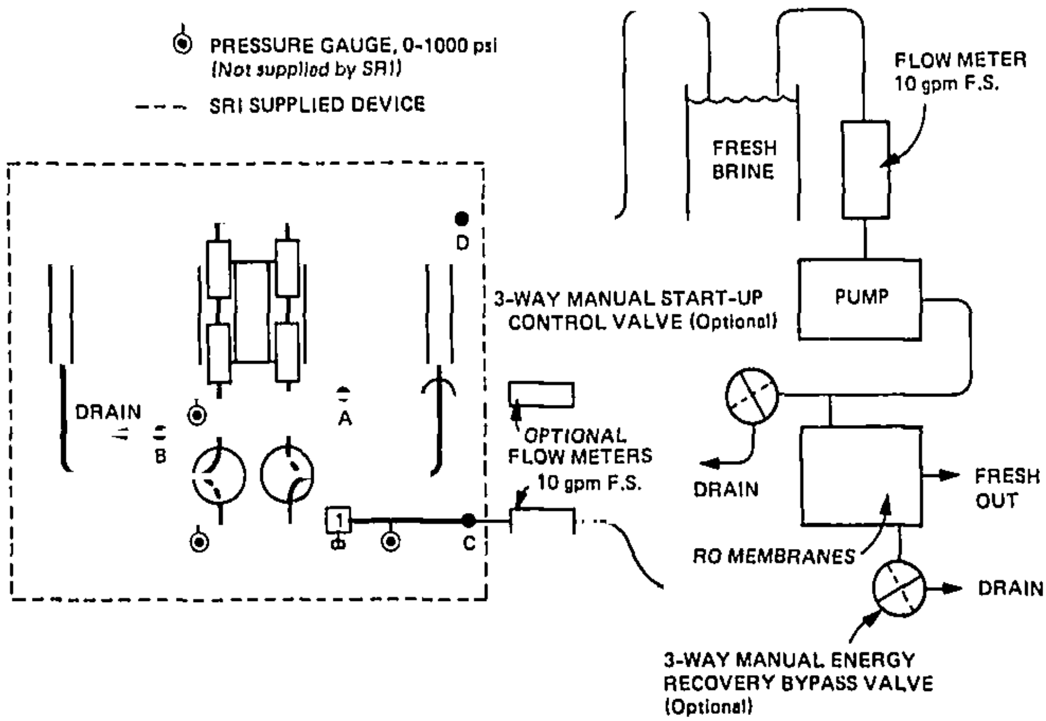

FIGURE A-1 ENERGY-RECOVERY DEVICE HOOK-UP DIAGRAM

2. Connect an HP line from the output port of a feedwater pump to a TEE at the reverse-osmosis (RO) elements. Join port A on the ER device with the other available TEE port at the RO elements with an HP line. During startup of the system, it will be necessary to isolate the ER output (port A) from the ER input (port C). This

can be done by using an easily removable fitting at the RO TEE or by installing a three-way valve at a convenient point in the connecting line between port A and the RO TEE. This valve should connect port A to the RO TEE or to a drain (refer to Figure A-1). The pump may be a positive displacement or centrifugal type and should provide at least 2 gal/min at 1000 psi. The ER device functions best at pressures around 800 psi, so the RO elements should be able to withstand 800 psi. Testing at lower pressures with lower pressure RO elements is acceptable. The size and number of the RO elements may be varied at will. The ER device may be tested with no RO elements.

3. Connect the pump input port to a brine supply tank with a flow metering device (~10 gal/min full scale) in the connecting line. This line need not be HP.

4. Connect port B on the ER device to a drain. A HP line need not be used. Spent brine will be exiting this line.

5. Connect port C on the ER device to the brine output port of the RO elements. If desired, a bypass valve may be installed in this line to exclude the ER device at will. These connecting lines should be HP lines.

6. If you wish to calculate the hydraulic efficiency, it is necessary to measure inlet and outlet flows to and from the ER device. The ER outlet flow can most easily be measured by installing a flow meter between ER port A and RO input. The input flow can be measured by installing an identical flow meter between ER port C and the RO membrane output. Be careful NOT to install <u>low pressure</u> flow meters in these HP lines.

7. Connect port D on the ER device with the brine supply. This should be a HP line 6 ft or less in length.

8. Connect pressure gauges (1000 psig full scale) at the three locations shown in Figure A-1.

9. Place filters over the pump and ER intake lines to prevent particles in the feedwater from clogging the pump or ER device. A fine (25 mesh) wire screen wrapped over the hose ends is sufficient.

10. Connect an air supply regulated to 40 psig to the solenoid air valve.

11. Check that the main power switch is off (down) and connect the power cord to 115 Vac 60 Hz.

12. Set the pump speed to 1-1/4 gal/min ± 1/4 gal/min.

13. Check that all connections are tight.

OPERATING INSTRUCTIONS

1. Perform all hookup instructions.

2. Turn on the main power switch.

3. Press the switching buttons on the control box. The right switch should activate the solenoid air valve and cause the pneumatically activated three-way valves to be seated down. The left switch should deactivate the solenoid air valve and release the three-way valves. If the three-way valves do not switch, check air and power supplies. Do not operate the ER device if control switches do not activate three-way valves.

4. The ER device must be filled with water before operating. This can be accomplished by opening control valve 1 on the ER device and temporarily connecting the output of the ER device to a drain. Do this by disconnecting the line from the ER device to the RO membranes or by switching the optional three-way valve in this line over to drain.

