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RENEWABLE ENERGY RESOURCES
FIELD TESTING

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TECHNOLOGY REVIEW FOR FIELD TEST #8

PV-POWERED DESALINATION PLANT AT EL KASR

JULY 1986

FINAL

Prepared for

Egyptian Electricity Authority
Cairo, Egypt

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Prepared by

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FOREWORD
TECHNOLOGY REVIEW

The Egyptian Electricity Authority (EEA), the United States Agency for International Development (USAID/Cairo), and a group of U.S. consultants form a team responsible for conducting field test demonstration projects for 11 renewable energy applications in Egypt. These demonstration projects include the use of photovoltaic (PV), wind, and solar thermal systems for water pumping, ice making, desalination, industrial process heat, and grid connected electricity generation. The specific objectives of the 4-year program are to: (1) demonstrate the viability of renewable energy technologies in Egypt, (2) comprehensively strengthen Egyptian technical and institutional capabilities in the full spectrum of renewable energy planning and decision-making, and (3) establish the infrastructure necessary to ensure that renewable energy technologies, that have been proven successful are available for widespread use in Egypt.

Each field test demonstration project contains seven generic tasks: technology review, application review, conceptual design, preparation of a statement-of-work for a tender document, proposal evaluation, supervision of hardware installation, and performance evaluation. The technology review for one of these field tests, a photovoltaic-powered desalination plant, is presented in this document.

The photovoltaic powered desalination plant that will be evaluated in this field test consists of two basic systems: the power system and the desalination equipment. The performance evaluation of the total system is the key element of this field test since it will assist in assessing the viability of photovoltaic power for the desalting application at other locations in Egypt.

This report assesses the component and system technologies of the photovoltaic powered desalination plant that will be examined in Field Test #8 and provides a representative selection of manufacturers and system integrating contractors, hardware system specifications, and examples of field experience with other PV-powered desalting system applications.

This document is subtask 3.8.2 to the field test requirements under Contract AID 263-123C-00-4069-00, Task Area 3.

TABLE OF CONTENTS

SECTION		PAGE
1.0	EXECUTIVE SUMMARY	1
1.1	Project Objectives	1
1.2	Intent of the Technology Review	1
1.3	Technology Perspective	2
1.4	Manufacturers and Hardware Systems	3
1.5	Conclusions and Recommendations	4
2.0	FIELD TEST OBJECTIVES AND DESCRIPTION	5
2.1	Project Objectives	5
2.2	Description of the Field Test	5
3.0	HISTORICAL PERSPECTIVE ON COMPONENT TECHNOLOGIES	12
3.1	Desalination Equipment	12
3.2	Diesel Generators	12
3.3	Batteries	13
3.4	Photovoltaics	14
4.0	POWER SYSTEM TECHNOLOGY	16
4.1	Power System Options	16
4.2	Field Test #8 Load	17
5.0	REVIEW OF FIELD TEST HARDWARE	21
5.1	Desalination	21
5.2	Photovoltaics	33
5.3	Structures	34
5.4	Batteries	34
5.5	Power System Controller	35
5.6	Diesel Generators	36
5.7	Inverters/Rectifiers	36
5.8	System Monitoring and Instrumentation	36
5.9	Brine Disposal	37

TABLE OF CONTENTS (Continued)

SECTION PAGE

6.0 MANUFACTURER PROFILES..... 38

6.1 Photovoltaic Module Manufacturers..... 38
6.2 Desalination Equipment Manufacturers..... 42
6.3 Battery Manufacturers..... 43
6.4 Inverters/Rectifiers..... 45
6.5 Controllers..... 46
6.6 Diesel Generator Manufacturers..... 47
6.7 Integrating Contractors..... 48

7.0 EQUIPMENT/PRODUCT SPECIFICATIONS..... 53

8.0 RELEVANT PROJECTS..... 59

9.0 CONCLUSIONS..... 61

APPENDICES - Separately Bound

A. Report on Desalination Technology

B. Relevant Professional Papers on PV-Powered Desalination Projects

C. Product Literature

D. Instrumentation System Specification and Data Requirements for a Photovoltaic-Powered Desalination System

LIST OF EXHIBITS

EXHIBIT		PAGE
2-1	Field Test #8 Location	6
2-2	Schematic Illustrating Water Flow to Roman Wells	7
2-3	Schematic Illustrating Water Flow to Roman Well Collection Point	9
2-4	Photo of Candidate Site for Field Test #8	10
3-1	Worldwide Photovoltaic Market Projections	15
4-1	Idealized Operating Curve- Reverse Osmosis	18
4-2	Idealized Operating Curve- Electrodialysis	20
5-1	Osmosis - Reverse Osmosis Process	22
5-2	Simplified RO Flow Diagram	23
5-3	Reverse Osmosis Permeator	25
5-4	Details of Spiral Wound Module Construction	26
5-5	Spiral Wound Membranes Vessel	27
5-6	Electrodialysis Process	29
5-7	Electrodialysis Membrane Arrangemtent	31
5-8	Comparison of Reverse Osmosis and Electrodialysis Features	32a
6-1	Manufacturers - Products/Services	39
7-1	Equipment Data Base	54

1.0 EXECUTIVE SUMMARY

1.1 Project Objectives

The primary objective of Field Test #8 is to provide the Egyptian Electricity Authority (EEA) with practical working experience in the design, operation, and evaluation of a photovoltaic-powered desalination system. This objective will be accomplished by demonstrating and evaluating a photovoltaic-powered desalination plant at El Kasr, a small village on the Mediterranean Coast near Mersah Matruh. Data generated from this field test will be used to help determine if the desalination project should be replicated at other sites in Egypt.

1.2 Intent of the Technology Review

There are a number of key factors that provide the context for technology reviews and support the evaluation of the desirability to proceed with a particular field test. The first factor is the degree to which the field test contributes to the objectives of the overall Renewable Energy Field Test REFT Project. The purpose of the Project is to investigate selected renewable energy options. Its specific objectives are to:

- Comprehensively strengthen Egyptian technical and institutional capabilities in the full spectrum of renewable energy planning and decision-making for technologies and applications
- Develop and sustain an Egyptian renewable energy infrastructure by establishing data bases, information systems, and organizations that effectively serve both the public and private sectors
- Design, install, and evaluate a series of field tests that utilize commercially available technologies in applications having potential for widespread use in Egypt
- Complete formal managerial and technical training, both on-the-job and specialized, and an intensive information dissemination program.

An assessment of the contribution a specific field test makes to the REFT Project objectives must consider the criteria necessary for a successful demonstration of a PV power system. The Technology Review is primarily concerned with the evaluation of commercially available hardware and systems required for

successfully designing, installing and operating the power system and the necessary desalination hardware. The criteria used to evaluate technologies are listed below, although not necessarily in their order of importance.

- Commercial availability of hardware systems
- Hardware performance/system reliability
- Operation and maintenance costs
- Potential for widespread development in Egypt.

A review of the component and system technologies involved with this field test has been performed to support a decision of whether or not to proceed with the demonstration. Included in this report are a representative listing of system integrating contractors and hardware literature and a collection of available literature that describes design and application experience with PV-powered desalination systems. This Technology Review is supplemented by technical information provided in the PV System Technology Reference Notebook, which was published in May 1985.

1.3 Technology Perspective

The basic operating concept of this field test is to use photovoltaic power when insolation conditions permit. A modestly sized battery bank augments the power from the photovoltaic array during the brief periods of low insolation (such as when a cloud passes over), in the morning, or late in the afternoon. A diesel generator is the backup for power when the PV-powered subsystem is not working or when the need for potable water exceeds the supply that can be desalted using power from the PV array.

The subsystems being evaluated are:

- Photovoltaics
- Batteries

- Power Conditioning
- Desalination.

(Diesel genset performance is of lesser interest since it is considered a mature technology.)

There are two candidate desalination technologies: reverse osmosis and electrodialysis. These two technologies are attractive as a match for PV power since they are fundamentally more energy efficient than conventional distillation methods. Reverse osmosis requires a high pressure on the feedwater side of a permeable membrane that passes only pure water. Electrodialysis works on the principle of the electrically charged ions of the impurities in the water being attracted to oppositely charged electrodes, thus leaving the less "salty" water behind. Two main questions need to be answered: (1) Can the combination of two proven technologies, PV and desalination (reverse osmosis or electrodialysis) be effective in a remote Egypt location? (2) Can maintenance and monitoring of the system be sustained so that the plant is considered reliable?

1.4 Manufacturers and Hardware Systems

A selection of manufacturers, integrating contractors and hardware system specifications are provided in this document. Section 6 contains a listing of representative companies and their respective product or service. It is likely that no single company will have the broad capabilities needed to respond to the tender document; therefore, it is probable that an integrating contractor, who may or may not be a PV or desalination system manufacturer, will coordinate the design, equipment selection, testing, procurement, shipping, installing, start-up, and training among a bidding team of companies.

1.5 Conclusions and Recommendations

The findings in this Technology Review support the recommendation to proceed with Field Test #8.

- Individual subsystem components for this field test are proven, reliable, and commercially available.
- Although operational experience with PV-powered desalination systems is limited, this review indicates that there should be no insurmountable technical problems associated with this demonstration project.
- The system should be sized and designed for minimum maintenance and should avoid complex designs that are not proven.
- The system should be of a modular design for ease of replicability in other remote locations throughout Egypt.
- PV-powered desalination systems are a logical development step for future remote power system applications.

2.0 FIELD TEST OBJECTIVES AND DESCRIPTION

2.1 Project Objectives

The objectives of Field Test #8 are to:

- Demonstrate, in a remotely located Egyptian environment, the viability of a PV-powered stand-alone desalination system
- Demonstrate a capability to desalt brackish water that has a wide range in salinity from about 1000 ppm to about 12,000 ppm
- Demonstrate if the system can be maintained in a remote location
- Determine start-up and operation and maintenance costs of the system
- Develop, through training, a working capability in Egypt to design, procure, install, maintain, and analyze the performance of a PV-powered desalination plant
- Identify modifications that should be made in replicated systems in other locations in Egypt

2.2 Description of the Field Test

The PV-powered desalination system is to be a stand-alone ststem; that is, it will have no support from an electric utility. The desalination system will operate on power from the photovoltaic array when the sun shines, possibly with the help of a supplemental battery bank. At night or during periods of low insolation, the system will not operate unless it is manually switched to a standby diesel genset. An important objective is to build a desalination system that can be replicated in other locations in Egypt with minimal changes.

Feedwater will be taken from the brackish water supply in the El Kasr area. (Exhibit 2-1 illustrates the location of El Kasr.) Much of the water in El Kasr is from "Roman wells" near the beach. Roman wells (so named because they were built in the days of the Roman Empire) are trenches dug into the bedrock near the shore. Rainwater filters through the sand and runs over the bedrock until it is caught in a trench (Exhibit 2-2). The trench runs parallel to the shoreline and is inclined so that the water runs to a collection area, where it is pumped

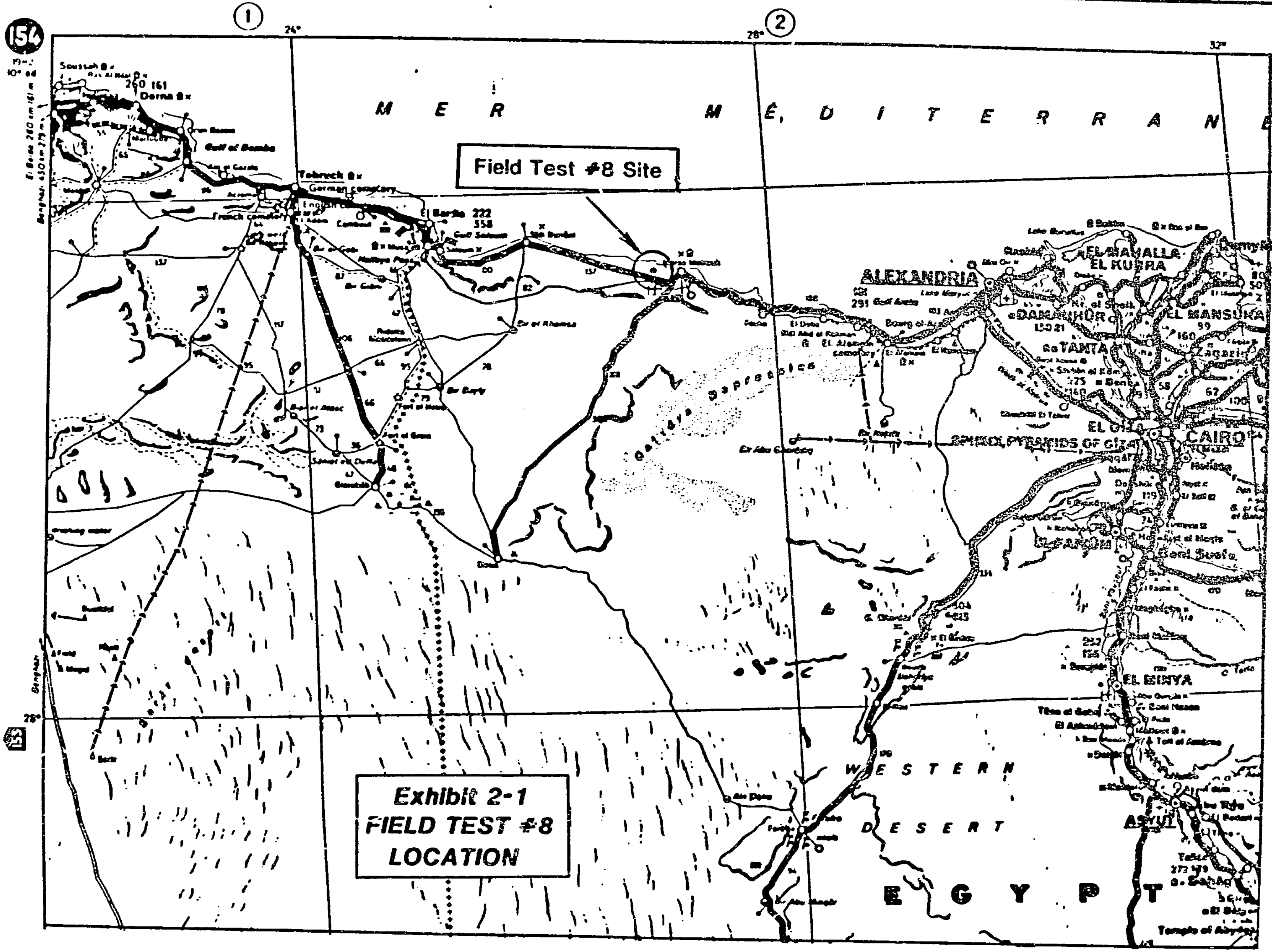


Exhibit 2-1
FIELD TEST #8
LOCATION

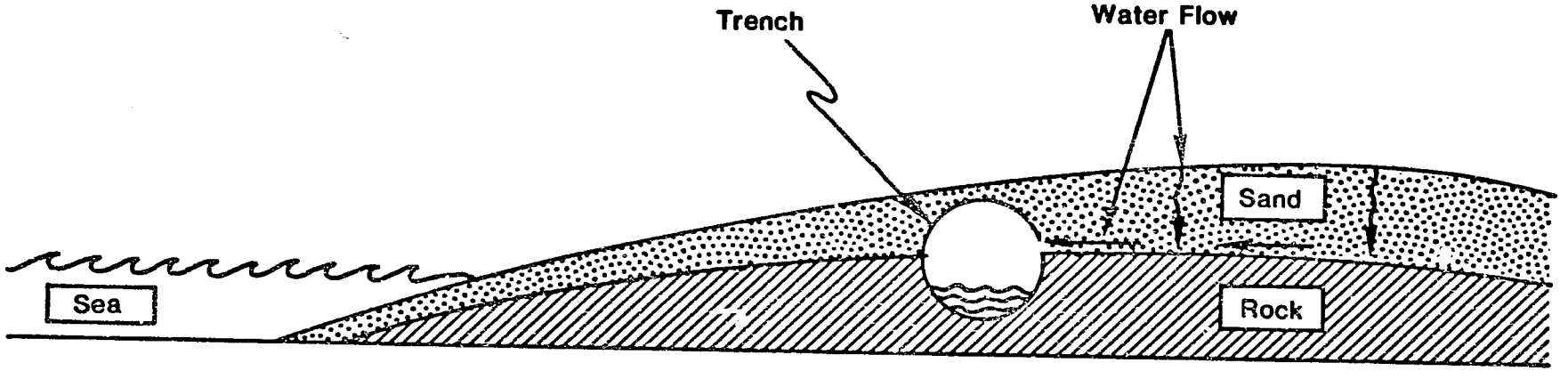


Exhibit 2-2
SCHEMATIC ILLUSTRATING WATER FLOW TO ROMAN WELLS

to an above-ground reservoir (Exhibit 2-3).

There are two sites on the beach that serve as collection points for the water accumulated in the Roman wells (Exhibit 2-4). The representatives of the governorate of Mersa Matruh prefer that one of these sites be used for the location of the desalination plant. The water is collected at these sites in a comparatively small storage reservoir and pumped to another site about 12 km. to the east. This site, the Central Collection Station, has six separate 200 cubic meter concrete tanks that get conventional well water that is mixed with the water from the Roman wells. This site is a second possiblity for location of the desalination plant.

A third possible site, called Mowah, was the distribution point for brackish water during a project team visit in November 1985. At this site, there are two 200 cubic meter per day electrodialysis units installed that were scheduled to go into operation in November 1985. These units are powered by the electrical grid with diesel generator backup.

The system that comprises Field Test #8 consists of:

- A desalination system capable of desalting brackish water and delivering from 10 to 20 cubic meters of product water per day
- Pump(s) and plumbing to transport brackish feedwater from a holding reservoir to the desalination system
- Pump(s) and plumbing to transport desalted water to a holding tank
- Pump(s) to transport the concentrate water to the sea or a holding pond
- Photovoltaic array and associated structure and wiring
- Power conditioning system
- Battery bank for storage of energy from the PV array
- Auxiliary diesel genset
- Fence around PV array
- Building(s) to house the diesel engine, power conditioning system, and desalination system.

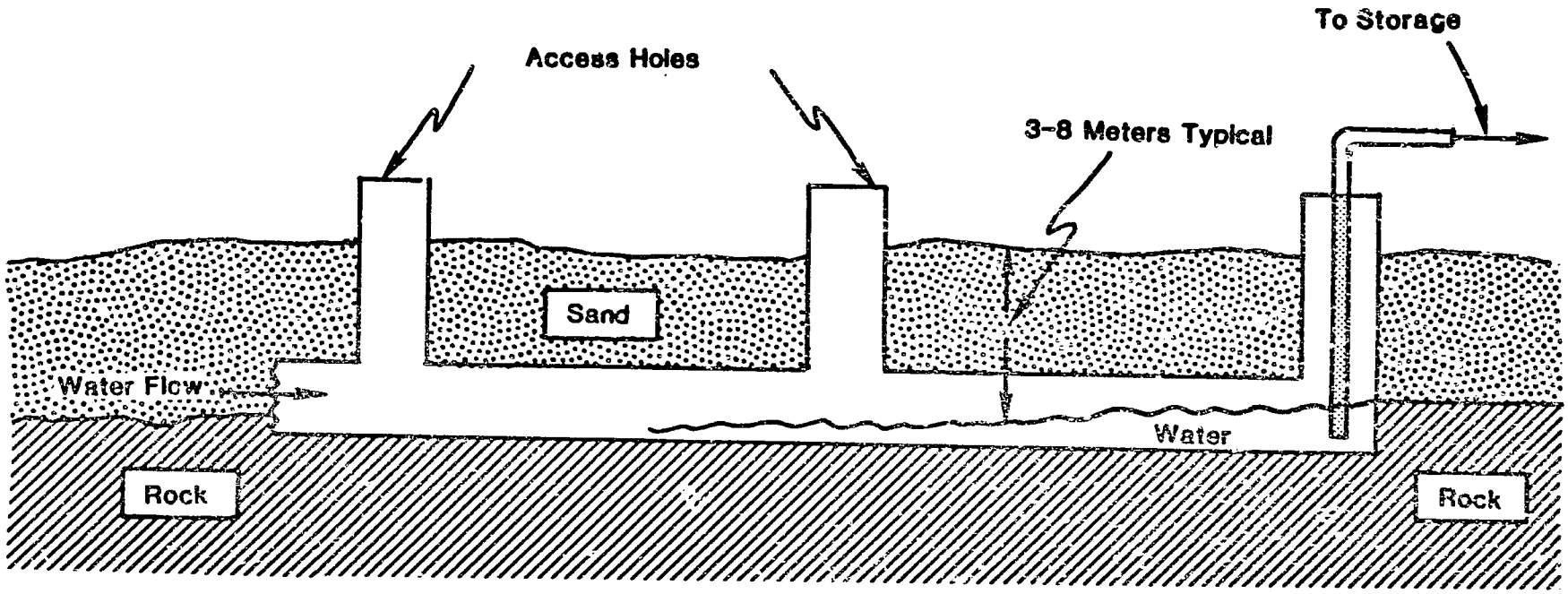


Exhibit 2-3
SCHEMATIC ILLUSTRATING WATER FLOW TO ROMAN WELL COLLECTION POINT

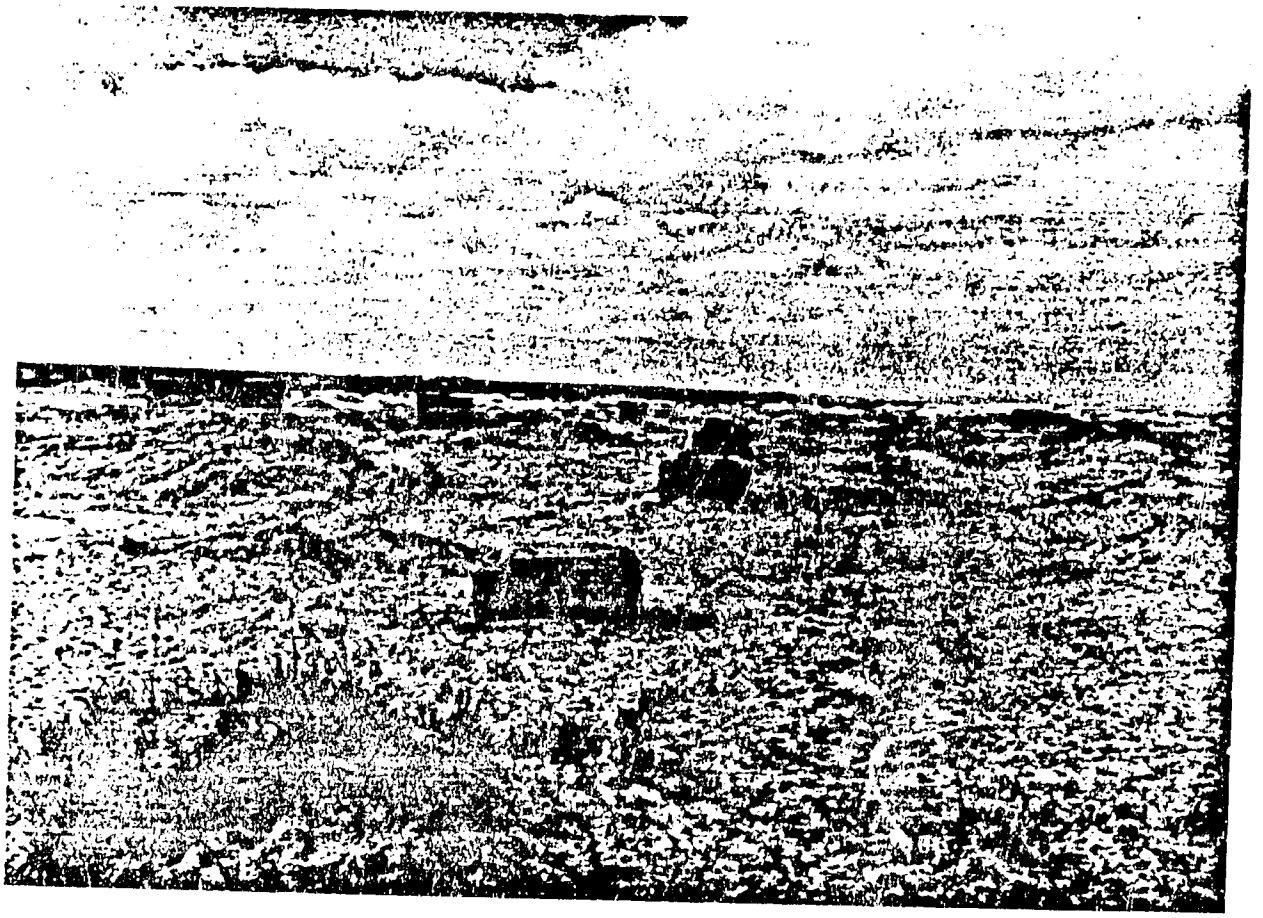


Exhibit 2-4

PHOTO OF CANDIDATE SITE FOR FIELD TEST #8

View Looking West. Blocks in Middle of Photo are Access Ports for Roman Wells. Building on Left is Pump House.

The mode of operation will be as follows:

- A suitably sized PV-array (20-35 XW peak) will be the prime power source and will be supplemented by a battery storage subsystem, which will power the desalination equipment during periods of low insolation.

- Normal operation of the plant will take place only when the sun shines. The system will be turned off at night.

- When there is a need for water beyond what the photovoltaics power system will provide, the diesel can be manually turned on. In this way, the diesel can be operated at near full load, which is the most efficient operating condition for a diesel engine.

3.0 HISTORICAL PERSPECTIVE ON COMPONENT TECHNOLOGIES

Field Test #8 will evaluate the effect of combining several technologies: desalination, photovoltaics, diesel generators, and batteries. During this field test, each hardware component will be tested on a technical, institutional, and economic basis. The integrated performance of the power system components, together with the desalination equipment, will also be evaluated.

This section provides a perspective on the past and current performance of each technology in order to identify possible areas of concern for this field test.

3.1 Desalination Equipment

There are two desalination technologies being considered for this field test, reverse osmosis and electrodialysis. Each of these technologies may be considered proven technologies in their own right; however, their use in a dedicated system with photovoltaics is limited in the case of reverse osmosis and nonexistent in the case of electrodialysis. Appendix A provides a review of desalination technology and Appendix B contains a number of reports on various PV-powered desalination units.

3.2 Diesel Generators

Diesel-powered electricity generation for remote power applications is another proven technology. Diesel generators have been installed in remote areas throughout the world for the past 30 years. Diesel generator technology development over the years has concentrated on increasing power density (more power per unit weight) and producing higher efficiency engines and generators that require less maintenance. The usefulness of diesel generators and their counterpart, gasoline generators, is based on the availability of fuel and maintenance, which represent the bulk of the cost of delivered energy.

A decision to employ diesel generators is not based on the technology, but on the reliable supply and associated costs of fuel and maintenance.

Until about the mid-1970's, few alternatives to diesel- or gasoline-powered generator technology existed for meeting remote demands for electricity. With the maturation of photovoltaic technology and the trend toward lower costs for PV modules, a case can be made for using photovoltaics.

3.3 Batteries

Lead-acid and nickel-cadmium storage batteries, best suited for photovoltaic power system applications, are proven technologies. Lead-acid storage batteries have been produced on a commercial scale for over 75 years. Nickel-cadmium batteries, first developed around 1900, did not come into common use until after 1945. Both lead-acid and nickel-cadmium batteries are available worldwide.

Development in battery technology is directed at lowering cost, increasing life, reducing maintenance requirements, and increasing efficiency. Progress toward these objectives is expected to occur slowly but steadily.

An important development in battery storage technology for PV systems is the commercial availability of deep cycle, sealed lead-acid batteries that use recombination battery technology. Recombination battery technology virtually eliminates water consumption by designing the battery cells to recombine any generated hydrogen and oxygen into water. This permits the battery to be sealed and results in a relatively maintenance free battery. Although the cost of these batteries is higher than "vented" lead-acid batteries, which require higher maintenance levels, their use in photovoltaic systems is expected to steadily increase.

3.4 Photovoltaics

The development and growth of terrestrial photovoltaics has been impressive over the past 20 years. The cost of photovoltaic equipment has dropped dramatically while performance has steadily increased. The reliability of today's photovoltaic modules is virtually 100%. This conclusion is based on published results of NASA Lewis' extensive PV application and evaluation experience. Related application experience worldwide supports this view. The productive life of photovoltaic modules is designed to be approximately 20 to 30 years. Ten year performance warrantees are now available from manufacturers.

The market for photovoltaics is expanding as the relative cost of photovoltaics compared to conventional energy sources decreases for specific applications. Projections made by Photovoltaic Energy Systems Incorporated (PV ESI) show that the worldwide market for photovoltaics might reach over 300 megawatts by 1995 (Exhibit 3-1).

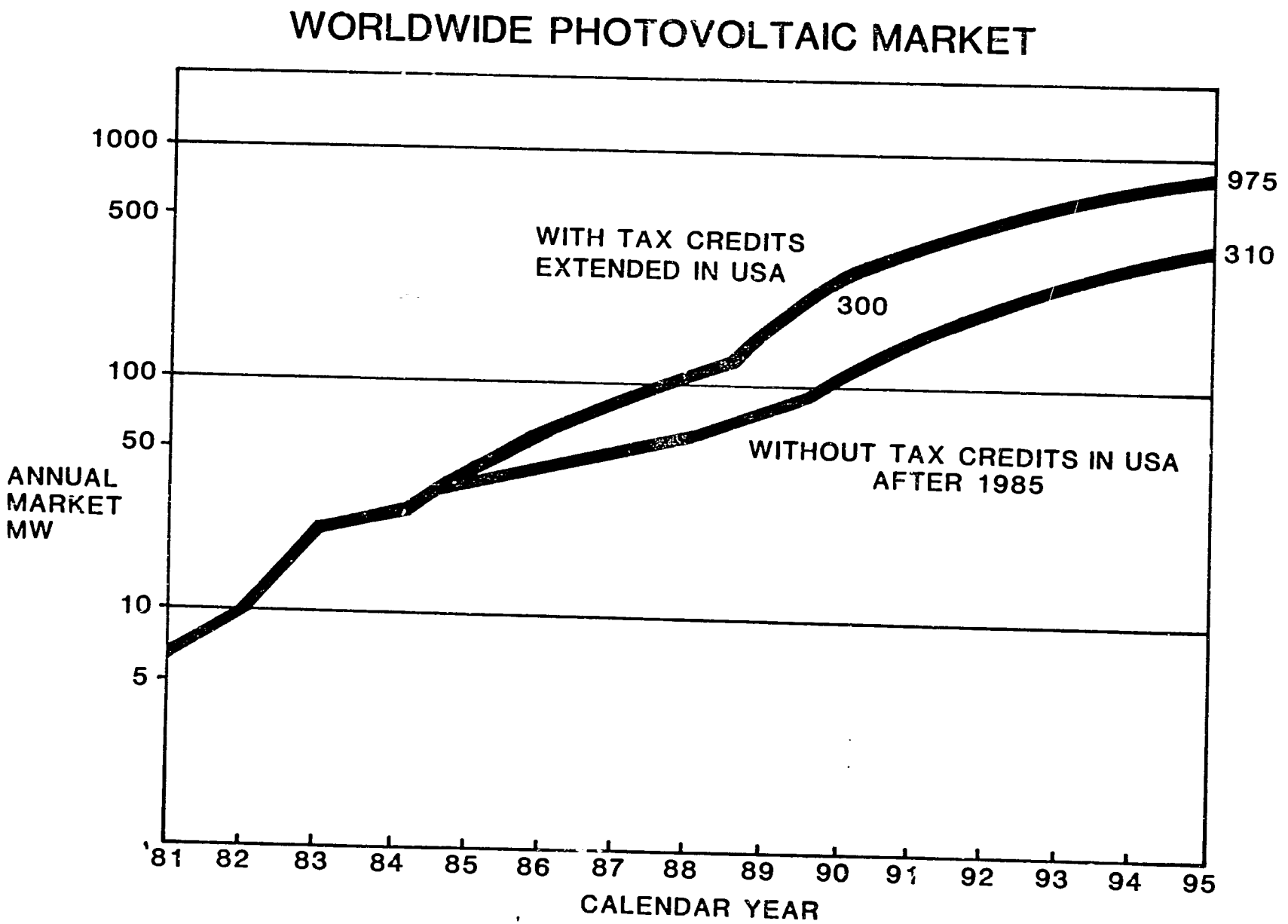


Exhibit 3-1
WORLDWIDE PHOTOVOLTAIC MARKET PROJECTIONS
(Photovoltaic Energy Systems Inc., Nov. 1985)

4.0 POWER SYSTEM TECHNOLOGY

4.1 Power System Options

The power technology being evaluated in this field test is photovoltaics. As background, this section provides a brief perspective on competing remote power technologies. Three basic "stand-alone" energy approaches are considered: diesel, photovoltaics, and hybrid power.

Diesel Generators

Diesel generators are considered to be the existing technology. They are available in a wide range of sizes from 2 kilowatts up to several hundred kilowatts rating. These generators operate with a thermal-to-electricity fuel conversion efficiency of 15 - 30 percent depending on the capacity factor and the quality of maintenance. For a standalone application, two diesel generator sets are normally required to provide for 100 percent backup and to operate the load during diesel maintenance periods.

Photovoltaics

Photovoltaic technology is the primary power technology under consideration in this field test. Photovoltaics have proven to be more reliable and to require less maintenance than diesel systems for remote power supply. Photovoltaic energy, however, is currently cost competitive to diesel generators only at low daily load levels, generally below 10 kilowatt-hours per day. Over the next 10 years, the cost of photovoltaic energy is projected to drop to a level where it will be competitive with diesel for numerous remote power applications.

PV/Diesel "Hybrid" Power Systems

A hybrid power system - the combination of a PV and diesel generator power system - uses the benefits and reduces the disadvantages of both technologies. This type of system is particularly attractive for applications that have a constant load or loads that occur at times that do not coincide with periods of sunlight (neither condition is necessarily present in this field test).

4.2 Field Test #8 Load

The electrical load profiles presented by the two types of desalination equipment (reverse osmosis and electrodialysis) are markedly different. The loads for a reverse osmosis plant are primarily the high pressure pump(s). For consistently high quality water, the pressure should remain steady. This requirement means that pump motors that fluctuate speed in relation to the intensity of the sun are not particularly well suited to this application. One way of satisfying this requirement is to use battery augmentation during periods of low insolation to help drive a constant speed motor. Exhibit 4-1 illustrates an idealized load/power profile for a reverse osmosis cycle.

Electrodialysis, on the other hand, is, in principle, a better match for a variable power source such as photovoltaics. No particular performance penalty occurs if the current fluctuates with insolation level. In fact the system is more efficient at lower current flows.

To illustrate this, assume the following example cases. In case 1, the feedwater flow rate of an electrodialysis unit is four cubic meters per day. The current required to the electrodes is 4 amps. The power required is 800 watts.

Now assume in case 2 that the power is reduced to 200 watts. Because the resistance of the electrodes remains constant, a mathematical relationship based on the I^2R form of Ohm's Law can be set up as follows:

$$\frac{P_1}{I_1^2} = \frac{P_2}{I_2^2}$$

Rearranging terms:

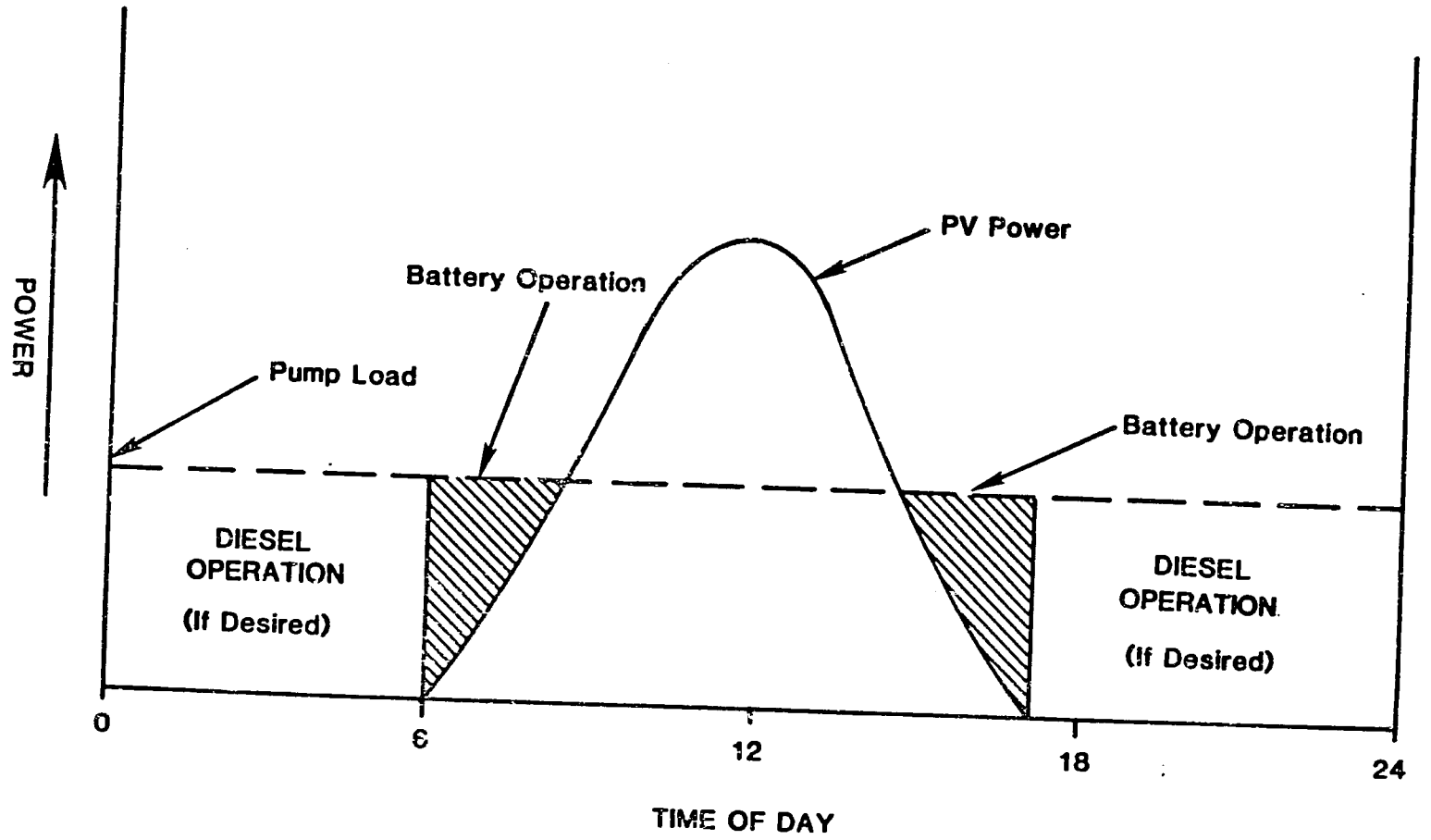
$$I_2 = (P_2/P_1)^{0.5}\ I_1$$

Substituting values:

$$I_2 = (200/800)^{0.5} \times 4 \text{ Amps}$$

$$I_2 = 2 \text{ Amps}$$

Exhibit 4-1
IDEALIZED OPERATING CURVE-REVERSE OSMOSIS

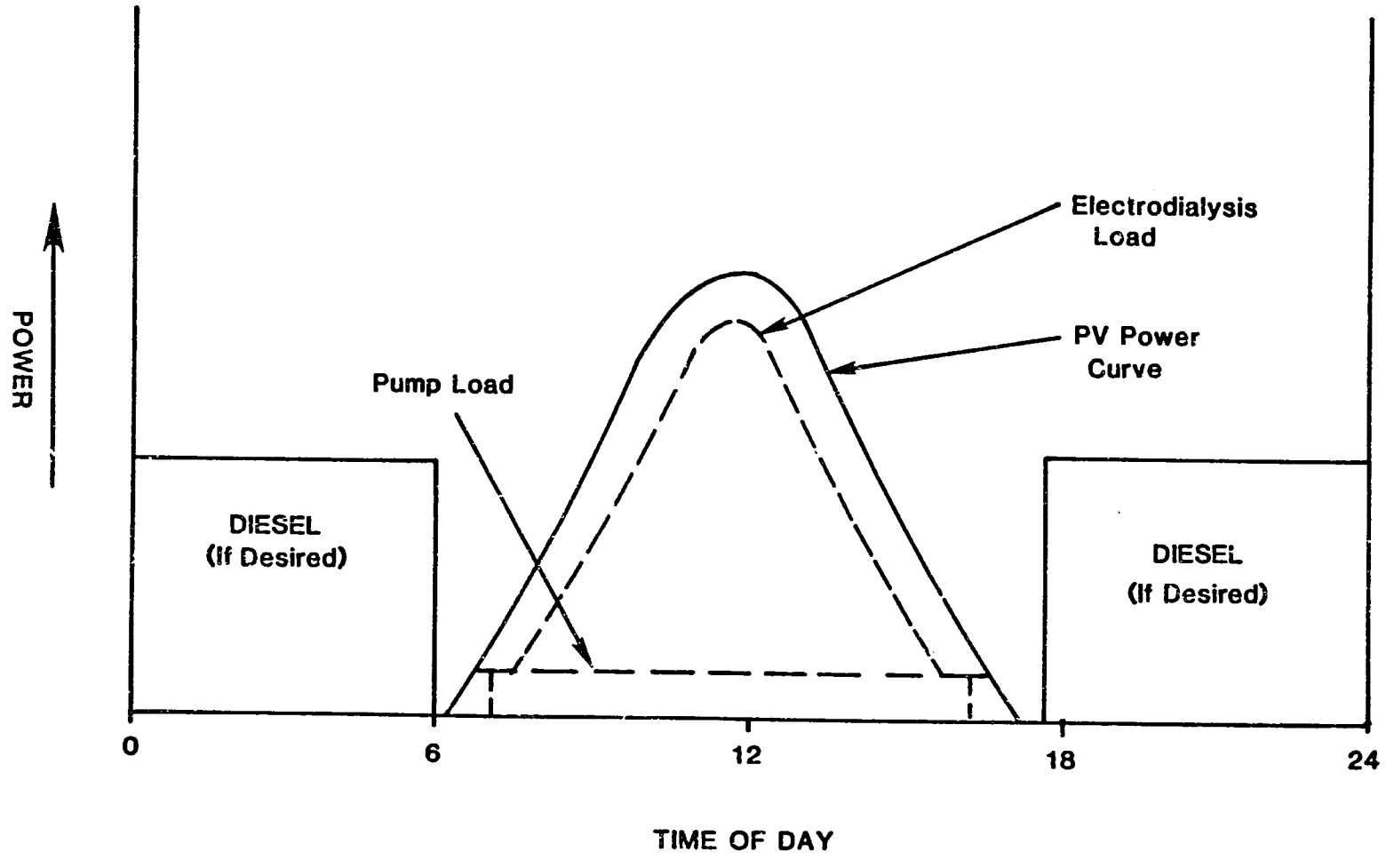


The control system controls the feedwater flow rate in direct proportion to the current. Therefore in case 1 the ratio of feedwater flow rate to power is 5 cubic meters per day per kilowatt and in case 2 it is 10 cubic meters per day per kilowatt.

The electrodialysis system could be greatly simplified by restricting its operation to sunlight hours only thereby eliminating the battery bank. If there is a requirement for more water, then the diesel can be operated on an as-required basis. Exhibit 4-2 illustrates an idealized load/power profile using electrodialysis).

Exhibit 4-2

IDEALIZED OPERATING CURVE-ELECTRODIALYSIS



5.0 REVIEW OF FIELD TEST HARDWARE

A discussion of the technology of photovoltaic modules, structures, batteries, and controllers is provided in the PV System Technology Reference Notebook, which was published in May 1985. This section summarizes that discussion and describes the specific equipment component technologies that will be used in this field test including desalination equipment and diesel generators.

5.1 Desalination

The operating principles of reverse osmosis and electrodialysis are well understood. This section will discuss these principles and describe all required subsystem components. A selection of manufacturers' literature is included in Appendix C.

Reverse Osmosis

The Osmosis-Reverse Osmosis Process described in Exhibit 5-1(a), (b), and (c) shows a chamber divided by a semi-permeable membrane, with a pure water solution on one side and on the other a solution of concentrated salts. The pure water passes through the membrane into the chamber containing the concentrated solution in an effort to bring the system to equilibrium.

In Exhibit 5-1(c), with the application of pressure to the concentrated solution, the pure water is driven back across the membrane, leaving behind the concentrated salts and creating once again a chamber with high purity water. Exhibit 5-1(c) represents the fundamental operating principles of Reverse Osmosis.

In Exhibit 5-2 we have a simplified Reverse Osmosis process flow diagram. A salt solution is pumped into a vessel containing a semi-permeable membrane. As pure water is passed through the membrane, the salt solution becomes increasingly concentrated and is passed from the system through a flow regulating valve. The regulating valve maintains the pressure required within the container, while the pump provides the necessary flow. The purified water that has crossed the mem-

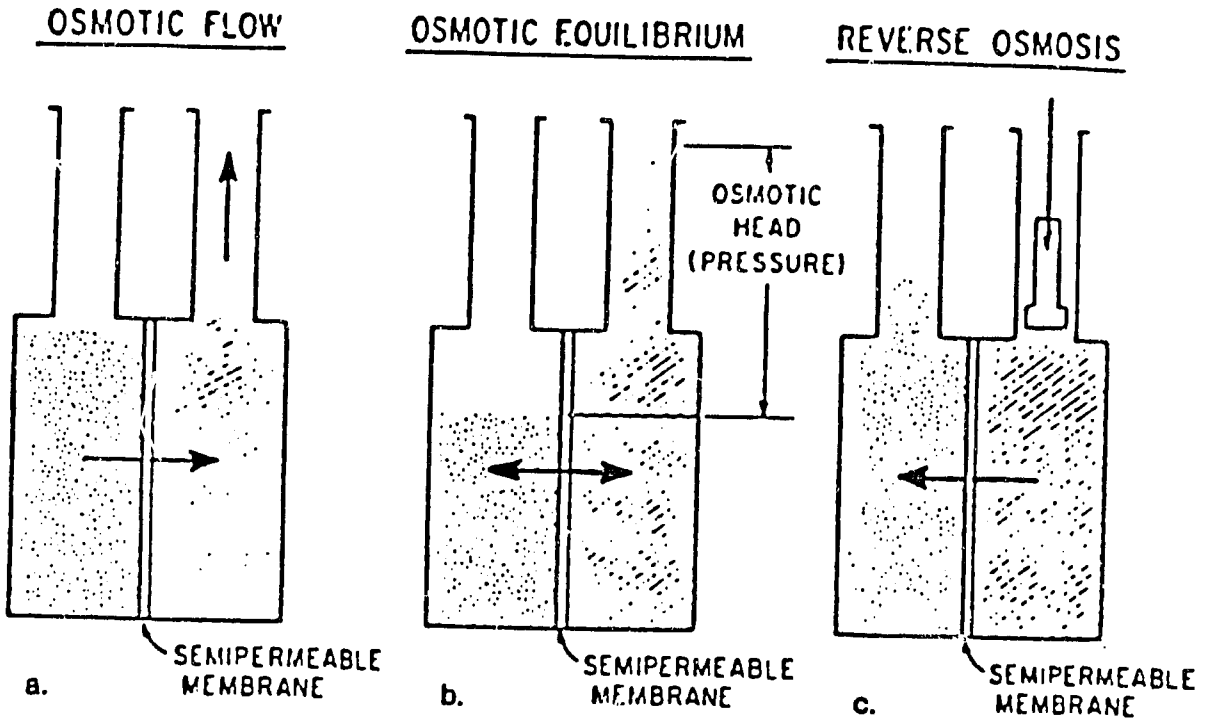


Exhibit 5-1

OSMOSIS-REVERSE OSMOSIS PROCESS

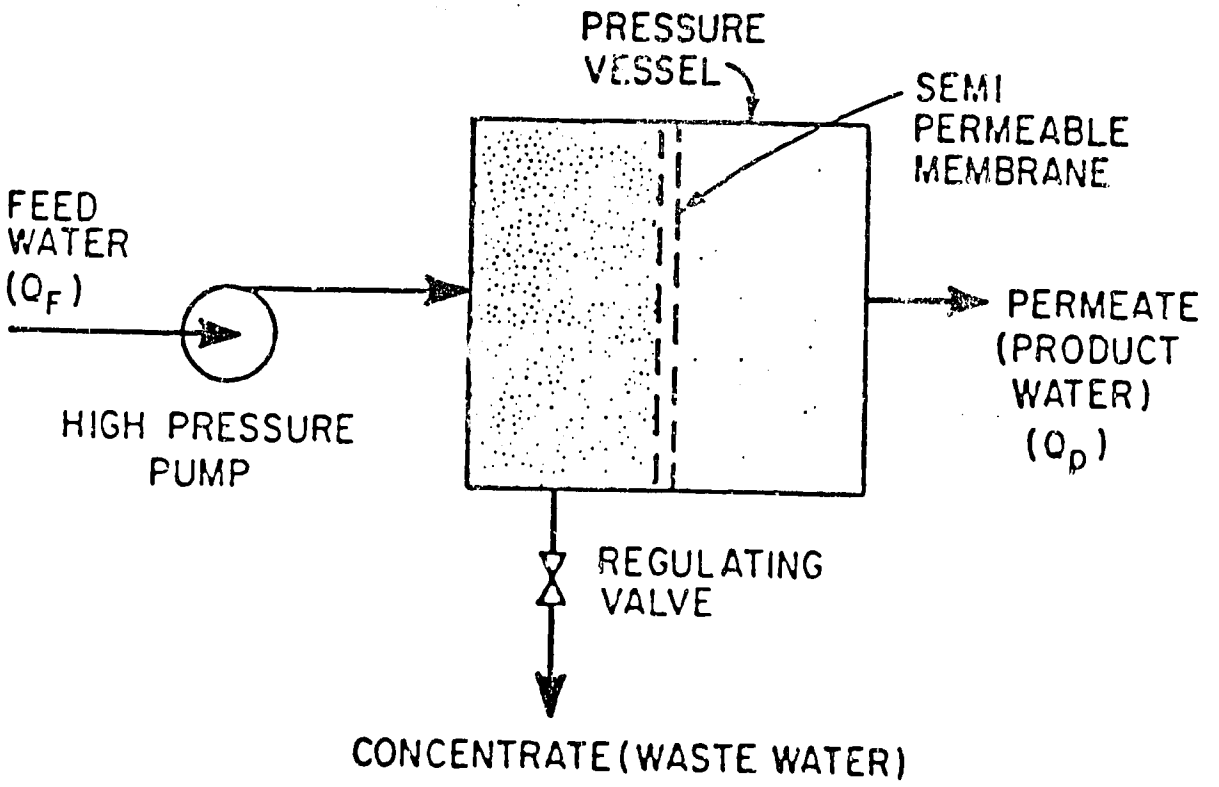


Exhibit 5-2

SIMPLIFIED RO FLOW DIAGRAM

brane is collected in the permeate or product water chamber.

The membranes used in the reverse osmosis process are of two standard designs, hollow fiber and spiral wound. Exhibit 5-3 describes the physical configuration of the hollow fiber permeators. The membrane is a fine fiber and many thousands are assembled parallel to each other in a fiber bundle. The bundled fibers are secured at each end in epoxy tube sheets. Typically these fibers have an inside diameter of approximately 42 microns, an outside diameter of approximately 85 microns, and a length of approximately 30 inches. The feedwater enters the perforated tube, which is at the center of the fiber bundle, and water passes through the bundle and out the concentrate port. As the water travels across the outer surface of the fibers, the purified water passes through the fiber wall. The salts are retained in the vessel and discharged out the concentrate port. The purified water travels down the center of the fiber and is collected at the product end of the permeator vessel.

Exhibit 5-4 describes the physical configuration of the spiral wound elements. The spiral wound elements are produced from sheet membrane. Two membrane sheets are glued back to back to form an envelope. When water, under pressure, is passed over the surface of the sheet, pure water passes through the membrane, while the salts are held back on the outer surface of the envelope. The membrane envelopes are separated by mesh spacers and rolled into the spiral configuration. The spiral element is secured in a fiberglass outer wrap, and a brine seal or gasket is assembled on the outside of each element. As shown in Exhibit 5-5, the elements are assembled in series in a vessel containing a maximum of six (6) spiral elements. This assembly of spiral elements is similar to the hollow fiber permeators.

The spiral elements come in 4 inch and 8 inch diameter sizes for the larger industrial and municipal applications. The feedwater enters the pressure vessel (which measures in excess of 20 feet with a six-element assembly) and

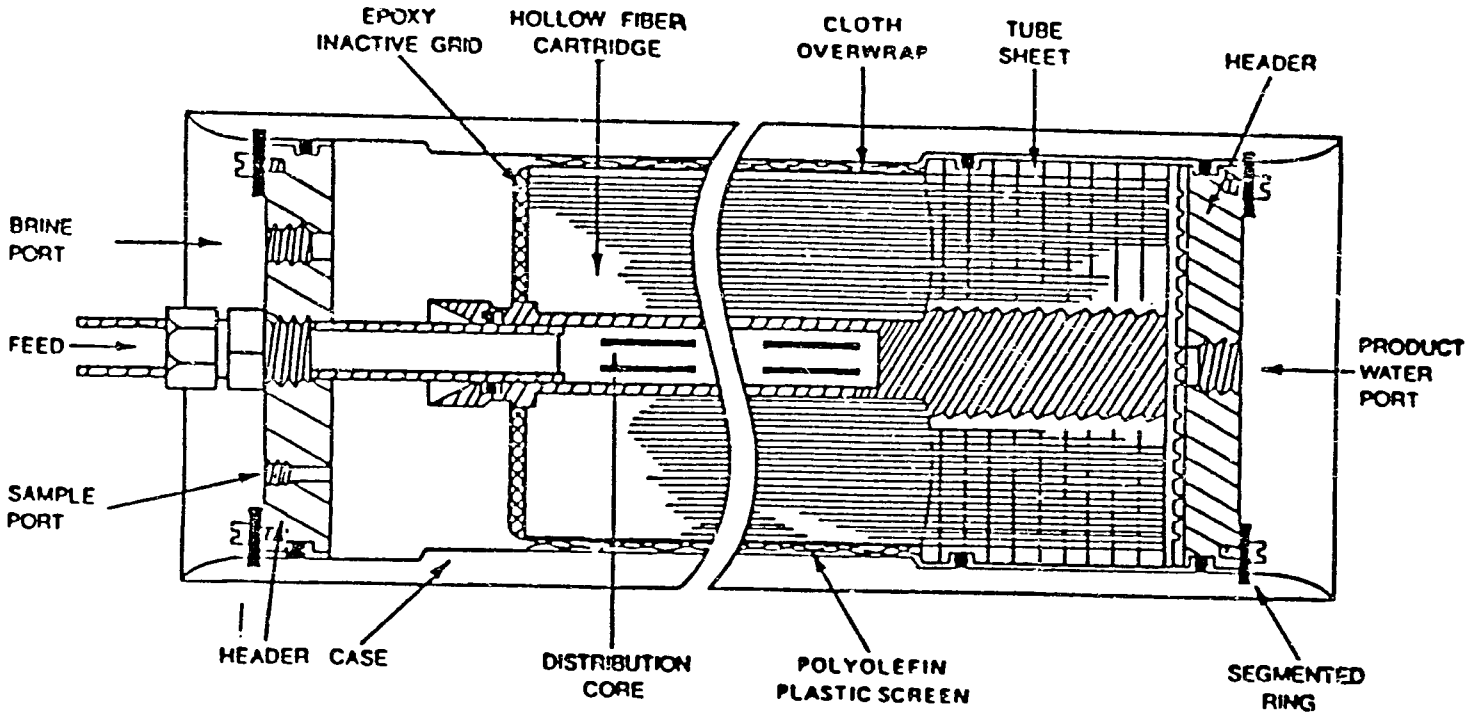
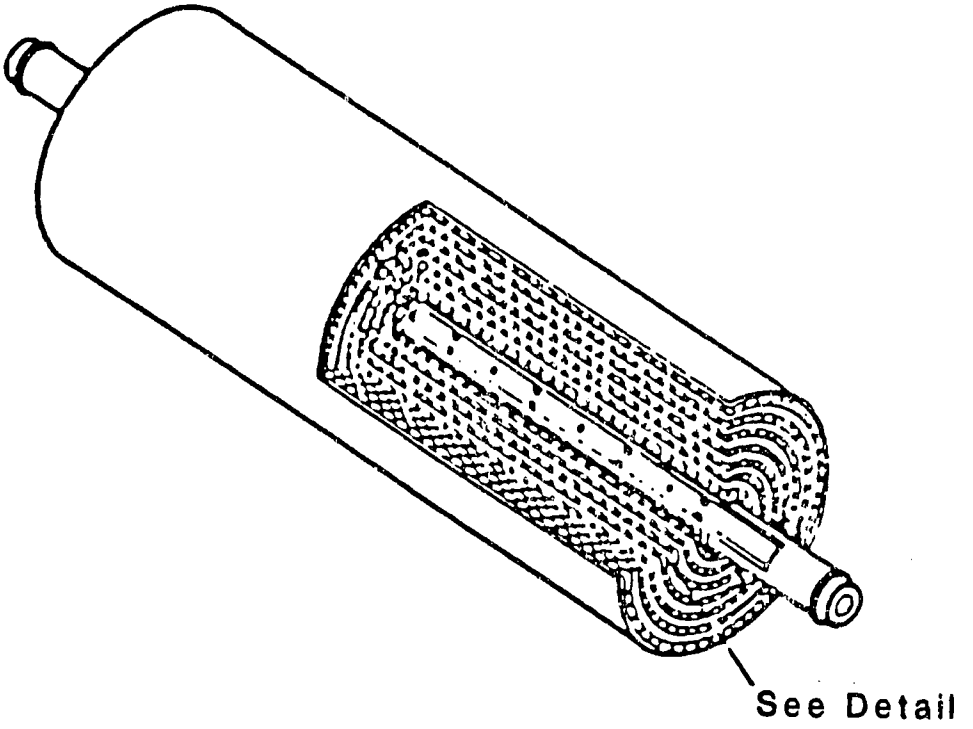


Exhibit 5-3

REVERSE OSMOSIS PERMEATOR



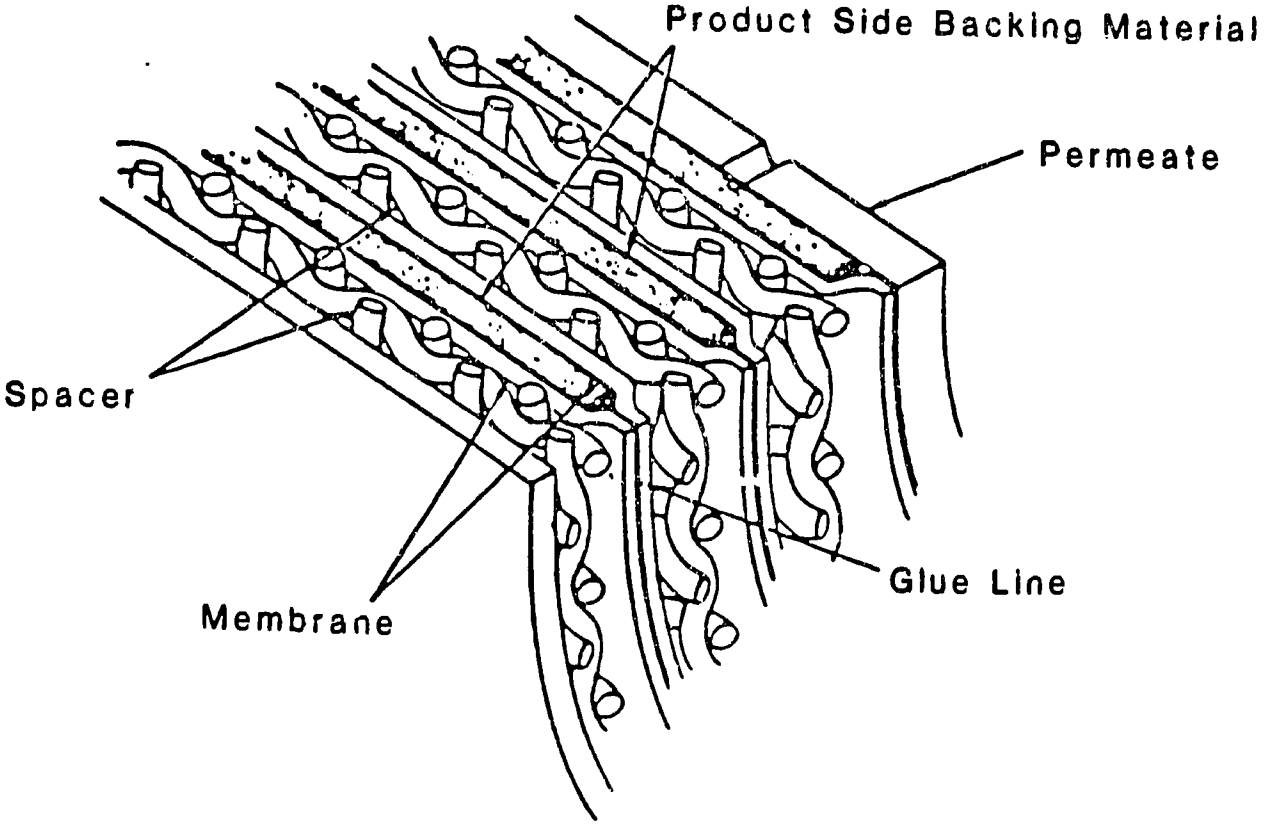


Exhibit 5-4

DETAILS OF SPIRAL WOUND MODULE CONSTRUCTION

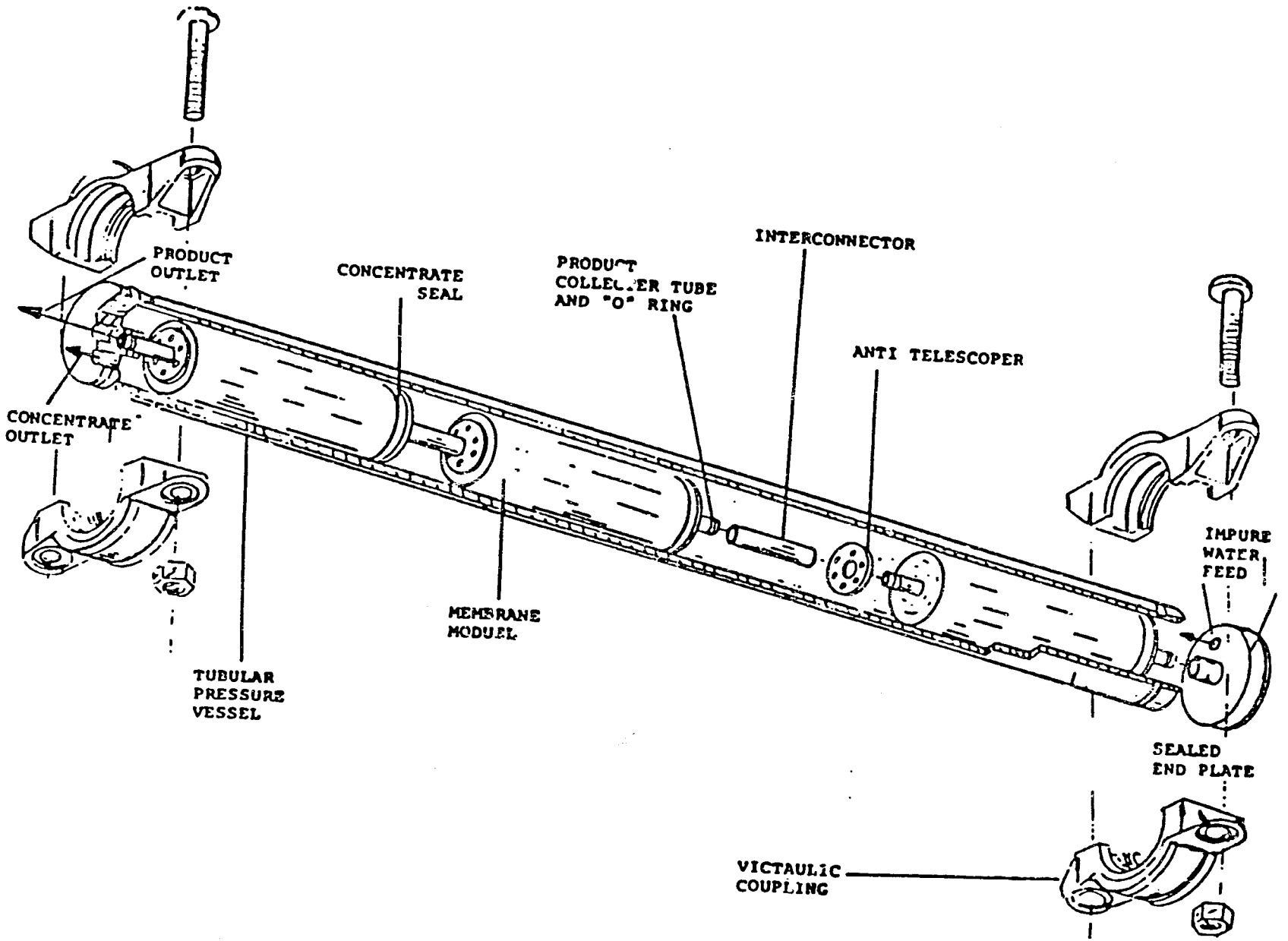


Exhibit 5-5
SPIRAL WOUND MEMBRANES VESSEL

passes down through the space between the membrane sheets, exiting at the opposite end of the 20 ft. container. The purified water passing through the membrane sheets is collected inside the envelope. It spirals down to the product tube, which collects the purified water and allows it to be transported out of the pressure vessel on either end. The pressure vessels, like the permeators, are assembled in parallel arrangements and piped to headers.

In general, the spiral wound and hollow fiber units are competitive both from a technical and cost standpoint, and the selection of one versus another depends very much on the quality of the feedwater, the desired effluent quality, and the general environment in which the systems must operate.

Details of the reverse osmosis process are presented in Appendix A.

Electrodialysis

In the context of the membrane processes, Electrodialysis (ED) is a process that removes the smaller component of a saline solution, salt, from the larger component, water, by means of direct current electricity and ion selective membranes. Electrodialysis is an electrochemical separations process in which ions are transferred through membranes from a less concentrated to a more concentrated solution as a result of the flow of direct electric current.

To understand this process more clearly, let us asssume a rectangular tank with an electrode at either end and filled with a sodium chloride (NaCl) solution (Exhibit 5-6). When a DC potential is applied across the electrodes, the following occurs:

1. Cations (Na^+) are attracted to the negative electrode.
2. Anions (Cl^-) are attracted to the positive electrode.
3. The water dissociation reduction reaction occurs at the cathode.

$$2H_2O + 2e \dashrightarrow 2(OH)^- + H_2$$

4. The water dissociation oxidation reaction occurs at the anode.

$$2H_2O \dashrightarrow 4H^+ \quad O_x \quad + \quad 4e^-$$

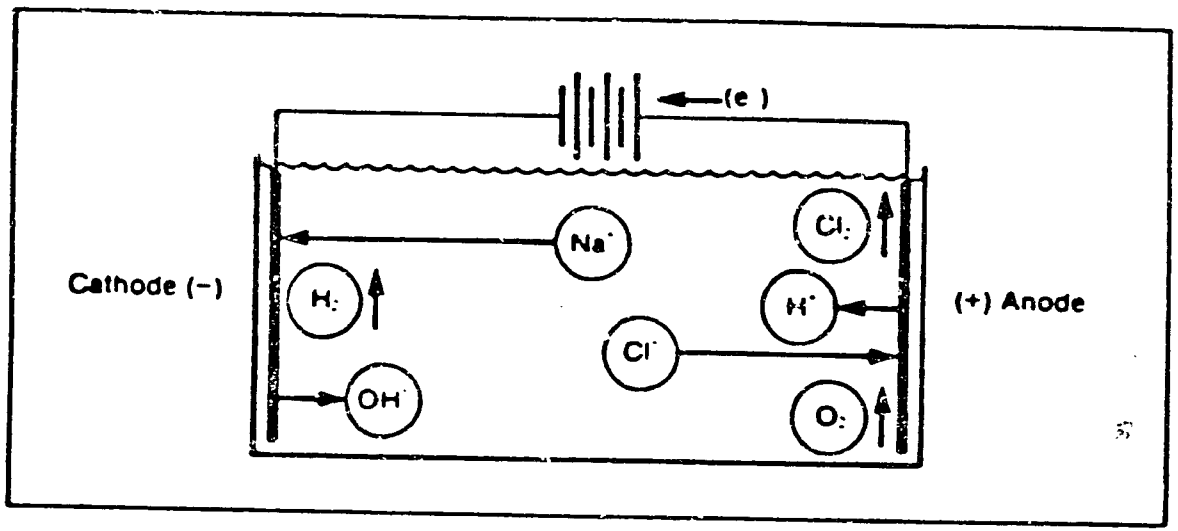


Exhibit 5-6

ELECTODIALYSIS PROCESS

5. A reaction involving the formation of chlorine gas may also occur at the anode.

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

To control the movement of ions in the tank containing the ionic solution and electrodes, several membranes can be added to form water-tight compartments as shown in Exhibit 5-7. Two types of membranes are shown.

1. Anion Transfer Membrane: Allows only the passage of negatively charged anions (Labeled A in Exhibit 5-7)

2. Cation Transfer Membrane: Allows only the passage of positively charged cations (Labeled C in Exhibit 5-7)

When a DC potential is applied across the electrodes the following happens:

Compartments 1 and 6: These compartments contain the metal electrodes. Chlorine gas and H^+ ions are produced at the anode, while hydrogen gas and OH^- ions are produced at the cathode.

Compartment 2:
1) Cl^- ions pass through anion membranes (A) into compartment 3.
2) Na^+ ions pass through cation membrane (C) into compartment 1.

Compartment 3:
1) The Na^+ ions cannot pass through the anion membrane and remain in compartment 3.
2) The Cl^- ions cannot pass through the cation membrane and remain in compartment 3.

Compartment 4:
1) Cl^- ions pass through the anion membrane into compartment 5.
2) Na^+ ions pass through the cation membrane into compartment 5.

Compartment 5:
1) The Na^+ ions cannot pass through the anion membrane and remain in compartment 5.
2) The Cl^- ions cannot pass through the cation membrane and remain in compartment 5.

The overall effect shows that compartments 2 and 4 have been depleted of ions and the ions have concentrated in compartments 3 and 5.

ED membranes have ion selectivity (anion/cation) and electrical conductivity. The selectivity of cation and anion membranes is about 90% for solutions of less than 0.5 to 0.7 N, but decreases at higher ion concentrations. Membranes having

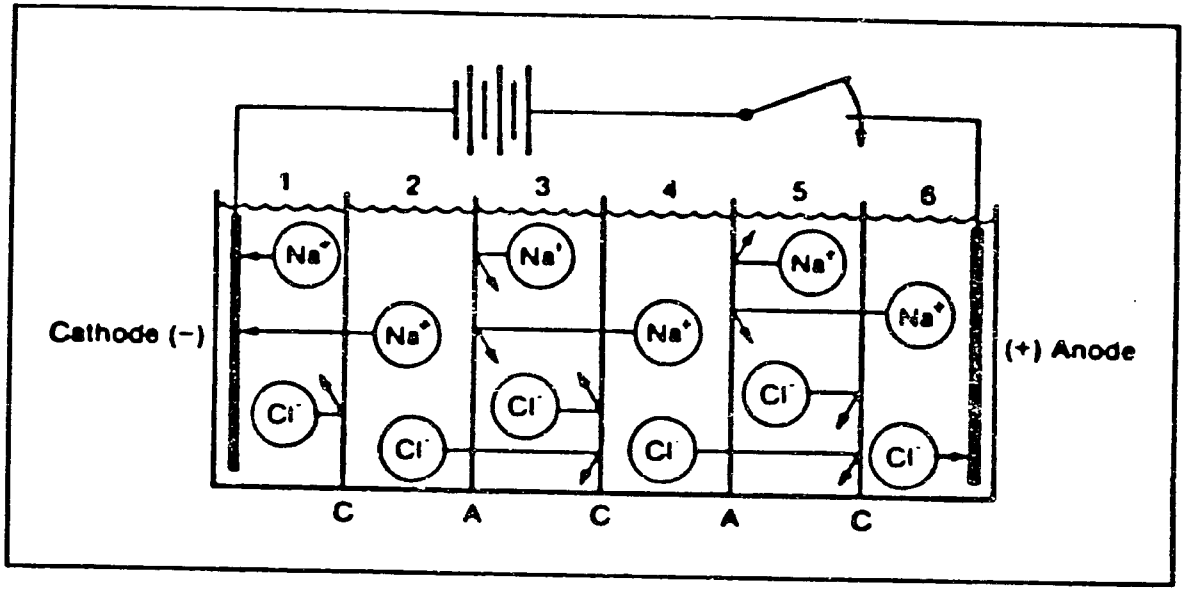


Exhibit 5-7

ELECTRODIALYSIS MEMBRANE ARRANGEMENT

low electrical resistance consume less energy, thus increasing the efficiency of the ED system. Resistance of membranes decreases as the solution concentration increases. Also, electrical resistance of membrane systems changes with temperature.

As shown in Exhibit 5-7, alternating compartments of demineralized solutions and concentrated solutions are formed in this membrane cell when a DC potential is applied across the electrodes. When properly manifolded, this unit will yield two major and separate streams; demineralized and concentrate waters, and two minor streams from the electrode compartments. In normal applications several hundred of these demineralizing and concentrating compartments are assembled into a "membrane stack" to obtain the desired water flow rate. These membrane stacks are the heart of the ED system.

The basic building block of an ED system is the membrane stack. A repeating section within the stack is called a "cell pair" and consists of a:

- Cation transfer membrane
- Demineralized water flow spacer
- Anion transfer membrane
- Concentrate water flow spacer

A typical membrane stack may contain from 300 to 500 cell pairs representing the same number of parallel hydraulic flow paths.

The capacity of the system, that is the quantity of treated water needed, determines the number of cell pairs, and the size of the pumps and piping. The fraction of the salt to be removed determines the configuration of the membrane stack array. Details of the electrodialysis process are presented in Appendix A.

A table comparing reverse osmosis and electrodialysis features is shown in Exhibit 5-8.

The feedwater should be pumped from the well to a collection tank which should have volume enough for a 1 to 3 day supply. This allows enough time for some of the heavier-than-water particulate matter to settle to the bottom of

EXHIBIT 5-8

Comparison of Reverse Osmosis and Electrodialysis Features

Factor	Reverse Osmosis	Electrodialysis
Scientific Principle	High Pressure on Feedwater Side of Membrane; Reverse Osmotic Pressure Passes Product Water, Brine Stays Behind	Ions of Dissolved Impurities are Attracted To Positive or Negatively charged Electrodes Leaving Product Water Behind
Technology Maturity	Many Large Plants in Operation with Conventional Power	Less Mature Technology; Mostly in Brackish Water; Smaller Applications
Typical Salinity Range Applications	All Salinities	Lower Salinities as are found in Brackish Water
Tolerance to Change in Salinity from Design Case?	Yes, at a cost of Higher Power Consumtion and Lower Flow Rates Lower Flow Rates	Yes, at a cost of Higher Power Consumption and Lower Flow Rates
Tolerance to Change in Power Supply	No, Decreased Performance in Product Water Quality	Yes, Flow Rate and Power to Electrodes are automatically Adjusted
Primary Electrical Load	High Pressure Pumps	Current Flow to Electrodes
Specific Power Consumption ($KW-HR/m^3$ of Product Water)[1]	For 1000 TDS - 0.90 For 12000 TDS - 1.81	For 1000 TDS - 0.61 For 12000 TDS - 6.67
Capital Costs - Estimated ($ Per m^3 Per Day Capacity)	Large Municipal - 200 Industrial - 260 Small (<200m^3/Day) - 530 Seawater 790 - 1060	Industrial 260 Small (<200m^3/Day) - 530

[1] These values are developed in the Application Review/Conceptual Design.

the tank. Depending on the condition of the feedwater, it may be necessary to add acid to balance the ph to prevent scale buildup. Chemicals may be added to coagualte other impurities or to treat biological impurities. Filters may be needed to mechanically separate these impurities from the water.

There must be a pump or gravity feed to get the water to the high pressure pump inlet. In the case of reverse osmosis, the high pressure pumps must be capable of efficiently elevating the pressure to as high as 600 psi (the pressure needed to overcome osmotic pressure in brackish water).

After the pressure passes through the high pressure pump, it goes to the desalination unit. After separation into concentrate and product water, there must be a provision for transporting two different types of water to storage areas. The concentrate water must either be disposed of in an open-air evaporation area or piped to the sea. How the disposal process is accomplished is site specific.

The amount of floorspace needed for this equipment is comparatively small. For instance, the desalination equipment at the EEA High Tension Laboratory site is housed in a small building measuring approximately 3 x 4 meters. This building includes space for an inverter.

5.2 Photovoltaics

Photovoltaic modules are available worldwide. They have been proven in numerous applications and under harsh conditions. Most field experience has involved single crystalline, poly-crystalline, and ribbon technology flat plate silicon photovoltaic modules. (The term "flat plate" refers to direct use of the sun's energy; that is, there is no enhancement or concentration of the sun's energy.) Although concentrating photovoltaic modules are available, they have had limited operating experience in developing countries. Amorphous silicon technology has also received much attention over the past few years, and projections are that it will someday replace all other photovoltaic technologies

as the least cost option. However, for the most part, amorphous silicon is still being used on very small applications (square centimeters in size) such as calculators and watches.

5.3 Structures

Fixed and adjustable tilt array mounting structures are commercially available. Fixed structures are constructed of galvanized pipe, aluminum or galvanized steel angle, and wood and concrete. Adjustable tilt structures permit the tilt of panels (groups of modules) or subarrays to be manually adjusted. Adjustable tilt structures can be designed using the same basic materials and configuration as a fixed structure. However, the operation and maintenance requirement for tilting and for wind loading specifications needs to be taken into consideration.

The building site at El Kasr is very near the Mediterranean shore. Therefore, the entire plant must be designed taking into account the corrosive nature of the salt air. This includes structural support materials for the photovoltaic array, junction boxes for the electrical connections, electrical connections on batteries, instrumentation systems, and all parts of the desalination equipment.

Special purpose photovoltaic modules have been designed in the United States for use by the Coast Guard. These modules are designed to withstand a salt spary environment somewhat more severe than is expected to be encountered at El Kasr.

Other components such as junction boxes, wiring, structural materials, and electronic components are commonly used in salt air environments. It requires no advancement in the state of the art to use them, only awareness of the situation by the designer.

5.4 Batteries

The two most common batteries used for PV applications are lead-acid and

nickel cadmium. Lead-acid batteries are the preferred choice primarily because of their lower cost. Lead-acid batteries are sometimes referred to by the type of electrode used; for example, lead-antimony, pure lead, or lead-calcium. Lead-acid batteries are manufactured in sealed and vented configurations. For remote applications and sandy areas, sealed batteries are often preferred over vented batteries because the loss of electrolyte and the potential for contamination are greatly reduced. However, sealed batteries are more expensive than vented batteries. Vented batteries can be fitted with "recombination caps," which greatly reduce the loss of electrolyte due to overcharging and evaporation. The decision parameters for selecting a battery system should be life-cycle cost, maintenance, and reliability. It is recommended that lead acid, sealed or vented batteries be selected for this application. If vented batteries are used, they must contain provisions for minimizing electrolyte and water loss.

5.5 Power System Controller

The power system controller (PSC) is defined as the equipment components that determine the source of power and its level relative to the load demand. The power sources in this application are the PV array and the battery. The loads are predominantly the desalination equipment, but the battery can also act as a load. The PSC may also contain a PV array maximum power tracker, voltage regulators, and other power regulation equipment. However, our definition is limited to considering the PSC by its primary functions of power source management and regulation. Depending on the sophistication level of the design, the PSC may provide for the following functions:

- Efficient management of PV and battery power
- Regulation of charge and discharge rates of the battery system
- Protection of battery system against low and high states of charge.

5.6 Diesel Generators

Self-contained diesel engine/generator sets for remote AC power are commercially available in a wide range of sizes from many manufacturers. Diesel/generator sets that produce DC power are also commercially available, but generally only on a special order basis. One method of obtaining DC power is to use a conventional AC diesel generator in conjunction with an AC to DC rectifier. A list of companies that supply DC diesel generators and AC to DC rectifiers is provided in Section 6 of this Technology Review.

The operating efficiency of a diesel/generator set refers to the fuel-to-electricity conversion efficiency. Typically it is 30 percent for new engines operating at rated load. However, it may drop to as low as 15 percent under partial load and/or poor maintenance practices.

5.7 Inverters/Rectifiers

In this application an inverter could be used to convert DC power from the PV/battery side of the power system to AC power compatible with the load. A rectifier rather than an inverter is required if the loads are to be DC. A rectifier will convert AC produced power from a conventional diesel/generator to DC power for DC load operation and battery charging.

The performance of stand-alone inverters in developing countries has been poor. In addition, there are efficiency penalties and added costs for their use. The alternative system, DC power and DC loads, would require either an integrated or separate rectifier in the form of a "battery charger." There are a number of suppliers of commercial inverters and rectifiers; Sections 6 and 7 list some of these suppliers.

5.8 System Monitoring and Instrumentation

Two levels of instrumentation are required for this field test: monitoring and troubleshooting/repair. The purpose of each level of instrumentation is as

follows:

Level	Purpose
Monitoring	To provide system and component performance information for evaluating long-term technical, financial, and institutional performance.
Troubleshooting/ Repair	To determine system and component performance on site, over short intervals, in sufficient detail to identify faults, make repairs, or perform modifications.

It is recommended that monitoring instrumentation be automated for data collection and transmission (by physical or automatic means) and that the troubleshooting/repair level of instrumentation be provided by procuring portable site-usable instrumentation. Accessible locations in the wiring must be part of the system design in order to provide for current-voltage curve tracing of the array and branch circuit level.

A specific instrumentation data requirements list was prepared following a sub-contractors meeting held on December 10, 1985, at Meridian Corporation. This list which is included as Appendix D provides the recommended performance data requirements for this field test.

5.9 Brine Disposal

The three methods commonly used to dispose of brine are:

1. Pipe to the sea where the brine is mixed with seawater.
2. An evaporation pond where the brine is put into a shallow holding reservoir and the water is allowed to evaporate, leaving salts behind.
3. Injection back into the ground.

Of the three methods, the first two are possibilities for the location for FT #8. If the feedwater source is the Roman wells then injection would not be a good idea because of the danger of contamination of the feedwater.

6.0 MANUFACTURER PROFILES

This section provides brief overview of the major U.S. manufacturers of PV systems, desalination equipment, batteries, inverters, controllers and diesel generation equipment. Also provided is a representative selection of integrating contractors who have PV system application experience. PV-related product literature from these companies is included in the Technology Reference Notebook (previously submitted under Task 2.1.1). Exhibit 6-1 is a tabular summation of section 6. A selection of product specifications is provided in Section 7.

6.1 Photovoltaic Module Manufacturers

ARCO Solar, Inc.
21011 Warner Center Lane
Woodland Hills, California
800-ARCO-SOL

ARCO Solar, Inc. is the world's leading volume manufacturer of photovoltaics. The company has a worldwide distribution network.

ARCO has built its photovoltaic business by manufacturing single-crystal silicon modules. Typical module efficiencies are approximately 10 percent. ARCO has recently claimed a significant increase in efficiency, to 12.5 percent, by an improved manufacturing process and a better module packing factor. Cells are made using screen-printed silver metallization. Encapsulant is ethylene vinyl acetate (EVA) with a tough white plastic film backing.

ARCO modules have passed the Jet Propulsion Laboratory (JPL)-sponsored Block V environmental tests and some models have passed the Underwriters Laboratory tests for certification. Standard modules are available in 30, 40, and 43 watt sizes. Prices range from 5 to 7 dollars per peak watt.

ARCO offers a 10-year module performance warranty.

Exhibit 6-1 MANUFACTURERS-PRODUCTS/SERVICES

MANUFACTURERS	PRODUCT/SERVICES						
	Photo-voltaics	Batteries	Diesel Gen Sets	Controllers	Inverters/ Rectifiers	Desalination Equipment	Integrating Contractors
Arco Solar	●						
Solarex	●						
Mobil Solar	●			●			●
Solavolt	●			●			●
Water Services of America				●			●
Ionics						●	
Aquatron						●	
Marland						●	
Culligan						●	
GNB		●				●	
Exide		●					
Allied C&D		●					
Chloride		●					
Abacus							
Heart Interface					●		
Best Energy							
Nova				●	●		
Chronar/Tri-Solar				●	●		
BOSS				●			●
Allis-Chalmers				●			
Caterpillar			●				
Lister			●				
Kurz & Root			●				
Kato Engineering			●		●		
Bechtel			●		●		
Integrated Power							●
Hughes Aircraft				●			●
Simpler Solar							●
Stone & Webster							●
							●

Solarex Corporation
1335 Piccard Drive
Rockville, Maryland 20850
301-948-0202

Solarex Corporation is the second largest PV manufacturer (by sales volume) in the world and has modules installed worldwide. Solarex advertises itself as a systems company and sometimes bids directly on PV system projects rather than going through distributors.

Solarex uses polycrystalline silicon for their standard modules. This type of silicon is made by a process in which the silicon is cast in a near-square shape. Proponents of this type of technology maintain that this process is inherently less expensive and has less waste than single crystal silicon because less silicon is sawed off the ingot. Typically, Solarex module efficiencies are approximately 9 to 10 percent on a module area basis though modules for selected projects have achieved nearly 12 percent efficiency ratings. Solarex modules have passed the JPL-Block V environmental tests. Standard Solarex modules come in 36, 42, 46, and 140 watt sizes. Encapsulant is EVA with a tough white plastic film backing. Module prices range from 5 to 7 dollars per peak watt.

Mobil Solar Energy Corporation
16 Hickory Drive
Waltham, Massachusetts 02254
617-890-1180

Mobil Solar Energy Corporation is the leading producer of "ribbon" silicon photovoltaic modules in the U.S. It has commercially offered modules for several years.

Mobil Solar modules are made from "ribbon" silicon (the name refers to the way the silicon is manufactured). Proponents of this process feel that it is a very good approach toward manufacturing low-cost silicon solar cells because it avoids the losses associated with sawing silicon made from single crystal or polycrystalline cast silicon ingots. This silicon manufacturing process is being developed to make it more efficient and less costly. Typical Mobil Solar

module efficiencies are on the order of 8.4 percent.

Modules are manufactured in 40 and 180 watt sizes. They have passed the JPL-Block V environmental tests. Typical module prices range from 5 to 7 dollars per peak watt.

Mobil has made a concentrated effort to develop a market in the Middle East. Two functioning desalination installations in the Middle East one in Jeddah, Saudi Arabia and one in Doha, Qatar, are powered by Mobil Solar modules. Additionally, Mobil Solar modules power a street lighting project in Riyadh, Saudi Arabia.

Mobil has long maintained the policy of perfecting the ribbon technology before going into full volume production. Therefore, Mobil has sufficient field performance experience to support its guarantees of the reliability and performance of its "ribbon" technology.

Solavolt International
P.O. Box 2934
Phoenix, Arizona 85062
Telex 249901

Solavolt International modules are made using polycrystalline silicon. Their most popular module is one that produces 40 watts at standard conditions. This module has passed the JPL-Block V environmental tests.

Solavolt is a joint venture formed from the former photovoltaics units of Motorola and Shell Oil Company. Solavolt is currently reputed to be working on a proprietary process known as the "ribbon-to-ribbon" technology, that has yet to be introduced commercially.

Solavolt has been very active in setting up distributorships world-wide. Solavolt (and its predecessor Motorola) have modules installed in many locations including Gabon, Africa, pumping/irrigation sites in the southwest U.S. and the Southwest Residential Experiment Station in New Mexico. Costs for the Solavolt modules are in the 5 to 7 dollar price per peak watt range.

6.2 Desalination Equipment Manufacturers

Water Services of America
P.O. Box 23848
Milwaukee, Wisconsin 53223-0848
414-354-6470

Water Services of America (WSA) has teamed with Mobil Solar to build two PV-powered desalination projects in the Middle East - one in Jeddah, Saudi Arabia, and one in Doha, Qatar. WSA (conventionally powered) reverse osmosis plants are installed throughout the world, including many in the Middle East. To service this market area, WSA has a distributor located in Al-Khobar, Saudi Arabia.

Ionics, Incorporated
Head Office
Water Systems Division
65 Grove Street
Watertown, Massachusetts 02172, USA
617-926-2500

Ionics Incorporated specializes in electrodialysis desalination equipment and is the only American company that manufactures such equipment. Ionics has had installations worldwide. One of its most publicized installations in a desert environment is in Libya where, it is reported that an installation capable of producing 159 cubic meters of water per day has been functioning since 1977. In addition, Ionics has two 200 cubic meter per day units at Mowah, one of the candidate sites for the El Kasr facility.

Aquatron
Route 1, Box 638 Rosethorne Rd.
Marrero, Louisana 70072
504-689-2024

Aquatron manufactures reverse osmosis equipment. Its client base has primarily been with the oil industry and the U.S. Navy. It has sold some units to several localities in Saudi Arabia.

Sweet Water
A Subsidiary of Marland Environmental Systems Inc.
P.O. Box 501
Great Falls, Virginia 22066,

Sweet Water manufactures reverse osmosis systems. It makes three different types of equipment: one primarily designed for sea water, one for brackish water, and one for water fouled with contaminants. It custom designs each unit using an advanced computer-based design approach. Sweet Water has sales and service representatives throughout the world, including Cairo, Amman, Jeddah, Qatar, and Abu Dhabi.

Culligan USA
1 Culligan Parkway
Northbrook, Illinois 60062
312-498-2000

Culligan is the best known water treatment company in the U.S. In addition to a wide range of water treatment products, it manufactures a line of reverse osmosis desalination products.

Culligan has sales and service representatives in 90 different countries throughout the world. Its international offices are located in Italy, France, and Spain.

6.3 Battery Manufacturers

GNB Batteries Inc.
2010 Cabot Boulevard West
Langhorne, Pennsylvania 19047
215-750-2600

GNB Batteries Inc. is a well established leader in the manufacture of industrial grade, deep-cycle batteries. GNB manufactures the "Absolyte" battery: a sealed, maintenance-free, deep-cycle lead-acid battery that recombines the hydrogen and oxygen. The Absolyte battery has been well received by PV system companies for use in remote harsh environments. Since sealed batteries are generally more expensive than vented batteries, the initial capital cost, in dollars per kilowatt-hour of rated capacity, for an Absolyte is approximately

50 percent more than an equivalent rated vented battery.

Exide
101 Gibraltar Road
Horsham, Pennsylvania 19044
215-674-9500

Exide is another reputable manufacturer of lead-acid batteries. Their batteries have been used in numerous photovoltaic system applications around the world. The principal battery model used in photovoltaic systems is a vented, deep-cycle lead-acid battery. Exide offers the option of gas recombination caps to reduce electrolyte and water loss, minimize contamination, and improve operating safety.

Allied C&D Power Systems
3043 Walton Road
Plymouth Meeting, Pennsylvania 19462

Allied C & D Power Systems is the largest manufacturer of industrial batteries, chargers, and associated power equipment in the world, (according to their company literature). C&D manufactures fully integrated power systems and provides installation service and maintenance for its energy systems through more than 75 sales and service organizations in the U.S. and Canada.

Chloride Group PLV
P.O. Box 305
North Haven, Connecticut 06473
203-777-0037

Chloride Group PLV is a leading manufacturer of lead-acid batteries. A London based company, Chloride has distributors around the world. They have a manufacturing plant located near Cairo, Egypt.

Chloride makes sealed and vented batteries. Their POWERSTORE model battery is a sealed, maintenance-free recombination electrolyte battery. Chloride distributor Simpler Solar Systems indicates that the POWERSTORE is available in cell sizes up to 2 volts and 240 ampere-hours at a 20 hour discharge rate. Larger lead-acid vented batteries are available up to 1000 ampere-hours.

6.4 Inverters/Rectifiers

Abacus Controls Inc.
P.O. Box 893
Somerville, New Jersey 08876
201-526-6010

Abacus Controls, Inc. is a major supplier of inverters to the photovoltaic industry. Solarex has used Abacus inverters on several stand-alone photovoltaic systems installed in South America and on one relevant project at East Oweinat, Egypt. Abacus makes inverters in a number of sizes capable of being used in this field test (35 kW total capacity).

Heart Interface Corporation
1626 S. 341st Place
Federal Way, Washington 98003
800-732-3201

Heart Interface Corporation is a manufacturer of small inverters for remote power commerical and private applications. Heart Interface makes stand-alone inverters up to 5 kW capacity.

Best Energy Systems Inc.
P.O. Box 280
Necedah, Wisconsin 54646

Best Energy Systems Inc. manufactures stand-alone inverters. Inverters are commercially offered in sizes up to 10 kW for stand-alone, hybrid power systems and utility interface.

NOVA Electric Manufacturing Company
263 Hillside Avenue
Nutley, New Jersey 07110
201-661-3434

NOVA Electric Manufacturing Company is an electronics company, founded in 1966, that designs and manufactures inverters and rectifiers. All NOVA products feature modular designs with easily replaceable subassemblies. This feature results in a MTTR (Mean Time to Repair) of approximately 30 minutes. NOVA claims that its power conditioning equipment achieves better than 20,000 hours as a Mean Time Between Failure. NOVA's PV power system installed in Sadat City, Egypt, uses a 10 kW NOVA inverter and reports good operational performance.

6.5 Controllers

Chronar/Tri-Solar, Inc
10 DeAngelo Drive
Bedford, Massachusetts 01730
617-275-1200

Chronar/Tri-Solar Inc. is a company formed by the merging of Chronar and Tri-Solar. Chronar designs and sells manufacturing plants for producing amorphous silicon technology photovoltaic modules. Tri-Solar is an established PV systems company specializing in PV pumping systems and controller development. Chronar/Tri-Solar manufacturs a "smart" microprocessor-controlled, programmable controller, developed under contract to NASA-Lewis Research Center (U.S. National Aeronautics and Space Administration Lewis Research Center), that may be used for operating and monitoring PV/diesel power systems. The controller is microprocessor-based and includes power tracking. Field experience with this controller is limited, but approximately 20 controllers were installed in a Middle-Eastern country in 1985.

Solarex Corporation
1335 Piccard Drive
Rockville, Maryland 20850
301-948-0202

Solarex Corporation as a PV systems company, designs, manufactures, and sells PV system controllers. Solarex offers a limited function series regulator, SR model and a full function controller identified as the ACR model. The ACR model, controller has been used in numerous PV applications around the world, ranging from health centers to irrigation systems. Development of the ACR controller has been continuous since the first units were manufactured around 1981. The standard ACR controller can be customized with voltage sensing relays that can be used for starting a diesel generator, sounding an alarm, or performing other functions.

Balance of Systems Specialists
7745 East Redfield Road
Scottsdale, Arizona 85260
602-948-9809

Balance of Systems Specialists (BOSS) designs and manufactures PV system controllers. BOSS offers full engineering and support services and can customize its controllers to meet the requirements of this Field test.

6.6 Diesel Generator Manufacturers

Onan
1400 73rd Avenue, NW
Minneapolis, Minnesota 55432
612-574-5000

Onan is a principal manufacturer and distributor of gasoline and diesel engine generators. Diesel generator packaged power systems are available in sizes ranging from 3 to 1000 kW and 50 or 60 Hertz AC.

Allis-Chalmers
P.O. Box 1563
Harvey, Illinois 60426
312-339-3300

Allis-Chalmers is a reputable, established manufacturer of diesel engines and generators. Standard units are available in sizes ranging from 10 to 300 kW and 50 or 60 Hz. Allis-Chalmers offers limited warrantees of up to 3 years or 10,800 hours. A 2-year or 3600 hour warrantee covering the electrical systems and the diesel engine is offered on "continuous" duty diesel applications.

Caterpillar (Representative)
Alban Engine Company
1401 Cherry Hill Road
Baltimore, Maryland 21225
301-355-6700

Caterpillar is a world renowned manufacturer of medium to large diesel engine generators. They have a strong technical and parts support network throughout the world. Packaged power systems are available in sizes starting at 50 kW.

Lister Diesels Inc. (Representative)
555 E. 56 Highway
Olathe, Kansas 66061
913-764-3512

Lister Diesels Inc. is a division of Hawker-Siddeley, an English company incorporated in the U.S. Lister makes packaged diesel generator power systems in sizes ranging from 3 to 130 kW. Lister/Hawker-Siddeley supplies electrical and mechanical equipment and service for their equipment throughout the world.

Kurz and Root Company
P.O. Box 1119
Appleton, Wisconsin 54912
414-739-9441

Kurz and Root Company is a manufacturer of AC and DC generators, DC motors, motor generator sets, and engine generator sets. Kurz and Root offers standard AC generators in sizes ranging from 10 to 250 kW. They also offer DC generators on a customized basis, matched to the load and the drive engine.

Kato Engineering
P.O. Box 47
Mankato, Minnesota 56001
507-625-4011

Kato Engineering manufactures AC and DC generators in sizes from 1 kW to 3 megawatts. Kato Engineering estimated the cost for a 25 kW, 230 volt compound wound, 1800 RPM DC generator for direct coupling to an engine at $5,500. The generator would be delivered in 150 to 180 days.

6.7 Integrating Contractors

In an effort to identify possible contracting companies that could act as the prime or integrating contractor, a number of organizations are listed below. These companies have acted as the integrating contractors on photovoltaic projects in the past.