5. Turn on the pump and check that:

   - ER inlet pressure is below 100 psig
   - Water begins flowing through inlet flow meter.

6. Allow system to run for 10 minutes to purge air from the ER device. Monitor the inlet pressure, making sure that it does not rapidly increase past 100 psi. If inlet pressure escalates, relieve it by pushing control buttons (left if solenoid valve is on, or right if solenoid valve is off) and, turn pump off immediately. Perform limit switch adjustment instructions.

7. To purge the remaining air from the system, elevate the right side of the ER device to approximately a 30° angle from the horizontal when the solenoid valve is on. When the three-way valves switch, lower the right side and raise the left. Repeat.

8. The device is now ready to be connected to the RO elements. Turn off the pump and switch the ER output (port A) over to the RO membrane input. With the feedwater pump at 1-1/4 gal/min, the ER device should operate below 400 psig, inlet pressure. Turn on the pump and monitor the ER inlet pressure, allowing the device to switch a few times. If air is out of the device, the ER inlet pressure will drop and rise within 1 second of the three-way valves switching. If air is still pesent in the device, turn off the pump and repeat steps 4 through 8.

9. With air purged from the system, the ER output pressure may be varied from 0 to 950 psig. Inlet and outlet flows and pressures may be used to calculate the hydraulic efficiency. The pump speed

and control valve setting may now be varied as long as the ER outlet pressure remains below 950 psig.

CAUTIONS

1. Do not allow an outlet pressure of more than 950 psig in any mode of operation. If an outlet pressure above 950 psig is reached, reduce it immediately by:

   - Opening control valve 1.
   - Pushing appropriate control button to change pumping direction.
   - Shutting off the pump.

2. Never run the system without first performing hook-up and operating procedures.

3. Do not pound or tap on cylinder walls. This may damage sealing surface on the inside of the cylinder.

4. Do not run system with cylinder end plates loose. This may bring the system out of alignment or damage components.

5. Use only stainless-steel hose connections.

6. Do not allow the ER device to sit with salt solutions inside. Flush the system with fresh water after each use.

TROUBLESHOOTING

Problem: Three-way valve not activating.

Probable causes:

- Power is off
- Air line(s) disconnected
- Limit switch level out of adjustment: see adjustment instructions.

Problem: Leaking cover plate.

Probable causes:

- Cover plate bolts loose: tighten in diagonal pattern to 20 ft/lb.
- Cover plate seals worn: check and replace if necessary.
- Limit switch seals worn: check and replace if necessary.

<u>Problem</u>: Slow pressure response.

Probable causes:

- Air accumulating within the system: check (tighten) inlet hose fittings.
- Pressure drop on ER intake hose is large. Pressure in the cylinder may be low enough to vaporize brine: increase ID and/or decrease length of hose to port D.

<u>Problem</u>: Poor efficiency in one or both directions.

Probable causes:

- Flow and pressure ratios low:
  - Check that flowmeters are clean and indicating properly.
  - Check that three-way valves are seating properly--usually manifest by low flow in one direction only.
  - Check Teflon piston seals--may be leaking if low flow in one direction. Check seals on right piston if low flow when driving to left (solenoid valve off) and vice versa.
  - Check T-seal in center housing--may be leaking if low flow in both directions.
- Pressure ratio low
  - Check Teflon® piston seals for wear
  - Check T-seal in center housing for wear.

NOTE: To check the Teflon® piston seals or the center shaft T-seal, it is necessary to disassemble the ER device. This is a fairly large job and should be done only if absolutely necessary.

LIMIT SWITCHES

1. Level adjustment: To adjust the position of the electric limit switches:

   - Turn power off and unplug.
   - Remove cover plates on limit switch housing.
   - Loosen limit switch mounting screws.
   - Position switches so that approximately 1/16-inch travel of the mechanical pushrod will activate each switch.

- Turn power on and check that switches are functioning properly by tripping each switch with a screwdriver blade.
- Reassemble.

2. Seal replacement. Pushrod seals should be replaced every 500 hours of normal operation or if the endcap breather hole(s) begin leaking water.

   - Turn power off and unplug.
   - Remove limit switch cover plate.
   - Remove limit switch housing.
   - Remove pushrod housing.
   - Pull pushrod out from endcap.
   - Replace seals: O-ring #135 (2) and O-ring #130 (1) for each pushrod.
   - Reassemble.

THREE-WAY VALVES (Cleaning and proper seating)

1. Unplug power/air connections.
2. Disconnect all pneumatic and hydraulic lines on the three-way valves.
3. Remove each valve from the mounting block structure.
4. Remove helical spring by unscrewing in CCW direction.
5. Dislodge any contaminants on the valve seats by briskly raising and lowering the valve pushrod onto the upper and lower seats. Turn the pushrod several turns whiled the valve is seated. Repeat.
6. Flush the valve under running water.
7. Reassemble. No further adjustment should be necessary.

INSTRUCTIONS FOR DISASSEMBLY OF CYLINDERS (Piston seal and center shaft seal replacement)

1. Unplug power/air connections.
2. Disconnect all fluid lines to cylinder assembly.
3. Remove limit switch housings.
4. Remove end plates.

5. Pull cylinders free from pistons (do not strike cylinders or pistons).

6. Remove check valve assembly.

7. Remove (unscrew) tie rods.

8. Remove piston lock nuts and pistons and slide the pushrod free from the center housing.

9. Disassemble the center housing and unscrew the T-seal mounting fixture.

10. Remove and inspect seals. Replace as necessary.

11. Reassemble in reverse order.