Chronar/Tri-Solar
10 DeAngelo Drive
Bedford, Massachusetts 01730
617-275-1200

Tri-Solar, acquired by Chronar in 1985, has been an integrating contractor since its inception. Chronar/Tri-Solar has performed as the integrating contractor on many international PV-powered projects. Two of their most notable application areas are PV pumping and village electrification. Chronar/Tri-Solar is currently involved in a major PV lighting systems project in Saudi Arabia.

BDM International Inc.
7915 Jones Branch Drive
McLean, Virginia 22043
703-821-5000

BDM's Renewable Energy Division is based in Albuquerque, New Mexico. They have been the integrating contractor for a number of projects both in the United States and throughout the world. These projects include:

- A 1 Megawatt grid interactive, tracking flat plate PV power system at Hisperia, California
- A 35 Kw installation at McClellan Air Force Base near Sacramento, California
- A demonstration installation in Taipai
- A residential demonstration project at the Southwest Residential Experiments station in Las Cruces, New Mexico.

Hughes Aircraft Company
P.O. Box 9399
Long Beach, California 90810
213-513-3487

Hughes Aircraft Company is based in Long Beach, California, and, over a period of about 5 years, has been the integrating contractor for a number of PV-powered installations. They have acted as the integrating contractor for a number of remote power applications for the U.S. Navy at China Lake, California. Other installations include:

Communications and village power installations in Indonesia and the Marshall Islands for NASA-Lewis Research Center

Design studies and a demonstration project to illustrate low-cost construction methods for Sandia National Laboratories

Georgetown University Intercultural Center, a 320 kW grid-interactive installation in which the PV modules are integrated into the roof of the building.

Integrated Power, Inc.
7624 Airpak Road
Gaithersburg, Maryland 20879
301-963-5884

Integrated Power Inc. was formed in 1983 and specializes in engineering and installation of stand-alone PV-battery systems. They have also done significant development engineering of PV/diesel hybrid power systems.

Mobil Solar Energy Corporation
16 Hickory Drive
Waltham, Massachusetts 02254
617-890-1180

Mobil Solar Energy Corporation is based in Waltham, Massachusetts, near Boston, and has had a systems integration capability since about 1981. Mobil currently has a representative in Saudi Arabia who is an engineer specializing in PV systems design and applications.

Mobil has emphasized developing PV-powered desalination. Two installations have been built and are currently operating --one in Jeddah, Saudi Arabia, and one in Qatar. In addition, Mobil has a cooperative venture with the University of New South Wales in Australia for a brackish water desalting experimental program. Other Mobil installations include:

- Street lighting project in Dubai, United Arab Emerates
- Impact 2000, a PV-powered residence demonstration project in the Boston area designed to publicize PV.

Simpler Solar Systems Inc.
1217 Walton Drive
Tallahassee, Florida 32312
904-385-5686

Simpler Solar Systems Inc. has been in business since 1980. The company designs, tests, and installs PV-powered systems and specializes in stand-alone

systems in remote areas.

Simplier Solar Systems Projects include:

- o Medical facility (Bulape Hospital) in Zaire
- o PV-powered water pumping installation for irrigation in the Bahamas
- o Recreational homes in Florida
- o Projects for church-sponsored groups in the Caribbean.

Solarex Corporation
1335 Piccard Drive
Rockville, Maryland 20850
301-948-0202

Solarex Corporation has been integrating systems using its own modules for about 10 years. Solarex has a distributor in Cairo. Solarex projects include:

- o The General Petroleum Company water pumping project in East Oweinat
- o PV-powered portable communications units for the Egyptian military in Egypt
- o A grid-independent solar-powered manufacturing facility in Frederick, Maryland
- o A 22 kW stand-alone rural hospital power system in Guyana, South America.

Solavolt
P.O. Box 2934
Phoenix, Arizona 85062
Telex 249901

Solavolt is another photovoltaic company that performs as a "systems" company. Solavolt has participated as a system integrating contractor on a number of projects, including the following:

- o A NASA-Lewis Research Center project for water pumping and village power in Gabon, Africa
- o Numerous irrigation and other pumping applications around the world.

Stone and Webster Incorporated
1875 Eye Street, N.W.
Washington, DC 20006
202-466-7415

Stone and Webster, Incorporated based in Boston, Massachusetts, is a large international construction, architectural, and engineering company. It has a

group within the company that is very active in photovoltaic engineering projects. Included in the projects it has engineered are:

- Beverly, Massachusetts High School grid-interactive 100 KW installation
- 50 kW grid-interactive demonstration project for Virginia Power (a utility) near Richmond, Virginia
- A 300 kW grid-interactive installation for Austin Power and Light in Austin, Texas (under construction in 1986)

7.0 EQUIPMENT/PRODUCT SPECIFICATIONS

A selected number of components and basic specifications are provided in Exhibit 7-1.

Appendix D contains a selection of manufacturer equipment brochures for this field test. The data on equipment are provided to show representative equipment specifications that may be received from bidders in response to the RFP. This listing of equipment is not in any way intended to support any manufacturers or products.

EXHIBIT 7-1 EQUIPMENT DATA BASE

Component	Manufacturer	Equipment Offered	Cost	Operating Efficiency	Other Relevant Specifications	Notes
Desalination Machinery	Water Services of America	Reverse Osmosis	(In general, the cost and operating efficiency of desalination equipment is dependent on amount and type of impurities, degree of purity desired in product water, and quality of maintenance.)			o Experience with Mobil Solar in Middle East
	Ionics	Electro-dialysis				o Experience in Libya, Egypt; installation at Mowah, near El Kasr
	Aquatron	Reverse Osmosis				o Experience primarily with oil industry, some experience in Saudi Arabia
	Sweet Water	Reverse Osmosis				o World-wide experience; distributor in Cairo
	Culligan	Reverse Osmosis				o Sales and service office in France, Italy, and Spain
Photovoltaic Modules	ARCO Solar, Inc. Chatsworth, CA	M53, 43 watts 17.3 Vpp M63, 30 watts 14.8 Vpp M73, 40 watts 164 Vpp	$5-7/Wp	11.5%	10-year performance guarantee, ± 10%	o Single crystal silicon o Largest manufacturer in the world o American Univ., Sadat City project o Egyptian representative

EXHIBIT 7-1 EQUIPMENT DATA BASE (Continued)

Component	Manufacturer	Equipment Offered	Cost	Operating Efficiency	Other Relevant Specifications	Notes
Photovoltaic Modules (cont.)	Solarex Corp. Rockville, MD	SX-146, 47 watts 18 Vpp SX-42, 42watts 16.5 Vpp PL-300, 135watts 17.5 Vpp	$5-7/Wp	9.9%	5-year min. performance guarantee	o Polycrystalline silicon o Second largest manufacturer in the U.S. o Egyptian representative o East Oweinat 10 kw project
	Solavolt International Phoenix, AZ	MSVN-4010 MSP43E, 36watts 18.8 Vpp	$5-7/Wp	8.7%		o Uses Wacker and Crystal Systems polycrystal silicon o Gabon, West Africa community power system project
	Mobil Solar Power Corp. Waltham, MA	Ra-40 Ra-180, 180 watts-48 volt	$5-7/Wp	8.4%		o Ribbon technology o Numerous installations in Arab countries
	Chronar/Tri-Solar Princeton, NJ		$6/Wp	<5%	Development modules	o Amorphous silicon modules
Battery Storage	GNB Batteries, Inc. "Absolyte" Langhorne, PA	35A21-397 AH 45A21-510 AH 75A21-850 AH (12-hour discharge rate)	$150-200/kwh	65-80%	50% DOD, 2800 cycles	o Recombination battery technology o Egyptian distributor

EXHIBIT 7-1 EQUIPMENT DATA BASE (Continued)

Component	Manufacturer	Equipment Offered	Cost	Operating Efficiency	Other Relevant Specifications	Notes
Battery Storage (cont.)	EXIDE Warminster, PA	6E 120-13-750AH 3E-120-27-1652AH	$145-176/kwh $145-176/kwh	65-80%		o Recombination caps offered o East Oweinat project
	Allied C&D Plymouth Meeting, PA	CP75E13-450 AH CP75-25-900 AH CP125-1500 AH	$161/kwh $122/kwh $113/kwh	65-80%	Metallic casing	
	Chloride London, Eng.	6V-720 AH	$230/kwh	65-80%	Special battery design for PV applications	o American and Egyptian distributors
Power System Controller	Chronar/Tri-Solar Bedford, MA	Microprocessor-Based Controller	$3-5000	92-97%	Series regulated ampere hour recording battery SOC	o 23 placed in service 1985, Saudi Arabia o "Smart" controller
	Solarex Rockville, MD	ACR-6, modified	$2-3000	90-95%	Shunt regulated voltage sensing battery SOC	o Primarily PV battery controller but can be equipped with diesel remote start relay
	BOSS Scottsdale, AZ	Modular units Customized units	Not Avail.	90-95%	No off-the-shelf models available	o Services a wide variety of markets in U.S.
Inverters	Abacus Somerville, NJ	743C-3-200 783C-4-200		90%		o Inverters GPC E. Oweinat installation

EXHIBIT 7-1 EQUIPMENT DATA BASE (Continued)

Component	Manufacturer	Equipment Offered	Cost	Operating Efficiency	Other Relevant Specifications	Notes
Inverters (cont.)	Heart Interface Federal Way, WA	Inverters	$400-3650	92-95%	300-5000 watt inverters in standard product line	
	BEST Energy Systems Necedah, WI	M Series M 120-6000 M 120-12000		90%	Load demand switch engine-genset start transfer switch	o Wide experience in variety of applications o Standard models up to 12 kW capacity
	NOVA Electric Nutley, NJ	3.7 KVA Inverter 240 VDC Input	$27,900	89% (FOB)	50 Hz, sinewave, 3 phase	o Also supplies rectifiers o Egypt experience: Sadat City; 10 KVA inverter
Diesel Gensets	Onan Minneapolis, MN	25DL6-25KW 30DL6-30KW	$ 7500 $ 9000	.40 liters/kwh (23% efficient) .32 liters/ (29% efficient)		
	Allis-Chalmers Harvey, IL	AC6 25	$13,000	0.34 ltrs. kwhr (27% efficient)	5 yr.-1500 hr warranty	o Standard model prices, FOB factory o Large range of capability
	Caterpillar Peoria, IL	Model 3304 NA 50 KW	$12,500	0.30 liters/ kwh (31% effic.)	Trailer or skid mounted	o Worldwide distribution & service reps.
	Lister, England	HR-3-25kw HL-4-34kW	$300/kw		Air-cooled engines on some models	o American distr. Witchita, Kansas

EXHIBIT 7-1 EQUIPMENT DATA BASE (Continued)

Component	Manufacturer	Equipment Offered	Cost	Operating Efficiency	Other Relevant Specifications	Notes
D-C Generator	Kato Engineering Mankato, MN	20 kw-250V output	$6800			
		25 kw-250V output	$7000			
		30 kw-250V output	$8000			
	Kurz & Root Appleton, WI	Custom jobs				No recent experience

8.0 RELEVANT PROJECTS

Worldwide experience in PV-powered desalination is very limited. All desalination units are reverse osmosis; none are electrodialysis. Only four installations are known to exist:

1. A Mobil Solar/Water Services of America-installed plant in Jeddah, Saudi Arabia
2. A Mobil Solar/Water Services of America-installed plant in Doha Qatar
3. A Mobil Solar/Australian cooperative venture
4. The AEG Telefunken EEA installation at the High Tension Laboratory north of Cairo.

o JEDDAH, SAUDI ARABIA

Key technical characteristics of this plant include the following:

PV Rated Power	8 Kilowatts
Feedwater Salinity	42,800 PPM
Product Water Volume	500 gallons per day
Product Water Quality	200 parts per million
Specific Energy Consumption	65 watt-hours/gallon

REFERENCE: Photovoltaics International, June/July 1983, "DESALINATION: A PV Oasis," p. 24.

o DOHA, QATAR INSTALLATION

The unit in Doha is a follow-on to the unit in Jeddah. It incorporates several lessons learned from the Jeddah experience. Key parameters include:

PV Array Size	11.2 Kilowatts
Output Water Quality	500 ppm
Water Output	1500 gal/day

Elimination of the data-logging system

Elimination of the second stage reverse osmosis plant

Inclusion of an energy recovery unit

- MOBIL SOLAR INSTALLATION IN AUSTRALIA

PV Array Size	1.2 Kilowatt
Feedwater Salinity	2000-5000 ppm
Output	105-185 gallons per day
Specific Energy Consumption	15-19 Kilowatt-Hrs/Gallon

- EEA INSTALLATION AT HIGH TENSION LABORATORY

PV Array Size	8 Kilowatt
Installe	AEG Telefunken
Feedwater	From well on Laboratory grounds

Water quality, flow rate, and specific energy consumption data not available.

9.0 CONCLUSIONS

Field Test #8 is composed of commercially available subsystems that have been in operation worldwide. These subsystems include:

- o Desalination subsystem: either electrodialysis or reverse osmosis. Both of these technologies have been proven effective when the systems are designed correctly and when proper maintenance is performed.
- o Photovoltaics. Photovoltaics have repeatedly been shown to be the least troublesome parts of a remotely located PV-powered application.
- o Diesel gensets.
- o Controllers.
- o Batteries.
- o Inverters

There is limited experience with the combination of these technologies, that is, PV-powered desalination systems. For reverse osmosis, Mobil Solar has sponsored two installations in the Middle East: One is in Jeddah, Saudi Arabia, and one is in Doha, Qatar, United Arab Emerites. In addition, the EEA has a functioning reverse osmosis PV-powered experiment on the grounds of the High-Tension Laboratory north of Cairo. There are no PV-powered electrodialysis installations currently in operation. A critical factor in the success of a desalination plant located in a remote location such as El Kasr is the skill, training, and motivation of the host organization that must maintain and monitor the operation.

12 AUG 1988

APPENDIX TO
TECHNOLOGY REVIEW FOR FIELD TEST #8
PV-POWERED DESALINATION PLANT
AT EL KASR

JULY 1986

FINAL

Prepared for:

Egyptian Electricity Authority
Cairo, Egypt

U.S. Agency for International Development
USAID Mission: Cairo, Egypt

Submitted to:
Louis Berger International, Inc.
Washington, D.C.
(Contract AID 263-0123C-00-4069-00)
(Meridian Task No. MC-173-380)

Prepared by:

Meridian Corporation
Falls Church, VA 22041

APPENDICES

A. Report on Desalination Technology

B. Relevant Papers on PV-Desalination Projects

C. Product Literature

D. Instrumentation System Specification and Data Requirements for a Photovoltaic Powered Desalination Project

APPENDIX A

REPORT ON DESALINATION TECHNOLOGY

Prepared For:

Meridian Corporation
5113 Leesburg Pike, Suite 700
Falls Church, VA 22041

(Contract AID 263-0123C-00-4069-00)

Prepared By:

Watson Desalination
8710 Barnett Street
Manassas, VA 22110

A. INTRODUCTION

Reverse Osmosis and Electrodialysis have been selected as the desalination processes of choice for the proposed solar and wind driven Desalination Systems.

This technology review provides a general examination of the Reverse Osmosis and Electrodialysis processes.

We will examine the basic concepts behind each process and then review their specific applications, using wind and solar power as the energy source.

We will examine the most recent developments in the technology and how they can best be utilized.

B. CURRENT STATE OF THE ART

1.0 PRINCIPLES OF REVERSE OSMOSIS

1.11 Osmosis and Reverse Osmosis

The Osmosis-Reverse Osmosis Process described in Figures 1(a), (b), and (c) shows a chamber divided by a semi-permeable membrane, with a pure water solution on one side and on the other a solution of concentrated salts. The pure water passes through the membrane into the chamber containing the concentrated solution in an effort to bring the system to equilibrium.

In Figure 1(c), with the application of pressure to the concentrated solution, the pure water is driven back across the membrane, leaving behind the concentrated salts and creating once again a chamber with high purity water. Fig. 1(c) represents the fundamental operating principles of Reverse Osmosis.

In Figure 2 we have a simplified Reverse Osmosis process flow diagram. A salt solution is pumped into a vessel containing a semi-permeable membrane. As pure water is passed through the membrane,

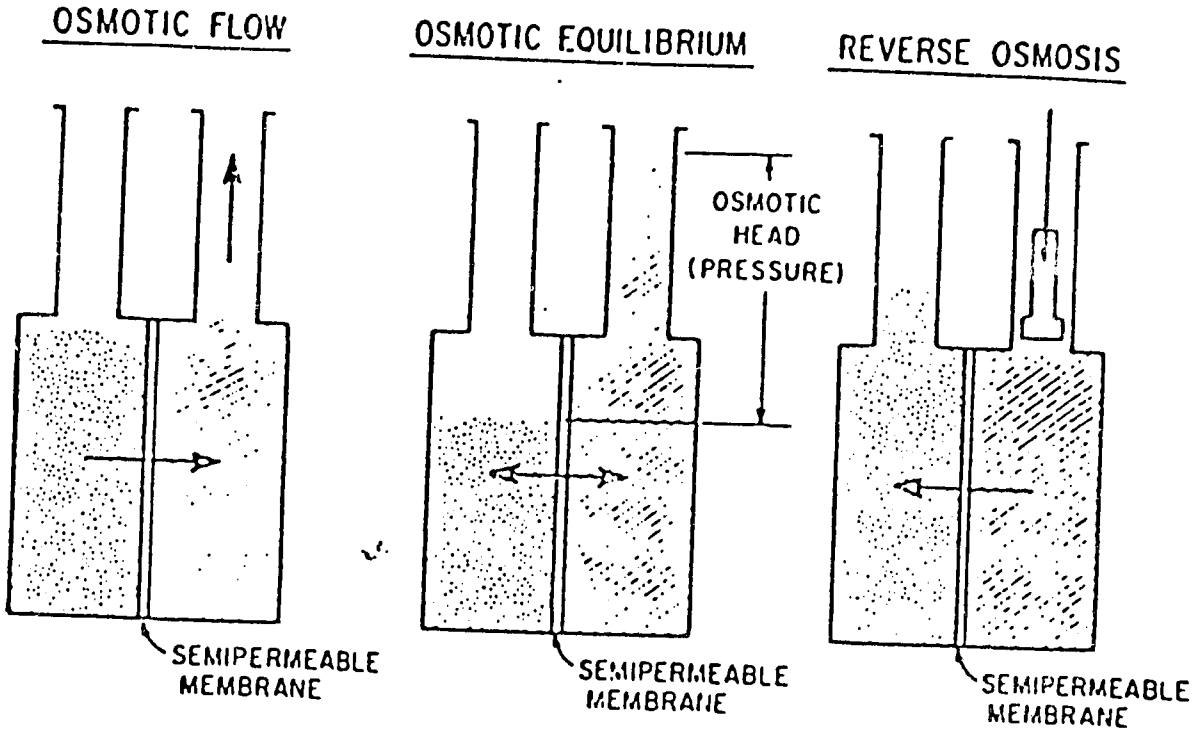


FIGURE 1a. FIGURE 1b. FIGURE 1c.

SIMPLIFIED RO FLOW DIAGRAM

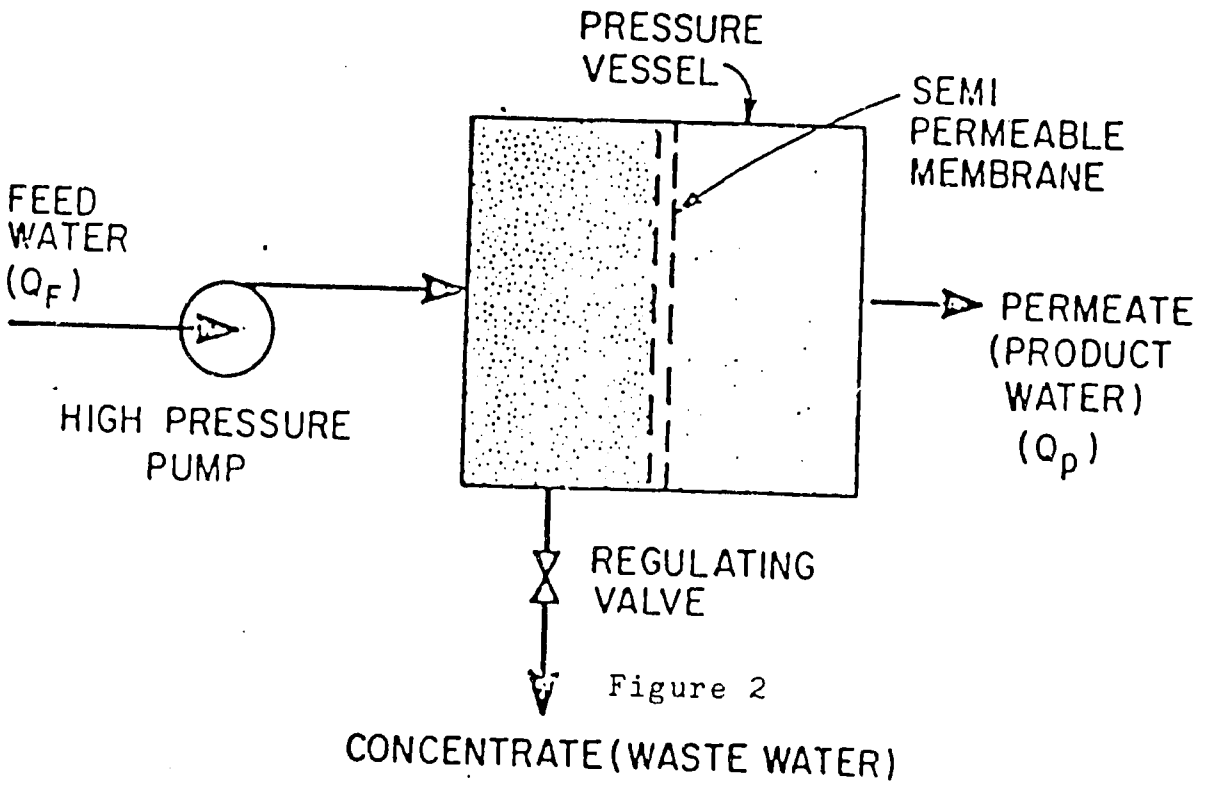


Figure 2

the salt solution becomes increasingly concentrated and is passed from the system through a flow regulating valve. The regulating valve maintains the pressure required within the container, while the pump provides the necessary flow. The purified water that has crossed the membrane is collected in the permeate or product water chamber.

1.12 Water Passage

The passage of water across the semi-permeable membrane is determined by the following equation:

$$QP = KW\ (PFD - \pi)$$

KW is a water permeability constant that defines the natural ability of the particular membrane to permit the passage of purified water.

The flow through the membrane is determined by the difference between the feed pressure (PFD) and the osmotic pressure (π) of the solution being treated. Since the pressure and salt concentrations are changing as you go through the membrane vessel, the final productivity is determined by the difference between the average feed pressure and the average osmotic pressure.

The productivity can be changed by varying the feed pressure selected for the system.

Different membranes, produced by various manufacturers, will have different KWs, reflecting the chemical composition and the method of fabrication of the specific membrane element.

1.13 Salt Passage

The passage of salt through the membrane is defined by the following equation:

$$QS = KS\ (CFB - CP)$$

KS is the salt permeability constant and like KW reflects the natural ability of the specific membrane to limit the amount of salt passed through the membrane. CFB is an average of the feed and brine concentration,and CP represents the average salt concentration of salts in the purified product water. The passage of salt is a function of the difference between the average feed concentration and the purified product concentration. Therefore, the higher the salt concentration of the feed solution, the more salt there will be in the product effluent. The ability of the membrane selected to reject salt, and the level of salts in the water to be treated, will determine the quality of the effluent product water.

1.14 Relationship Between Water and Salt Passage

The ratio of the product water produced to the feed water brought into the system for treatment is defined as the system recovery. Since the overwhelming majority (95% or better) of the salts entering the system are held back by the membranes, the degree of the concentration of the feedwater is determined by the recovery. If we assume that we are feeding 100 gpm into the system, with 75 gallons being removed as purified water, then we have a 75% recovery system. The brine or waste stream consists of 25% of the original feed volume and contains almost 100% of the original salts. Therefore, we have concentrated the feed salts by a factor of 4. This is expressed in the equation:

$$\text{Concentration Factor} = \frac{1}{1-Y}$$

The equation shows that as you increase the recovery, you increase the concentration. By increasing the TDS of the feed-water and/or recovery, you will increase the osmotic pressure of water produced at a given feed pressure (PFD).

This will increase the osmotic pressure and, as indicated in the QP equation, reduce the amount of water produced at a given feed pressure (PFD).

The recovery therefore influences the quality of the product water, as well as the volume of purified water that can be produced by a given element.

When this is combined with a feedwater that may vary anywhere from 300 to 10,000 MG/l, we can see that the output of a given membrane and the water quality it produces will vary widely.

If we vary the feed pressure as indicated in equation QF, the volume of product water produced will vary.

If we have a constant salt passage and a varying water passage, product quality will vary with applied pressure.

A reduction in pressure will result in lower flow and a product containing a greater amount of salts per unit volume (MG/l). Similarly, an increase in pressure will reduce the ratio of salt to water, giving a higher quality purified product.

Where high recoveries are desired with high feed concentrations, we must employ a membrane that will permit only a small percentage of the salt to pass through. Thus the membranes used for desalting the ocean are much "tighter" than one we will be using to treat brackish water containing from 300 to 10,000 MG per liter of salt.

1.15 Temperature Effects

The effects of temperature on the Reverse Osmosis process are defined as follows:

$$TF = (1.03)^{T-25}$$

TF is a factor that shows the percentage increase or decrease in flow resulting from changes in temperature above and below the standard 25°C.

Figure 2, previously described, defines the basic principles and components of a Reverse Osmosis system. We would like to review the membrane components and the general system configuration.

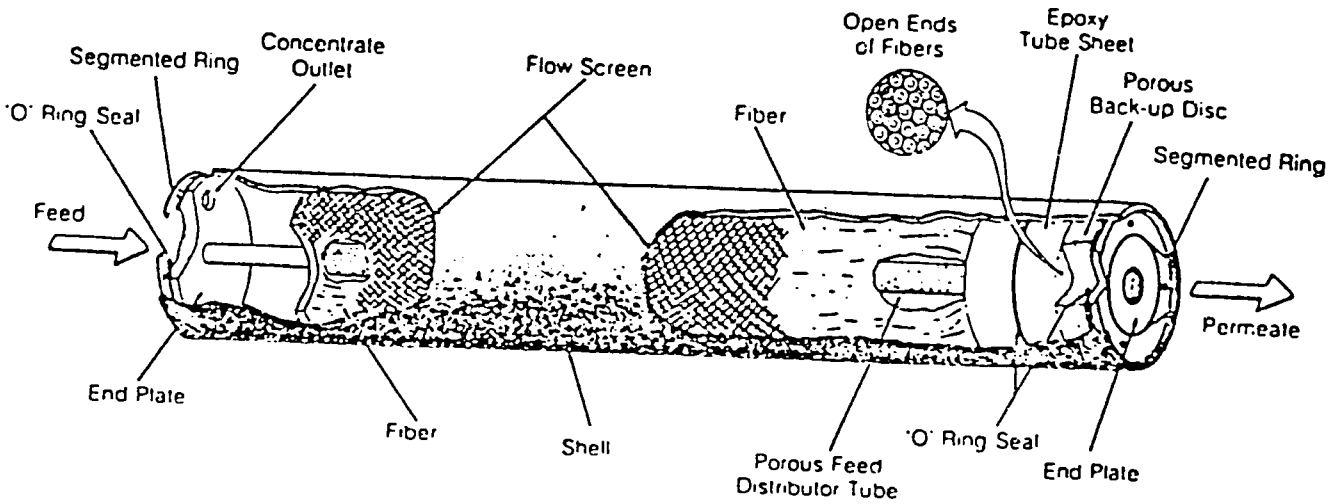
1.16 MEMBRANES

Hollow Fiber

Figure 3 describes the physical configuration of the Hollow Fiber permeators. The membrane is a fine fiber and many thousands are assembled parallel to each other in a fiber bundle. The bundled fibers are secured at each end in epoxy tube sheets. Typical of these fibers are the Du Pont B-9 membranes, having an inside diameter of approximately 42 microns, an outside diameter of approximately 85 microns, and a length of approximately 30 inches. The feedwater enters the perforated tube, which is at the center of the fiber bundle, and water passes through the bundle and out the concentrate port. As the water travels across the outer surface of the fibers, the purified water passes through the fiber wall. The salts are retained in the vessel and discharged out the concentrate port. The purified water travels down the center of the fiber and is collected at the product end of the permeator vessel.

The flow path through the hollow fiber permeators requires a 180° change in direction (see Fig. 3), before the water can exit through the concentrate port. This flow pattern encourages particulate material to deposit on the closely packed fibers.

Fig. 3



DU PONT

Reverse Osmosis Permeator

DOWEX Reverse Osmosis Permeator

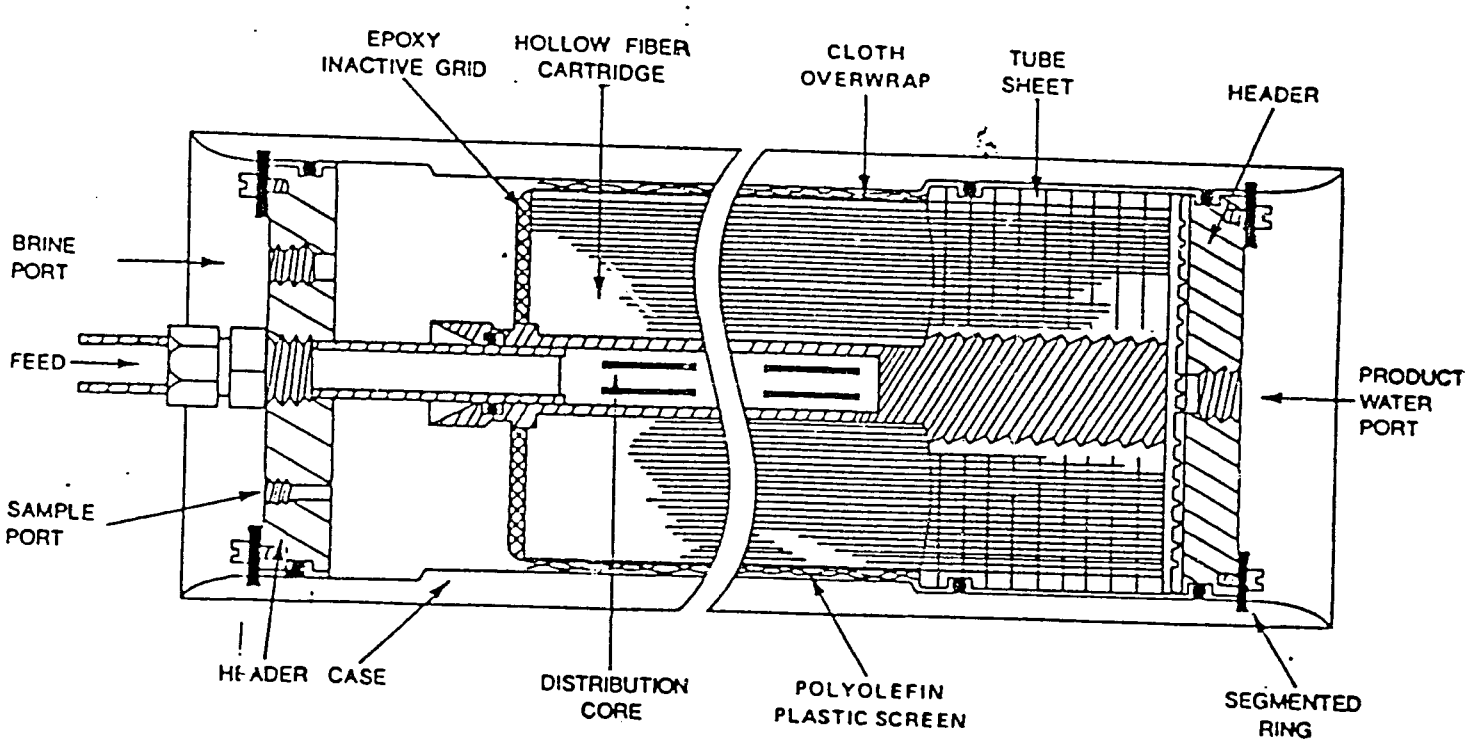


Figure 3 cont'd

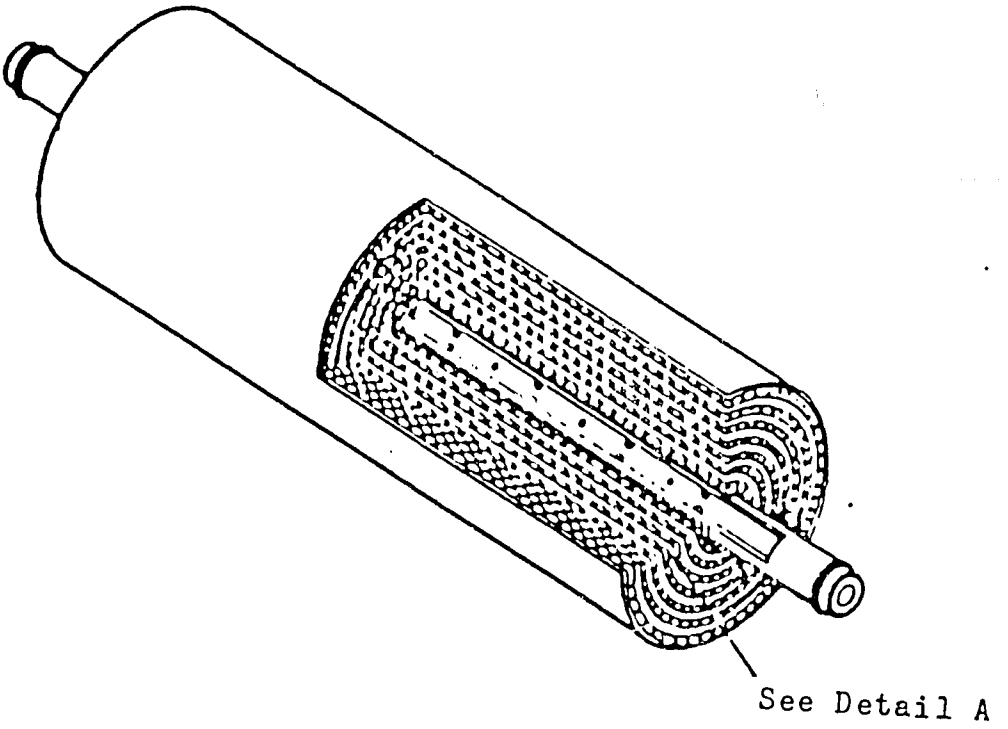
Spiral Wound Configuration

Figure 4 describes the physical configuration of the Spiral Wound elements. The Spiral Wound elements are produced from sheet membrane. Two membrane sheets are glued back to back to form an envelope. When water, under pressure, is passed over the surface of the sheet, pure water passes through the membrane, while the salts are held back on the outer surface of the envelope. The membrane envelopes are separated by mesh spacers and rolled into the spiral configuration.

The spiral element is secured in a fiberglass outer wrap, and a brine seal or gasket is assembled on the outside of each element. As shown in Figure 5, the elements are assembled in series in a vessel containing a maximum of six (6) spiral elements. This assembly of spiral elements is similar to the hollow fiber permeators.

The spiral elements come in 4" and 8" diameter sizes for the larger industrial and municipal applications. The feedwater enters the pressure vessel (which measures in excess of 20 feet with a six-element assembly) and passes down through the space between the membrane sheets, exiting at the opposite end of the 20 ft. container. The purified water passing through the membrane sheets is collected inside the envelope. It spirals down to the product tube, which collects the purified water and allows it to be transported out of the pressure vessel on either end. The pressure vessels, like the permeators, are assembled in parallel arrangements and piped to headers.

DETAILS OF SPIRAL WOUND MODULE CONSTRUCTION



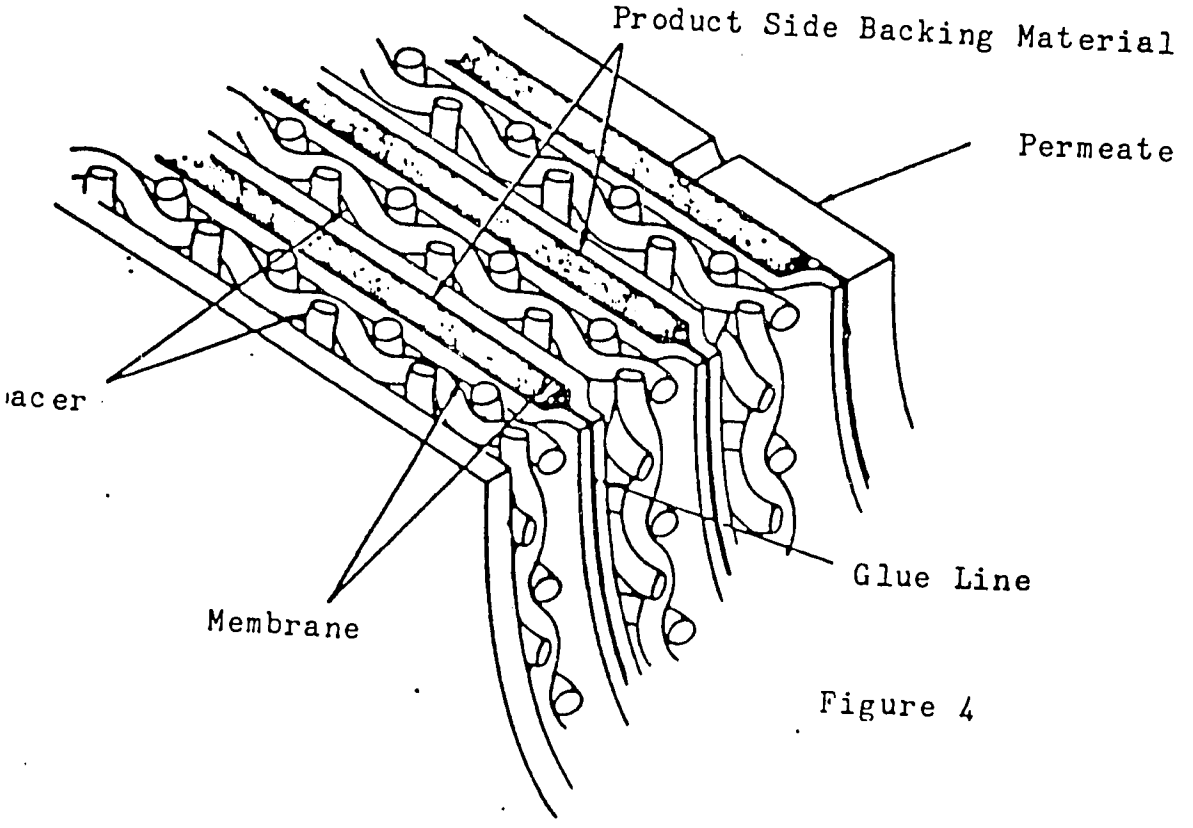


Figure 4

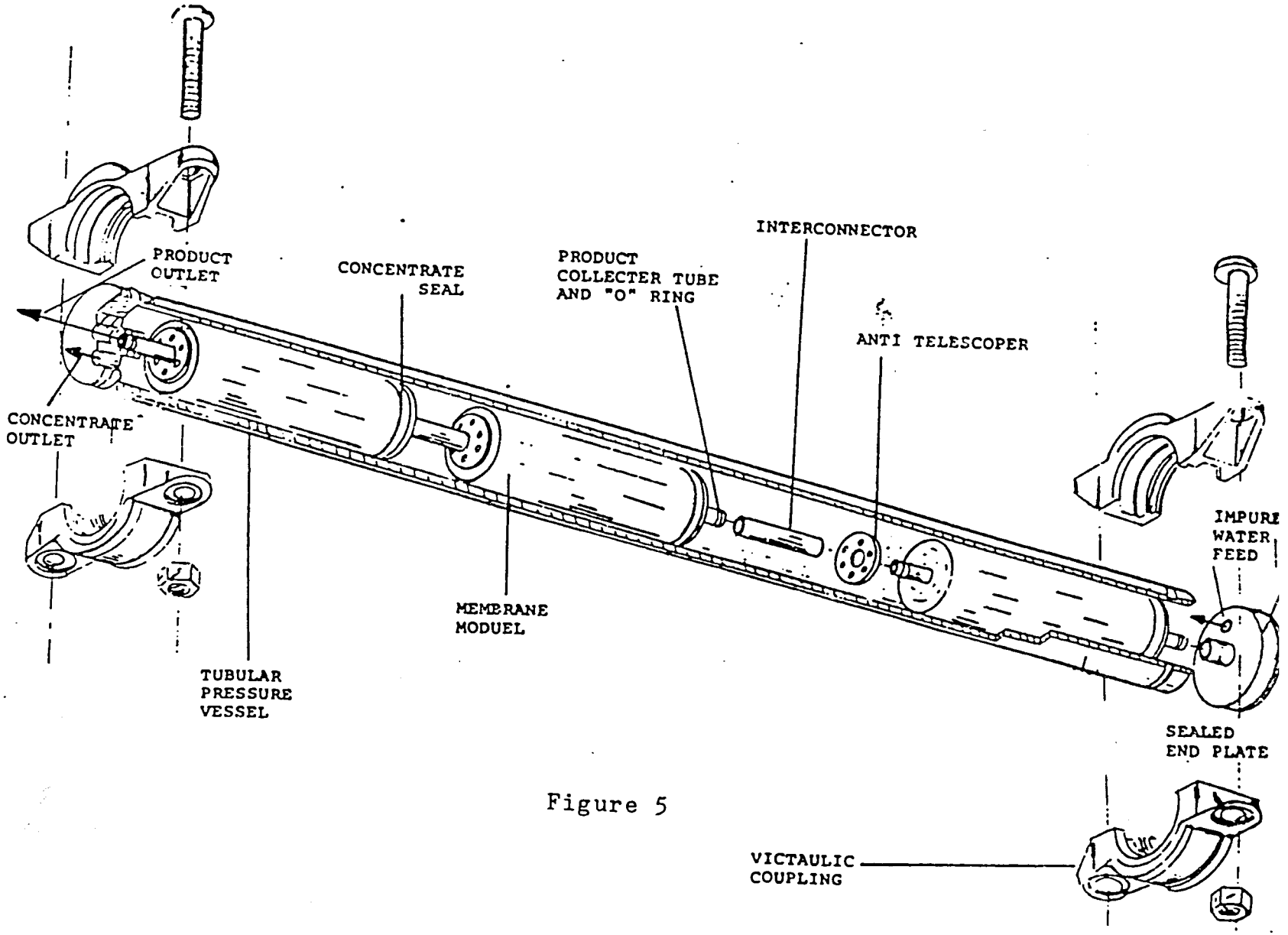

PRODUCT
OUTLET
CONCENTRATE
SEAL
PRODUCT
COLLECTER TUBE
AND "O" RING
INTERCONNECTOR
ANTI TELESCOPER
CONCENTRATE
OUTLET
IMPURE
WATER
FEED
MEMBRANE
MODUEL
TUBULAR
PRESSURE
VESSEL
SEALED
END PLATE
VICTAULIC
COUPLING

Figure 5

The spiral elements are available in polyamide, cellulose acetate, and triacetate materials. The various membrane elements have different characteristics and limits regarding product volume produced, salt rejection levels, temperature capabilities, etc.

The spiral membranes have a relatively high product flow per unit area (flux) and thus a tendency for polarization concentration. The high concentration of salts at the membrane surface increases the passage of salt and the danger of scaling. To minimize the polarization effects, a minimum brine flow must be maintained. The minimum brine flow is defined as that required to maintain a given ratio between the product flow of an element and its brine flow. This ratio varies from 2 to 5, depending on the contamination level of the feedwater and the salt concentration of the water being treated.

With the relatively linear flow path through the element and the high surface velocities, the spiral elements have good resistance to fouling. Since the brine spacing material can be made larger, it is possible to design a spiral element to handle water with higher levels of particulate contamination.

Membrane Materials

The cellulosic membranes have lower maximum operating temperatures and are limited in the pH range in which they can operate. The cellulosic membranes can treat water having a maximum of 1 ppm of residual free chlorine.

The non-cellulosic membranes are generally quite sensitive to chlorine, and systems should be designed on the assumption of zero chlorine in the feed. They have good chemical resistance

with an operating pH range of 4 to 9. The non-cellulosic membranes have excellent temperature capabilities, with 40°C being a reasonable maximum. Higher temperatures can be handled under special operating conditions.

The newest family of non-cellulosic membranes are the thin film composites. They consist of a sheet of porous but strong and chemically resistant polysulphone, coated with a thin layer of material that polymerizes and forms a very thin but tight active membrane layer. This type of membrane has high rejection properties, while still maintaining excellent flux due to the thin cross section of the active layer. The composite structure has good chemical resistance (pH range 2 - 12) and excellent high temperature characteristics. They are generally, however, sensitive to chlorine in the feedwater.

The composite structure is most commonly used in the spiral wound configuration.

In general, the spiral wound and hollow fiber units are competitive both from a technical and cost standpoint, and the selection of one versus another depends very much on the quality of the feedwater, the desired effluent quality, and the general environment in which the systems must operate.

1.17 System Array

The Hollow Fiber permeators and Spiral Wound pressure vessels are arranged in parallel in the required number necessary to produce the desired amount of product water.

Membrane systems function best where there are uniform flow parameters. As indicated in Figure 6, the membrane devices are arranged in parallel, and parallel groups are assembled in series.

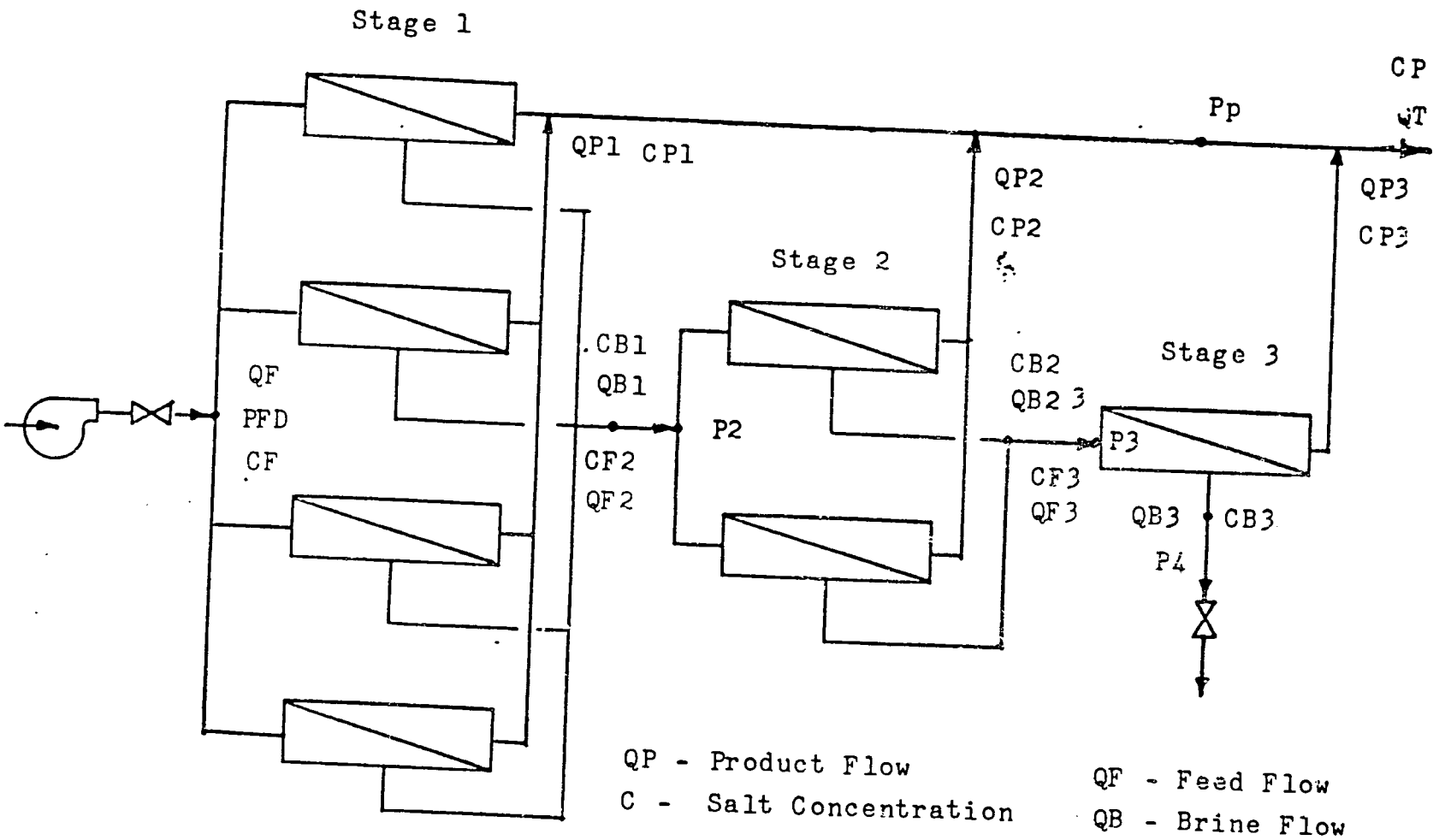

Stage 1
Stage 2
Stage 3
QF
PFD
CF
QP1 CP1
CB1
QB1
CF2
QF2
P2
QP2
CP2
CB2
QB2 3
CF3
QF3
P3
Pp
CP
QT
QP3
CP3
QB3
CB3
P4
QP - Product Flow
C - Salt Concentration
QF - Feed Flow
QB - Brine Flow

Figure 6

To maintain the proper velocities and uniform hydraulic patterns, the membrane vessels are assembled in a pyramid configuration. For example, four pressure vessels in the first stage would feed their reject (brine) to the second stage containing two pressure vessels. If there was a third stage, the effluent from the second stage would be fed to a single third stage device.

Where higher recoveries are required, there may be three stages rather than two. Where only two stages are used, as many 2 x 1 building blocks are assembled as are necessary to meet the capacity requirements of the system.

Systems should be designed as close to the 2 x 1 format as practical, based on the system capacity, choice of membrane, feedwater concentrations and desired recovery. With recoveries in excess of 85%, a three-stage system having a 4 x 2 x 1 basic array would be required. With recoveries less than 60%, a single-stage design would be typical. Systems operating at recoveries in excess of 60% and below 85% employ a two-stage design.

1.18 Pretreatment

The successful operation of a Reverse Osmosis system requires the removal of foulants in the feedwater and the prevention of scale to protect the membrane elements from contamination.

Fouling Control

The removal of particulate matter that interferes with the operation of the R.O. system or results in excessive cleaning and maintenance is essential. The fouling potential of the feedwater is determined by measuring the Silt Density Index (SDI).

An SDI of three or less is required by Du Pont for warranteed operation. Dow requires an SDI of four. The Spiral Wound manufacturers do not place the same emphasis on the SDI measurement, but an SDI of five or less is considered good operating practice.

Fouling can be divided into two categories, namely, plugging and surface fouling.

Plugging

Plugging occurs when larger particulates block the flow channels and create high pressure and disrupt the flow path through the device.

In the hollow fiber elements, the plugging may occur in the initial layer of fiber just outside the feed distribution tube.

In the spiral units, plugging occurs when material is deposited on the face of the feed end of the element. The material deposits on the exposed ends of the brine spacers. Plugging tends to occur in the 1st stage of the system. On occasion, if the very fine particulates agglomerate as they pass through the first stage, they will deposit on the entrance to the second or third stage elements. The primary symptom of plugging is increased pressure drop across the permeator or spiral pressure vessel assembly.

Surface Fouling

Surface Fouling occurs when very small size particulates (colloids) are deposited on the surface of the membrane. These particulates concentrate in the system in the same way as the dissolved salts. The surface foulants are distributed throughout the system, with higher concentration in the latter stages (2nd or 3rd stages).

The primary symptoms of surface fouling are a loss in productivity and an increase in salt passage. The foulants act as

a sponge and hold the high salt concentrations at the membrane surface.

Iron

Iron fouling can result from iron oxidizing out of solution or as a byproduct of corrosion in the system. Selection of materials for the R.O. system is very important to avoid this type of fouling. Iron fouling shows up as discreet particles or as a gelatinous substance. If iron fouling is discovered early enough, it can be readily chemically cleaned.

Colloidal Silica

Colloidal silica is one of the most tenacious forms of fouling. The material cannot be dissolved and it clings to the membrane's surface. The only solution is coagulation to remove the colloids before they enter the system.

H2S

Hydrogen sulfide is normally a gas; however, when exposed to excessive oxygen, it will react with metal present in the water to form metallic sulfides.

An air-tight system from the well head to the product and brine discharge will minimize the effects of H2S produced foulants.

Organics - Bacteria

This type of fouling is most common with surface water supplies. It results in the formation of slimes that bind the membrane surface. This fouling can be chemically cleaned, using biocides and detergent cleaners.

Removal of Foulants

The fouling particulates may be large and therefore removed by a simple sand filter or other forms of media filtration. However, as is often the case, if the feedwater contains

a high level of colloidal material, then these must be removed by conventional clarification or by an in-line coagulation system. In-line coagulation consists of feeding a coagulant into the pipeline ahead of a dual medial filter. The colloids are conglomerated and captured on the media bed and then removed in the backwash cycles. This is the simplest and generally the most effective method for removal of colloids that would otherwise foul the Reverse Osmosis system.

Scale Control

A major source of problems for the Reverse Osmosis system is the precipitation of salts from the water being treated, due to the concentrating effect of the Reverse Osmosis process. If the calcium, sulfate, alkalinity, silica, and other salts in the feedwater will precipitate when operating at the desired recovery level, then steps must be taken to remove some of the components that generate the precipitates in question.

Calcium Carbonates

The major scaling problem comes from the precipitation of calcium carbonate. This results from a concentration of the calcium and alkalinity in the feedwater and will deposit in the final stages of the R.O. system, where the feedwater has been concentrated to its maximum degree.

The probability of developing calcium carbonate scale can be determined by calculating the Langelier Saturation Index of the brine stream, as described in Figures 12 and 13.

The scaling potential of a water with a positive Langelier can be reduced by removing one of the components in the calcium carbonate reaction.

LANGELIER SATURATION INDEX
($CaCO_3$ SATURATION INDEX)

- CRITERIA USED FOR DETERMINING THE NEED FOR CALCIUM CARBONATE SCALE CONTROL.

$LSI = pH - pHs$

$pHs = \epsilon pCa + p\,ALK + C$ - FROM GRAPH

TO CALCULATE pHs, NEED TO KNOW:

- CALCIUM CONC. OF REJECT ($CaCO_3$)
- ALKALINITY OF REJECT ($CaCO_3$)
- TDS OF REJECT
- pH OF REJECT

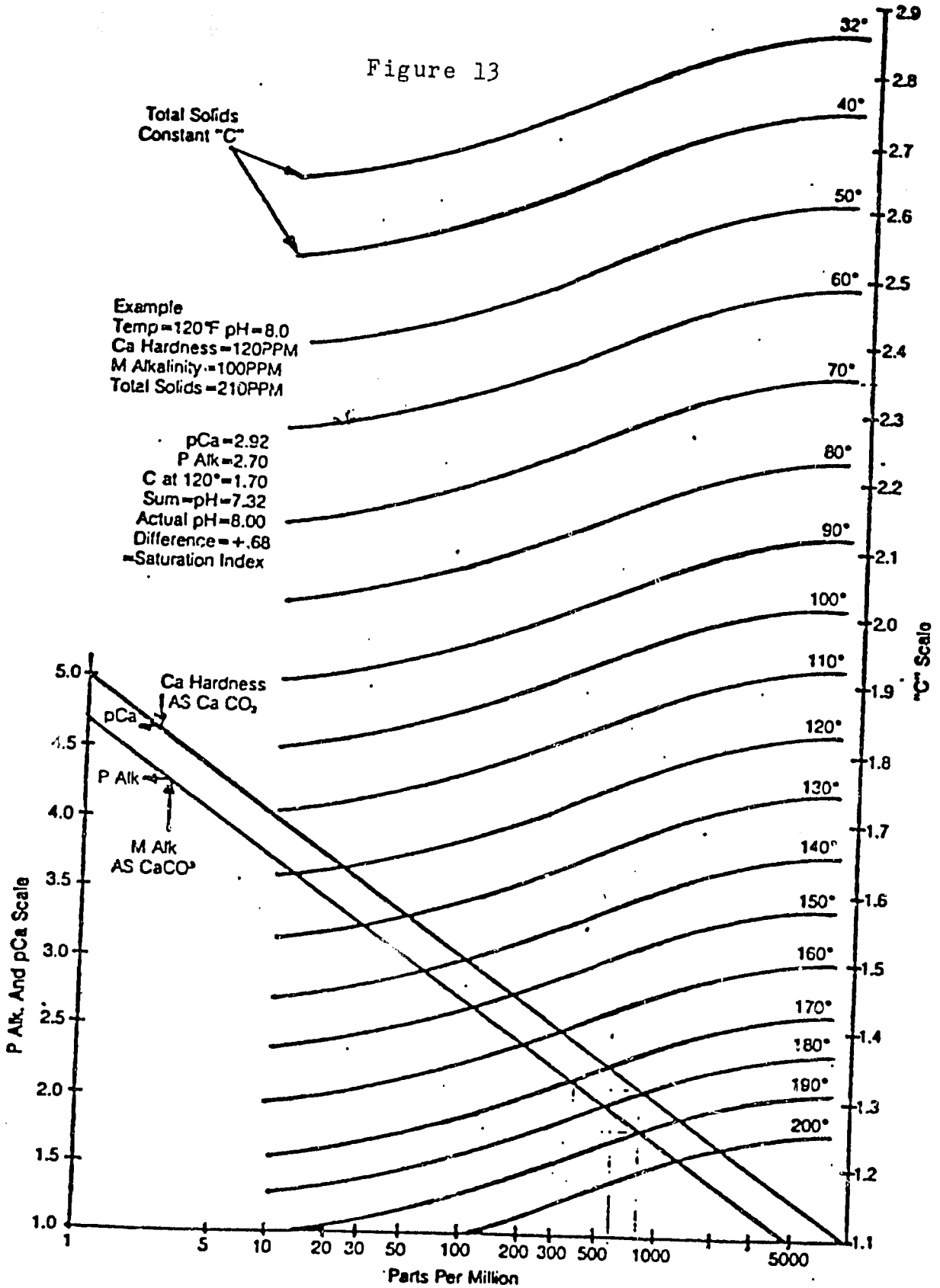
IF LSI IS POSITIVE = SCALE FORMING

IF LSI IS 0 = NEUTRAL

IF LSI IS NEGATIVE = CORROSIVE TENDENCIES

Figure 12

Figure 13


Total Solids
Constant "C"
Example
Temp=120°F pH=8.0
Ca Hardness=120PPM
M Alkalinity=100PPM
Total Solids=210PPM
pCa=2.92
P Alk=2.70
C at 120°=1.70
Sum=pH=7.32
Actual pH=8.00
Difference=+.68
=Saturation Index
Ca Hardness
AS Ca CO3
pCa
P Alk
M Alk
AS CaCO3
P Alk. And pCa Scale
Parts Per Million
"C" Scale
32°
40°
50°
60°
70°
80°
90°
100°
110°
120°
130°
140°
150°
160°
170°
180°
190°
200°
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1
5
10
20
30
50
100
200
300
500
1000
5000
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1

The most common solution to this problem is the feeding of acid, which reduces the pH of the feedstream and destroys the alkalinity present in the feedwater. The alkalinity is converted to CO_2, thus eliminating one of the components required for the precipitation of calcium carbonate.

An alternate solution is the softening of the water and the removal of the calcium hardness, thus preventing the formation of calcium carbonate. This softening can be done by conventional ion exchange processes. Where the hardness level is not excessive, the ion exchange techniques are preferred because of their simplicity and lower capital costs. However, where high levels of calcium are present, it may be necessary to use cold lime softening.

Calcium Sulfate

The next major scaling problem is that of calcium sulfate. In this instance, the feeding of acid will not help, but the formation of the calcium sulfate must be inhibited by the addition of an anti-scalant. Sodium Hexametaphosphate, and a number of commercially available anti-scalant materials specifically designed to prevent scaling, can be used to show the rate of scale formation. With the use of anti-scalants, a precipitation that might occur normally in a matter of minutes will now take hours. This permits the passage of the feedwater through the system and out into the waste stream before the precipitation can occur.

The calcium sulfate scaling potential can be determined by calculating the (CA) and (SO_4) ion product (IP).

$$IP = (CA \quad X \quad (SO4)$$
Moles/liter Moles/liter

The IP calculated should be compared to the Ksp given in Figure 15 . The ionic strength of the brine can be calculated as shown in Figure 14 and then used to determine the maximum allowable Ksp without pretreatment.

If the IP is greater than Ksp, then pretreatment is required. Up to a maximum Ksp of 1×10^{-3}, anti-scalants can be added; above this point, the offending Ca must be removed or the recovery reduced.

The use of specially developed anti-scalants to prevent both $CaCO_3$ and $CaSO_4$ scale should be evaluated. These new anti-scalants are being used in a number of installations to prevent both forms of calcium scale. With these new anti-scalants, it may be possible, depending on the specific situation, to eliminate a need for acid addition.

Silica

The third and most difficult material that may precipitate in the Reverse Osmosis system is Silica. Silica scalants vary in chemical composition, depending on the components in the feedwater with which the silica may react. The potential for silica scale depends not only on the amount present in the feed, but also on the temperature and pH of the feedwater.

A conservative value for the maximum allowable silica in the brine system can be determined from the following:

$SM = T \times 4$ (Mg/l as SiO_2)

SM = Maximum Allowable Silica in Brine

T = Temperature of Brine ^{o}C

$$I = \frac{1}{2} \sum mi Zi^2$$

Where

I = Ionic Strength of Brine

i - ion

MW = Molecular Weight

mi = Molality of ion (i/(MW X 1000))

= Sum of all ionic Species

Example

Recovery = 75% CF = 4

	Feed Mg/l	x CF=Brine Mg/l	MW	mi	Z^2	$miZi^2$
CA	80	320	40	.008	4	.032
MG	24	96	24.4	.0039	4	.0156
NA	553	2212	23	.096	1	.096
HCO3	244	976	61	.016	1	.016
SO4	480	1920	96	.02	4	.08
Cl	567	2268	35.5	.064	1	.064
	1948	7792				.3036

$$I = \frac{1}{2} (.3036) = .1518$$

Figure 14

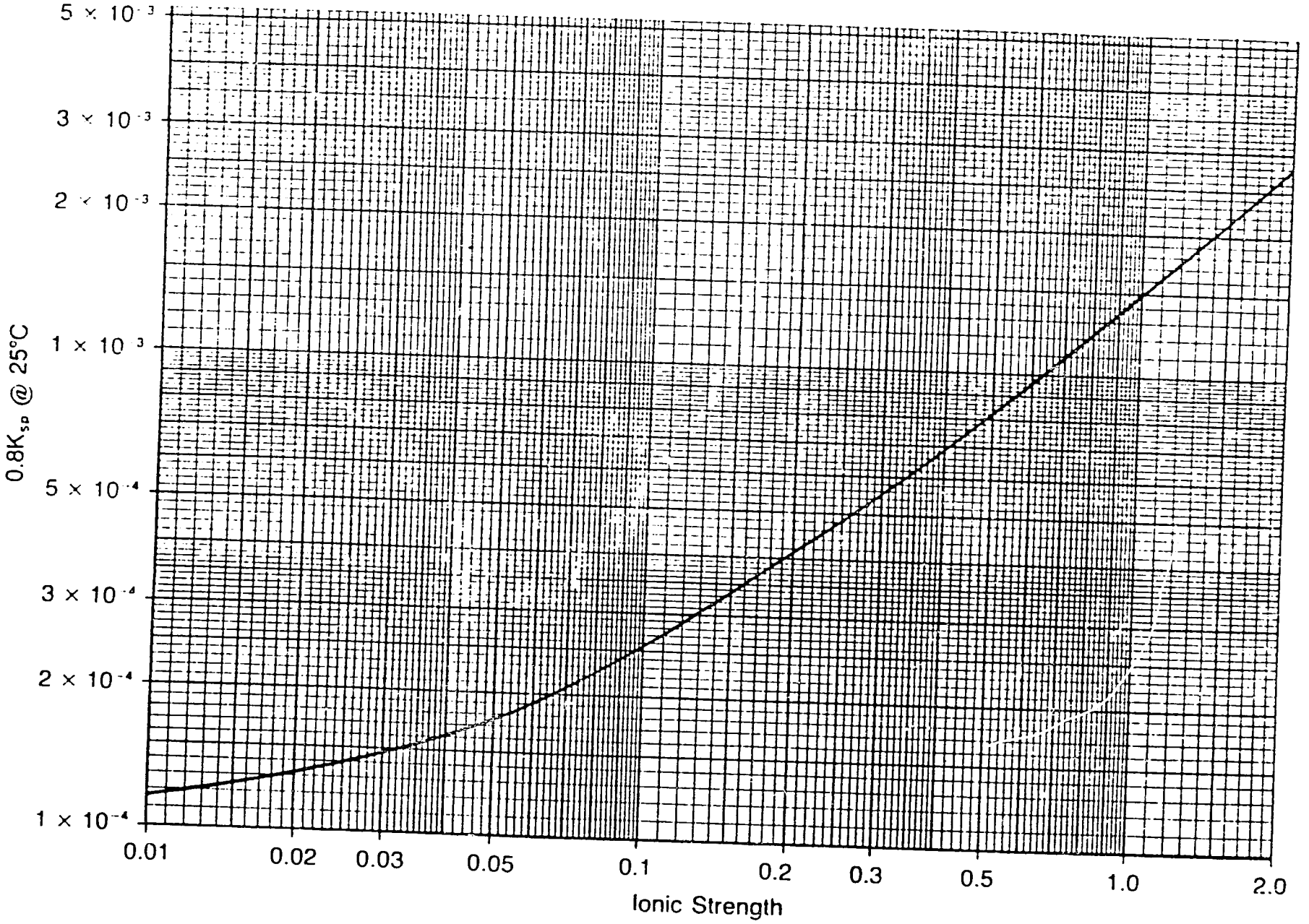


Figure 15 **$0.8K_{sp}$ for $CaSO_4$ vs. Ionic Strength**

Silica solubility is affected by pH. With pH above approximately 8, the allowable amount of SiO_2 in the brine increases significantly. If the pH is seven or less, the limits can be increased by a factor varying from 1.0 at pH 7 to 1.35 at a pH of 4.0.

Silica precipitation can be minimized by operation at higher temperatures, since increased temperature increases the solubility of silica in the feedwater.

It should be remembered that as you increase the recovery, you increase the concentration of the salts in the feedwater. Therefore, if there are excessive levels of calcium, sulfate, or silica in the water, the danger of precipitation can be removed by reduction of the system recovery.

The tendency for salts to precipitate depends not only on their specific concentrations but on the temperature, pH, and ionic strength of the brine stream.

1.2 DEVELOPMENTS

1.21 Energy Recovery

The development of energy recovery devices have reduced the energy requirements of Reverse Osmosis systems by 30% to 40%. The types of recovery systems are the (a) Pelton Wheel Impulse Turbine; (b) the Multistage Vertical Reaction Turbine; and (c) the Horizontal Reaction Turbine. The reaction turbines are basically reverse running centrifugal pumps, integrated with the primary turbine pumps and using the reject flow and pressure to drive the primary turbine pump.

The Pelton Wheel Turbine Pump converts the reject flow and pressure into a velocity head that drives the Pelton Wheel (water whee

which in turn drives the primary motor-pump set.

1.22 Low Pressure Membranes

The development of the thin film composite membranes and their high product flow and high salt rejection capabilities permit the reduction of the brackish systems' operating pressure from 420 psi to approximately 225 psi. This represents a reduction in energy requirements of approximately 45%. The brackish composite membranes, while designed for 225-250 psi operation, can operate at pressures up to 600 psi. This flexibility allows a system to operate over a wide range of feedwater conditions, while still taking advantage of the reduced energy requirements.

1.23 High Rejection Membranes

The composite membranes, when applied to the treatment of Seawater, provide high rejection and relatively high product flow rates. This permits the design of systems having lower energy requirements than in the past.

The Seawater systems have limited flexibility because of the high TDS, but the composite membranes have improved the ability to vary operating pressures and system recoveries.

2.0 PRINCIPLES OF ELECTRODIALYSIS

In the context of the membrane processes, Electrodialysis (ED) is a process that removes the smaller component of a saline solution, salt, from the larger component, water, by means of direct current electricity and ion selective membranes. The salts are concentrated in a separate stream within the ED membrane cell.

Electrodialysis (ED) is an electrochemical separations process in which ions are transferred through membranes from a less concentrated to a more concentrated solution as a result of the flow of direct electric current.

To understand this process more clearly, let us assume a rectangular tank with an electrode at either end and filled with a sodium chloride (NaCl) solution (Figure 7).

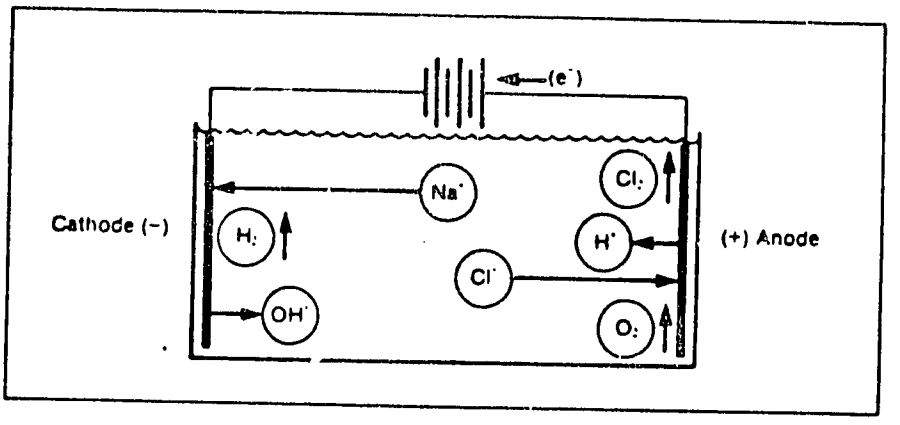


Figure 7

When a DC potential is applied across the electrodes, the following occurs:

1. Cations (Na^+) are attracted to the negative electrode.
2. Anions (Cl^-) are attracted to the positive electrode.
3. The water dissociation reduction reaction occurs at the cathode.

$$2H_2O + 2e \rightarrow 2(OH)^- + H_2$$

91

4. The water dissociation oxidation reaction occurs at the anode.

$$2H_2O \rightarrow 4H^+ \; O_x + 4e$$

5. A reaction involving the formation of chlorine gas may also occur at the anode.

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

Effect of Anion and Cation Transfer Membranes

To control the movement of ions in the tank containing the ionic solution and electrodes, several membranes can be added to form water-tight compartments as shown in Figure 8.

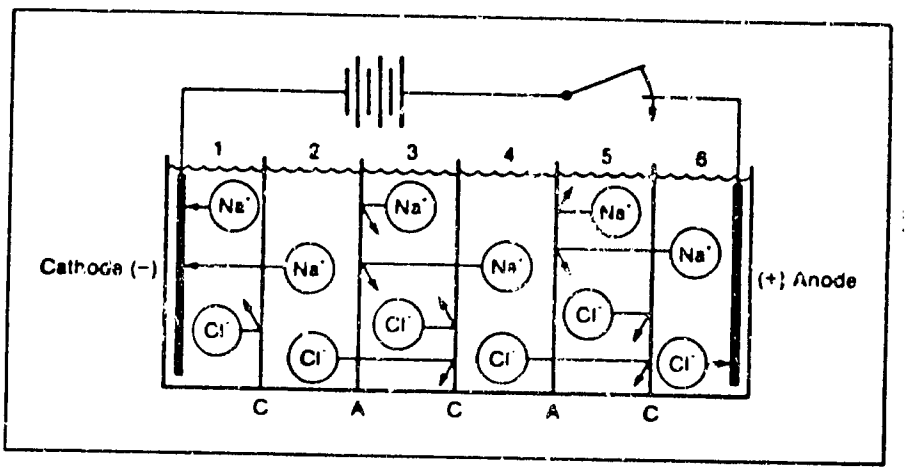


Figure 8

Two types of membranes are shown.

1. Anion Transfer Membrane: Allows only the passage of negatively charged anions (Labeled A in Figure 8).

2. Cation Transfer Membrane: Allows only the passage of positively charged cations (Labeled C in Figure 8)

What occurs when a DC potential is applied?

Compartments 1 and 6: These compartments contain the metal electrodes. Chlorine gas, oxygen gas and H^+ ions are produced at the anode, while Hydrogen gas and OH^- ions are produced at the cathode.

Compartment 2:

1) Cl^- ions pass through anion membranes (A) into compartment 3.

2) Na^+ ions pass through cation membrane (C) into compartment 1.

Compartment 3:

1) The Na^+ ions cannot pass through the anion membrane and remain in compartment 3.

2) The Cl^- ions cannot pass through the cation membrane and remain in compartment 3

Compartment 4:

1) Cl^- ions pass through the anion membrane into compartment 5.

2) Na^+ ions pass through the cation membrane into compartment 3.

Compartment 5:

1) The Na^+ ions cannot pass through the anion membrane and remain in compartment 5.

2) The Cl^- cannot pass through the cation membrane and remain in compartment 5.

The overall effect shows that compartments 2 and 4 have been depleted of ions and the ions have concentrated in compartments 3 and

Membrane Properties

ED membranes have ion selectivity (anion/cation) and electrical conductivity. The selectivity of cation and anion membranes is generally about 90% for solutions less than 0.5 to 0.7 N, but decreases at higher ion concentrations. Membranes having low electrical resistance consume less energy, thus increasing the efficiency of the ED system.

Resistance of membranes decreases as the solution concentration increases. Also, electrical resistance of membrane systems changes with temperature.

Faraday's Law

Faraday's Law as related to the ED process states that the passage of 96,500 amperes of electric current for one second will transfer one gram equivalent of salt. Faraday's Law is the basis for calculating the amount of electric current needed in an ED system to transfer a specific quantity of salts. Faraday's Law as used in ED calculations is:

$$I = \frac{F^{*} \times F_d \times N}{e \times N^{*}}$$

where:

I = direct electric current in amperes

F*= Faraday's constant = 96,500 ampere seconds/equivalent

N= change in normality of demineralized stream between the inlet and outlet of the membrane stack.

F_d= the flow rate of the demineralized stream through the membrane stack (liters per second)

e = current efficiency

N^{*} = number of cell pairs

Ohm's Law

$$E = I \times R$$

The potential (E) of an electrical system is equal to the product of current (I) and the system resistance (R).

E is expressed in volts, I is expressed in amperes, and R is expressed in ohms.

To determine the voltage requirements for a given system, the current is determined from Faraday's Law and the resistance is determined by the components of the membrane stack and the solution under treatment.

Membrane Stack Design

As shown in Figure 8, alternating compartments of demineralized solutions and concentrated solutions are formed in this membrane cell when a DC potential is applied across the electrodes. When properly manifolded, this unit will yield two major and separate streams; demineralized and concentrate waters, and two minor streams from the electrode compartments. In normal applications several hundred of these demineralizing and concentrating compartments are assembled into a "membrane stack" to obtain the desired water flow rate. These membrane stacks are the heart of the ED system.

The basic building block of an ED system is the membrane stack. A repeating section within the stack is called a "cell pair" and consists of a:

- Cation transfer membrane
- Demineralized water flow spacer
- Anion transfer membrane, and
- Concentrate water flow spacer.

A typical membrane stack may contain from 300 to 500 cell pairs representing the same number of parallel hydraulic flow paths.

The capacity of the system, that is the quantity of treated water needed, determines the number of cell pairs, and the size of the pumps and piping. The fraction of the salt to be removed determines the configuration of the membrane stack array.

Staging

The manner in which the membrane stack is arranged is called staging. The purpose of staging is to provide sufficient membrane area and retention time to remove a specified fraction of salt from the demineralized stream.

Typically, maximum salt removal for any hydraulic stage is 55-60 percent with normal design values at 40-50 percent. To increase the amount of salt removed in an ED system, additional hydraulic stages must be incorporated. In systems where high capacities are required, additional hydraulic stages are made by simply adding more stacks in series to achieve the desired water purity (Figure 9).

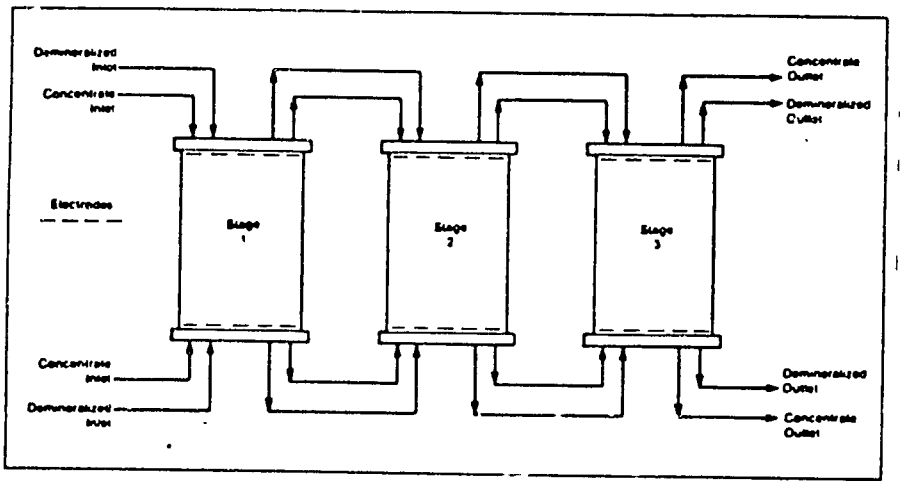


Figure 9

2.2 Development

2.21 Electrodialysis Reversal (EDR)

A major variation of the classical unidirectional ED process is called electrodialysis reversal (EDR). The system is designed to minimize the need for chemical addition. The EDR system uses electrical polarity reversal to continually control membrane scaling and fouling.

The polarity of the electrodes is reversed 3 to 4 times each hour. This reverses the direction of ion movement within the membrane stack, thus controlling film and scale formations. This is shown in Figure 10, in which the polarity of the electrodes in tank A is opposite that of tank B.

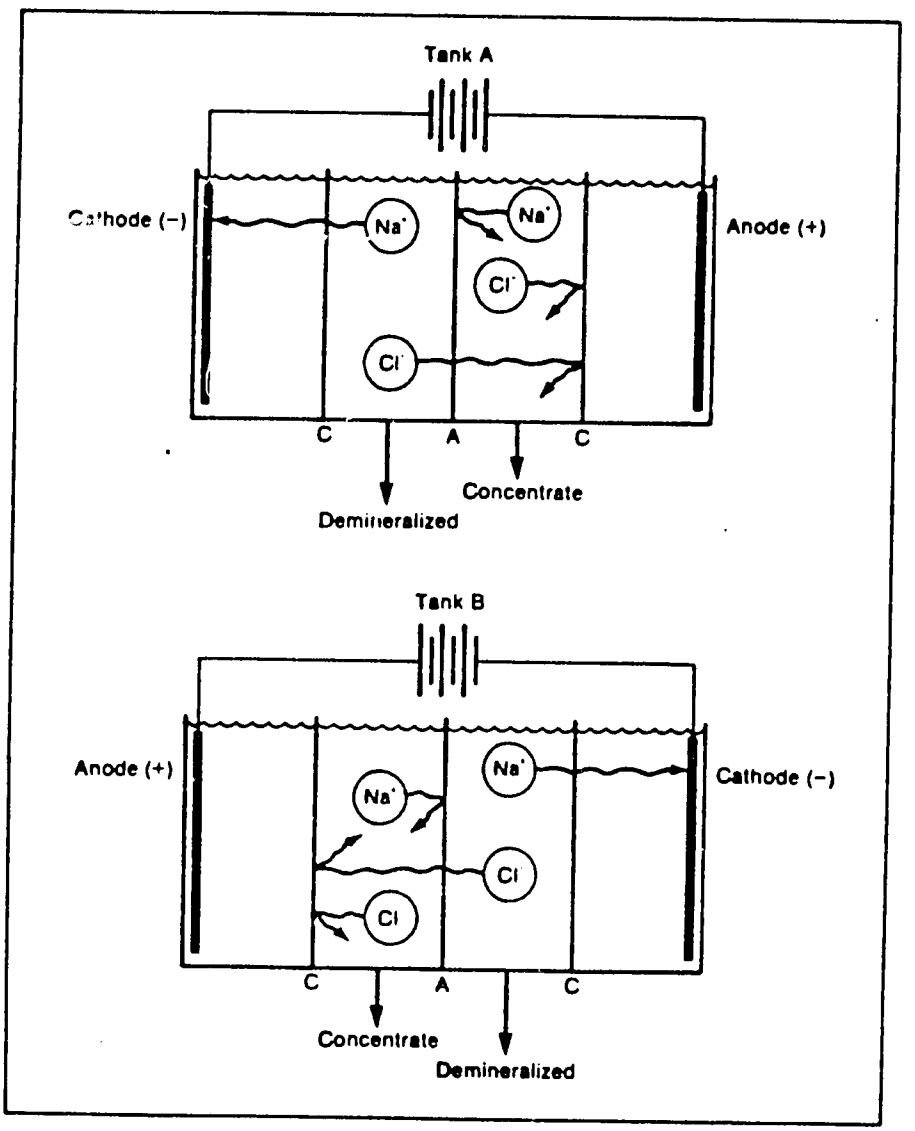


Figure 10

In a typical system, reversal occurs approximately every 15 minutes and is accomplished automatically. It can be seen from Figure 10 that upon reversal, the streams which formerly occupied demineralizing compartments become concentrate streams, and the streams which formerly occupied concentrate compartments become demineralized streams.

Because of reversal, no flow compartment in the stack is exposed to high solution concentrations for more than 15 to 20 minutes at a time. Any build-up of precipitated salts is quickly dissolved and carried away when the cycle reverses. Figure 11 is a typical EDR flow diagram.

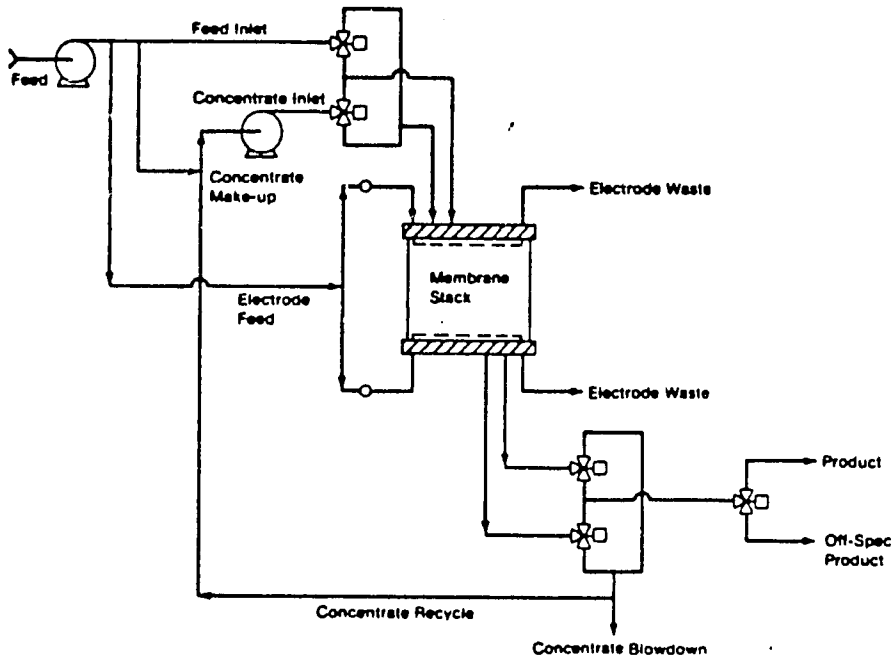


Figure 11

To summarize, the EDR process has five major effects on the operation of a membrane system:

- breaks up surface films, thus preventing scale
- breaks up freshly precipitated scale and flushes it to waste
- reduces slime or similar formations on membrane surfaces
- minimizes the need for continuous-feed of acids or complexing chemicals
- allows continuous operation at $CaSO_4$ supersaturation of 200%.

The reduction in scaling potential using the EDR permits increasing the recovery. This reduces power requirements because of the reduced flow and also because the increased salt concentration in the concentrate chambers reduces stack resistance.

2.22 New Anion Membrane

The new Aliphatic anion membrane permits continuous operation with .5 ppm chlorine residual. In addition, the surface characteristics of the anion membrane inhibit organic fouling, particularly when operating on surface waters.

C. SOLAR AND WIND DRIVEN SYSTEMS

The variable nature of Solar and Wind power requires different design priorities compared to systems using conventional power sources.

The variable peak power capacity and the variable distribution with time require a desalting plant that is energy efficient and can adjust its operating parameters to accommodate a varying power supply.

The system must also be able to adapt to changes in the feedwater. This is not a problem for the seawater application, but is essential for the brackish unit. The report on the site visit indicates a possible variation in feedwater TDS of from 1000 to 10,000 mg/l. It is important to have a feedwater source with a stable total dissolved solids (TDS) content. Varying TDS will create varying power demands and/or unit productivity.

Reverse Osmosis and Electrodialysis systems can be designed (within limits) to accommodate TDS changes. However, the design will become more complex, both as to operating techniques and the hardware supplied. In areas where the plant operators will have minimum technical skills, it is imperative that the operation is kept as simple as possible.

The desalination systems and the feedwater they are treating should be selected to

a) Provide efficient use of available power

b) Meet varying feedwater conditions

c) Allow for simplicity of operation and maintenance.

1.0 Reverse Osmosis

1.1 Seawater

The seawater system will require maximizing recovery at minimum operating pressures. Increased recovery generally requires higher pressure; therefore a balance must be created to provide the quantity and quality of water desired with the most efficient use of power.

The higher TDS and temperature of the seawater may require a 2-pass product staged system. This will require a seawater stage feeding its product water to a brackish stage. Both stages would be operated at maximum possible recoveries and employ high rejection membranes.

1.2 Brackish Water

The efficient use of power requires operation at the maximum recoveries that will provide the desired quantity and quality of product water. The power consumption will be in the range of 6 - 8 KW/1000 gals of product without energy recovery. With energy recovery, this will be reduced to 4 - 6 KW/1000 gals of product. The actual power will depend on the feed TDS, recovery, and operating pressures.

If the TDS of the feedwater increases, the recovery must be reduced and pressure increased to maintain the same quantity and quality of treated water. These adjustments may require additional membranes, pumping capacity, and/or conversion from 2-stage to a single-stage system. If reduced capacity from a single system is acceptable, then standby systems can be used to adjust to high TDS conditions.

A single oversized system can be designed that, for example, produces the daily capacity in 4 hours. If the TDS doubles, half the product water can be recycled to the feed stream, thus maintaining a constant feed concentration. This will require operation for 8 hours to produce the daily capacity.

The choice of how best to adjust to the TDS changes depends on:

a) The extent of TDS swings

b) The relative capital costs

c) The relative energy requirements

d) The ease of operation

The capital cost of these small systems is relatively modest and primary consideration should be given to efficient use of energy and ease of operation and maintenance.

Maximum membrane life and minimum maintenance (system cleaning) require adequate pretreatment of the feedwater. This is essential to prevent scaling and/or particulate fouling of the membrane system. The feedwater being treated must be carefully analyzed as to its chemical composition and particulate content (Silt Density Index).

2.0 Electrodialysis

2.1 Seawater

The electrodialysis process has a long history of successful treatment of brackish waters. Although there have been a number of seawater test systems, the process has not established itself as an economic and reliable method for treating seawater. We will therefore consider electrodialysis only for the treatment of brackish waters.

2.2 Brackish Systems

The wind and solar driven systems we are proposing require:

a) The efficient use of available power

b) The flexibility to operate with varying feedwater concentrations

c) Simplicity of operation and maintenance.

The electrodialysis system can use directly the DC power produced by the photovoltaic units. This improves the efficient use of the power, with inverters (DC to AC) only required for the low pressure feed pumps and the brine and product recirculation pumps. The power consumption will be in the range of 15 KW/1000 gals. of product water. The actual power will depend on the feedwater, TDS, recovery, and quality of effluent required (system voltage and current requirements).

If the TDS increases, a conventional ED unit would require additional stacks. This would increase the power requirements in order to maintain the same quality and quantity of treated water.

If a reduction in treated product water is acceptable, then recirculation of a portion of the product water back to the feed inlet will reduce the effective operating TDS.

This dilution of the feedwater will permit operation at a relatively constant feedwater TDS.

As in the case of R.O., this may require the designing of an oversized system.

Variations in available power can be compensated for by reducing the amount of water being treated and the product water being produced.

The E.D. system requires less power with increased water temperature, due to the reduction in stack resistance. The maximum operating temperature is 46°C.

As in the case of Reverse Osmosis, the feedwater must be evaluated for scaling and fouling potential. Scaling potential can be minimized by the use of Electrodialysis Reversal. If there are excess particulates in the feedwater, a filter system may be required.

If the Reverse Osmosis membranes become excessively fouled, the elements must be replaced. In the case of E.D., the stacks can be disassembled and the sheet membranes scrubbed. This requires a large amount of labor, if the cleanings are frequent, and is only practical where there is a large pool of low cost labor.

APPENDIX B

RELEVANT PROFESSIONAL PAPERS

ON PV-POWERED DESALINATION PROJECTS

DESALINATION: A PV Oasis

by Jerry Crutcher

Water is essential to the survival of both plants and animals. Therefore, the history of mankind has been and is inextricably linked to the need to ensure reliable access to a sufficient supply of high quality water for consumption by humans and animals and for irrigation. Until very recently, only two solutions were available to a civilization which had outgrown its water supply. The first was to migrate toward water, to move people. The second was to move water.

As world population and water usage increased during the last fifty years, it became increasingly difficult and expensive for the people of some arid regions to rely on either of these traditional solutions. However, the groundwater in these regions was becoming seriously depleted or was gradually becoming too saline to drink. Another solution to the problem of ensuring an adequate supply of good water had to be found for these arid regions. Large seawater desalination plants became recognized as a viable solution. Plants were built to supply water for coastal cities as diverse as Key West, Florida and Jeddah, Saudi Arabia. Desalination plants utilizing a wide variety of desalination techniques have been built. Among the techniques used were multi-stage flash evaporation, vertical tube evaporation, vapor compression evaporation, vacuum evaporation, electrodialysis, and reverse osmosis. However, multi-stage flash (MSF) evaporation and reverse osmosis (RO) have been the most common methods, accounting for more than half of the total installations.

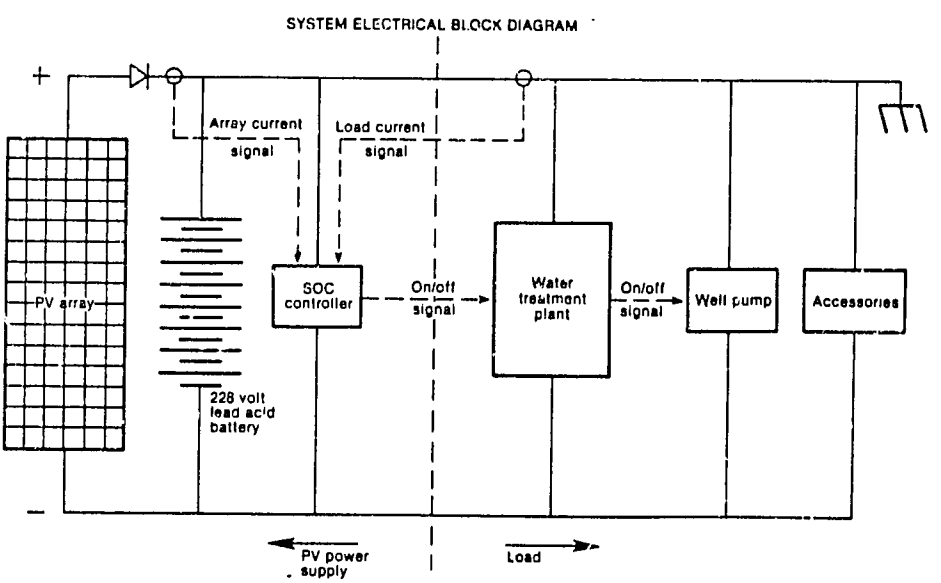
MSF plants require large amounts of thermal energy to evaporate the water, combined with a smaller amount of electricity to pump the water through the unit. They are usually powered by oil or natural gas. Most of the fuel is used to heat the water, the rest drives an electrical generator. These units work by evaporating the feedwater to separate it from the salt and then recondensing the vapor as product. The heat released by the condensing product from one stage is used to heat the evaporator of the next stage, hence the term multi-stage.

RO units use a process similar to filtration rather than evaporation. As the name implies, these units work by reversing a natural process called osmosis. In osmosis, when two solutions of different salinities are separated by a semi-permeable membrane (i.e., a membrane that allows the water molecules to pass through but not the salt ions), the water molecules will pass through the membrane from the less saline solution to the more saline solution. This process will continue until the pressure caused by the difference in height is sufficient to counteract the force generated by the salinity difference. This pressure is called the osmotic pressure.

In reverse osmosis, a high mechanical pressure sufficient to overcome the osmotic pressure is applied to the more saline solution. This forces the water molecules to pass through the membrane from the more saline solution to the less saline solution, thereby separating the fresh water from the salty feed water. Reverse osmosis units require electrical power because the primary energy consumers are the motors that drive the high pressure pumps.

Desalination plants are large energy consumers. This fact, combined with the increasing number of installations around the world, has caused a large number of people to consider solar powered desalination. There are many ways that desalination can be accomplished using solar energy. The simplest is the solar still where water is a covered basin evaporates directly by sunlight and then recondenses on the inner surface of the cover. These units, while simple and inexpensive, require large collector areas and are prone to small leaks which severely degrade efficiency and increase maintenance costs.

Another possible way to build a solar-powered desalination plant is to install a medium to high temperature (250°C to 400°C) thermal



collector system to provide the heat energy required by a MSF plant. This type of system has several drawbacks. The first is complexity. High temperature thermal collectors are usually tracking systems, which are complicated and increase installation costs. The field-installed plumbing required by these systems also increases installation costs. Another requirement that increases complexity is the need for some electricity to drive the pumps. These factors combine to increase costs and decrease reliability. Another drawback to these systems is the fact that MSF plants are not usually manufactured in small sizes because it is not cost-effective to make units smaller than 200,000 gallons per day (GPD). Finally, solar powered MSF plants require large energy storage facilities. It is not practical to design a system which operates during daylight hours only because of the time required to start and stop the MSF unit.

A third possible design for a solar powered desalination system is a photovoltaic-powered reverse osmosis plant (PV/RO). In this design, a PV power supply is built to provide the electricity required by the RO unit. Mobil Solar has been working on desalination systems of this type since 1978 and believes that PV-powered RO plants have some significant advantages over other solar powered desalination systems.

Photos courtesy of Mobil Solar Energy Corp.

The first advantage of PV/RO is efficiency. RO units typically use 30-80 Watt-hrs. of electricity to produce one gallon of product water. This compares very favorably with the 2400 Watt-hrs. of heat energy required to produce one gallon of product water from a solar still. It also compares favorably with the approximately 200 Watt-hrs. of heat (plus some electricity for pumping) required by an MSF unit to produce a gallon of product.

The second advantage is modularity. RO units are available in sizes ranging from a few GPD to many millions of GPD. When combined with a PV array of the appropriate size, systems tailored to a given application, large or small, can be created.

The third is the good match between energy source and load. RO units require only electricity to operate; they can be designed to run on dc rather than ac. Also, RO

JEDDAH PV/RO SYSTEM

The Jeddah installation, the first of its kind in the world, is a seawater desalination system powered entirely by photovoltaics. The system was first operated in January 1981 and formally dedicated on May 10, 1981.

The array is directly connected to the load with the battery bank connected in parallel. This arrangement allows the majority of the energy generated to be supplied to the load directly with the batteries taking in any excess and supplying any shortages. The battery bank is there simply to match the load demand profile to the array output provile. This arrangement maximizes system efficiency because most of the energy generated goes directly to the load. This arrangement also allows the use of a relatively small battery bank. Battery bank charger management is done by the state-of-charge (SOC) controller. The SOC controller is an integrating amp-hr controller which accomplishes its tasks by varying the number of hours each day that the RO unit operates based upon the amount of energy generated that day.

Array	
Open Circuit Voltage (Voc)	315 V
Short Circuit Current (Isc)	36.4 A
Peak Power Voltage (Vp)	260 V
Peak Power Current (Ip)	30 A
Rated Power (Wp)	8000 W
Battery Bank	
Nominal voltage	228 V
Ampere-hour rating	194 Ah
Capacity	45 kWh
RO Unit	
Feedwater Salinity	42,800 PPM
Product Water Salinity	200 PPM
Salt Rejection	99.5%
Feedwater Flow Rate	5.2 GPM
Product Water Flow Rate	1.5 GPM
Power Consumption (Including Feed Pump)	4.8 kW
Product Water Volume (7 hrs.)	500 GPD
Specific Energy Consumption	65 WH/gal

units can be started and stopped relatively easily. This means that systems can be designed where the RO unit operates during daylight hours only and the product water is stored for night use. This arrangement minimizes both battery bank size and overall system losses. Combining all of these advantages, we find that PV/RO systems have smaller collector areas, are easier to install, and can be more easily tailored to a given application than a solar powered MSF plant.

Since 1980, Mobil Solar has been involved in the design and fabrication of four PV/RO systems. Two of these are seawater desalination plants for use in the Middle East. One of these was installed in 1981, the other is scheduled for installation in the fall. Both of these were designed in conjunction with Water Services of America, an RO unit manufacturer. The other two systems are brackish water desalination systems which were done in conjunction with the Solar Energy Research Institute of Western Australia (SERIWA). The first brackish water system was installed in 1982; the second will be installed in the next few months.

The first of these systems was an 8 kWp seawater system installed in Jeddah, Saudi Arabia (see box). This system was designed as a laboratory in the field to test and verify certain design concepts, such as directly connecting the load to the array without the use of a voltage regulator, and automatic start-up and shut-down of the RO unit each day. As such, it is heavily instrumented. Since this is a completely "stand-alone" system (there is no back-up or electrical generator), a substantial portion of the energy (about 16%) is used to run the data-logging system. In its two and a half years of operation, this installation has proven that the basic design concepts are sound. It has also shown that energy losses in the batteries and controls can be kept quite small. After the energy used by the datalogger is factored out, more than 92% of the remaining energy generated goes into desalting water. The energy efficiency of the RO unit is also good considering the stringent requirements for the product water (500 PPM is the normal upper limit for product water salinity rather than the 200 PPM limit in this system). It uses 65 Watt-hrs. per gallon of product water.

The second unit was designed and fabricated for the University of Qatar. It is now waiting to be installed. This unit incorporates numerous small improvements based on lessons learned in Jeddah. With these improvements, this system is expected to produce 3 times as much water with an array only 40% larger than the one in Jeddah (1500 GPD with an 11.2 kWp array). This unit will use only 40 Watt-hr. per gallon of product. These systems demonstrate that PV/RO is capable of desalting some of the world's saltiest water.

The two brackish water systems demonstrate one of the other advantages of PV/RO systems over thermal systems. The energy consumption of an MSF desalination system is essentially fixed because the water has to be evaporated. However, the energy consumption of an RO unit varies with the salinity of the feedwater. The lower the salinity, the lower the energy consumption.

The first Australian system demonstrates this fact. This is a very small (1.2 kWp) test system installed at SERIWA's test center in Perth, Australia. This unit is designed to make 105 to 185 GPD with feedwater salinity ranging from 2000 to 5000 ppm. Its measured energy consumption has varied from 15 to 19 Watt-hrs per gallon of product produced. This specific energy consumption should be reduced to 10 Watt-hrs. per gallon or less in larger units which are more efficient. Tests on this unit have proven sufficiently interesting to encourage SERIWA and Mobil to proceed with a larger unit for field testing. This unit will be installed at the Wannoo Roadhouse, an isolated gas station and rest stop complex in the outback, 600 km north of Perth. This unit is powered by a 6 kWp array, and the system will be installed later this year.

It is clear that the pressures which have caused many countries in the arid regions of the earth to turn to desalination to ensure an adequate supply of good water will continue to mount. For this reason, the expectation is that desalination units will be installed around the world in increasing numbers. Because of the enormous energy consumption of these units and the expectation that real energy costs will be growing, a significant number of the people purchasing these units will be exploring the possibility of solar power for their desalination units. Based on our experiences with the four units described here, Mobil Solar believes that PV/RO will be a strong contender for powering these installations, particularly in the small to medium sizes. Declining module prices will serve to make PV/RO more price competitive. High system efficiencies mean smaller array fields which are also more simple to install than large fields of thermal collectors, all leading to reduced costs. Also, companies such as Dow are working on the development of new low-pressure RO membranes which offer the promise of even lower specific energy consumption for the RO unit versus other desalination methods, thereby magnifying the advantages of the PV/RO system. Finally, the modularity of a PV/RO system which allows it to be tailored in size to the specific application is an important consideration because the near term markets for solar powered desalination plants will be in outlying areas where small to medium quantities of water are required. In these areas, it is not possible to justify the cost of a large desalination plant. However, it will be possible to build PV/RO plants that produce water at a lower cost than having it trucked in from afar. For these reasons, Mobil Solar believes that desalination is a growing application for photovoltaics. +

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IONICS, INCORPORATED

DESALTING 36,000 ppm WELL WATER WITH ELECTRODIALYSIS— A FIVE YEAR REPORT

by
Henry C.. Valcour, Jr.
and Kevin D. McElhinney
Ionics, Incorporated

Presented at - Water, The Essence of Life
Conference - Manama, Bahrain - Nov./Dec. 1981

Desalting 36,000 ppm Well Water With Electrodialysis – A 5-Year Report

By Henry C. Valcour, Jr. and Kevin D. McElhinney
Ionics, Incorporated

ABSTRACT

The author reported on the design and initial operation of this unidirectional electrodialysis plant in July 1977. The 36,000 ppm TDS well water is saturated with calcium sulfate and contains high levels of hydrogen sulfide (reported as high as 190 ppm). The 42,000 USGPD plant has now been in service for nearly 5 years and has never failed to provide the potable water needs of the desert camp that it serves.

The operation of the pretreatment section of the plant has been modified to reduce the amount of lime fed to the solids contact clarifier, thereby reducing the quantity of acid required for pH reduction of the feed water.

The only major modification to the electrodialysis portion of the plant has been the installation of new type anion membranes. The membrane stacks are now primarily equipped with two types of anion membranes, both of which operate at a lower electrical resistance and higher ion transfer efficiency. The result of these more efficient anion membranes is a lower power consumption and higher production rate. Improvements to the electrode system have resulted in continuous membrane stack operating periods of over 6000 hours between disassemblies.

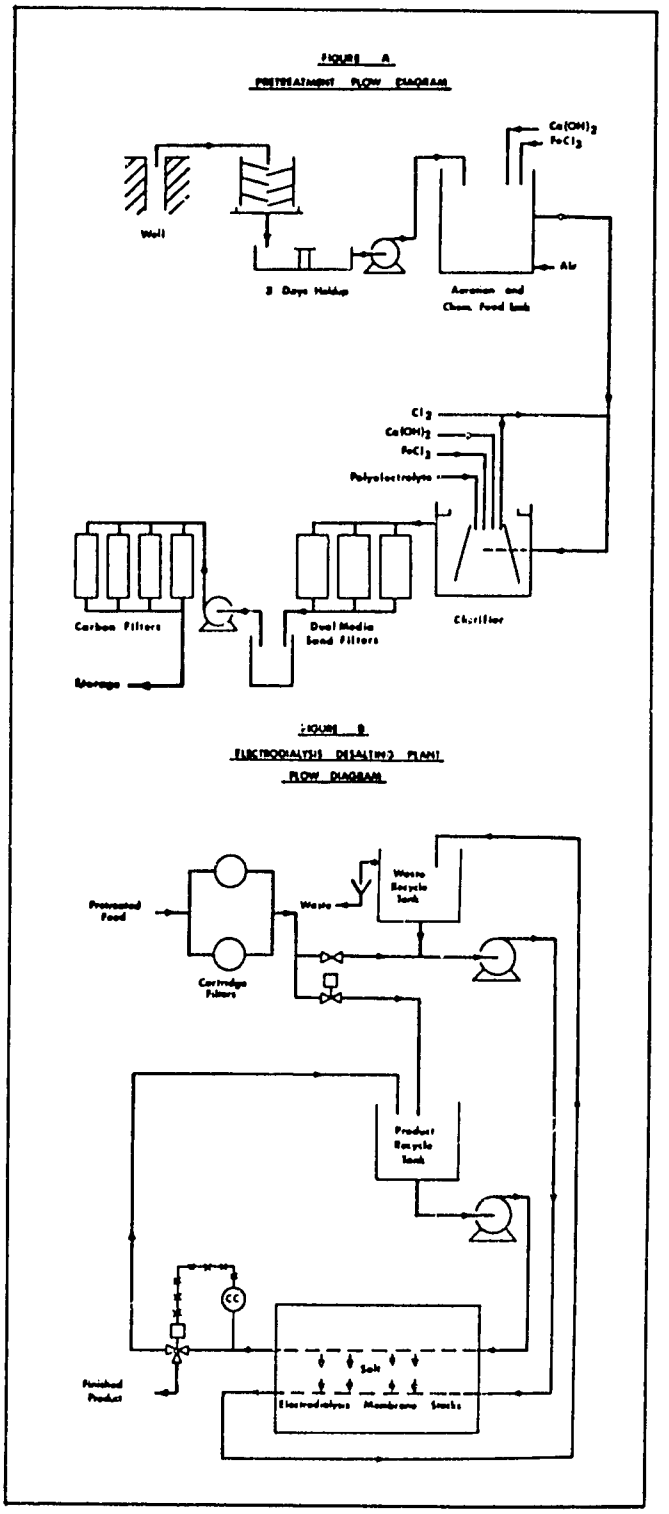
Equipment to increase the capacity of the plant by 50% is scheduled for installation and start-up in 1981.

INTRODUCTION

An electrodialysis (ED) water desalting plant was installed and started up at an oil gathering center in the Libyan desert in January 1977. The well water for the facility contains 36,000 ppm total dissolved solids (TDS), large quantities of hydrogen sulfide and is saturated in calcium sulfate. The product water output of the plant has been maintained at or above its 42,000 USGPD (159 m^3/d) design rate for nearly five years and has met the entire potable water needs of the people it serves.

The design and start-up of this unique ED application was reported by one of the authors in July 1977 (Ref. 1). The installation includes independent pretreatment and desalting sections. See Figures A and B. The 120 USGPM (27.3 m^3/hr) pretreatment plant was designed to remove all traces of hydrogen sulfide and includes aeration, a solids contact clarifier, dual media filtration and activated carbon polishing filters. Chemical feed capability includes hydrated lime, ferric chloride, polyelectrolyte and chlorine.

The ED desalting plant consists of four independently-operated lines of membrane stacks each with its own DC power supply. The two main hydraulic streams (the water being desalted and the waste water) are each recycled through their own fiberglass batch tanks. There is a constant feed water makeup and blowdown for the waste loop to carry away the salts removed from the desalted water in the membrane stacks. Separate small streams are used to flush the anode and cathode electrode compartments contained in the stacks. Acid is added to the waste and cathode streams to prevent calcium carbonate scaling. Sodium hexametaphosphate is also added to the waste water to control calcium sulfate.



OPERATING HISTORY

Initial Changes

The first few month's operation of the pretreatment portion of the plant indicated excellent results in removal of the hydrogen sulfide (H_2S) from the well water. In fact, the vast majority of the gas is eliminated to the atmosphere as the well water passes through a cascading type aerator before discharging to holdup ponds. The ponds provide approximately 3 days holdup time where any remaining H_2S is oxidized to sulfur. The clarifier and filter portion of the pretreatment system are relied upon to remove colloidal sulfur and other suspended matter. Temporary hardness is reduced by only approximately 25% in order to conserve lime and minimize subsequent pH adjustments.

The principal pretreatment operating problem is scale buildup in the 4 inch PVC raw water pipeline which extends approximately 300 feet from the raw water ponds to the plant proper. The scale is predominantly a mixture of calcium sulfate and calcium carbonate and is controlled with hydrochloric acid flushing once every 2 to 3 months.

Initial operation of the electrodialysis portion of the plant indicated the need to make two field modifications. The membrane desalting modules were rearranged to reduce hydraulic head loss and thereby insure adequate recirculation rates. The number of desalting stages was reduced but the membranes per stage were increased to maintain approximately the same total membrane area. A minimum water velocity must be maintained in the membrane cells in order to prevent scale formation due to hydrolysis of the water molecule.

Another early operational change was to replace sulfuric acid feed with hydrochloric acid. This was done to minimize calcium sulfate scaling problems within the membrane cells. The use of hydrochloric acid also eliminated a calcium sulfate crystalline growth experienced in the cathode electrode wash system.

MECHANICAL CHANGE

The above-mentioned need to provide adequate water recirculation rates was further enhanced by the use of larger diameters for selected pipe runs. Larger impellers were also fitted to the two main recirculation pumps which, fortunately, had large enough motors to handle the added loads. This additional head further insured the use of optional recirculation rates.

The single most time-consuming maintenance requirement in an electrodialysis desalting plant is the disassembly and reassembly of membrane stacks for servicing. Consequently, manufacturers and operators alike are always striving to prolong the period between stack disassemblies. The membrane stacks in use at this plant are of a configuration and size that requires from 10 to 20 man-hours to accomplish a complete servicing.

The use of more efficient electrode sealing and more durable electrode power connectors plus adequate care in reassembly has extended the time between stack disassemblies to over 6000 hours.

MEMBRANE CHANGES

An electrodialysis system includes two types of ion exchange membranes: anion selective and cation selective. The type of anion membrane originally specified for this plant (Ionics 103 QZL) exhibited signs of internal scaling by calcium sulfate within 1000 hours of operation. An ED system can operate successfully with small amounts of such scale. However, it was felt that this particular installation could not tolerate an anion scaling problem and a program was initiated to field test other types of anion membranes.

MEMBRANE SYSTEM CHANGES

An ED membrane desalting stack is constructed of multiple cell pairs arranged hydraulically in parallel but electrically in series. Each cell pair consists of two membranes (anion and cation) plus two hydraulic flow paths. One path contains fluid being desalted; the other path contains fluid being concentrated.

There are two plant operating parameters of particular interest in this installation that are affected by certain properties of the anion membrane used to make up the cell pairs. These anion membrane properties vary enough among the different membranes available to make significant differences in the power consumption production rate of a given plant.

Electrical power is consumed in an ED plant to move the dissolved salts through the membranes and thereby reducing the level of total dissolved solids, in this case from 36,000 ppm to 500 ppm. (It should be noted that power consumption in a high salinity ED application depends to some extent on the membrane area used in the facility. An economic balance must be achieved between the added capital cost of additional membrane area and the resulting lower power consumption.)

The use of anion membranes of differing electrical resistivity will, therefore, have an effect on the power consumption of a given ED installation.

Power consumption is also affected by the efficiency of the membranes. Efficiency in this case is a measure of just how effective the anion selective membrane is in not allowing cations also to be transported through the membrane and cation selective membranes not allowing anions to pass.

Production rate of an ED plant is affected by the amount of water transferred through the membrane with the dissolved salts. The amount of water transferred is a function of the electrical current being used and, of interest in this instance, varies with the chemical structure of the anion membrane.

Several new formulations of anion membranes became available subsequent to the construction of the ED plant. Consequently, the program to try various anion membranes had the goal of not only eliminating scaling problems but also of increasing production. The desire to increase production was supported by the owner of the plant in order to contend with increasing demands for potable water.

The various anion membranes were tested by replacing an entire anion set in a given membrane stack. This provided the ability to closely monitor performance and measure changes. Two types of anions (referred to by Ionics, Incorporated as 204 SZL and 204 RZL) showed particular promise and were inserted in two entire lines of membrane stacks out of the four that make up the plant.

Carefully monitored tests of these two lines have indicated a potential plant production increase of over 20% when all anions are eventually replaced. The greater production is due to higher salt transfer efficiencies rates. This benefit is in addition to achieving the original goal of eliminating the calcium sulfate scaling problem. Testing also indicated a 20% potential reduction in desalting power consumption if plant production was maintained at its design level of 42,000 USGPD (159m³/d).

The other two lines of membrane stacks are fitted out with other types of test anions which are operating satisfactorily but not as well as the 204 series. They will be kept in use until no longer serviceable, at which time they will be replaced by the newer types.

CURRENT STATUS

The plant is approaching its fifth anniversary of operation and has never failed to meet the potable water demands of the camp. Owner's personnel staff the plant during the daytime shift. The plant runs unattended for the other 16 hours. Operation is generally maintained on a continuous basis with one or two of the four separate lines turned off and on to suit product water requirements. Overall demand varies with camp population and ranges from 75% to up to 120% of rated plant output of 42,000 USGPD. Peak loads which can last for several days are met from increased plant output and from product storage.

As mentioned previously, membrane stack maintenance, which requires disassembly of a stack, has been reduced considerably since the plant was commissioned in January 1977. Stacks are averaging 5000 hours between disassemblies, thus necessitating a servicing of one of the eight stacks in each line every three or four weeks.

Table A contains current typical operating data. Power consumption varies with the feed water temperature and the figures shown can be considered as average over a 12 month period.

TABLE A

OPERATING DATA

RAW WATER TDS	36,000 ppm
RAW WATER TEMPERATURE	75°F
PRODUCT WATER TDS	500 ppm
PRODUCTION	45,000 USGPD (170 m³/d)
WASTE	70,000 USGPD (265 m³/d)

Chemical Consumption - Expressed as pounds/1000 U.S. Gallons of product water.

Lime (as 90% CaO)	14.1
Ferric Chloride (as 39.6% $FeCl_3$)	0.810
Hydrochloric Acid (as 28% HCl)	18.21
Sodium Hexametaphosphate	9.23
Polyelectrolyte	0.006

Power Consumption - Expressed as kwh/1000 U.S. Gallons of product water.

Pretreatment Section	8
ED Section	105

Table B contains the raw water analysis which has remained constant.

TABLE B

FEED WATER ANALYSIS

ELEMENT	ppm as the ion
Sodium	10,500
Potassium	375
Calcium	2,030
Magnesium	360
Chloride	17,900
Bicarbonate	1,270
Sulfate	3,580
TDS (Gravimetric)	35,700
pH	7.1

CONCLUSIONS AND OBSERVATIONS

The nearly five years of operational experience of this installation has demonstrated the ability of electrodialysis to reliably handle high TDS and high calcium sulfate waters at attractive recovery rates. Many factors have contributed to the success of this installation, but two that stand out are the durability of the membrane stack components and the dedication of the operating staff.

The availability of new anion membranes with lower electrical resistivity and lower water transport values provides the ability to build an ED sea water desalting plant of reasonable capital cost with desalting power consumption in the 40 to 50 kwh per 1000 U.S. gallon range. The increased resistance to fouling of these new anion membranes and the mechanical improvements to membrane stack construction have resulted in greatly reduced stack maintenance requirements and extended membrane life even on high salinity applications.

An additional measure of the success of this ED application is the fact that the owner has purchased an additional plant to increase rated plant output by 50%.

REFERENCE

1. Desalting 36,000 ppm Wells in the Libyan Desert with Electrodialysis; by Henry C. Valcour, Jr.; presented at the National Water Supply Improvement Association, 5th annual meeting at San Diego, California - July 1972.

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DESIGN, CONSTRUCTION AND OPERATION OF 1.2kW PHOTOVOLTAIC REVERSE OSMOSIS DESALINATION PLANT

W.L. James, B.E., M.I.E.Aust. – M.ASME – M.ASHRAE, M.AIRAH, Projects Engineering, Seriwa.

SUMMARY A photovoltaic-reverse osmosis desalination plant producing 500 to 1,000 lts/day of drinking water is described. The project is a joint venture between Mobil Oil Australia Ltd, its United States affiliate Mobil Solar Energy Corporation, the Western Australian company Osmotron Australia and SERIWA.

The plant has been installed at the SERIWA/SECWA Test Centre and has been operating continuously seven days a week since April 1982 and with the exception of a few controller problems is proving to be a reliable combination requiring little or no maintenance. Controller logic and selective loading can make better use of the photovoltaic array. Although the plant in its present form is not yet competitive with conventional systems, developments in both fields point to lower costs.

GENERAL

Mobil Oil has installed several solar desalination plants in the Middle East using Mobil Solar Energy Corporation's U.S.A. ribbon cell modules.

This project is an experimental solar desalination unit which in the future could assist Western Australia's water situation in remote areas, using the State's greatest natural energy resource - sunshine. Because the need is mainly in remote areas beyond the electricity grid such as roadhouses and homesteads, the emphasis has been on reliability.

SYSTEM DESCRIPTION

The photovoltaic array was designed to be used as the power source for the desalination system and for a separate pump to draw water from the ground. Due to the impracticality of drilling a bore hole at the Test Centre, it was decided to replace it by a simulated load. In this case an A/C load using a static inverter was chosen to gain an operating experience with inverters.

The photovoltaic array output is directed through the controller which regulates the array output to the desalination plant, inverter and battery. Current from the array that does not go to the desalination plant and inverter is directed to charging the battery. When the array is not producing sufficient current to supply the desalination unit or inverter, the battery provides the needed extra energy. The controller also provides a signal to an external relay to automatically disconnect the desalination unit when the battery drops to a low voltage and also starts the R.O. unit when there is sufficient sunlight.

A small metal shed houses the battery bank, system controller, inverter and reverse osmosis unit. A five metre high stand supports the raw water feed tank which gravity feeds the saline water to the R.O. unit. Both the desalinated (drinking) water and concentrate (waste high salt solution) are returned to the tank for re-mixing.

The reverse osmosis principle consists of pressurising a saline water solution across a semi-permeable membrane. Water molecules are permeated through the membrane while salts are effectively retained by the membrane and passed to waste.

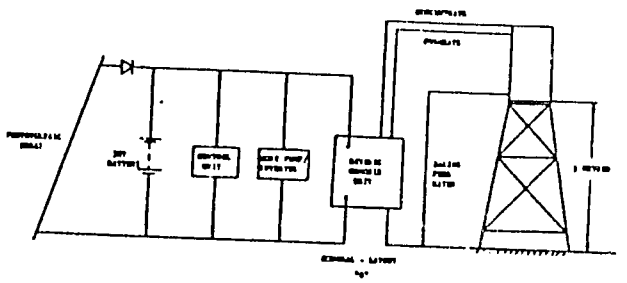


FIGURE I

SYSTEM OPERATION

Photovoltaic Array Subsystem

The PV array is the power supply for the desalination system. It provides power to the desalination unit during the day as well as charges the batteries which supply energy when the sun is not out. The array is rated at 1200 W peak, i.e. 1200 W at an insolation (solar intensity) of 1000 W/m² at 28°C cell temperature. It will supply a 22 ampere load for eight hours on a clear day.

The PV array consists of 30 Mobil Solar Energy Corporation Ra40 modules wired in six parallel strings of five series modules each. Each module is supplied with an integral by-pass diode to protect against the loss of the power output of a whole array if one module is shaded or damaged.

Array output power depends on insolation, temperature and dirt accumulation. The total energy available to the array is proportional to the direct intensity of the sun multiplied by the cosine of the angle between the sun and the normal to the plane of the array. Output power

also depends on temperature. For a given insolation level, array peak power decreases with increasing cell temperature at approximately four-tenths of one percent per degree Celsius (0.004 C^{-1}). Over a period of time (and prior to rain or cleaning), accumulation of dirt will typically decrease the output by six to eight percent. In temperate climates, rainfall tends to wash the array clean, restoring the output to nearly its original value. In arid regions, it may be necessary to wipe the array front clean with a soft dry cloth every month or two.

The array is supported by a steel structure that includes telescoping legs for adjusting the array angle over a range of 25°. The support legs and feet are galvanised which will also reduce the maintenance requirements of the PV array subsystem by reducing corrosion. The epoxy-painted steel frame is designed for long life with minimal maintenance and will withstand wind loads of 350 kpa (230 mph). The wiring is enclosed in PVC conduit to protect the insulation. Drip loops and weep holes are provided in the junction boxes to prevent moisture build-up within the conduit.

Control System

The control subsystem consists of a voltage regulater and a load disconnect interface. The regulator limits the array output to the battery to prevent overcharge; the load disconnect interface provides a signal to an external relay which automatically disconnects the desalination unit at some low battery voltage to prevent battery over discharge. The controller components are conveniently located in a weathertight enclosure which is mounted inside the desalination shed.

The voltage regulator is a shunt regulator which has been specifically designed for applications containing solar PV solar systems with lead-acid batteries. The regulator output voltage is temperature compensated to optimise battery charging voltage as a function of temperature. A separate Schottky diode has been incorporated to prevent battery discharge through the array during periods of no sun (e.g. at night).

A master-slave configuration has been utilised to limit the battery charging current. There are five slave units connected in parallel with the master, each controlling up to 6 amperes. The master regulator develops a voltage reference which is temperature compensated to assure that the battery is not over or under-charged. This compensation is achieved by the use of a remote, linear temperature sensor which is located in the battery's electrolyte.

When the battery approaches a state of full charge, the voltage sensor turns on transistor Q1 (see Figure II) at 38.4 V at 25°C which short circuits the array output. In this manner, excess power is dissipated in the array rather than by a massive shunt regulator. PV arrays can be operated continuously in a shorted condition without damage or degradation. During periods when the array is shorted, the battery is isolated from the array by the blocking diode, CR1. When the voltage drops by 1.2 volts from the 38.4 V, 25°C reference (or, to 37.2 V at 25°C), the transistor is switched off, removing the short across the array.

When the batteries reach a low state of charge, i.e. if the terminal voltage drops below 32.0 volts, the master regulator provides an output signal to an external relay to automatically disconnect the desalination unit.

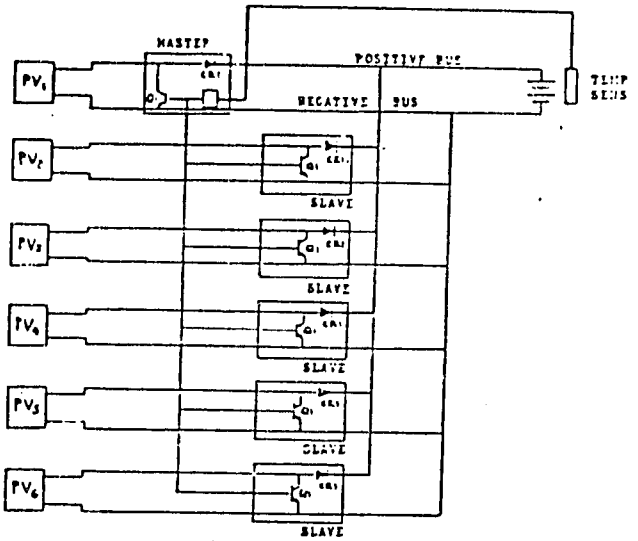


FIGURE II: SIMPLIFIED DIAGRAM OF MASTER/SLAVE SET-UP

(This voltage is factory-adjustable.) The unit is reconnected based upon two conditions, 1) if the battery voltage is greater than 32 volts and 2) if the array voltage shows that there is sufficient sunlight to provide power (via the PV array) to the desalination unit and charge the batteries.

The output signal provided by the master regulator is meant to open and close an external relay which would connect and disconnect the desalination unit (12 A dc for the pump plus 10 A dc for the inverter).

REVERSE OSMOSIS UNIT

The Osmotron unit uses a one-third HP, 32 V dc motor which drives a positive displacement pump. The machine will deliver 500 to 1000 litres of drinking water for an 8 to 10 hour daily operation with a salt rejection rate of approximately 88%. That is, the permeate salinity content will be approximately 12% that of the feed water. The expected recovery rate of 20% is the ratio of the volume of drinking water produced as a percentage of the water feed volume. This particular unit uses cellulose acetate membranes. The approximate maximum input salinity level recommended in 5000 ppm of total dissolved salts.

BATTERY BANK

A nominal 32 V battery bank is used for system starting and to achieve continuous operation during periods of intermittent solar radiation during the day. (The system controller does not allow operation outside of sunrise and sunset.) The type of battery chosen was the Dunlop tubular positive plate traction battery type 3 No. LTN 106V and the total capacity is 3.4kWhr. The batteries are housed in a steel box inside the shed.

PERFORMANCE

The system has operated continuously since April 1982 and it si monitored with a Hewlett Packard HP-1000 computer-data acquisition system. The volume of saline water, desalinated water and the state of charge of the battery (specific gravity) are manually recorded.

ARRAY

The silicon cells are manufactured by Mobil Solar Energy by the edge-defined, film fed growth (EFG) method. The main features of the EFG technology include the ability to grow crystals of a predetermined shape, such as ribbon, which obviates the need for slicing and polishing crystals.

The array is facing north and it has telescoping legs which allows tilt adjustment. No cleaning has been carried out as winter rains have kept the surfaces clean. The typical maximum array power output has been in the order of 900 watts for midday AM1 autumn - winter - spring conditions. Solar radiation can exceed 1000 W/m² on clear days and average ambient temperatures of 15° to 25°C at midday.

The array efficiency is in the range of 5% to 8% with a typical figure being 6.5% at one sun, AMI and ambient temperatures at 25° to 30°C. It is expected that the array efficiency will be lower for summer with midday temperatures of 35° to 40°C. See Table I and Figure IV for typical clear day performance values.

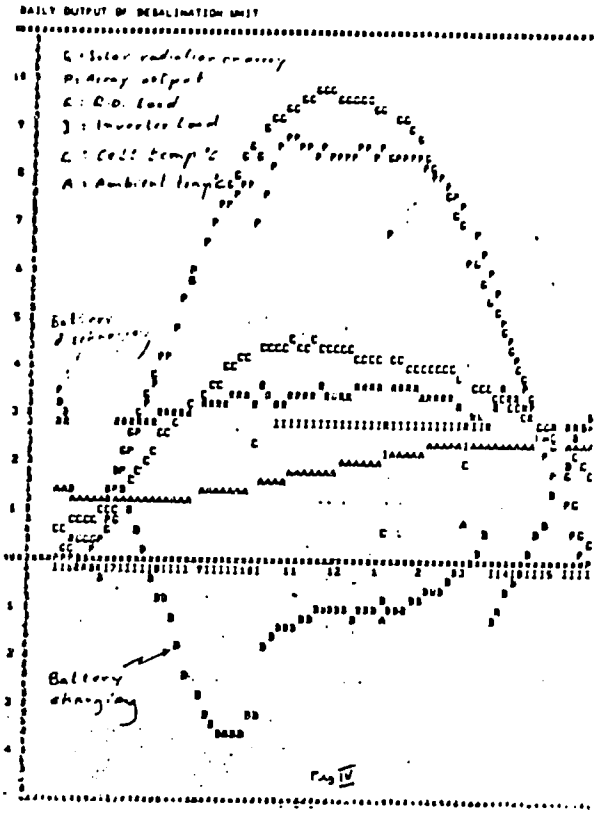


FIGURE IV

DESALINATION PROJECT

DATA FOR DAY NO. 300 FIRST RECORD AT 5: 40: 46: 54:
AND TAPE RECORD NUMBER 15 AT 309

TIME	SOLAR RADN	PV O/P	BATT	RO UNIT	INVERTER	TEMPERATURES AMBIENT	P.V. CELL	ROOM	FEED H2O	SALINITY PRODUCT	EFFICIENCIES SYSTEM	ARRAY
	ENERGY FLOWS											
	Kwhr	Kwhr	Kwhr	Kwhr	Kwhr	°C	°C	°C	°C	ppm	%	%
[illegible]	.004	.00	.10	.10	0.00	13.1	6.5	15.4	10.5	489.5		.16
[illegible]	.620	.02	.04	.03	0.00	12.8	8.5	14.3	11.1	471.1	5.28	3.93
[illegible]	4.075	.24	.00	.30	0.00	12.6	16.5	16.0	12.4	495.0	7.33	5.94
[illegible]	7.863	.51	-.15	.32	0.00	12.8	29.0	16.2	15.9	498.5	4.10	6.47
[illegible]	11.663	.73	-.34	.35	0.00	13.9	30.0	16.5	19.8	503.3	2.97	6.27
[illegible]	13.073	.80	-.25	.35	.14	13.1	40.7	14.2	21.4	503.4	3.54	5.77
[illegible]	14.902	.86	-.12	.37	.31	17.8	44.8	17.4	28.9	512.8	4.54	5.73
[illegible]	14.031	.85	-.10	.37	.32	19.8	43.5	17.9	30.9	517.6	4.63	5.71
[illegible]	13.931	.82	-.10	.36	.30	16.3	35.4	13.1	26.0	513.1	4.79	5.07
[illegible]	12.066	.70	-.05	.36	.31	23.4	39.8	19.0	33.3	527.3	5.59	6.48
[illegible]	8.723	.60	-.02	.33	.20	21.7	32.6	16.9	29.4	527.2	6.04	.05
[illegible]	5.479	.34	.01	.33	0.00	24.9	29.0	20.1	28.3	537.9	5.94	6.20
[illegible]	1.627	.06	.19	.25	0.00	24.8	21.8	20.3	25.1	543.6		3.95
[illegible]	.220	.00	.20	.19	0.00	24.4	16.8	20.2	21.2	547.2		.10

TOTAL DAILY AGGREGATE DATA

TOTAL ARRAY AREA = 15.53 sq. m

TOTAL DAILY SOLAR RADIATION (Kwhr) : 109.995
TOTAL DAILY P.V. ENERGY (Kwhr) : 6.611
TOTAL DAILY BATTERY STATE (Kwhr) : -.520
(-ve is drawn pv's , +ve is batt. output)
TOTAL DAILY R/O UNIT LOAD (Kwhr) : 4.002
TOTAL DAILY INVERTER LOAD (Kwhr) : 1.586
DAILY SYSTEM EFFICIENCY (%) : 5.080
DAILY P.V. EFFICIENCY (%) : 6.011

TABLE I

I-V tests have been carried out for single modules and sub-arrays. One of these is shown in Figure III.

REVERSE OSMOSIS PLANT

As noted the R O unit has a maximum input salinity level of 5000 ppm and on occasions this amount was exceeded.

The plant has been producing between 400 to 700 litres of drinking water for an 8 to 10 hour operation per day. Table II shows the plant output over a six month period.

The recovery rate began at 20% for low input salinity levels and subsequently declined to 16% to 17% for higher salinity levels but after an overhaul and cleaning the recovery rate increased

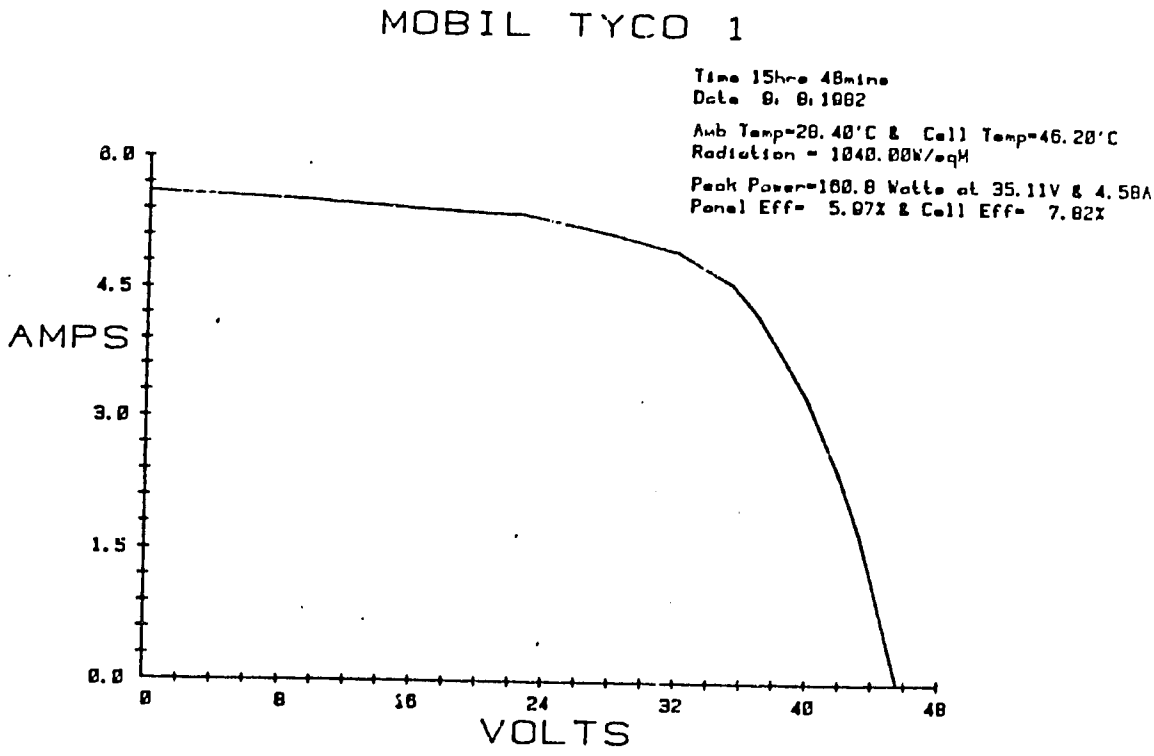


FIGURE III

TABLE II

PERIOD	FEED WATER SALINITY (ppm)	DRINKING WATER PRODUCED TOTAL (litres)	AVERAGE/DAY (litres)	ENERGY CONSUMED (kWh/m³)
MAY	2000	9277	618	4.0
MAY	2000	9064	604	4.2
JUNE	3000	4928	329	4.4*
JUNE	3000	5733	409	4.4
JULY	4000	5741	359	5.0
JULY	4000	7084	545	5.2
AUGUST	4000	6912	532	4.8
AUGUST	4000	10521**	619	5.8
AUGUST	3500	10438**	746	2.7
SEPTEMBER	3500	9097	827	4.2

* Controller installed
** Abnormal values due to monitoring failure

to 19% to 20% even at the higher salinity levels. The salt rejection rate declined from 88% to 83%.

The load characteristics of the DC motor have not been fully investigated at this stage. However, the manufacturer's specifications indicate an efficiency of around 65%. The data gathered tends to confirm this.

BATTERIES

The batteries have operated satisfactorily but for a controller failure which discharged the bank almost completely on one occasion.

From the data, even on the worst case day of very low solar radiation (still within the controller light threshold) the battery bank discharged only up to 0.9kWhr (approximately 2½ hours operation) which is 26% discharge from a fully charged state.

The battery bank has proven valuable in intermittent weather enabling a smooth plant operation.

A graph of battery state of charge versus load is shown in Figure V.

CONTROLLER

If the plant has had any problems, these have been due to controller and switchgear. Lack of experience with dc equipment as well as the scarcity of dc power components has led to some failures. These have been mainly related to relays as well as electronic components.

The reduced size of the battery bank and the two (R.O. and inverter) relatively large size loads caused frequent hunting of the controller switching. Changing controller set points showed a slight improvement only.

It was therefore decided to operate the loads separately and switch the inverter load controlled by system voltage. A small circuit was devised which switches the inverter on at 39 V and disconnects it at 35V (Figure VI). The inverter load tends to hold the array near its peak power point and prevents dumping of costly

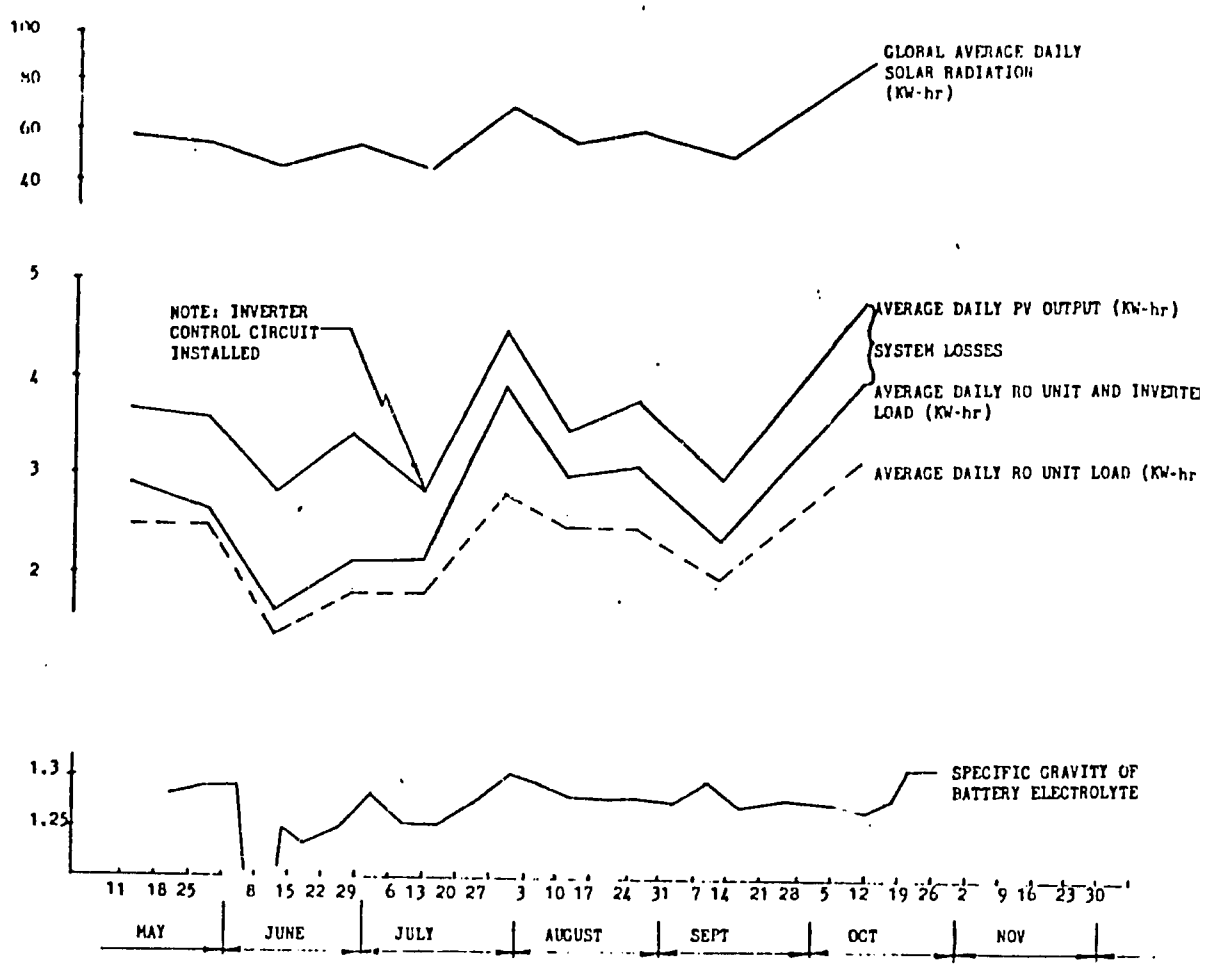


FIGURE V

photovoltaic array output. The effect is an increase in output and can be reaily noticed in Figure V.

CONCLUSIONS

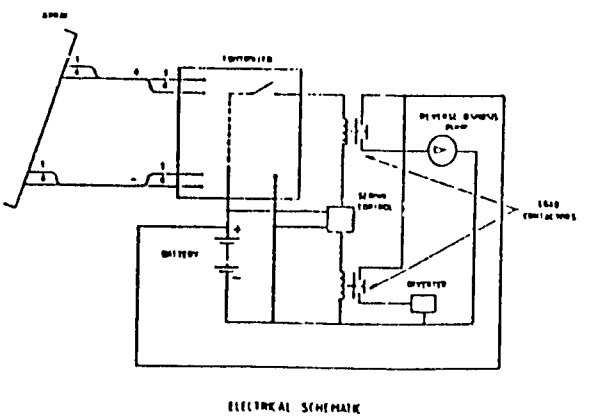
Photovoltaic and reverse osmosis are two fields of proven reliability and rapid developments.

Provided these developments reduce the capital costs they will prove an adequate solution for relatively non-attended applications. In some remote applications, reliability is sometimes more important than first cost.

The addition of batteries smooths the plant operation through periods of intermittent solar radiation and allows some energy collection in the early morning and late afternoon which would otherwise be lost with fixed or tiltable photovoltaic arrays. However, batteries require controls which generally prove expensive and reduce the reliability of the system.

Fixed arrays have a typical triangular energy output curve (Figure IV) through the day which makes it difficult to utilise it in an efficient manner. Generally loads are of a constant pattern and they have to be adequately fitted under this output curve to achieve a good degree of array utilisation. Ample battery storage can partially correct this but battery operation adds losses and costs to the system.

Where variable loads exist or loads with storage other than electrical (i.e. dc variable speed pump, water storage, ice making) these should be preferentially used to operate at the top end of the triangle, thus eliminating electrical storage. Most controllers in stand-alone equipment are designed mainly to protect the battery and therefore dump power which could otherwise be used. Emphasis should be aimed at developing reliable control devices that will switch these loads to make maximum use of this energy.Tracking arrays provide a more rectangular daily energy curve and can cope better with fixed loads. The daily output is also increased. The development of tracking devices for thermal solar collectors are gradually making them more reliable. In cases where wind speeds are not extreme and there is some degree of maintenance available, the tracking device should prove a better proposition.



ELECTRICAL SCHEMATIC

FIGURE VI

Mobil Solar Energy Corporation

PHOTOVOLTAIC POWERED SEAWATER DESALINATION SYSTEMS EXPERIENCE WITH TWO INSTALLATIONS

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ABSTRACT

Two photovoltaic (PV) powered seawater desalination units have been designed and fabricated for installation in the Middle East. The first unit, an 8 kW (peak) system installed near Jeddah, Saudi Arabia, has been operating since January 1980. The second unit, an 11.2 kW (peak) system will be installed near Doha, Qatar in early 1983. The second unit incorporates many improvements based on operational experience with the earlier unit. Both use a simple interconnection scheme that is commonly used with small water pumping systems but is unique in desalination systems of this size and complexity. In this scheme, the reverse osmosis (RO) desalination unit is directly connected to the PV array with a battery bank connected in parallel with the load. The absence of any voltage regulator or DC to DC converter in this interconnection scheme make these systems inherently very efficient and reliable. In both installations, the RO equipment has been specially designed by Water Services of America to operate on DC, so that this equipment could be directly connected to a PV power supply.

The simple interconnection scheme used in these systems does, however, impose some special constraints on the system design. This paper discusses some of the special design considerations presented by directly connected PV/RO systems. Such considerations include variations in flow rate through the reverse osmosis unit caused by fluctuations in the DC bus voltage and prevention of overcharge damage to the battery bank without a voltage regulator. It also explains how these design constraints were overcome in the two systems. Operational data from the Jeddah unit is presented. This data supports the conclusion that future commercial versions of these systems can be expected to have excellent overall system efficiencies.

INTRODUCTION

In the Middle East and in many other areas of the world, finding an adequate supply of high quality water is very difficult. This fact coupled with the desire to develop these areas for agricultural and other purposes has led to the construction of a large number of seawater desalination plants throughout the world. Most of these plants are powered by conventional energy sources, primarily oil and gas. However, the rising cost of this energy coupled with the fact that the arid areas of the world have very high insolation levels, has generated considerable interest in solar powered desalination systems. A large number of possible systems have been proposed. The simplest is the single effect solar still. Others have been fairly elaborate, such as high temperature

concentrating collectors running a multi-stage flash evaporator with an associated Rankine cycle engine to provide electricity for pumping. Until recently, all of these systems have been driven by thermal collectors. Over the last four years, Mobil Solar Energy Corporation has been designing and building photovoltaic powered desalination units as an alternative to these thermal systems. This paper documents our experiences to date with two units.

Reverse osmosis (RO) desalination equipment was used in both units. There are several reasons why RO was chosen for these systems. The first is energy efficiency. RO units will typically consume 30-80 watt-hours of electricity per gallon of product water produced from seawater. This compares very favorably with the 2400 watt-hours of heat energy required to produce one gallon of product water from a single effect solar still. It also compares favorably with the approximately 200 watt-hours required by a multi-stage flash evaporation (MSF) unit to produce a gallon of product. The second reason for choosing RO is the type of energy required. RO units require only electricity to operate. This electricity is used primarily to drive high pressure pumps. Also, RO units can be designed to operate on DC. Third, RO units are modular. They are available in sizes ranging from a few gallons per day (GPD) to many millions of GPD. All of these reasons combine to make RO an excellent choice in a PV powered desalination system.

Both of the units discussed in this paper are designed for use in the Middle East. The first is installed in Jeddah, Saudi Arabia. It has been operating since January 1981. The second unit, which incorporates several refinements in design based on experience with the first, will be installed in Doha, Qatar in January 1983. Both of these systems are 100% photovoltaic-powered with no back-up power source of any kind. The RO units in both installations accept feed water with a salt content of 42,000 parts per million (PPM) and are designed to operate on DC electricity. Both RO units were designed and built by Water Services of America in cooperation with Mobil Solar.

JEDDAH SYSTEM DESCRIPTION

The Jeddah system is owned and operated by Mobil Saudi Arabia, Inc. This unit, the first of its kind in the world, has been described in previous work (1,2,3). It has an array rated at 8 kW (peak) and it provides approximately 500 GPD of high quality drinking water from seawater for Mobil's employees in the Jeddah area. In addition, the installation is designed as a research station to investigate the operating parameters of systems of this kind. For this purpose, the installation includes a complete datalogging system which continuously monitors the performance of both the photovoltaic power supply and the desalination unit. The datalogging system is also

121

powered by the PV power supply since the entire installation is designed as a self-contained stand-alone system. There is no back-up power supply of any type. The data collected at this site has been used to verify the original design predictions and to refine operating procedures to achieve maximum output. This installation is also used as a demonstration center where the principles of photovoltaics and photovoltaic powered desalination can be explained to interested parties.

A schematic diagram of the water flow through the Jeddah system is shown in Figure 1. Feed water is pumped from a shallow seawell through the pretreatment section where it is filtered and the pH is lowered to prevent scaling of the RO membranes. The pressure is then boosted to 850 PSI at the inlet to the RO membrane assembly. Since one of the requirements at this site is very low salinity product water (less than 200 ppm), the RO membrane assembly has two stages. The product water from the first stage is repressurized to 200 PSI and fed into the second stage inlet. Coming out of the membrane assembly, there are two water streams. The waste water, which carries away the salt from the membranes, is reinjected in another seawell remote from the feed water well. The product water is degasified, pH adjusted, and sterilized before it is pumped to the storage tank. All of the pumps in this system operate on 240 VDC. This was done to avoid the energy losses and motor starting problems associated with a DC to AC inverter. This combined with the fact that DC motors in these sizes (14 to 5 hp) are more efficient than AC motors help to increase the overall system efficiency.

The electrical block diagram for the Jeddah installation is shown in Figure 2. In this system, the PV array is directly connected to the various loads with the battery bank connected in parallel with the load. The state-of-charge (SOC) controller shown in Figure 2 is an integrating amp-hour controller with low voltage protection which was custom-designed and built by Mobil Solar. There is no voltage regulator in this system; the DC bus voltage floats with the battery terminal voltage. Also, the system is designed so that the major loads (water treatment plant and well pump) operate in the daylight hours only. This means that a very high percentage of the energy generated by the PV array is used directly by the RO unit without passing through the battery bank. Increasing the overall system efficiency was the reason for both of these choices.

DESIGN CONSTRAINTS

All of the choices described above help improve the system efficiency but they also introduce some new constraints on the system design. One of these constraints is stabilization of the flow rates and pressures through the RO unit. In a conventionally powered RO unit, the pumps all operate at a

FIGURE 1: SYSTEM SCHEMATIC WATERFLOW

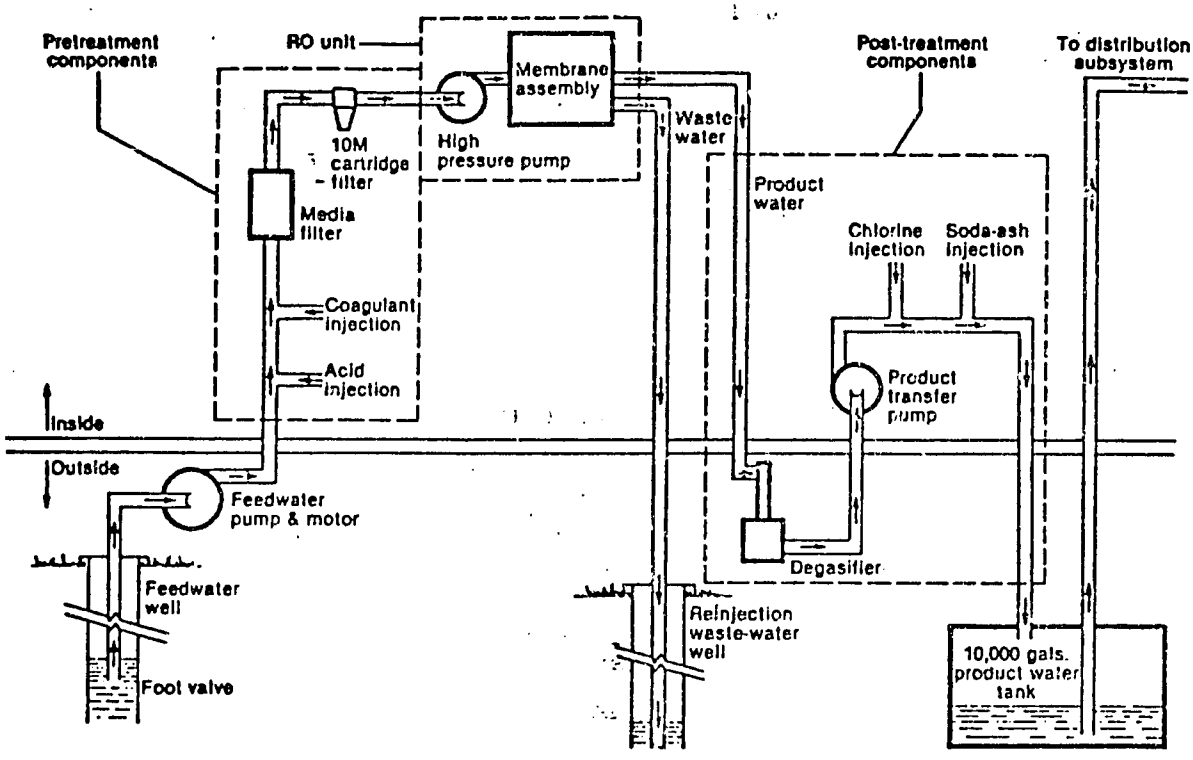
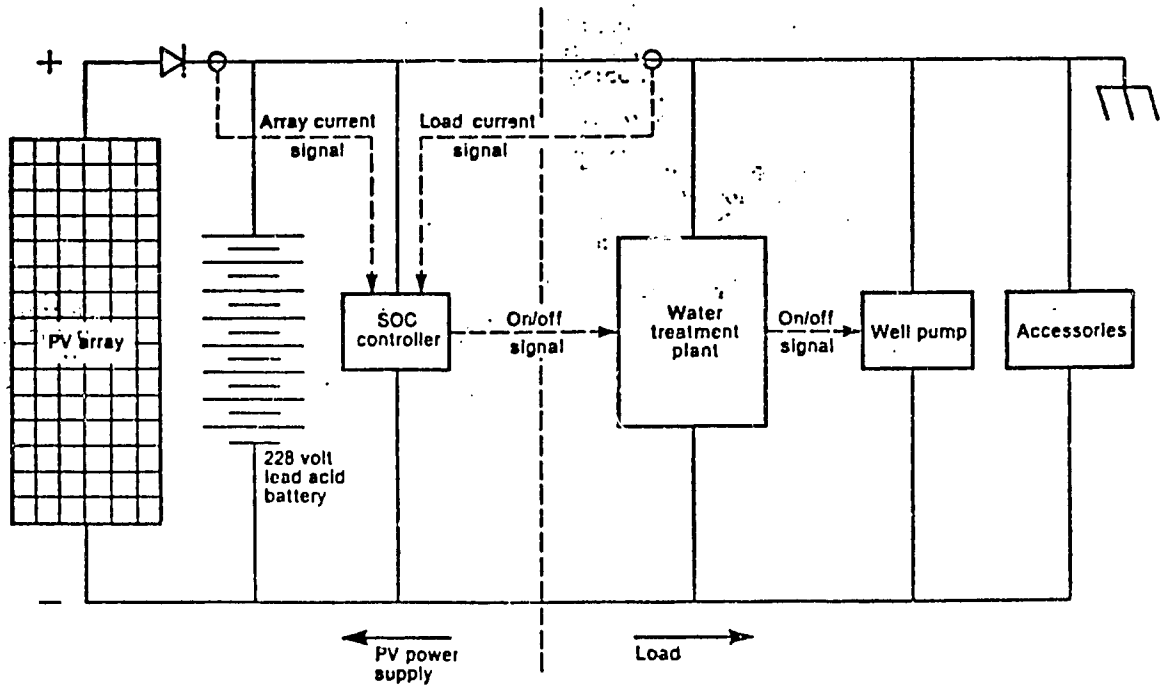


FIGURE 2: SYSTEM ELECTRICAL BLOCK DIAGRAM



constant speed because the AC input line is voltage and frequency regulated. The flow rates and pressures, therefore, stay fairly constant; they need only occasional adjustment. However, in a DC powered unit with a variable input voltage, the DC motors will rotate at varying speeds and, hence, the flow rates and pressures will vary. This feature becomes important in a two-stage RO unit like the one in Jeddah because the characteristics of the two high pressure pumps are not the same. Therefore, they do not change flow rates at the same rate when the input voltage varies. This causes the pressure in the interstage holding tank to vary erratically. This potential problem was designed around in the Jeddah unit by setting the first stage so that it produced sufficient water to feed the second stage at the lowest operating voltage and it produced a slight excess at higher voltages. The interstage tank is fitted with a pressure regulating valve which bleeds off the excess at high voltages. This excess is blended back into the first stage feed water. This arrangement effectively stabilizes the interstage tank pressure and the efficiency losses are quite small because the amount of water recirculated is quite low (less than 5% of the first stage product). Also, blending the excess first stage product water with the feed water lowers the feed water salinity which lowers the first stage membrane pressure and the pumping power required.

A second consideration that needs to be addressed in systems of this type is protection of the battery bank from damage by overcharging. Normal design practice in low-voltage systems is to have the peak power voltage of the array at the highest expected cell operating temperature be at or near the full charge voltage of the battery and to provide a voltage regulator to protect the batteries. The effect that this approach has, is that whenever the array is actually charging the batteries it is operating on the low voltage side of the peak power point. In these systems, the ratio between the nominal battery voltage (228 volts) and the array open circuit voltage (320 volts at rated conditions) has been reduced so that the array typically operates at the peak power voltage or slightly over. This has the effect of making the PV power supply self-regulating. When the RO unit is not operating, the system voltage rises sharply and the array current is depressed sufficiently to protect the batteries from overcharging. For the batteries used in these systems, the maximum charging current allowed when the batteries are above 95% SOC is 8 amps. In operation, the charging current drops to 8 amps at approximately 270 volts (2.37 volts/cell) and it drops to less than 1 amp at 290 volts (2.54 volts/cell). When the RO unit is operating, the system voltage varies from 228 to 245 volts except for short period in the afternoon just before shutdown when it drops below 228 volts.

124

OPERATING DATA FROM JEDDAH

Figure 3 illustrates the self-regulating nature of the Jeddah installation. It shows that the array output for the month of April, 1982 tracks the amount of energy available quite closely except for the period from 4/8 to 4/11. During this period, the product water tank was full so that the RO unit operated only a short time each day (see Figure 4). This caused the system voltage to rise which in turn caused the array current to drop sharply resulting in the dip in output shown in Figure 3.

Figure 4 shows the amount of energy supplied to the desalination plant and the amount of energy supplied to all loads for the month of April, 1982. The difference between these graphs is the amount of energy consumed by the datalogging equipment which is about 16% of the total energy. In a commercial system this energy would be available to produce more water. The overall system efficiency in Jeddah is very high; less than 8% of the energy generated is lost in the batteries and consumed by the controls. The desalination plant (including the well pump) consumes 65 WH/gal of product produced.

QATAR SYSTEM DESIGN

The design of the Qatar system incorporates several changes which will allow it to make more water per watt (peak) of array. The first of these is the elimination of the datalogging system. The Qatar system is designed as a prototype commercial system not as a research facility as in Jeddah. This change will increase output by 16%.

The second design change in the Qatar system is the elimination of the second RO stage. This will make the system simpler, eliminate the need for the bypass arrangement used in Jeddah, and increase the system efficiency slightly. On the negative side, it increases the product water salinity from less than 200 ppm to less than 500 ppm. However, this product water quality is still within World Health Organization recommended guidelines for drinking water.

The third major change in the design of the Qatar unit is the inclusion of an energy recovery unit. The waste water in a seawater RO unit exits the membrane assembly at pressures ranging from 700 to 900 PSI. Several possible methods exist for recovering some of the energy in this water stream and putting to good use. Energy recovery units are commonly used on larger seawater RO units, but are not normally used on small RO units because the energy savings does not justify the cost. However, if the RO unit is powered by photovoltaics, the cost of an energy recovery unit can be justified.

125

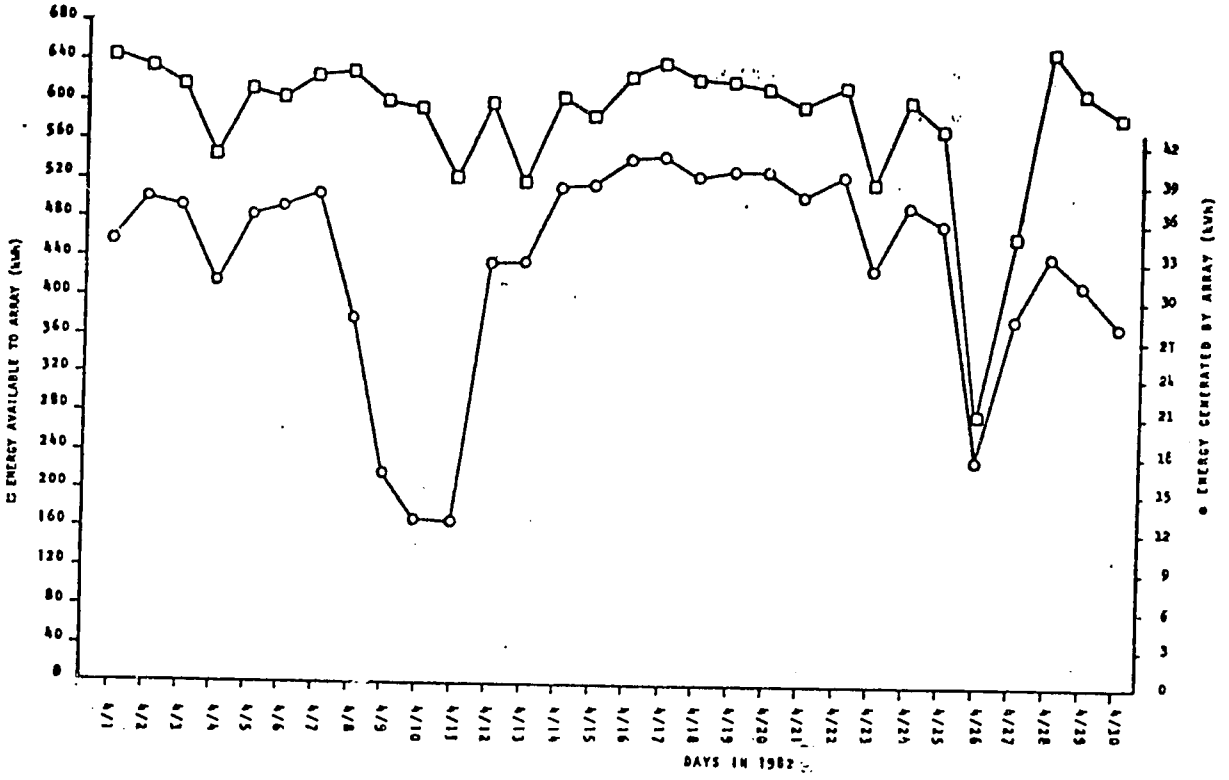


FIGURE 3: Energy Into/Out of Array

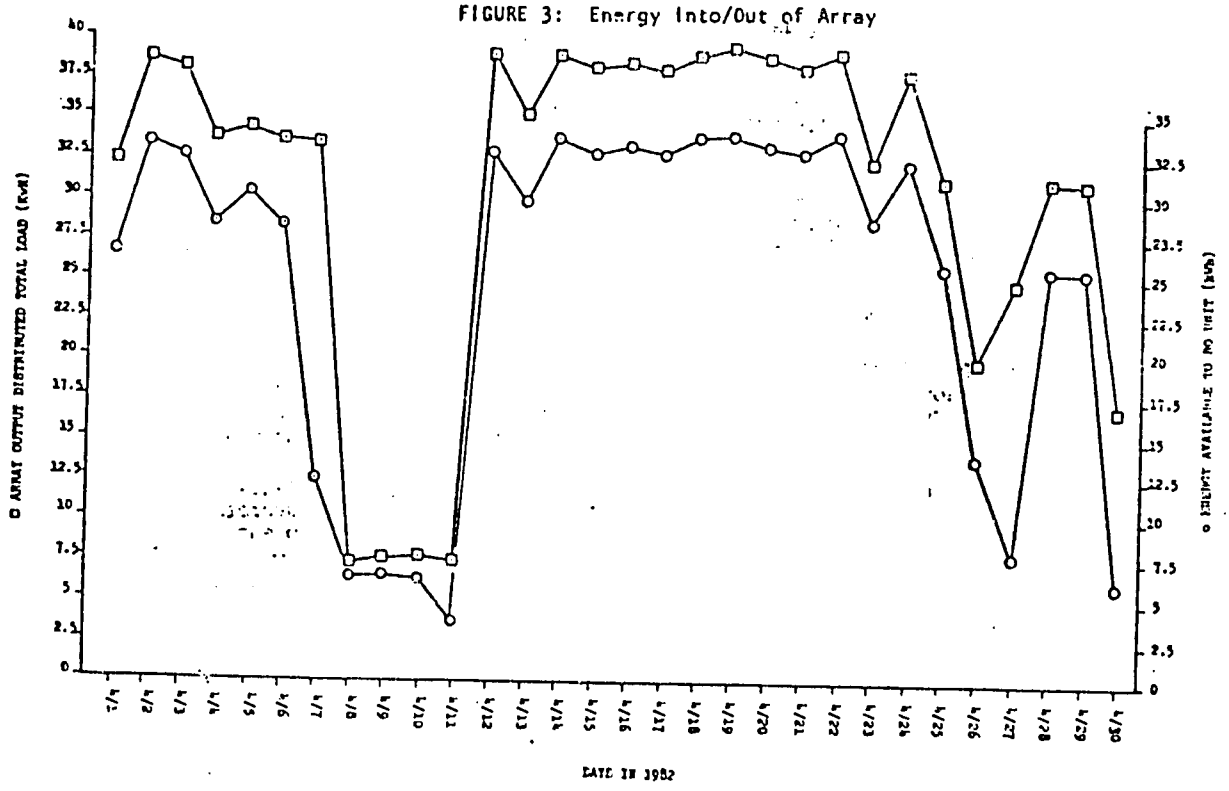


FIGURE 4: RO Unit as Portion of Total Load

126

As a result of these changes, both the RO unit efficiency and the overall system efficiency will be better in Qatar than in Jeddah. The RO unit in Qatar will require less than 40 WH/Gal of product water. The overal system will produce an average of 1500 GPD from an 11.2 kW (peak) array.

CONCLUSIONS

Based on Mobil Solar's experiences with PV powered desalination systems, the following conclusions can be reached. One, PV powered reverse osmosis is an excellent combination for solar powered desalination. Two, RO units can be made very efficient even in relatively small sizes. Three, very high overall system efficiencies can be achieved. Fourth, and finally, it should be possible to design future commercial PV powered RO systems that will desalt seawater with smaller collector areas and lower costs than other forms of solar powered desalination.

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2. J. R. Wood, J. L. Crutcher, A. J. Norbedo, A. B. Cummings, 15th IEEE Photovoltaic Specialists Conference (New York: IEEE: 1981) p. 1219.

3. Jerry Crutcher, "First PV Powered Desalination Unit Completes One Year of Continuous Operation, Modern Power Systems 2, 28 (1982).

127

CAPSULE PRESENTATION

Presented at

NWSIA CONVENTION
Washington, D.C.

June 2-4, 1981

BY

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Mobil Tyco Solar Energy Corp.
Walthan, MA

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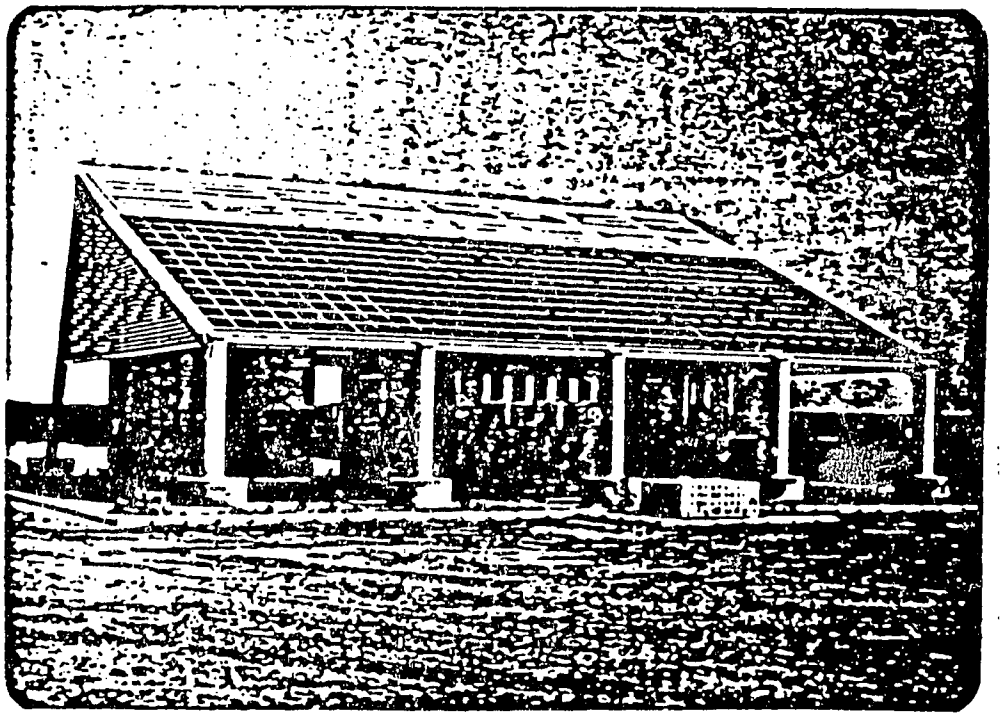
128

INTRODUCTION:

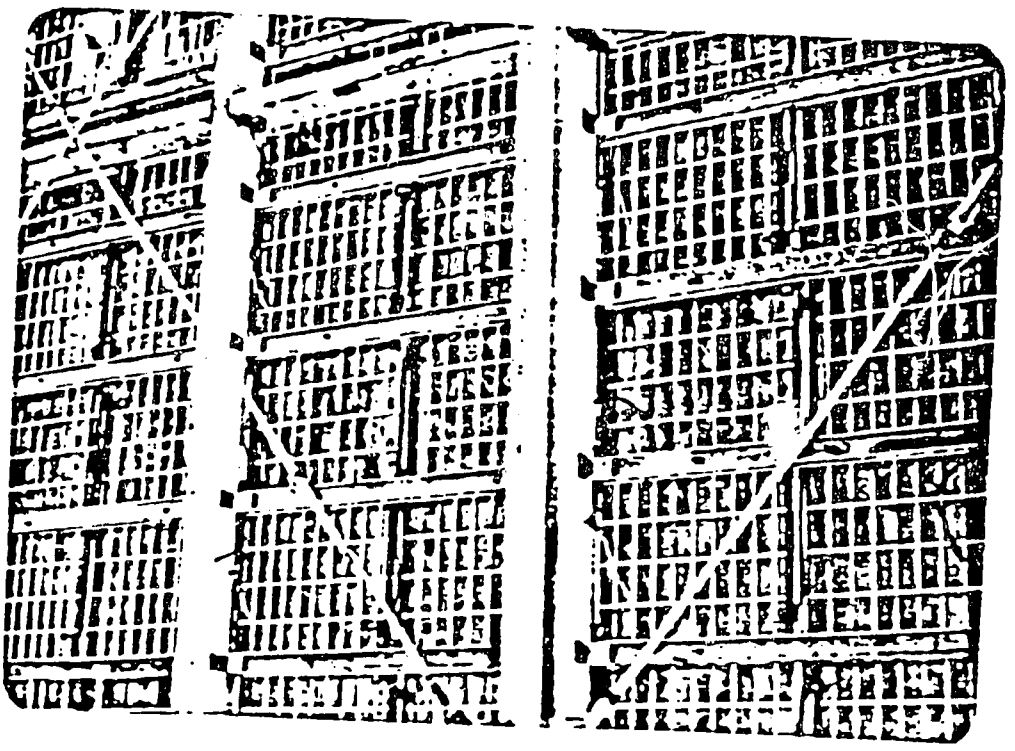
The World's first solar-powered seawater Reverse Osmosis system has been installed and is now operating in Jeddah, Saudi Arabia, on the eastern shore of the Red Sea. The system produces a quantity of water sufficient to meet the drinking water needs of a community of 250 people and also provide the power requirement of a complete digital logging system. The system is a "standalone" system with no power source except the sun. The complete system was designed and installed by Mobil Tyco Solar Energy Corp. and is owned and operated by Mobil Saudi Arabia. Water Services of America, Inc. designed and built the Reverse Osmosis system.



PHOTOVOLTAIC ARRAY:

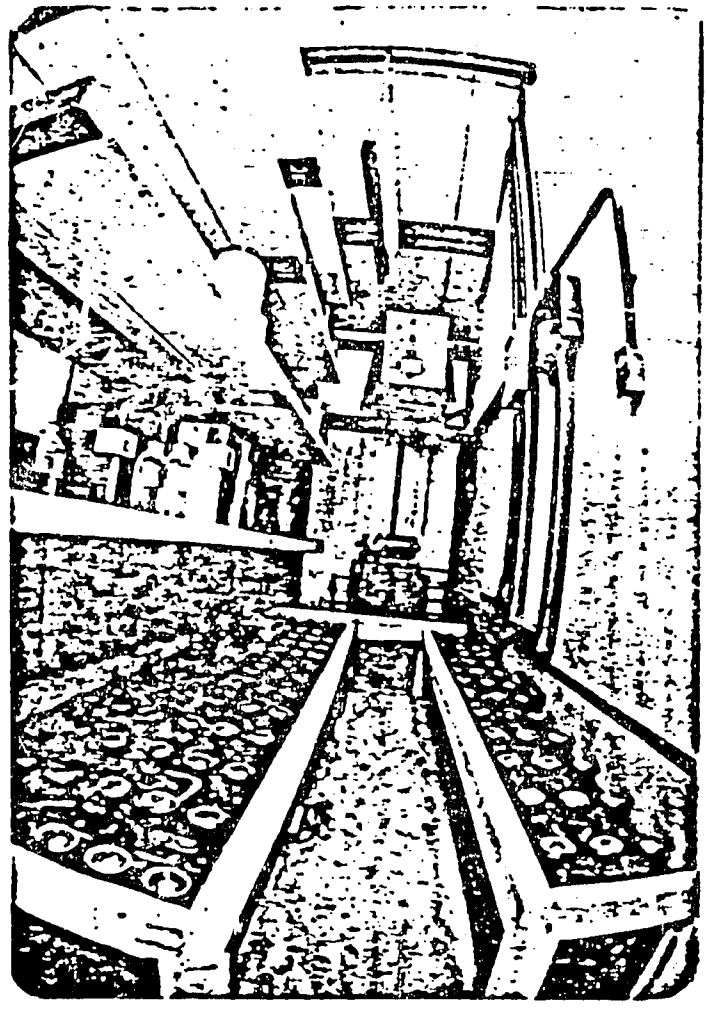
The power source is an 8 kW* (peak) array of Mobil Tyco ribbon photovoltaic modules. The module array support structure also serves as a sunshade for the equipment building. There are eighty 2" x 4" ribbon solar cells in each 17" x 44" module. The 210 modules were mounted in a 52' x 22' array. Overall array efficienty is 7.5% as a result of the high packing density of rectangular solar cells and the characteristics of ribbon technology. The array is tilted at the latitude angle of 23° and it is possible to walk on the array.

(*Under rated conditions of 100mW/cm^2 AMI insolation, 28°C cell temperature, operation at peak power voltage.)



BATTERY BANK:

The Battery Bank is made from a series connection of 40 lead acid units each having a 194 Amp. capacity, a nominal voltage of 6V and a cycling capacity of over 1,400 times. It acts as a short term energy buffer between the photovoltaic array and the electrical load.



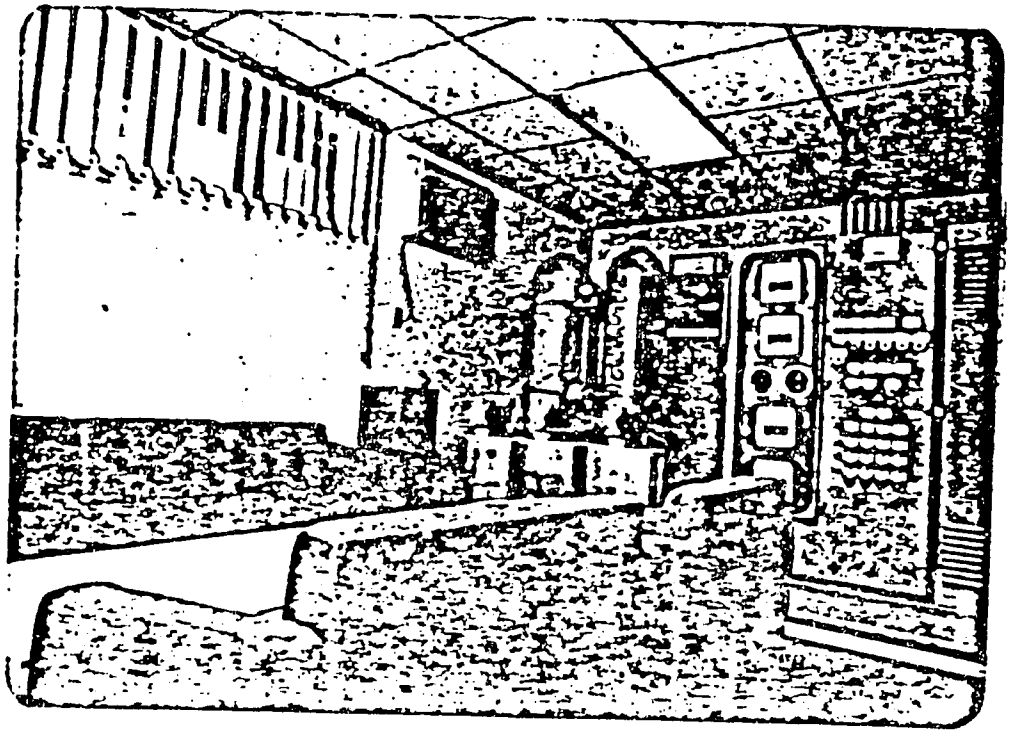
REVERSE OSMOSIS SYSTEM:

The feedwater is supplied by a seawell adjacent to the system. Water salinity is the same as the Red Sea or 42,800 ppm.

Desalination of Red Sea water requires ____% more energy than water of 37,000 ppm as found in other seas.

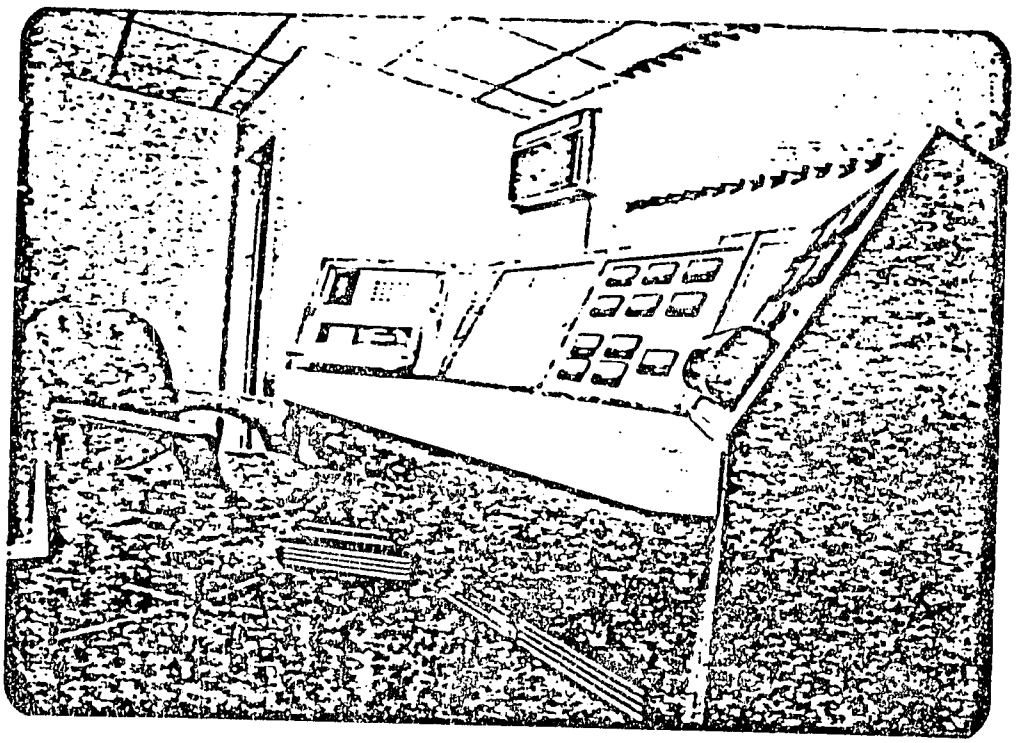
The RO system uses two membrane stages. The feedwater enters the first stage of two parallel-connected DuPont B-10 Permeators after acidification and filtration.

The product water then passes through the intermediate tank, is repressurized and pumped to two B-9 permeators reject staged. Overall recovery is 22% with a product flow of 1.2 gallons per minute. Water goes through degasification and then to atorage. Reject water goes to a nearby disposal well.



DATA LOGGING:

A digital computer with recorder, records 48 variables on magnetic tape every six (6) minutes. The data is being used to verify the validity of computer models used in the design phase.



DESALINATION SYSTEM CONSIDERATIONS:

- PROCESS DESIGN - Seawater Reverse Osmosis desalination technology was chosen because of the low energy consumption and ease of operation and maintenance. Seawater RO consumes less than one-half the energy of thermal desalination units.

- AC vs. DC - While usually AC induction motors are used in RO units, in a photovoltaic powered system it is desirable to use DC motors to avoid the cost, inefficiency, and starting-current complexities associated with an inverter. This, however, caused problems in that small DC motors available were not as efficient as AC motors. Also, RO system design became more complicated because of varying DC motor speeds which produces variable hydraulic operating conditions.

- EQUIPMENT RELIABILITY - Other energy tradeoffs were made at the expense of efficiency to assure a more reliable operation. For instance, an inefficient jet well pump was used in place of more efficient pumps.

- ENERGY RECOVERY DEVICES - Proven energy recovery pumps and turbines for a plant this small were not available at the time of manufacture. Such pumps are on test now and are under consideration.

WATER QUALITY - A decision was made to produce superior quality water. While single pass RO systems can produce water of 500 ppm quality, a second pass was installed to reduce salinity to below 100 ppm. This adds 25 to 30% to electrical consumption per 1,000 gallons product.

DELIVERY - The need for fast equipment delivery precluded design and ordering of more efficient equipment.

CONCLUSION:

Reliable water production to meet the drinking needs of small communities using the technologies of Seawater Reverse Osmosis and Solar Photovoltaic have been demonstrated. The abundance of sunshine in arid areas makes Solar RO particularly viable. Reliable system operation without other power source backup supplies has also been demonstrated. A simple DC power arrangement for the complete system has been shown to be effective.

The authors believe this demonstration system is just the start to more and larger Solar Powered Reverse Osmosis Desalination systems.

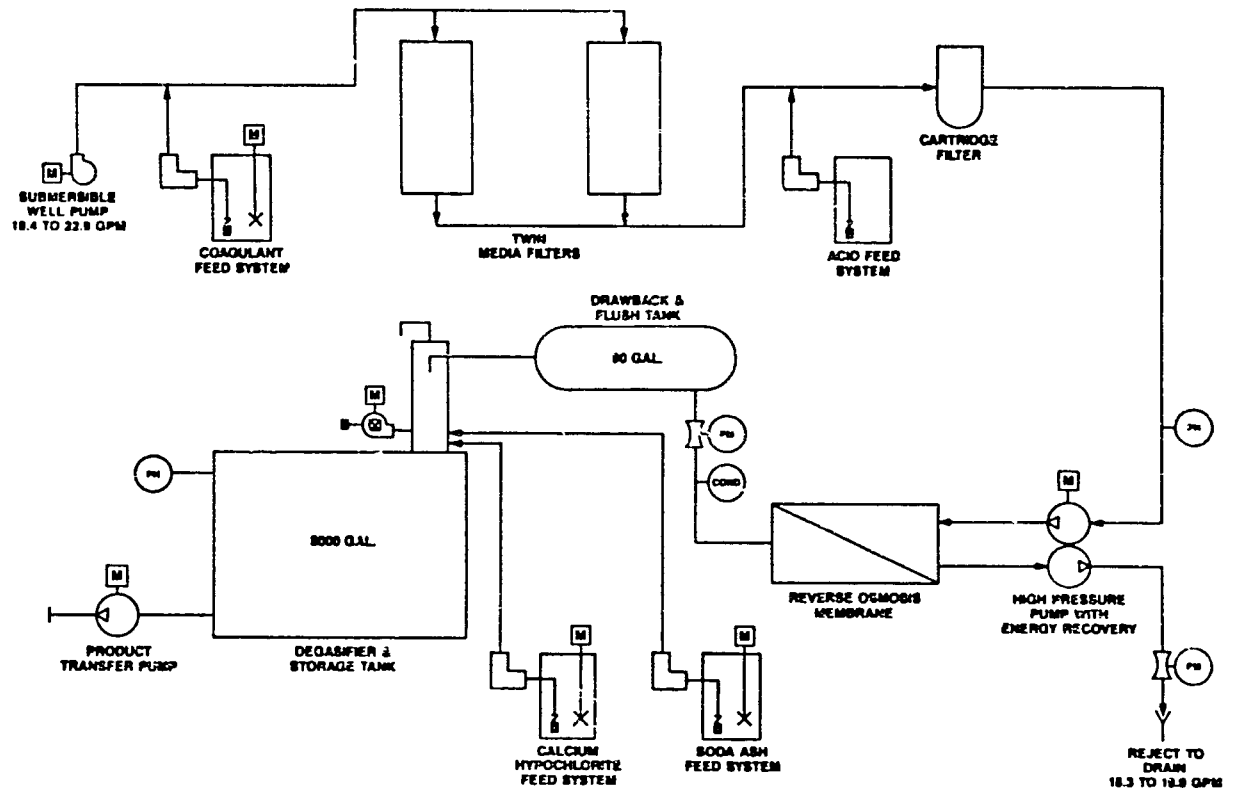
PROJECT SUMMARY

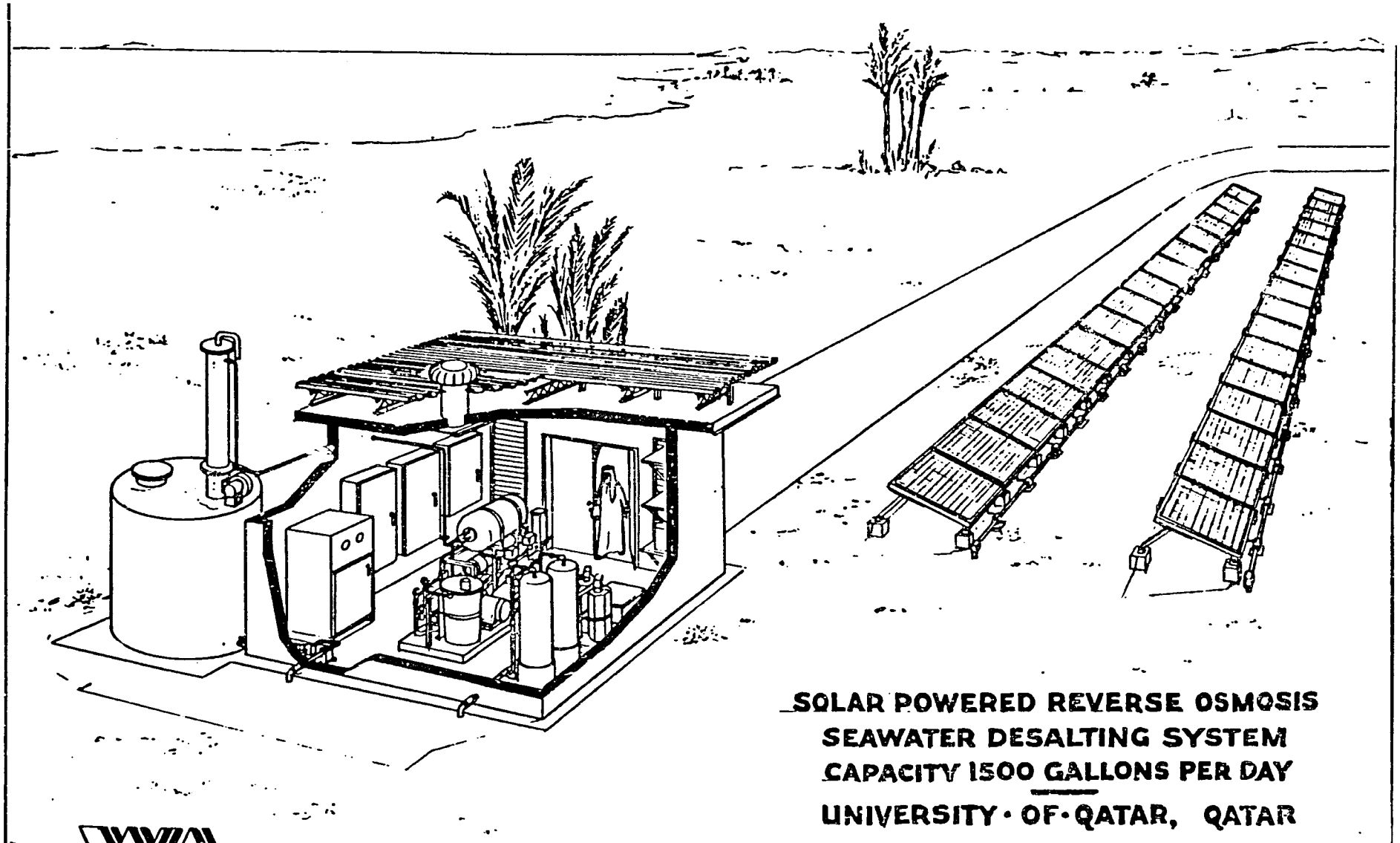
NAME: State of Qatar - Arabian Gulf
SIZE: 180 KGD
CONTRACT VALUE: $804,000
PLANT AWARD DATE: February 1981
PROJECT COMPLETION DATE: February 1982
CUSTOMER: State of Qatar
USE: Municipal Water Supply

PROJECT DESCRIPTION:

This plant is Qatar's first major Reverse Osmosis plant. This plant was a complete design, build, and commission contract with standy-by diesel power, connection to well field, connection to storage tanks, building, etc. Water Services' plant has demonstrated the reliability of Reverse Osmosis equipment in remote locations. The water produced by the plant supplies all of the drinking water needs for the remote population at the Saudi/Qatar border.

PROCESS DIAGRAM





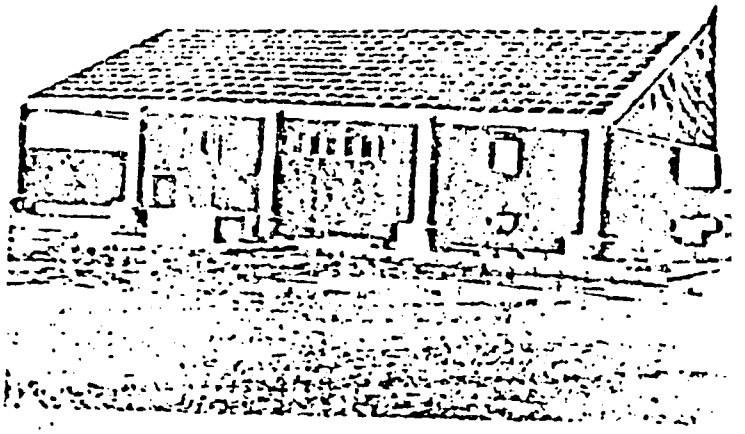
SOLAR POWERED REVERSE OSMOSIS
SEAWATER DESALTING SYSTEM
CAPACITY 1500 GALLONS PER DAY
UNIVERSITY · OF · QATAR, QATAR

DESIGNED AND BUILT BY WATER SERVICES OF AMERICA, INC. MILWAUKEE, WISCONSIN

WORLD'S FIRST SOLAR POWERED SEAWATER RO PLANT SUPPLIES WATER TO SAUDI ARABIAN FACILITY

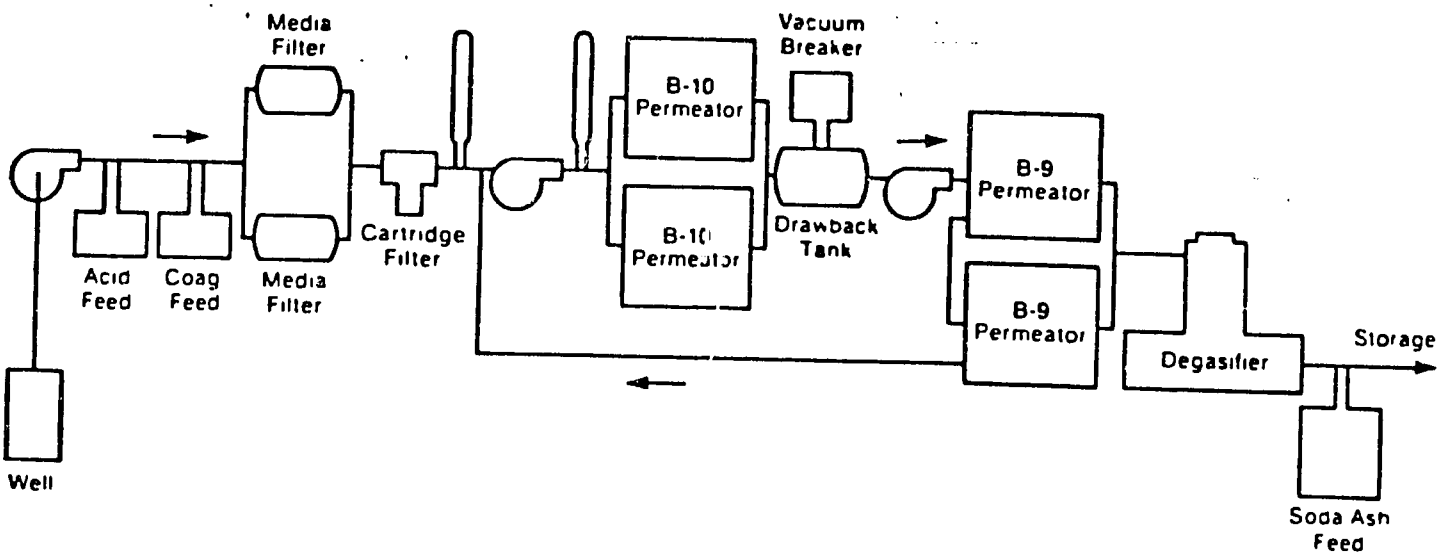
Abundant sunshine is helping to ease a potable water shortage at a club for Mobil employees near Jeddah, Saudi Arabia. The facility now receives its drinking water from the world's first solar-powered seawater reverse osmosis (RO) plant, which, in April, began desalting 1,000 gallons per day of seawater from the Red Sea. Using B9 and B10 Permeators, the RO system features Du Pont "Permasep" permeators.

The complete system was designed and installed by Mobile Tyco Solar Energy Corporation and is owned and operated by Mobil Saudi Arabia. Water Services of America, Inc. designed and built the RO system. The solar system uses an 8KW array of 210 ribbon photovoltaic cells to convert the sun's rays into electricity. A battery bank acts as a short-term energy buffer between the photovoltaic array and the electrical load.



World's first solar-powered seawater RO desalting plant is a "stand-alone" system with no power source except the sun. The module array support structure also serves as a sun shade for the equipment building.

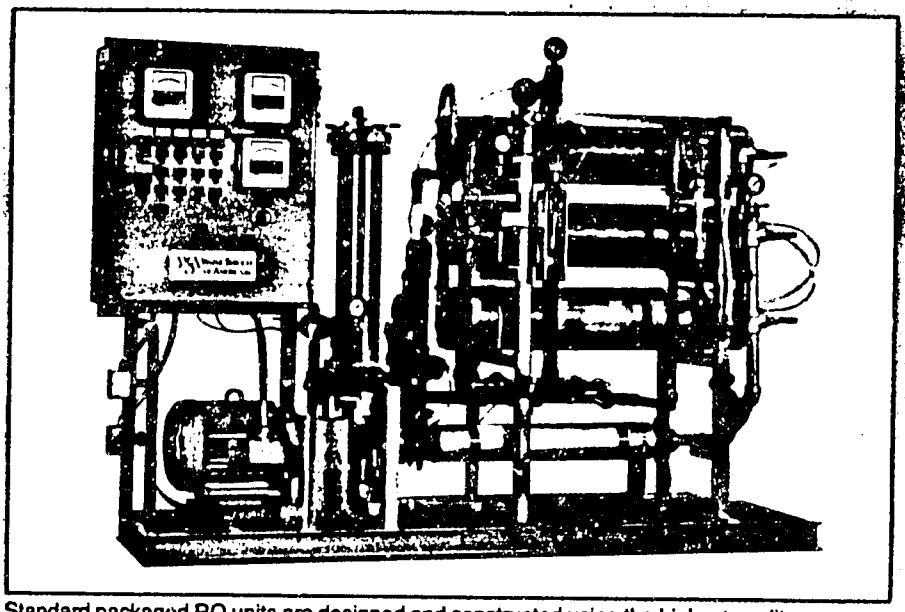
JEDDAH SOLAR POWERED UNIT



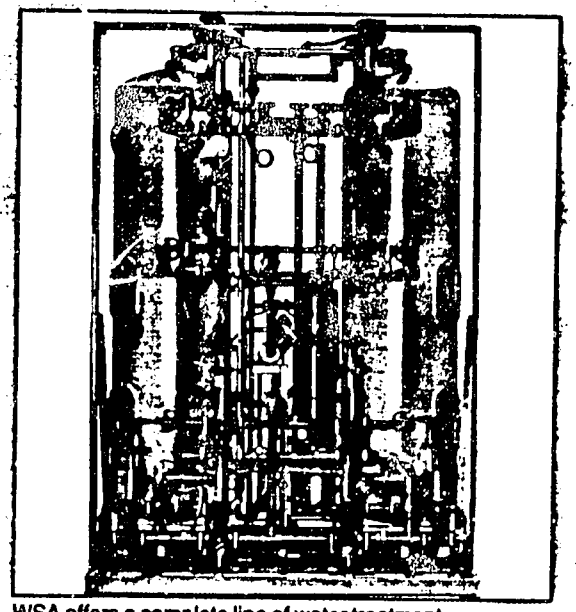
INTERNATIONAL DESALINATION AND ENVIRONMENTAL ASSOCIATION

WSA's Reverse Osmosis Systems purify sea and brackish water for the world.

WSA's Reverse Osmosis technology keeps pace economically with increased water demands.



Standard packaged RO units are designed and constructed using the highest quality corrosion resistant materials and state of the art controls and other proprietary design features which reduce operation and maintenance costs and provide long equipment life.



WSA offers a complete line of water treatment equipment for single source responsibility. Accessory equipment can be designed and built to complement and complete both standard and custom designed systems to meet various water quality requirements.

Our professional engineering staff and experienced field service group routinely take projects from concept to completion. This capability assures product uniformity and improvement, short term project completion, and customer satisfaction.

The Earth's supply of water is finite. The demand for potable water increases each year. Pollution becomes more serious and harder to control while industry requires higher purity water. The challenge is clear. Total cost effective energy efficient systems for pollution control, potable, process, and high purity water for municipalities, private water systems, resorts, offshore, and industrial installations are available from WSA.

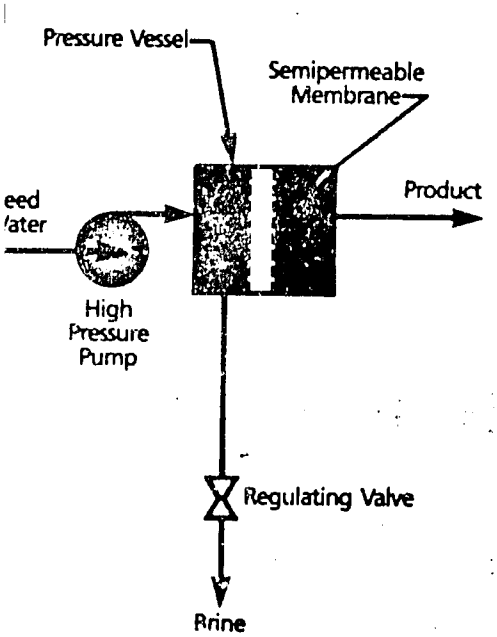
With proven technology and experience, WSA can provide solutions to your particular pure water requirements. Large or small, packaged or custom water treatment plants are designed, built, operated and maintained by WSA, a leader in the RO industry.

Learn more about the indisputable advantages of WSA's Reverse Osmosis technology. Please write for technical data sheets, and more detailed information on WSA RO installations.

WATER SERVICES OF AMERICA, INC.

Where technology is measured in payback.

P.O. Box 23848, Milwaukee, WI 53223 • Telephone (414) 354-6470 • TWX 910-262-3354 WSA MIL



SIMPLIFIED RO FLOW DIAGRAM

The world looks to Water Services of America for the latest application of Reverse Osmosis technology to meet the accelerating demands for fresh water. The need for fresh water on this planet grows at the rate of 10 to 15% per year. The source is finite. To accommodate population increases and to permit industry and agriculture to expand, the world looks to engineers and scientists to ensure that our water requirements will be met. We can only achieve this formidable task by practicing the best known conservation methods, by improving the yield from traditional sources, and by using an important new source of fresh water — seawater and brackish water that has undergone thorough, cost-effective desalination.

Over the years, three primary systems have been developed for seawater desalination. Of these three systems, two (vapor compression and flash distillation) are relatively effective, but they use two to six times as much energy as the third: Reverse Osmosis (RO).

At Water Services of America, we've refined the RO process to its most efficient state-of-the-art. Our units are modular; installations can be expanded incrementally to fill growing requirements. Components are constructed of inert materials, corrosion-resistant plastics, and stainless steels. And with the WSA RO systems, no heat is required. The process runs at ambient temperatures.

Where will you find WSA Reverse Osmosis systems? Standard WSA systems are in use throughout the world providing fresh, safe drinking water for use in hotels, apartment buildings, condominiums, and resorts. Large, custom-designed WSA RO plants provide fresh, safe drinking water for municipalities from the U.S.A. to the Middle East.

Industrial process water is provided by WSA RO systems for use in boiler feed, printed circuit board manufacturing, electroplating and food and drug manufacturing. WSA offers a complete line of industrial water treatment equipment for use in conjunction with RO systems when ultrapure water is required.

WSA also custom designs systems, using standard components, for use in wastewater recovery and chemical reclaiming operations. These systems are typically used to reduce wastewater volume, recover valuable chemicals and to provide process makeup water from wastewater.

What is Reverse Osmosis, and how does it work for you? The principle of osmosis is found throughout nature. Osmosis enables our body's cells to receive nourishment and plants to obtain water from the soil. Simply stated, it is nature's effort to equalize liquids of varying salinity separated by a semipermeable membrane; water with fewer impurities will flow through a membrane to dilute the higher salinity water on the other side.

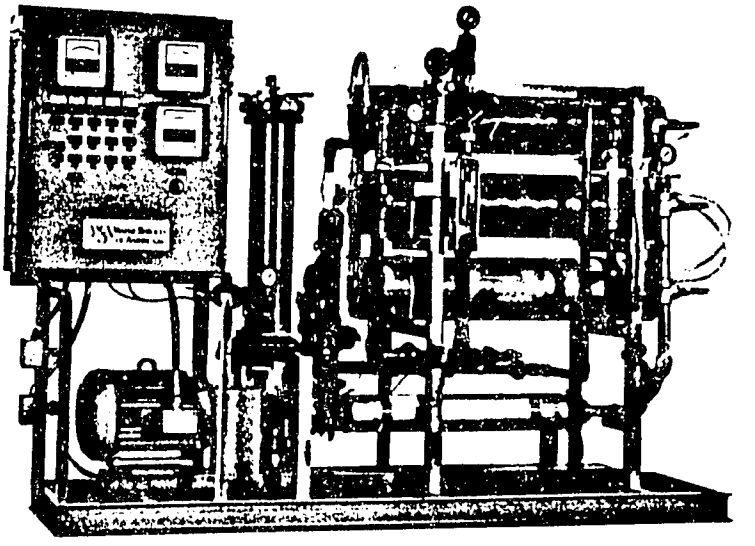
WSA engineers reverse this process by applying pressure to the high salinity water, forcing pure product water through the specially designed membranes. The concentrated solids left behind are flushed away from the membrane surface in the reject stream.

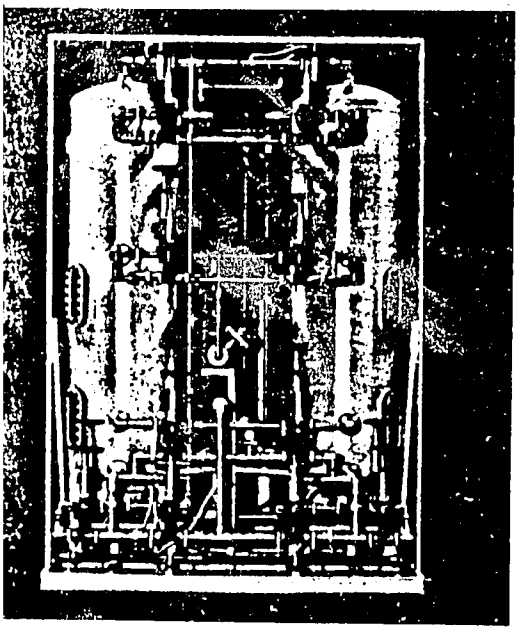
The system can produce fresh water — that is, containing fewer than 500 parts per million TDS (total dissolved solids) — from seawater in a single pass.

The membranes, like the walls of plant and animal cells, are microscopic, hair-like, hollow tubes or flat sheets assembled in a cylindrical module to provide the maximum membrane surface area for highest possible water productivity. A variety of membranes is available. WSA engineers analyze the feed stream to determine which type of membrane should be specified to provide the most efficient RO system.

WSA offers standard Reverse Osmosis systems in a variety of sizes. Units are preassembled and factory-tested.

The type of membrane, membrane array, and operating conditions are edetermined for each application by WSA gineers, working with computer istance in their own freshwater research oratory.





Auxiliary systems for filtration, degasification, deionization, ultrafiltration, clarification, softening, and other treatment processes are also available from WSA either "off the shelf" or custom-engineered for specific use.

Residents of the Florida Keys rely on the 3.0 million gallon per day production of his self-contained RO plant, (the first major seawater RO plant in the Western Hemisphere for production of potable water). The entire installation was put on line in seven-and-one-half months. The system is modularly designed and uses microprocessor controls that enable plant operators to tailor plant output to meet demand at the touch of a button.

Water Services of America has strategically located sales and service offices to serve the world market. Their experience and technical expertise make them indispensable to government and industry. Together with the WSA laboratory and engineering support group (located in the Milwaukee headquarters) the problem of supplying clean water for any purpose can be quickly and efficiently solved at the lowest initial cost and the lowest operating cost.

Learn more about the indisputable advantages of nature's own system for water purification, enhanced by WSA engineers. We have a number of technical data sheets, and more detailed information and case histories on actual Reverse Osmosis installations, designed and engineered by Water Services of America, the experts in Reverse Osmosis.

Call one of our regional offices, or our headquarters in Milwaukee.

The world needs clean water. We know how to get it — faster, with less energy. In water purification, WSA has the track record the world depends on.

PARTIAL LIST OF WSA RO INSTALLATIONS

Isle Arena, Colombia, South America: Oldest operating seawater RO system.

Jeddah, Saudi Arabia: World's first solar energy seawater RO plant.

Baku on Caspian Sea: World's first major seawater RO installation, 3.3 million gallons per day.

Corps of Engineers, Fort Irwin, California: First major fluoride removal plant utilizing RO.

Key West, Florida: First major seawater RO plant in the western hemisphere.

Cape Coral, Florida: Major brackish water RO plant in U.S.A.

Indian River County, Vero Beach, Florida: Municipal water system, 2.0 million gallons per day.

Makkah, Saudi Arabia: A WSA 4.0 million gallons per day RO system to supply water needs for the Holy City.

Trans Saudi Oil Pipeline: 10 WSA plants supply all the water needs for the pipeline system.

Qatar State Water Department at Ras Abu Samra: First major RO facility in Qatar.

IBM Research Triangle Park, North Carolina: Major ultrapure water facility for the electronics industry.

WSA

WATER SERVICES OF AMERICA

EDR

ElectroDialysis Reversal

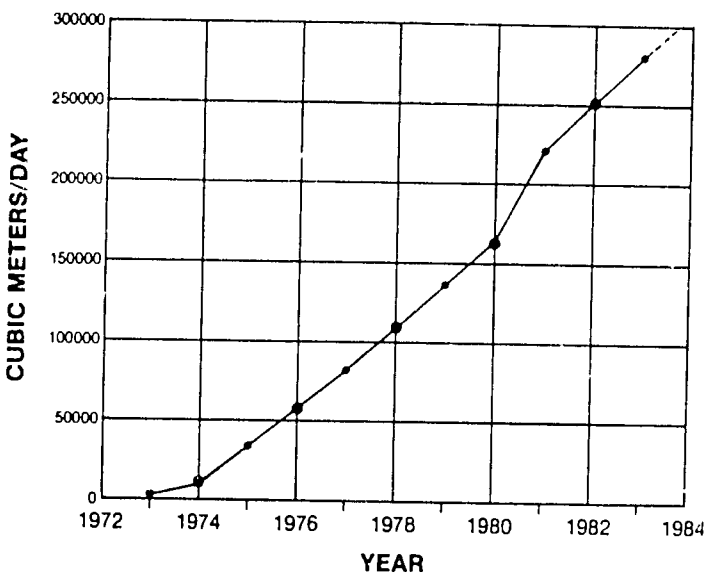
INTRODUCTION

The EDR process was developed in the early 1970s to solve operating and maintenance problems in unidirectional membrane based demineralizing systems. EDR is the only membrane process which is symmetrically reversible. Reversal inhibits the formation of scale and fouling films on the surface of membranes without addition of chemicals to the feed water, minimizes pretreatment and maximizes recovery of difficult to treat waters.

The EDR process removes ionized salts and minerals from water and concentrates them in a smaller volume of water by means of direct current electricity. The DC electricity moves ions from a demineralizing compartment through selective ion transfer membranes into adjoining concentrating compartments. At periodic intervals the direction of ion movement through the membranes and the identity of the concentrating and demineralizing compartments is reversed. (See process discussion that follows.) Reversing the direction of ion flow and interchanging concentrating and demineralizing compartments in the EDR process keeps the surfaces of the membranes clean and free of the scale and slime that occur in unidirectional membrane processes. Cleaner membrane surfaces keep EDR performance efficient and stable.

The practical result of EDR's reversal feature is that the process is more tolerant than other membrane processes of a wide range of troublesome organic, inorganic, colloidal, and biological contaminants in water. EDR is less dependent on chemical conditioning (such as pH correction, softening, or inhibitor feed), and is more forgiving of the physical and chemical upsets which affect real water supplies. A recent study on the state of the art of desalination technology, prepared by a leading engineering firm, gave EDR the highest technical evaluation among membrane processes. The high ranking is based on such factors as state of development, stability under design conditions, flexibility and reliability.

FIGURE 1
GROWTH OF EDR CAPACITY
INSTALLED OR UNDER CONSTRUCTION



EDR has been applied to a wide variety of real water situations which has led to a rapid growth in use since the process was first introduced in the early 1970s (see Figure 1). In 1972, there was virtually no EDR capacity in operation or under construction; in 1973, there was less than 5000 cubic meters/day; by 1978, there was about 100,000 cubic meters/day; and by early 1984, there was 300,000 cubic meters/day (80 million gallons).

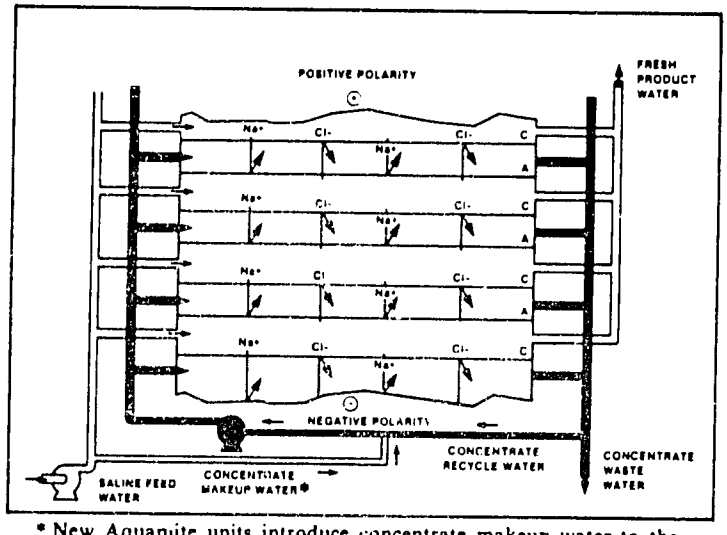
The major application of EDR for much of the 1970s was the demineralization of brackish waters of several thousands parts per million (ppm) of salts to potable levels below 500 ppm for municipalities, oil and construction camps, hospitals, schools, hotels, military bases, bottlers of beverages and purveyors of bottled water. Ionics' EDR AQUAMITE® systems have found great favor in remote locations and village water supply applications, where limited operator skills and availability of chemicals make other processes less attractive.

Starting in the late 1970s and accelerating into the 1980s, an increasing portion of new EDR capacity installed was used to produce high purity industrial process water from "fresh" industrial feed waters containing from a few hundred to over 1000 ppm total dissolved solids. In these cases, the EDR system replaced ion exchange systems or served as a "roughing demineralizer" ahead of an ion exchange "polishing" unit. Increased costs of regeneration chemicals for ion exchange systems and problems with the disposal of associated chemical wastes have facilitated the shift to EDR. Capital cost payback periods, based on chemical savings alone, range from under one year to about three years, depending upon the quality of the raw feed water (higher TDS feeds equal shorter payback periods).

Today, the EDR process is in use in 25 countries around the world, supplying quality drinking water and specified purity industrial process water to over 500 installations, the largest with a capacity of 24,000 cubic meters/day (6 million gallons). Typical industrial users of EDR include power plants, semiconductor manufacturers, the pharmaceutical industry, metals processors, cement plants, the petrochemical industry, food processors, textile manufacturers, and poultry and dairy applications.

ELECTRODIALYSIS (ED)

FIGURE 2
EDR CIRCULATION DIAGRAM



* New Aquamite units introduce concentrate makeup water to the discharge side of the recirculation pump.

The mechanism of operation of unidirectional electrodialysis is reviewed here as a basis for the understanding of EDR.

When salts and minerals dissolve in water, they break apart to form ions. Ions are particles of atomic or molecular size bearing positive or negative electrical charges. For example, common salt—sodium chloride—is ionized into a positively-charged sodium ion called a cation, and a negatively-charged chloride ion called an anion. These ions will migrate in a DC electrical field with the positively-charged sodium cations moving toward the negative pole (or cathode) and the negatively-charged chloride anions moving toward the positive pole or anode (Figure 2).

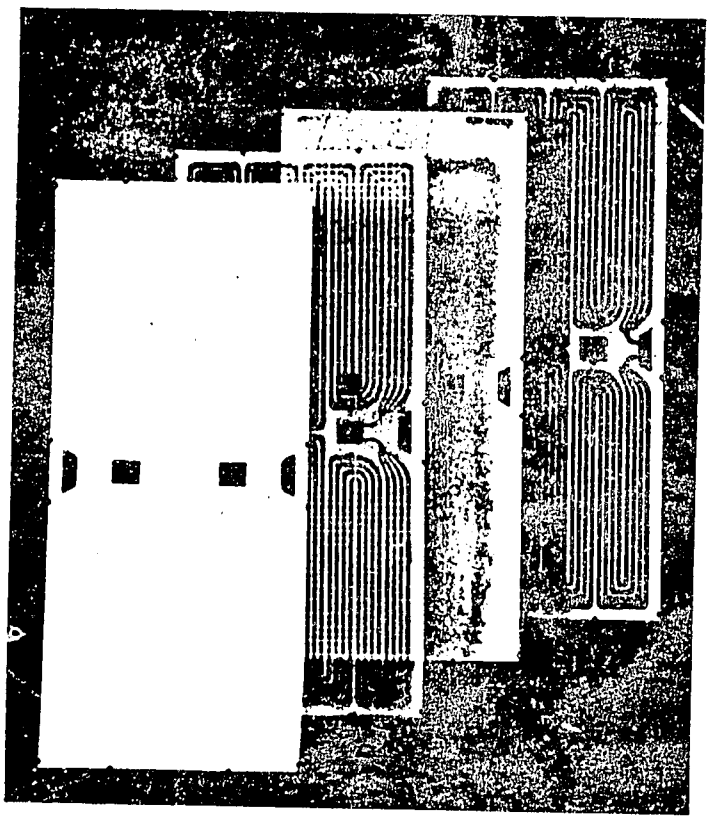
Ion transfer membranes, used to control ion movement in an ED unit, are made from either cationic or anionic ion exchange resins in sheet form. These are called, respectively, cation membranes and anion membranes.

146

Cation membranes, like cation exchange resin, have mobile or exchangeable cations (e.g., sodium, calcium, or magnesium) within their structure. As a result, cation membranes (marked "C" in Figure 2) will transfer cations—but exclude anions. Conversely, anion membranes, like anion exchange resin, have mobile or exchangeable anions (e.g., chloride, sulfate, or bicarbonate) within their structure. As a result, anion membranes (marked "A" in Figure 2) will transfer anions, but exclude cations.

Figure 2 depicts the operation of a classical ED array or "stack"—in which the elements described above, namely, dissolved ions, selective cation and anion membranes, and a DC electric field are combined to achieve both demineralization of water and concentration of removed ions in a waste stream.

FIGURE 3
EDR
ONE CELL PAIR
TWO MEMBRANES & TWO SPACERS



In the membrane stack, water containing dissolved ions is pumped between a cation and an anion membrane through a cut-out polyethylene spacer of about 1.0 mm thickness (Figure 3). The membranes are typically 0.5 mm thick. Each of the two membranes is bounded by another 1 mm liquid flow spacer, then a membrane of the alternate type, etc.

When a DC field is imposed on this array, all of the cations will move toward the negative pole. If the first membrane a cation encounters is a cation membrane, it will pass to the next water compartment, thus leaving behind a partly-demineralized cell. If the first membrane the cation encounters is an anion membrane, that ion will not pass. It is trapped in its original compartment, which becomes a concentrating compartment.

As can be seen from Figure 2, the anions undergo similar movements and restrictions in the opposite direction as they are attracted to the positive pole.

In an ED array, with alternating cation and anion membranes, each ion can move either not at all or one compartment at most before being blocked by an opposite membrane.

The net result of these membrane-controlled DC-induced ion movements is that one set of water-containing compartments becomes demineralized and the alternate set becomes concentrated.

The system described is classical or unidirectional ED. The term unidirectional refers to the fact that the polarity of the DC field is unchanging, the ions always move in the same direction, and the identity of the alternating water compartments remains unchanged; that is, a demineralizing compartment always remains a demineralizing compartment, and a concentrating compartment always remains a concentrating compartment.

Classical unidirectional ED was, the first of the membrane processes to be developed. It dominated membrane desalting in the 1950s and 1960s—although the total market was, by today's standards, quite small.

Classical unidirectional ED was a major historical advance over the thermal processes of evaporation or distillation which were used to desalt water prior to its development. However, unidirectional ED suffers from a number of limitations which are shared in varying degrees by other unidirectional membrane processes such as reverse osmosis (RO).

1) It is generally necessary to add acid and/or complexing agents such as SHMP (sodium hexametaphosphate) or to presoften the water to be treated to achieve stable operation—even over a matter of hours. This preconditioning requirement results from the presence of small amounts of calcium carbonate, calcium, strontium, or barium sulfate, or iron in the water, all of which tend to precipitate at the membrane interface and degrade performance as concentration takes place.

2) Non-mineral substances in the water—organic and inorganic colloids, microbiological entities, or dissolved organics, tend to foul the membrane surface with no in-process means for their removal. Customarily, if the build-up of these substances can be tolerated for a week or a month, the process is stopped at such intervals for cleaning—which is more or less effective.

3) Even with the addition of complexing agents, uni-directional units show marked deterioration of performance in the presence of calcium sulfate saturation or organics over a period of a few months.

ELECTRODIALYSIS REVERSAL (EDR)

The mechanism of electrodialysis reversal differs from that of unidirectional ED in a very simple, but profound way. If one operates a unidirectional electrodialysis array—as shown in Figure 2—for a fixed limited period of time (e.g., 15 minutes) and then reverses the polarity of the applied DC field by an automatic switching mechanism and operates for an equal period of time in the reverse direction—and then continues in this manner of reversing operation indefinitely—one is operating an EDR system.

One can see by reference to Figure 2 that a compartment which was formerly a demineralizing compartment becomes a concentrating compartment when the current reverses (and vice versa). So, it is necessary to switch valves which feed and collect these two streams, shortly after the current is reversed. It is also necessary to divert both streams at the time of polarity reversal for a period of 0.75 to 1.5 minutes to purge both compartments before the demineralizing stream returns to making specified product.

Electrodialysis reversal, therefore, is achieved by symmetrical equal-time operation in alternating directions so that insoluble or sparingly-soluble substances which would otherwise coat the membranes will, during the reversed polarity period, tend to be removed.

EDR is unique among desalting processes in being capable of a reversal of this type because of two inherent characteristics: a) EDR membranes are symmetrical; they operate in the same way in both directions, and b) EDR stacks have a symmetrical configuration with the concentrating and diluting compartments being hydraulically and dimensionally identical.

An operating EDR unit requires a supply of pressurized feed water—in the range of 70 to 90 psi, a reversing DC power supply, and an array of demineralization stages in a membrane stack or stacks.

In order to conserve water, a concentrate recirculation pump is used to recirculate most of the water to the concentrating compartments. The actual waste concentrate flow is then simply regulated by a control valve in the feed line which controls the makeup to the recirculating concentrate loop and forces an equal amount of water out to waste (Figure 2).

EDR CAPABILITIES

Water Recovery: 90 to 95% of the feed water can be recovered as purified product by means of controlled recycle of the concentrate stream and other in-process steps. Simple recycle of the concentrate stream gives recoveries of 70 to 85%.

Electrical Energy: Energy consumption can be approximated by using 0.5 kwhr per cubic meter of product for pumping, plus 0.5 kwhr per cubic meter per 1000 ppm salts removed for ion transfer.

Pretreatment: Presoftening and cooling are generally not required. EDR systems can treat waters with a Langelier Index of plus 2.2 and temperatures to 45°C without special steps. Pretreatment is recommended when iron exceeds 0.3 ppm, and manganese and hydrogen sulfide exceed 0.1 ppm. Silica does not interfere with the process, and therefore, does not require removal or limit water recovery. EDR units are capable of long-term operation on waters having 5 minute SDI's of approximately 15—thereby minimizing filter use.

Chemical Additions: *No chemicals* are required for normal operation of an EDR system. Special, high recovery situations (see calcium sulfate, below) and periodic stack cleaning require minimal chemical use.

Stack Cleaning: Membrane stacks may be cleaned in three ways: 1) continually by means of reversal, 2) periodical chemical flushing, and 3) disassembly and scrubbing of membranes if plant upsets occur. EDR is the only system that allows periodic inspection of individual membranes, which results in lower membrane replacement.

Calcium Sulfate: Calcium sulfate saturation in the concentrate stream up to 175% can be tolerated with no chemical feeds to the EDR system. Addition of SHMP and/or acid, to the recirculating concentrate stream only, allows calcium sulfate saturations up to 400% resulting in high recoveries of difficult to treat waters.

EDR Membranes: Homogeneous, reinforced sheets of polymer, 0.5 mm thick, with fixed anion or cation transfer sites have excellent chemical and temperature stability. Continuous exposure to pH 1 to 10 and free chlorine to 0.3 ppm, and greater extemes for short-term cleaning is standard. Membranes can operate at temperatures above 55°C.

To summarize, the EDR process and system components are capable of long-term stable operation on waters containing a wide variety of mineral, colloidal, or microbiological constituents. The self-cleaning feature of reversal and the stability of the membranes combine to give long life and trouble-free service.

IONICS

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IONICS, INCORPORATED

STATE-OF-THE-ART OF THE ELECTRODIALYSIS REVERSAL (EDR) PROCESS IN 1983

by
William E. Katz

Presented at the 44th Annual Meeting
International Water Conference
Pittsburgh, PA — October, 1983
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Bulletin: TP 329

151

State-of-the-Art of the Electrodialysis Reversal (EDR) Process In 1983

William E. Katz

Ionics, Incorporated

INTRODUCTION

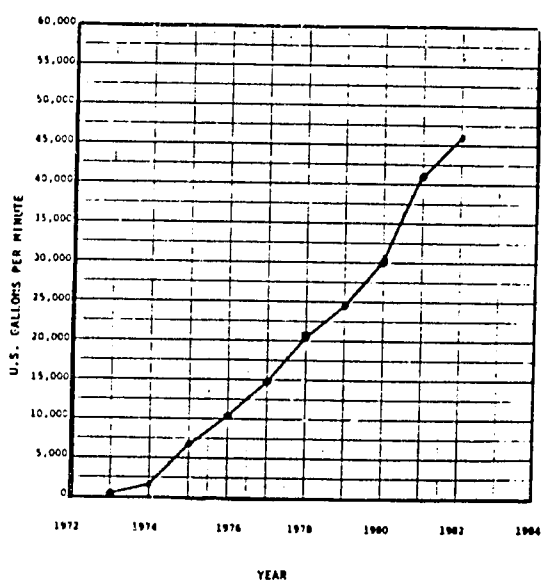
The Electrodialysis Reversal Process (abbreviated "EDR") removes ionized salts and minerals from water and concentrates them in smaller volumes of water by means of direct current electricity. The D.C. electricity moves ions from a demineralizing or diluting compartment through selective ion exchange membranes into an adjoining concentrating compartment.

EDR is the first commercially available membrane process which is symmetrically reversible, i.e., the direction of ion movement through the membranes and the identity of the concentrating and demineralizing compartments are reversed at equal periodic intervals, for example, every twenty minutes.[1] The reversal of direction of ion flow and the interchange of concentrating and diluting compartments in the EDR process keep the surfaces of the ion exchange membranes much cleaner than is possible in unidirectional membrane processes. Cleaner membrane surfaces keep EDR performance relatively stable in the presence of relatively high levels of collodial and slightly soluble constituents.

The practical result of the symmetrically reversible characteristic of EDR is that the process is more tolerant than other commercially available membrane processes of a wide range of troublesome organic, inorganic, colloidal, and biological contaminants in water. EDR is less dependent on chemical conditioning (e.g. pH correction, softening, or inhibitor feed), requires less pretreatment, and is more forgiving of the physical and chemical upsets and excursions which affect most real water supplies. A recent study on the state-of-the-art of desalination technology, prepared by a leading engineering firm, gave the EDR process the highest technical evaluation among membrane processes based on such factors as state of development, pretreatment requirements, necessary skill of operators, maintenance requirement, stability under design conditions, flexibility and reliability.[2]

The applicability of EDR to a wide variety of real water situations has led to a rapid growth of practical usage since the process was first introduced in the early 1970's (see Figure 1). In 1972, there was virtually no EDR capacity in operation or under construction. In 1973 there was less than 1,000 gallons per minute, by 1978 there was 20,000 gallons per minute, and by the end of 1983 there will be about 50,000 gallons per minute.

FIGURE 1
GROWTH OF EDR CAPACITY
INSTALLED OR UNDER CONSTRUCTION
(U.S. Gallons Per Minute)



The predominant application of EDR for much of the 1970's was the demineralization of brackish waters of several thousand parts per million total dissolved solids to potable levels of a few hundred parts per million for municipalities, oil and construction camps, hospitals, hotels, military bases, bottlers of beverages and purveyors of bottled water. However, starting in the late 1970's and accelerating into the 1980's an increasing fraction of EDR capacity has been utilized to produce industrial water or partially demineralized water from "fresh" industrial feed waters containing from a few hundred parts per million to perhaps 1000 parts per million. Such waters are typical of those used for industrial purposes in many parts of the world.

By mid-1983 five public utility steam-electric generating stations with an aggregate capacity of 4000 MW had chosen EDR to pretreat boiler feed water prior to ion exchange demineralization. EDR units were also in operation or under construction to provide pre-demineralization or direct process water for a major oil refinery, several smaller refineries, one of the world's largest natural gas processing plants, a major copper refinery, a major petrochemical complex, half a dozen cement plants, a modern mini steel mill, several electronics and semiconductor facilities, several food processing plants, a large truck manufacturing complex, a pharmaceutical plant, and a number of miscellaneous industrial installations.

Most of the EDR capacity to date has been for use overseas - primarily in the Middle East, Africa, and Southern Europe. Installations in the U.S.A. currently represent less than 10% of the total, but the U.S.A. market is showing accelerating growth as industrial applications increase.

INDUSTRIAL APPLICATIONS AND CHARACTERISTICS/SUMMARY

The following applications and characteristics of EDR in industrial water treatment are worthy of note and several will be discussed in more detail in this paper:

A. EDR is capable of controlled roughing demineralization of brackish feed waters of any salinity, and of "fresh" feed waters in the range of 20 to 1000 ppm total dissolved solids. Percentage EDR demineralization can be controlled from 50% to 99% by the number of ED stages utilized, the temperature of the water and other design variables. Electrical energy consumption can be approximated by 2.5 kw-hr per thousand gallons (for pumping at normal systems pressures of 70 to 90 psig) plus 0.25 kw-hr per thousand gallons per 100 ppm as $CaCO_3$ removed, in the range below 3000 ppm. Thus a typical mid-Western river or well water with 300 ppm as $CaCO_3$ would require 2.5 + (2.7 X 0.25) or 3.2 kw-hr per 1000 gallons for 90% demineralization.

B. On most natural brackish or fresh waters, EDR is capable of operating at typical water recoveries (ratios of product to feed water) of 65 to 80% *without any chemical feeds or conditioning* (e.g. pH correction, inhibitor feed, or presoftening). EDR is also capable of water recoveries up to 95%, with the addition of very small quantities of acid and/or inhibitors to the brine stream.[3] Control of water recovery in EDR units is simply accomplished over the range of 50% to 95% by adjustment of a single brine make-up valve.[4]

C. EDR has been shown capable of stable operation on feed waters with 5 minute silt density indices (SDI's) as high as 15. Such waters are typical of some untreated surface waters and can occur in treated surface waters with less than optimal pretreatment. Since a high percentage of industrial feed waters are surface waters, this capability of EDR is critical to its use for many industrial applications.[2]

D. EDR is capable of long-term stable operation demineralizing high calcium sulfate waters with relatively high recoveries up to calcium sulfate saturation levels in the brine stream of at least 400%.[3] Experiments are currently underway to determine an upper limit to calcium sulfate saturation in EDR units. Such a limit appears to be greater than 400%. Thus EDR is capable of demineralizing high calcium sulfate waters with little or no pre-softening - a major economic and operational advantage over processes requiring pre-softening.[5]

E. EDR has been shown capable of concentrating minerals and salts to levels of about 100,000 parts per million in the brine.[6] An experimental unit to concentrate 20,000 to 40,000 parts per million waste water to 120,000 parts per million is about to be tested by a major state water agency as part of a long-range agricultural waste water disposal and recycle study project.[7]

F. EDR is capable of stable operation on waters with barium, strontium, or high (up to 200 ppm) silica contents.[8]

G. In view of its stability in the face of high SDI's, trace constituents, and high $CaSO_4$, EDR is a candidate for use in concentration of cooling tower blowdown from large thermal power stations. Encouraging results have been obtained from small and medium scale pilot work on an actual cooling tower circuit slipstream with conventional clarification over the past year, and such work is continuing.

H. In view of a new chlorine resistant anion membrane, EDR is now capable of sustaining long-term continuous chlorine residuals of an least 0.3 ppm plus weekly cleanings with levels up to 20 ppm free chlorine, thus enhancing its ability to operate in biologically contaminated waters.

I. In common with older ED equipment, EDR units are capable of continuous operation at temperatures up to 45 degrees C, continuous pH range of 1 to 10, cleaning pH range of 0 to 13 - thus enabling use of a wide variety of cleaning agents.

J. Average membrane life in most EDR applications is in the 5 to 10 year range.

K. Modern EDR stacks require little if any manual disassembly for cleaning although the option for disassembly exists if necessary to deal with disasters such as sand, carbon, or other media migration into the stacks, gross dirt or mud loads, etc.

BASIC PRINCIPLES FOR ED AND EDR

A. Classical Undirectional Electrodialysis ("ED")

The mechanism of operation of unidirectional electrodialysis (abbreviated "ED") has been described many times but will be reviewed here as a basis for the understanding of EDR.

When salts and minerals dissolve in water, they break apart to form ions, for example, sodium chloride ionizes to form a positively-charged sodium ion and a negatively-charged chloride ion. These ions will migrate in a D.C. electrical field - with the positively-charged sodium cations moving toward the negative pole (or cathode) and the negatively-charged chloride anions moving toward the positive pole or anode. (Figure 2).

Ion exchange membranes can be made from either cationic or anionic ion exchange resins in sheet form. These are called, respectively, cation membranes and anion membranes.

Cation membranes, in common with any cation exchange resin, have mobile or exchangeable charged cations (e.g., sodium, calcium, or magnesium) within their structure. As a result, cation membranes (marked "cation" in Figure 2) will "pass" cations - but exclude anions. Conversely, anion membranes, in common with any anion exchange resin, have mobile or exchangeable anions (e.g., chloride, sulfate, or bicarbonate) within their structure. As a result, anion membranes (marked "anion" in Figure 2) will "pass" anions, but exclude cations.

FIGURE 2
BASIC ION MOVEMENT
ED/EDR

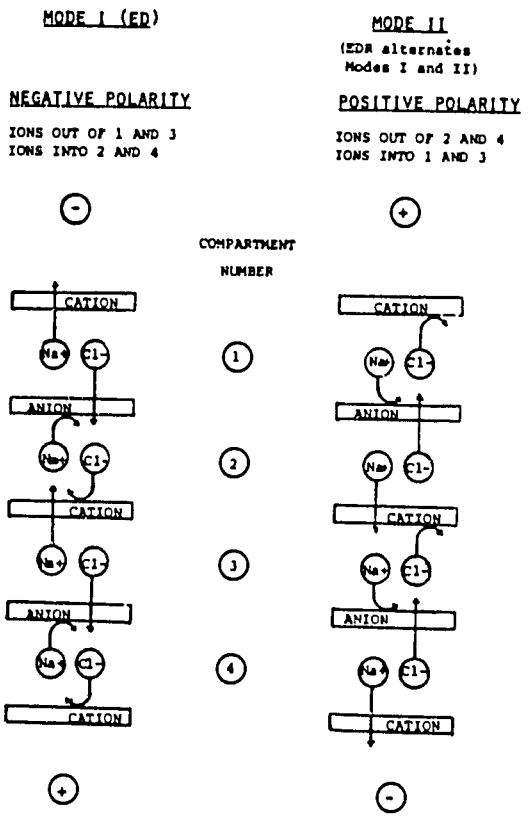


FIGURE 3
EDR
ONE CELL PAIR
TWO MEMBRANES & TWO SPACERS
(Showing Manifolds & Entry Ports)

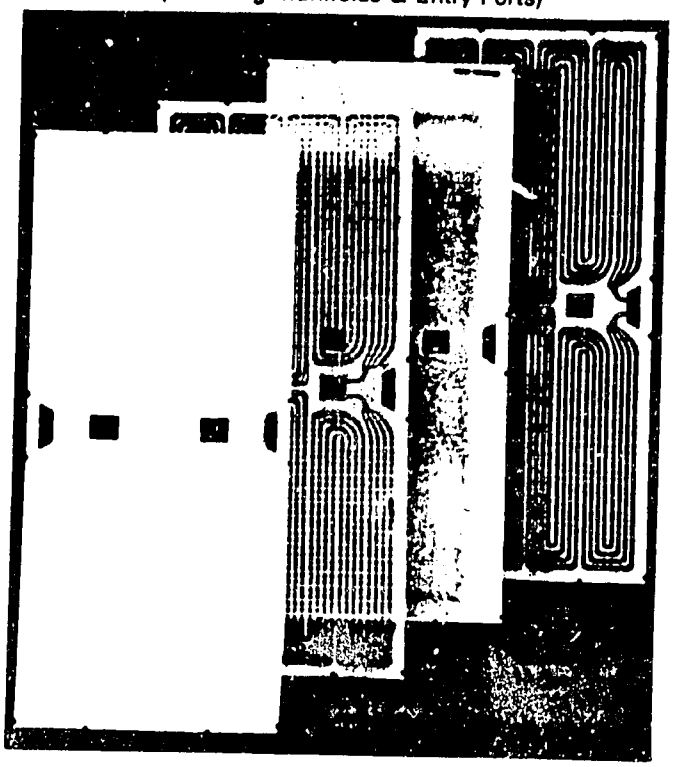


Figure 2 depicts under Mode I on the left hand side the operation of a classical electrodialysis array or "stack" - in which the elements described above, namely dissolved ions, selective cation and anion membranes, and a D.C. electric field are combined to achieve both demineralization or deionization of water and concentration of removed ions in a waste or brine stream of higher concentration.

In the membrane stack, water containing dissolved ions is pumped between a cation and an anion membrane separated by a cut-out polyethylene spacer of about 1.0 mm thickness (Figure 3). The membranes are typically 0.5 mm thick. Each of the two membranes is bounded by another 1 mm liquid space, then a membrane of the alternate type, etc.

When a D.C. field is imposed on this array, all of the cations will move toward the negative pole. If the first membrane a cation encounters is a cation membrane, it will pass to the next water compartment, thus leaving behind a partly-deionized or "diluting" compartment. If the first membrane the cation encounters is an anion membrane, that ion will not pass. It is trapped in its original compartment, which becomes a "concentrating" compartment.

As can be seen from Figure 2, the anions undergo similar movements and restrictions in the opposite direction as they are attracted to the positive pole.

The net result of these membrane-controlled D.C.-induced ion movements is that one alternate set of water-containing compartments (e.g., the odd-numbered set) becomes demineralized and the other alternate set (e.g., the even-numbered set) becomes concentrated.

The array or stack as described above depicts classical or unidirectional electrodialysis "ED". The term unidirectional refers to the fact that the polarity of the D.C. field is unchanging, hence the ions always move in the same direction, and the identity of the alternating water compartments remains unchanged, that is, a diluting compartment always remains a diluting compartment, and a concentrating compartment always remains a concentrating compartment.

Classical unidirectional electrodialysis ("ED") was, historically, the first of the membrane processes to be developed. It dominated membrane desalting in the 1950's, 1960's, and early 1970's, although the total market was - by today's standards - quite small.

Classical unidirectional electrodialysis was a major historical advance in that it was the first commercial process developed to desalt or demineralize water by use of membranes. However, unidirectional electrodialysis suffers from a number of limitations which are shared in varying degrees by other unidirectional membrane processes.

1. It is generally necessary to add acid and/or complexing agents such as SHMP (sodium hexametaphosphate) or to pre-soften the water to be treated to achieve stable operation - even over a matter of hours. The pre-softening requirement results from the presence of small amounts of calcium carbonate, calcium, strontium, or barium sulfate, or iron in the water, all of which tend to precipitate at the membrane interface or in the concentrating compartments and degrade performance as concentration takes place.

2. Non-mineral substances in the water - organic and inorganic colloids, microbiological entities, or polymeric organics tend to deposit on the membrane surface, with no-in-process means for their removal. Customarily, if the build-up of these substances can be tolerated for a week or a month, the process is stopped at such intervals for cleaning - which is more or less effective.

3. Even with the addition of complexing agents, unidirectional ED units showed marked deterioration of performance in the presence of calcium sulfate saturation over a period of a few months.[1]

B. Electrodialysis Reversal ("EDR")

The mechanism of electrodialysis reversal "EDR" differs from that of unidirectional electrodialysis "ED" in a very simple - but profound way. If one (1) operates a unidirectional electrodialysis array - as shown in Figure 2, Mode I - for a fixed limited period of time (e.g., 20 minutes) and (2) then reverses the polarity of the applied D.C. field by an automatic switching mechanism and operates for an equal period of time in the reverse direction (Figure 2, Mode II) - and (3) then continues this manner of reversing operation indefinitely - one is operating an "EDR" system.

One can see by reference to Figure 2 that a compartment which was formerly a diluting compartment becomes a concentrating compartment when the current reverses (and vice versa) so it is necessary to switch valves which feed and collect these two streams, shortly after the current is reversed. It is also necessary to divert both streams at the time of polarity reversal for a period of 0.5 to 1.5 minutes to purge both compartments before the diluting stream returns to making specified product.

Electrodialysis reversal therefore is achieved by symmetrical equal-time operation in alternating directions - so that insoluble or slightly soluble substances which would tend to coat the membranes or deposit in the concentrating compartments will tend - during the reversed polarity period - to be removed.

EDR is unique among desalting processes in being capable of a reversal of this type because of two inherent characteristics: a) EDR membranes are symmetrical; they operate in the same way in both directions, and b) EDR stacks have a symmetrical configuration with the concentrating and diluting compartments being hydraulically and dimensionally identical.

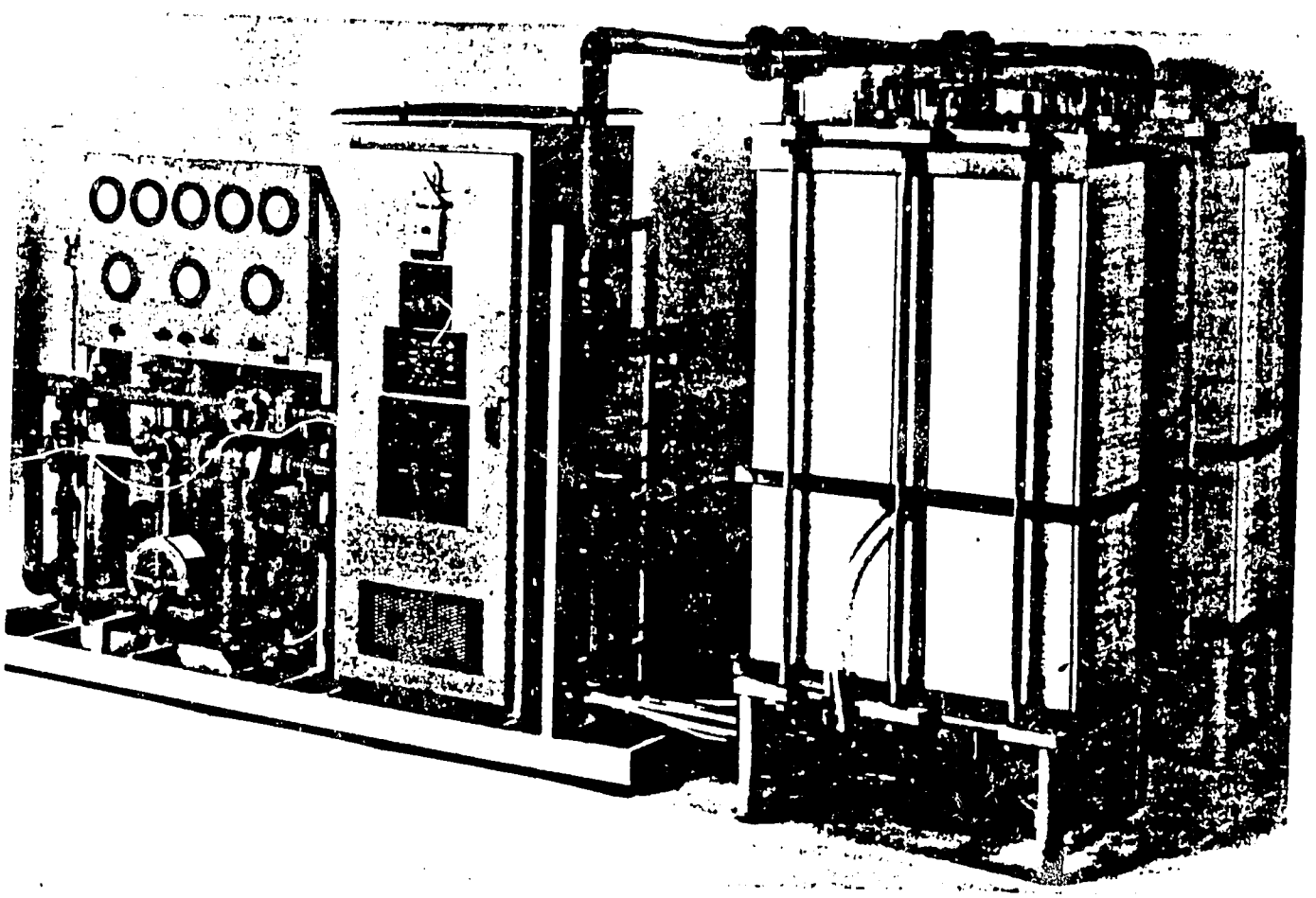
C. EDR Stacks, Stages, and Equipment

EDR stacks, stages, and equipment have been described in detail in the literature.[1] We will briefly review the main points so that the data below can be better understood.

As described above, the alternating diluting or concentrating compartments are bounded by alternating cationic and anionic membrances of 0.5 mm thickness. This repeating assembly of four elements (cation membrane, spacer/compartment, anion membrane, space/compartment) is called a "cell pair." The compartment itself is composed of the cut-out portion of a polyethylene spacer of 1.0 mm thickness, sandwiched between the pair of membranes. The concentrating and diluting spacers alternate, and are differentiated only by the entry ports or channels which connect the cut-out portion (in which the water flows) to the appropriate manifold. There are four manifolds which pass through the membrane-spacer sandwich carrying feed water in, demineralized water out, brine water in, and brine water out. The standard large EDR membranes have 18 by 40 inch dimensions and the spacers are of the same size. (Figure 3)

To form a membrane stack, hundreds of cell pairs are compressed between two platinized electrodes which alternate as anodes and cathodes as reversal takes place. The whole assembly (Figure 4) is compressed between steel end plates by metal tie rods to contain the liquids in the stack. Typically, membrane stacks have between 300 and 500 cell pairs. (Figure 4)

FIGURE 4
70 GPM PACKAGED EDR PLANT
WITH TWO MEMBRANE STACKS



A single pass through a membrane stack results (for waters below about 4000 ppm) in a partial percentage demineralization which depends upon temperature, ion composition, level of entering total dissolved solids, flow rate, and applied voltage. A typical range of partial demineralization per pass or "stage" is 30 to 60%. Higher temperatures, higher sodium chloride percentages, lower inlet total dissolved solids, lower flows, and higher applied voltages favor higher demineralizations per pass.

Since desired practical demineralizations are often in the range of 75 to 99%, it is necessary to use several stages of EDR demineralization. Practical numbers of stages vary from one or two to as many as 18 or 20 on sea water. For a partial demineralization of 50% per pass or "stage," one stage gives 50%, two stages 75%, four stages 93.8%, six stages 98.4%, eight stages 99.6%, etc.

Typical flows for a 500 cell pair single stage stack are in the range of 100 to 130 gallons per minute and typical pressure drops per stage are in the range of 7 psi to 11 psi in this flow rate range. Design pressure (for stacks) is usually kept at around 50 psig into the first stage of a multi-stage stack array. For units requiring more than 4 to 7 stages, further flow reductions below 100 to 130 gpm are necessary.

For EDR plants, where the desired output flow is in the range of 100 gpm or more, a single stack or group of parallel stacks is used as a single stage. However, for units with desired output flows of less than 100 gpm, several stages are contained in the same stack. In a single stage stack, all of the hundreds of alternating compartments flow in parallel off the manifolds. However, in multi-stage stacks, groups of cells flow in parallel to form one stage and the outputs of this group are collected and fed to another group within the same stack to form a separate stage. Groups of cells between any pair of electrodes constitute one "electrical stage." If two or more stages are grouped within a stack between one pair of electrodes these are called "hydraulic stages."

Figure 4 shows two multi-stage stacks comprising part of a packaged EDR unit of 70 gallons per minute net product output. The two stacks each contain 450 cell pairs and each have a net capacity of 35 gpm. They are identical to each other and arranged in parallel. Each stack has three hydraulic and two electrical stages. The two electrical stages are separated by a thick PVC block which is clearly visible about two-thirds of the way down from the top of each stack. The larger top section of each stack has two hydraulic stages within a single electrical stage defined between the top pair of electrodes. The smaller section at the bottom is a single hydraulic stage and also a single electrical stage defined between the bottom pair of electrodes.

An operating EDR unit requires a supply of pressurized feed water - generally in the range of 70 to 90 psi, a reversing D.C. power supply, and an array of demineralization stages in a membrane stack or stacks. The flow in the concentrating compartments within the stack is kept just slightly lower than the flow in the diluting compartments, since these compartments are identical in configuration, and one wishes to keep the pressure in the concentrating compartments just slightly lower than the pressure in the diluting compartments. In order to conserve brine water, a brine recirculation pump is used to recirculate most of the water to the concentrating compartments. The actual waste brine flow is then simply controlled by a control valve off the feed line which controls the makeup to the recirculating brine loop and forces an equal amount of water out to waste.

Water recovery - defined as the ratio of product water to feed water - can be simply controlled in this manner in EDR plants in the range of about 50 to 95%. There are some natural losses of water from the diluting to the concentrating compartments by endosmotic water transfer and intercompartmental leakage which place an upper limit on recovery. However, development work both on membranes and spacers is underway to raise the recovery limit and to allow even higher concentrations by EDR.

In Figure 4 one can see the major components of an EDR system with the two multi-stage stacks at the right and the skid at the left. The skid contains a feed pump, brine pump, cartridge filter, reversing and control valves, D.C. power supply and control cabinet, and hydraulic instruments.

ROUGHING DEMINERALIZATION

EDR plants are now in operation or under construction for use as roughing demineralizers ahead of ion exchange demineralizers in California, Arizona, Texas, Florida, New Jersey, Ohio, Wyoming, and a number of African and Middle Eastern countries. Capacities of individual installations currently in operation range from 25 gallons per minute to one thousand gallons per minute. Many of these EDR units have been retrofitted ahead of existing demineralizers in operating installations to adjust to changed operating conditions, for example, (1) increased salinity of the feed source, (2) a need for increased capacity, or (3) increases in waste disposal problems and costs.

Pre-demineralization by EDR leads to large reductions in frequency of regeneration of the downstream ion exchange demineralizer along with corresponding decreases in chemical consumption, waste disposal, and monitoring supervision, and a significant increase in demineralizer availability and capacity. The economics of EDR roughing demineralization will depend on many local factors, such as design of the ion exchange unit, water analysis, treatment objectives, waste disposal problems, local prices for chemicals and power, etc. However, the attraction of EDR pretreatment for ion exchange demineralizers is the simplicity, reliability and low operating cost of the EDR unit. In many cases where EDR units have been chosen, the performance stability of EDR on the water in question was first demonstrated by a pilot unit.

Results of demineralization by EDR at one installation in the Southwestern U.S.A. are given in Table I and Table II. Table I shows a 95% overall demineralization with individual ions varying from about 89% for bicarbonate to almost 97% for calcium, magnesium, and chloride.

One limitation of EDR in demineralization is that it removes only ionized substances so that silica is not removed. On the other hand, EDR units are not scaled by high silica waters (up to at least 200 parts per million) so that high recovery concentrations or demineralizations can be carried out by EDR in high silica waters.

Table II shows the detailed performance data for the packaged EDR unit which produced the demineralization in Table I. The unit has now been on line well over three years and performance has been stable. There is no chemical conditioning or feed to the unit. The unit has a diluting stream

TABLE I
30 GPM EDR DEMINERALIZATION
RESULTS AFTER THREE YEARS
(ppm as $CaCO_3$)

	Feed	Product	% Demineralization
Sodium	329	22	93.3%
Calcium	120	4	96.7%
Magnesium	117	2	96.7%
Total Cations	566	28	95.1%
Chloride	432	14	96.7%
Bicarbonate	80	9	88.8%
Sulfate	44	4	90.9%
Total Anions	556	27	95.1%
Conductivity (25°C)	1246	59	95.2%
pH	7.3	6.9	

Feed Water Temperature - 30°C.

TABLE II
PERFORMANCE DATA
30 GPM EDR AFTER 3 YEARS

FEED Sum of Ions — 561 ppm as $CaCO_3$
PRODUCT Sum of Ions — 28 ppm as $CaCO_3$

PRODUCT FLOW — 30 GPM (10% Off-Spec)
BRINE MAKE-UP — 5 GPM

DC INPUT	VOLTS	AMPS	WATTS
Electrical Stage 1	183	7.3	1330
Electrical Stage 2	183	2.0	366
TOTAL	183	9.3	1696

TOTAL DC ENERGY — 1.15 kwhr/1000 gallons[1]

[1] Assuming 90% Rectifier Efficiency

flow of 30 gallons per minute, a brine makeup of 5 gallons per minute, and a fifteen minute EDR cycle with 1.5 minutes or 10% off-spec time at the time of reversals. Thus its net output is 1620 gallons per hour. Since the overall removal is 95%, the average removal for each of the four hydraulic stages is 53%, and for each of the two electrical stages is 78%.

One can see clearly in Table II how the two electrical stages of this unit are working with a total rectifier output of only 1696 watts D.C. The first electrical stage requires 7.3 amperes at 183 volts, while the second stage (with 78% fewer ions) requires only 2.0 amperes. The ratio of amperes is approximately the same - as it should be - as the ratio of ions removed.

The unit is equipped with a single 450 cell pair 18 by 40 inch EDR stack with two electrical and four hydraulic stages. Overall mineral removal is from an average of 561 ppm to 28 ppm as $CaCO_3$ or 533 ppm as $CaCO_3$ removed. The D.C. energy used (allowing for a 90% rectifier efficiency) is 1.15 kw-hr per thousand gallons or 0.215 kw-hr per thousand gallons per 100 ppm as $CaCO_3$ removed. To this must be added pumping power, which in this small unit runs around 5 kw-hr/1000 gallons. On units of the 100 gpm and greater size, the D.C. power would be the same, but the pumping power would be roughly cut in half.

EDR is attracting increasing attention and usage in roughing demineralization because it is a stable, durable process with very attractive total energy efficiency. For waters of 100 to 1000 ppm as $CaCO_3$ or below (and this range covers most industrial waters in the U.S.A.) total pumping plus D.C. energy consulmptions of 2.8 to 5.0 kw-hr/1000 gallons are realistic and sustainable over long periods. *This means that a 200 gpm unit requires an electric supply of 35 to 60 kilowatts and can save from hundreds to thousands of tons of chemicals annually.*

OPERATING ON HIGH CALCIUM SULFATE

Calcium sulfate is one of the most common minerals found in natural waters. Important rivers in the Southwestern U.S.A. such as the Red River, Washita, Canadian, and Colorado have significant calcium sulfate components. Perhaps one-third to one-half of the mineralized ground water in the U.S.A. is of a calcium sulfate or gypsum character. Gypsum is a major contaminant of well waters on the West Coast of Florida and in many parts of the Middle East and North Africa.

If a raw water is more than 25% saturated in calcium sulfate, and one wishes to demineralize it with a recovery of 75 to 90%, one must create a waste stream which is saturated or supersaturated in calcium sulfate. Unidirectional membrane processes must be designed with care - and often with pre-softening - to avoid damaging and sometimes catastrophic precipitations of gypsum in operating units on feed waters with even modest calcium sulfate contents. In fact, calcium sulfate is an important limiting design contaminant in evaporation and ion exchange demineralizer design, as well as in unidirectional membrane processes.

Through a series of developments in EDR, which were demonstrated at the Roswell Test Center of the former Office of Water Research and Technology (OWRT), the ability of the EDR process to handle calcium sulfate concentrations in the waste stream to the 350 to 400% range of calcium sulfate has now been established. Table III shows the feed water used in this work, and a highly concentrated waste water.[3]

Prior to the Roswell tests, it had been demonstrated in commercial EDR installations at Dell City, Texas, and Junius Ponds, New York, that EDR units were capable of long term stable operation with calcium sulfate saturations in the waste stream up to about 150% with no chemical addition.[1] However, the range above 150% had not been explored. At Roswell it was decided to explore the limits on calcium sulfate concentration and Langelier Index for EDR units operating with no chemical feeds, and then to determine if addition of acid or inhibitors, such as "SHMP" (sodium hexametaphosphate), to the waste stream of an EDR would extend the useful range.

TABLE III
HIGH $CaSO_4$ EDR PERFORMANCE
94.1% Water Recovery
424.6% $CaSO_4$ Saturation*
ROSWELL TEST CENTER - OWRT

	FEED	BRINE	PRODUCT
Sodium as Na	303 ppm	3300 ppm	50 ppm
Calcium as Ca	190	3609	12
Magnesium as Mg	64	1192	5
Potassium as K	1	26	—
Chloride as Cl	560	7374	62
Sulfate as SO_4	413	8075	22
Bicarbonate as HCO	198	2416	56
Sum of Ions	1729	25,992	207
pH	7.20	7.05	6.30
Conductivity	2740	28,230	350
Langelier Index		+2.16	

* Marshall & Slusher

The conclusions from the first parametric tests were as follows:

1. The Langelier Index limit for EDR systems with zero chemical feed appears to be approximately +2.4, where carbonate scale formation occurs on both system piping and membranes.

2. The calcium sulfate saturation limit for EDR with zero chemical feed or with sulfuric acid addition appears to be between 220 and 250%. At roughly 250% calcium sulfate saturation, gypsum deposition on the brine piping becomes intolerable and some gypsum scale deposition occurs on the membranes.

3. Using acid addition to a Langelier Index of +2.0 in the brine stream and sodium hexametaphosphate addition, trouble-free operation was demonstrated to an average 440% calcium sulfate saturation for 300 hours. Higher levels of supersaturation may be obtainable, but are as yet uncertain."

It was then decided to determine if SHMP alone would inhibit all precipitation without the addition of acid, and these tests were positive. Finally a successful long term test at a water recovery of 90% (equal to 350% $CaSO_4$ saturation) on a calcium sulfate water of 1800 ppm was carried out on a full-size EDR package unit for 5000 hours, using only small amounts of SHMP in the brine.

These tests have established the ability of EDR to deal with high calcium sulfate water - without lime, lime soda, or ion exchange pre-softening. Further work is underway on application of this equipment to cooling tower blowdowns with high calcium sulfate.

OTHER APPLICATIONS

A great deal of additional data has been collected on the other industrial applications of EDR listed in the summary above. Several papers are contemplated by users of EDR equipment for future conferences. This paper has been conceived as an introduction or reintroduction of EDR to the industrial water treatment community. Symmetrically reversible EDR is being used with increasing frequency for industrial water treatment applications because of its durability, energy efficiency, and stability of operation when treating a wide variety of ground and surface water.

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Discussion

by

Dr. Robert Kunin, Consultant

on

State-of-the-Art of the Electrodialysis Reversal (EDR) Process In 1983

It is indeed a pleasure for me to comment on the very interesting paper and presentation of William Katz on the subject of electrodialysis (ED). The subject of electrodialysis has virtually been ignored by the International Water Conference and the **State-of-The-Art** presentation of William Katz is indeed a welcome one. The last paper on ED was delivered at the 1970 International Water Conference by Bill Katz of Ionics, Inc. During this 13-year interval, several large ED plants have been operating successfully around the world and much experience has been accumulated.

In some ways, I have looked upon electrodialysis as a natural extension of ion exchange technology whereby one is able to extend the practical total dissolved solids (TDS) limitations of ion exchange by the substitution of electrical energy for chemical energy. The development of new and improved ion exchange resins and ion exchange resin techniques and equipment have extended the practical limits of ion exchange *resin* technology in terms of total dissolved solids. For example, counter-current systems and the expanded use of weak electrolyte ion exchange resins in separate units or as stratified beds with the appropriate strong electrolyte ion exchange resins have extended the practical limits of conventional ion exchange resin technology. The advances in electrodialysis noted by Mr. Katz now permit one to combine ED with conventional ion exchange resin technology in a most effective and reliable manner. The ED can be used most effectively in lowering the TDS of high TDS levels to a point where the ion exchange resin systems can operate most effectively.

The EDR Process described by Mr. Katz apparently solves or effectively minimizes the fouling, poisoning and scaling problems which have plagued previous electrodialysis systems. The reversal of the electrode polarity prevents the accumulation of the $CaSO_4$ and $BaSO_4$ scale and minimizes the organic matter fouling of the anion exchange membranes to the extent that a membrane life of at least five years is routinely attained. It also appears that the old electrode problems associated with the ED have also been resolved. Further, it is also of interest to note that during the past thirteen years ion exchange resin technology has been improved to the extent that one can now effectively remove organic matter from surface water supplies without being seriously fouled. In fact, we now look at ion exchange technology as a means of removing organic matter.

It is quite reasonable to conclude that the EDR process could be competitive with RO as a "roughing" demineralizer, particularly for high TDS waters, prior to the ion exchange resin system. It is difficult, of course, to set forth firm limits of TDS which point to where each technology is *the* optimum technique. Much depends, of course, upon such factors as water composition, desired treated water quality, local availability and cost of chemicals, flow rate, power costs, etc. Mr. Katz may wish to discuss these items more fully.

It has been argued that one of the major advantages of RO as a "roughing demineralizer" is that, since the treated water passes through the membrane, colloidal matter is removed. In essence, it functions as an ultrafilter. However, by functioning as an ultrafiler, the RO membranes lose flux and their useful life is decreased. Using RO as an ultrafiler is not consistent with the silting index requirements for RO systems. The fact that ED does not have UF capabilities is not a disadvantage. It is best that the removal of colloidal matter be left to the primary clarification process or to post-demineralization with ultrafiltration.

The subject of electrodialysis further suggests employing ion exchange membranes electrochemically for producing the high purity caustic (NaOH) required by those employing ion exchange demineralizers. With the concern over mercury cells, the availability of caustic low in chlorides and chlorates may become a problem for many industries. It would appear that one could employ these electrolytic ion exchange membrane cells for producing high purity caustic at the site of the demineralizers. Perhaps Mr. Katz would like to comment on this matter.

ELECTRODIALYSIS REVERSAL FOR RELIABILITY IN WATER TREATMENT

Ionics, "The Water Company", manufactures and supplies a comprehensive line of water and wastewater treatment systems and instruments featuring unique technology developed in the Company's laboratories.

Ionics began in the water business with the invention of the ion transfer membrane in 1948 which resulted in the development of the classical ED (electrodialysis) process. In 1954, the ED process was introduced commercially to demineralize brackish waters in Saudi Arabia.

The *New* EDR (electrodialysis reversal) process was developed in the early 1970's to solve operating and maintenance difficulties encountered when injecting acids and chemicals into the system to control scaling. The elimination of chemical feeds and low-cost automatic operation earned rapid acceptance for the EDR process.

Today, hundreds of EDR systems, the largest with a capacity of 24,000 cubic meters per day (6 million gallons), demineralize water for industrial and municipal applications in over 25 countries around the world.

IONICS' AQUAMITE® EDR UNITS

The AQUAMITE units are packaged plants for Water Demineralization employing the proven process of electrodialysis reversal (EDR) to provide up to 4,000 cubic meters per day of fresh water from brackish water, or very pure industrial process water from normal water supplies. The AQUAMITE plant is tailored to each individual application while maximizing standard design components.

IONICS

IONICS, INCORPORATED

FOR MORE INFORMATION CALL OR WRITE:

Head Office
IONICS, INCORPORATED
65 Grove Street, Watertown, Massachusetts 02172
Telephone: (617) 926-2500 Telex: 922473

160

APPENDIX C

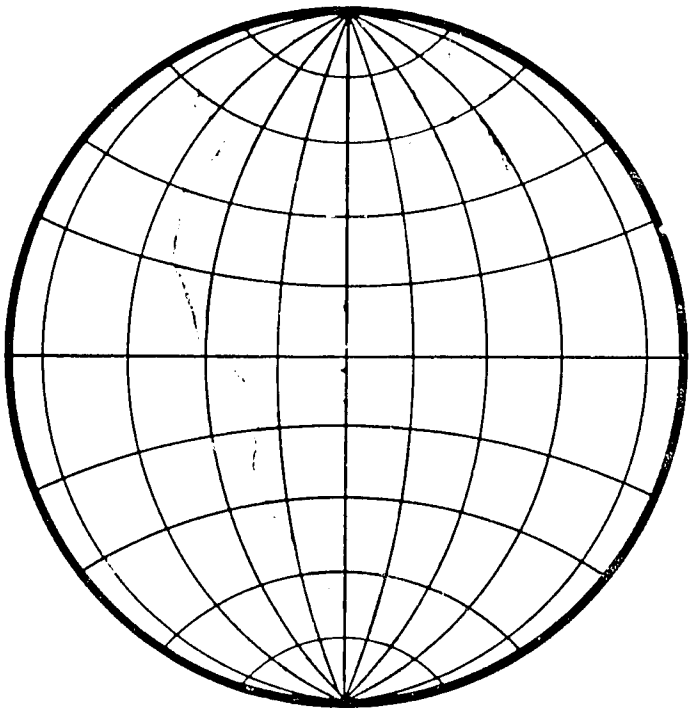
PRODUCT LITERATURE

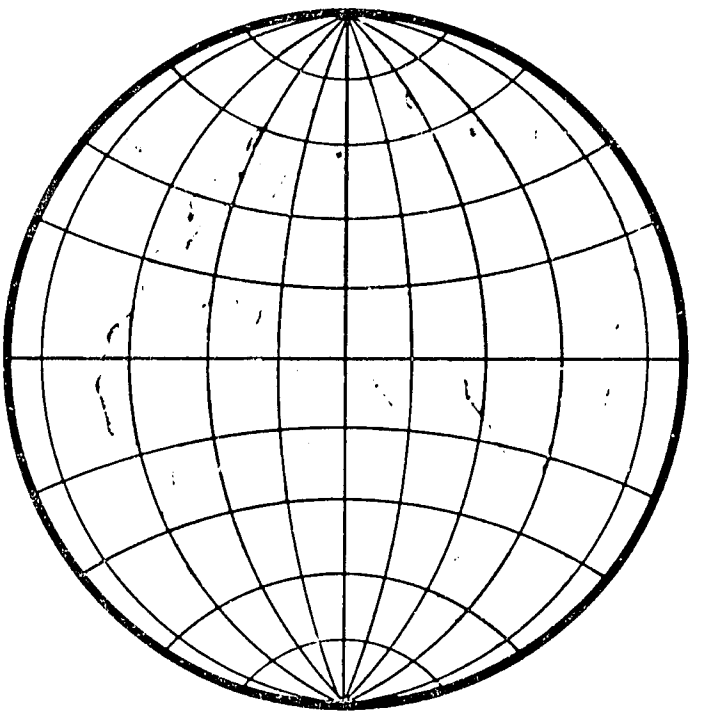
AQUATRON

INTERNATIONAL, INC.

Route 1, Box 638 Rosethorne Rd., Marrero, LA 70072 • Telephone (504) 689-2024
Telex ITT 460215 AQUA U1

AQUATRON IS INTERNATIONAL IN SCOPE





AQUATRON PRODUCTS are sold in the U.S.A. and many countries throughout the world

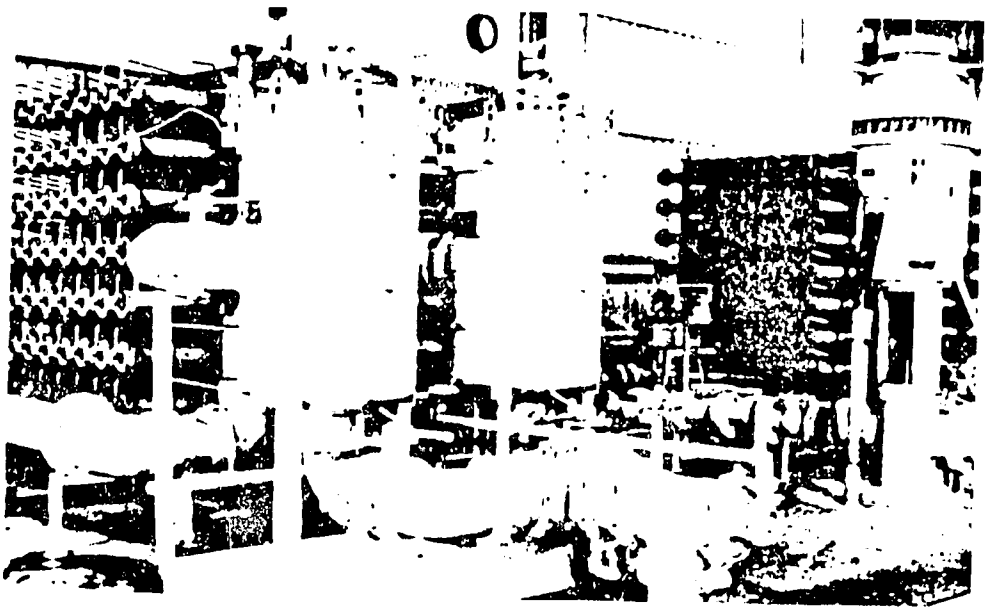
TO USERS SUCH AS:

★ Major oil companies, offshore and overseas ★ Hotels, motels, and condominiums ★ Hospitals and laboratories ★ Sea going vessels ★ Industrial sites ★ Sea side communities ★ Power generating plants (nuclear and fossil) ★ Chemical refineries ★ Paper mills

162

If you are thinking of *reverse osmosis* large or small, think *Aquatron International, Inc.*

We make *reverse osmosis* systems, from small eight gallons per day home and laboratory units



...to over 1,000,000 gallons per day packaged *reverse osmosis* systems

simple, low cost systems for water purification

WHAT IT DOES

AQUATRON - REVERSE OSMOSIS equipment simply and inexpensively purifies salty and bacterially contaminated water. By removing up to 99% of the dissolved minerals and virtually 100% of the bacteria, these systems provide drinking water from brackish or sea water sources.

HOW IT'S DONE

Source water, after pre-treatment, is pumped through a semi-permeable membrane material. This material permits the pure water to pass while rejecting the majority of the impurities; the rejected contaminants are continuously flushed from the membrane to drain.

What is *reverse osmosis?*

Nature has provided man with an abundance of water with over 70% of the earth's surface being covered with water. Unfortunately, only a small portion of it is suitable for human consumption. Of this portion, much of it contains various dissolved minerals (dissolved solids) and suspended solids. In addition to these natural solids, man has polluted his water with chemical and industrial wastes. These solids and chemicals, in sufficient concentrations, can render a water supply unacceptable for commercial application and unfit for human consumption.

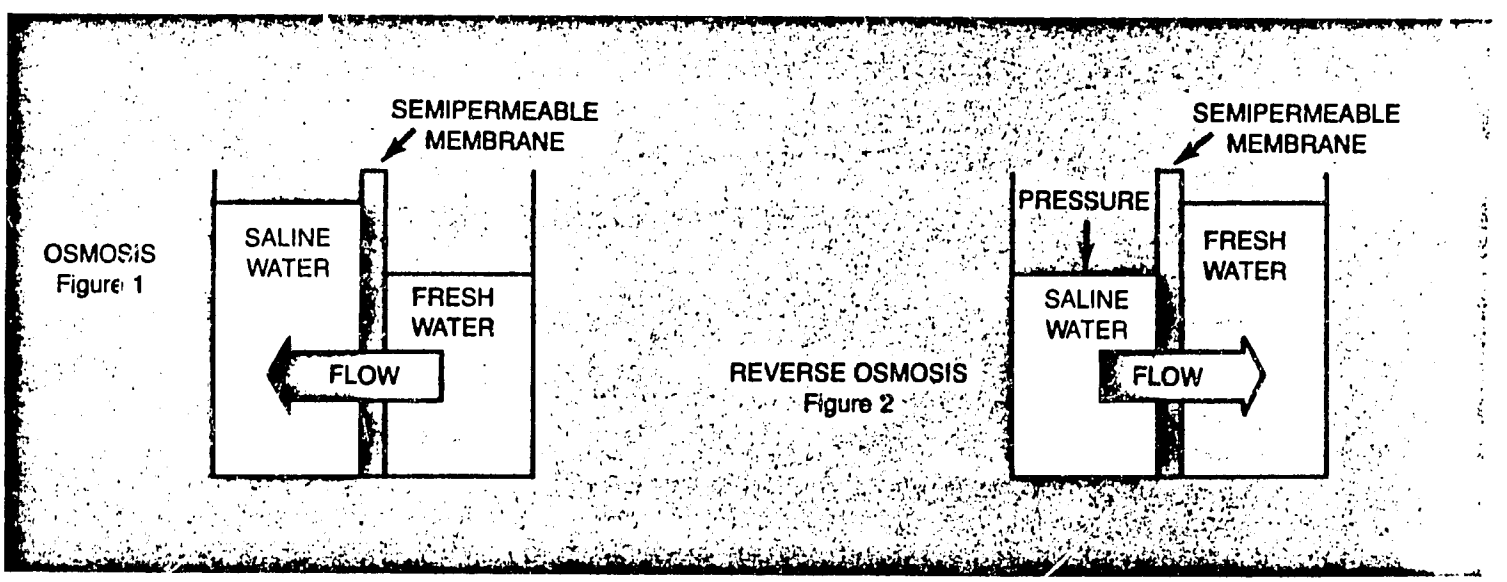
Working with a process known as reverse osmosis, scientists have been able to develop an osmotic membrane which will remove the dissolved solids from water. AQUATRON INT., INC. employs such an osmotic membrane and utilizes the process of reverse osmosis in their R.O. SYSTEMS. In order to understand the operation of the R.O. SYSTEM, it will be necessary to understand the process of osmosis and reverse osmosis. Osmosis is a phenomenon found in nature and is the process by which plant life absorbs minerals and nutrients from the soil. In figure 1, we have an example of osmosis.

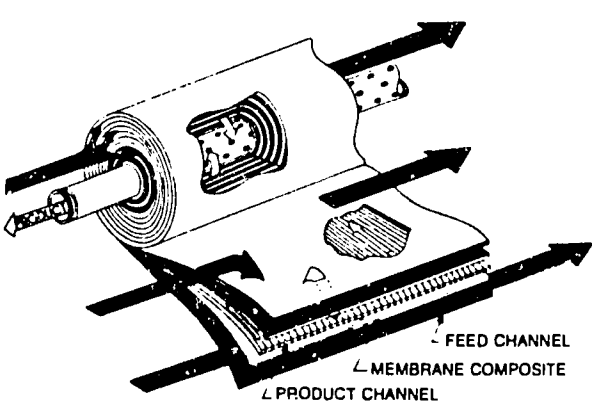
A container is divided by a membrane. On one side of the membrane is a highly concentrated solution of water and chemical salts. In the drawing we call this solution "saline water".

On the other side of the membrane, we introduce a high quality water, or water which contains little or no chemical salts. In the drawing this solution is referred to as "fresh water".

If we allow the container to remain in this condition for a period of time, sampling and analyzing the water in both halves would reveal that the fresh water is passing through the membrane and diluting the saline water. This is nature's way of correcting the imbalance between the two solutions. Scientists refer to this process as "osmosis". (Figure 1.)

It is also possible for the process of osmosis to be reversed. Scientists have found that they can create an imbalance in the other direction by applying pressure to the saline side of the container. The pressure creates an artificial imbalance and water will flow in the other direction in an attempt to reach an equilibrium. Figure 2 illustrates the reverse osmosis process. Note that the membrane allows only fresh water to pass through it in this direction.

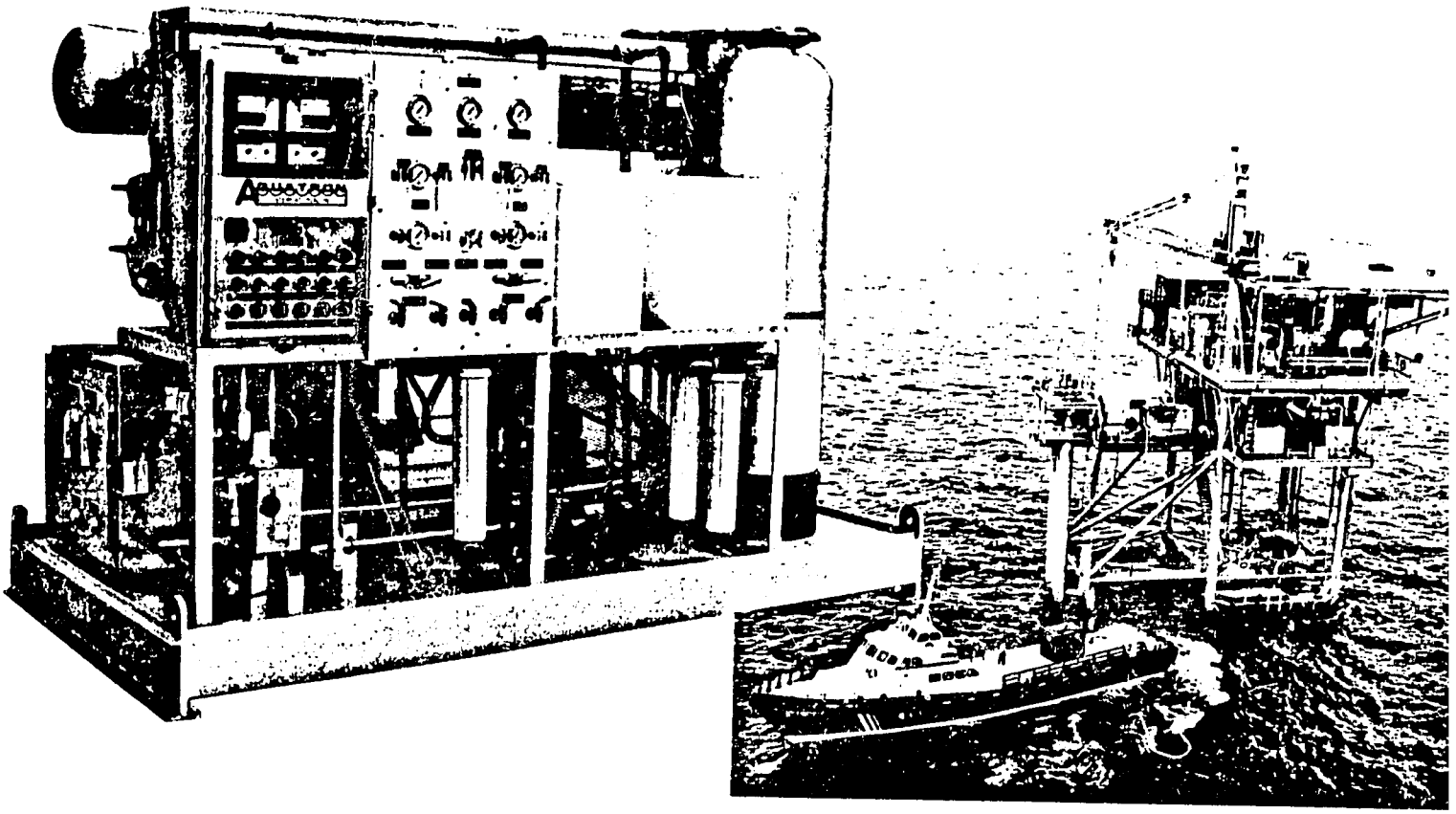




DESIGN FEATURES

AQUATRON INTL., INC. designs and manufactures systems employing various types of membranes. Selection is determined by the specific application and an analysis of the water. Water salinity, temperature and chemical composition are considered to assure an optimum membrane/application fit.

A spirally-wrapped sandwich of two membrane sheets is glued along a common edge and separated by porous backing materials. Pressurized feedwater passes longitudinally through the spiral package along a mesh separating the sandwiched layers. Permeate travels spirally through the material into a central perforating tube.



AQUATRON INTERNATIONAL, INC.

has serviced the offshore industry since 1975 by converting seawater to drinking water by *reverse osmosis.*

DESIGN FEATURES

Operation

Produces potable water from seawater, utilizing single-pass Reverse Osmosis technology.

Single control switch for instant start-up/stop of entire system.

Operation and maintenance are relatively simple - requiring daily check and routine maintenance.

Centralized instrument and control panel. All important operating parameters can be monitored and controlled from this panel.

Automatic shut-down when major fault occurs, with annunciation and visual display of cause.

Single chemical addition for control of scale. No acid addition is required.

No thermal or high salinity brine disposal problems. System capacity can be increased easily in the field. Multiple units can be interconnected to give larger capacities.

Installation

All standard systems are supplied on welded steel skids. These skids are sandblasted and epoxy-painted to a marine specification. Skids are easily moved by forklift.

Installation requires only skid placement and connection of electrical and water lines.

All systems are factory-operated in an eight-hour test run to insure reliable performance of all components.

Corrosion Resistance

All high pressure manifolding, valves, tubing and fittings are constructed of 316 stainless steel. High velocities are maintained to avoid pitting and crevice corrosion.

Aluminum bronze is used in the fluid end of the high pressure pump. This alloy gives excellent service in seawater application.

All wetted surfaces of the system are automatically flushed with fresh water upon shut-down.

All filtration equipment and membrane pressure vessels are constructed from Fiberglass Reinforced Plastic which is impervious to seawater corrosion.

All low pressure piping, valves and fittings are constructed from Sch. 80 PVC.

Stainless steel clamps and bolts are used throughout.

Maintenance

Designed-in accessibility of all components for ease of maintenance.

Easy-to-use system for cleaning the membranes.

Unattended operation - requires only daily check and log-taking.

Operating manuals contain easy to follow maintenance program and trouble-shooting chart.

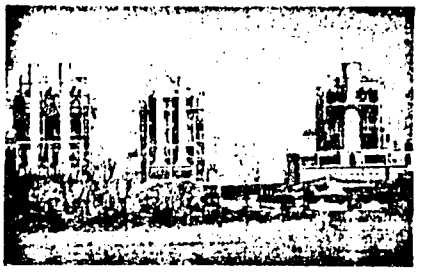
Chemical and power generating industry has called upon *Aquatron International, Inc.* to provide pure water by *reverse osmosis.*

Louisiana Power and Light Company has installed an Aquatron R.O. system ahead of their existing Demineralization units at their Taft, Louisiana generating plant.

The results have been better than expected.

Before installation of the R.O. system, the D.I. units had to be regenerated every 50,000 gallons of feedwater throughput.

Not only was regeneration of the D.I. units costly and time consuming, but disposal of the caustic soda

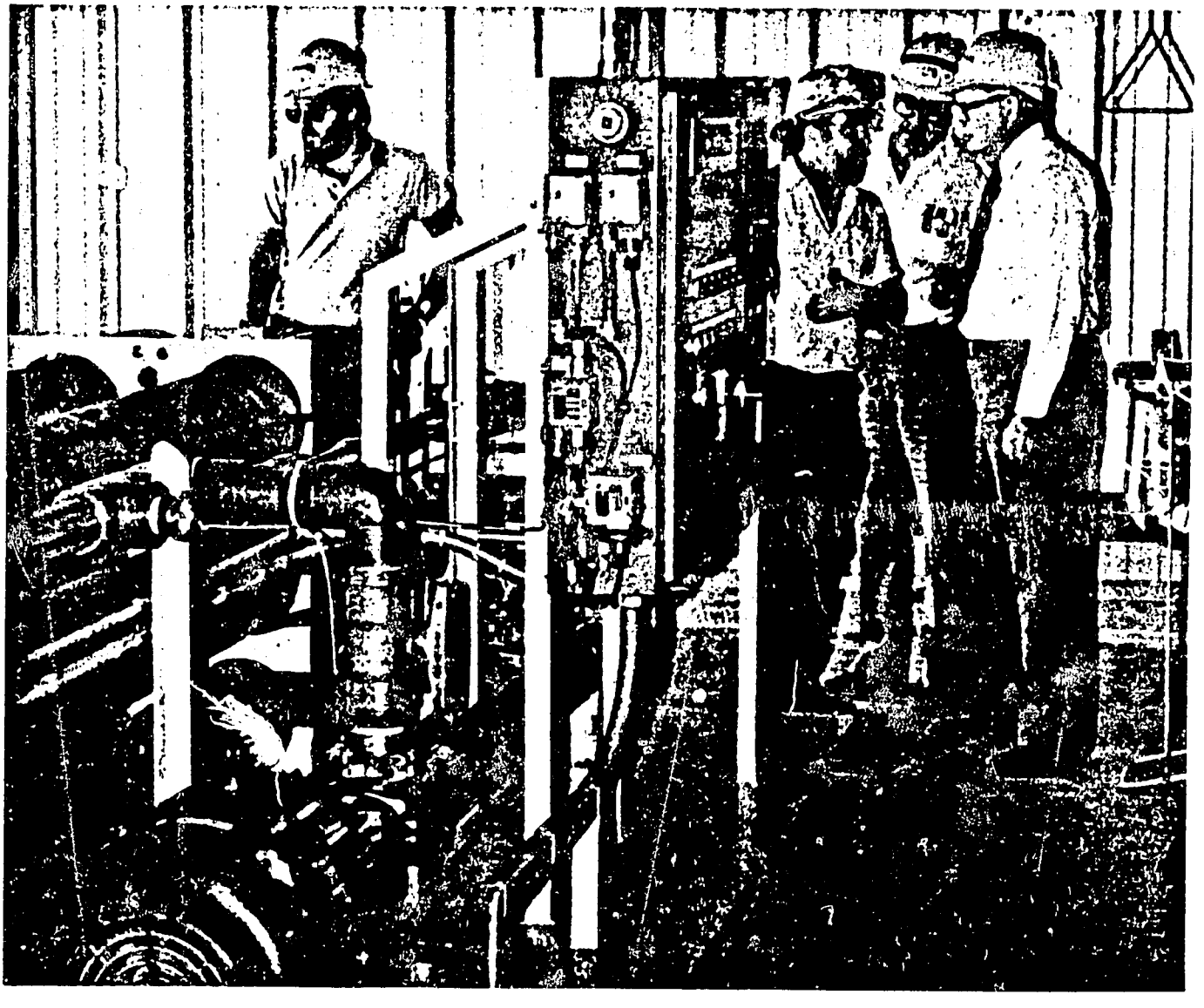


Louisiana Power and Light's Little Gypsy Generating Plant.

and sulfuric acid used in regeneration creates a severe environmental disposal problem.

After installation of the Aquatron R.O. system ahead of the D.I. units, regeneration has been extended from 50,000 gallons to over 2,000,000 gallons.

Needless to say LP&L is very pleased.

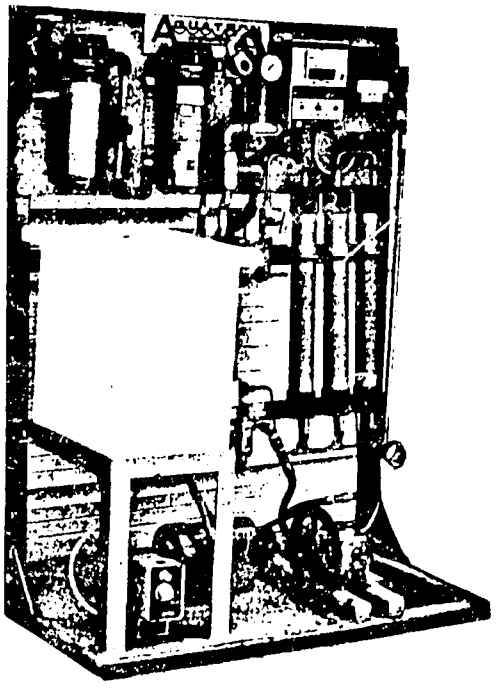


Louisiana Power and Light officials inspect new R.O. system at their Little Gypsy Generating Plant.

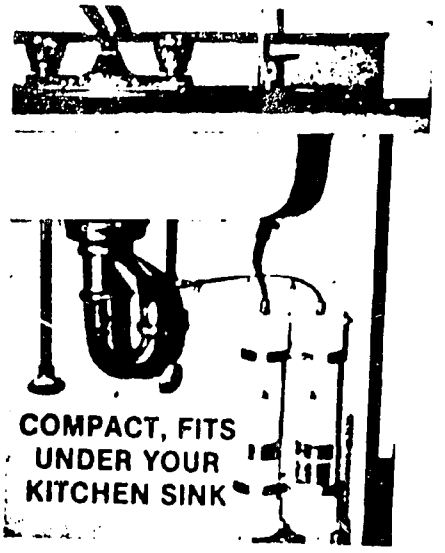
166

AQUATRON INTERNATIONAL, INC. manufactures water for practically

Brackish water systems capable of producing 120,000 gallons per day of potable water

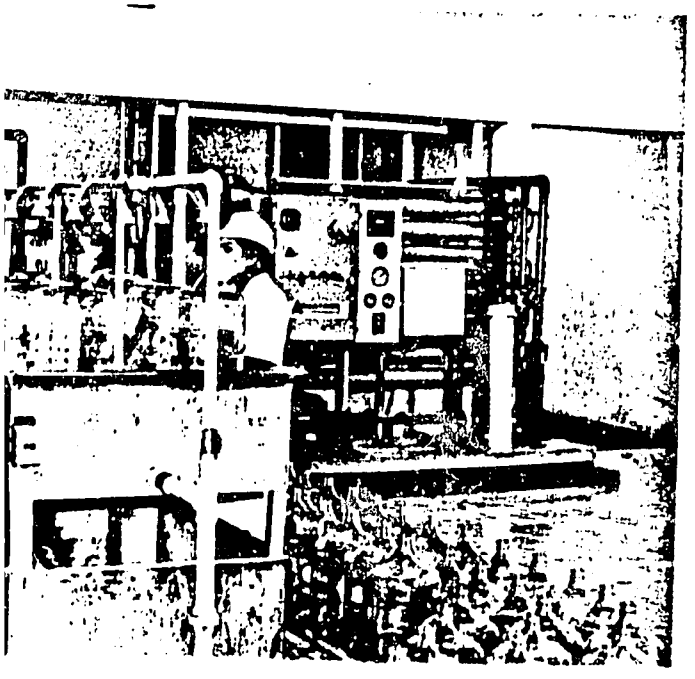


Small sea water R.O. SYSTEMS for boats and sea side homes

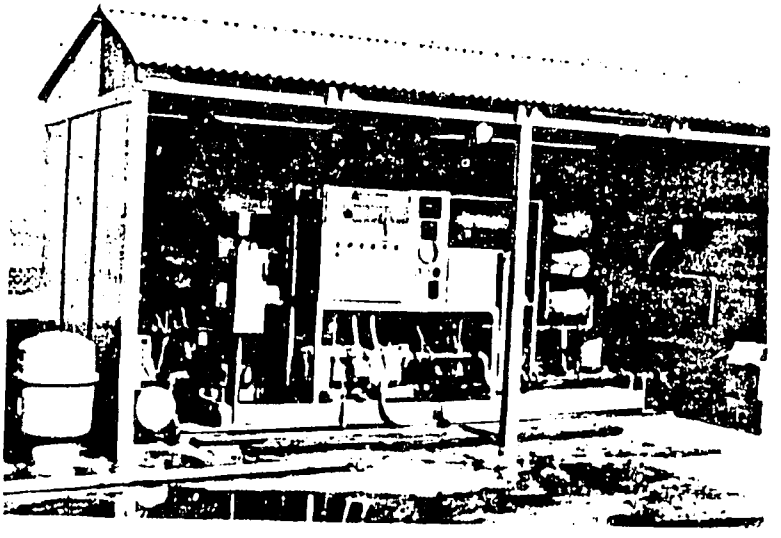


Under the sink water purifiers for home and businesses. Converts bad-tasting tap water into safer, delicious tasting bottled quality water. (U.S. Gov't. tested and registered.)

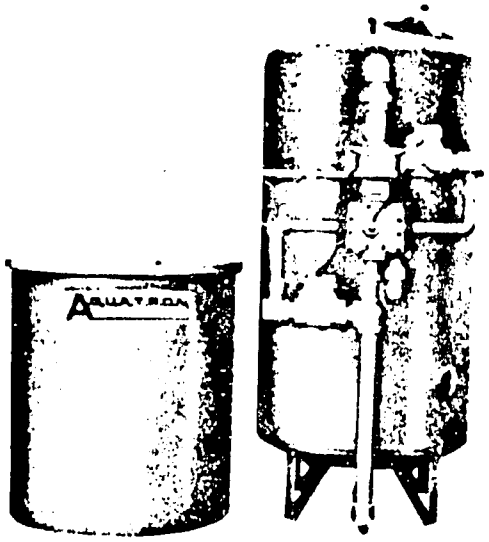
Bottled water planis, such as this system located in Ecuador, produces 20,000 gallons per day of ultra pure drinking water



65-K GPD brackish water reverse osmosis located in Saudi Arabia



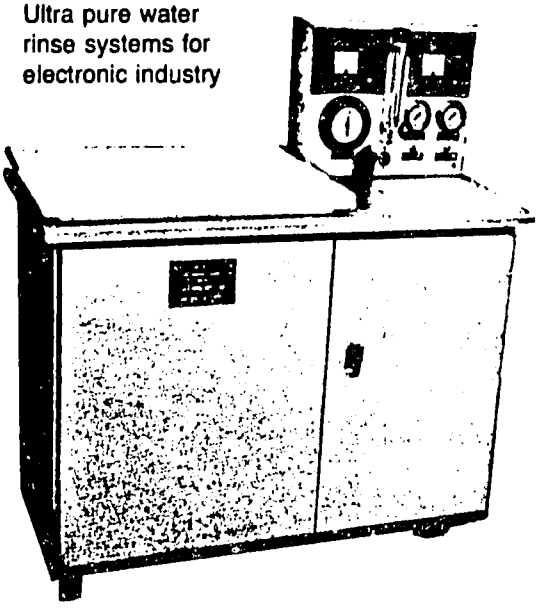
ırification and filtration equipment
'ery application.

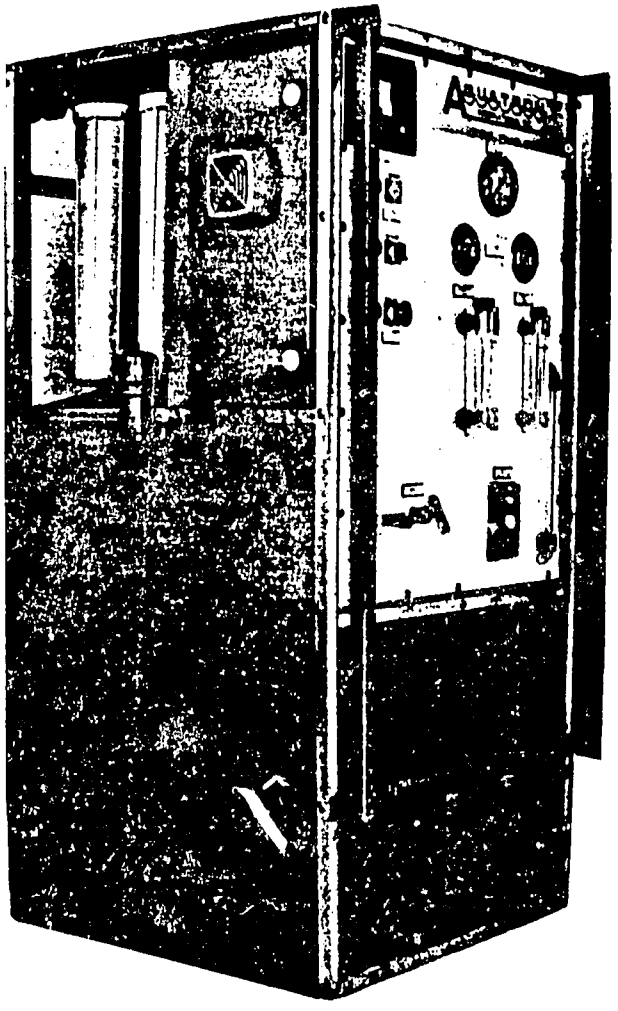


Hand held water purification units for travelers or emergency use

mmercial and industrial filters and water softeners

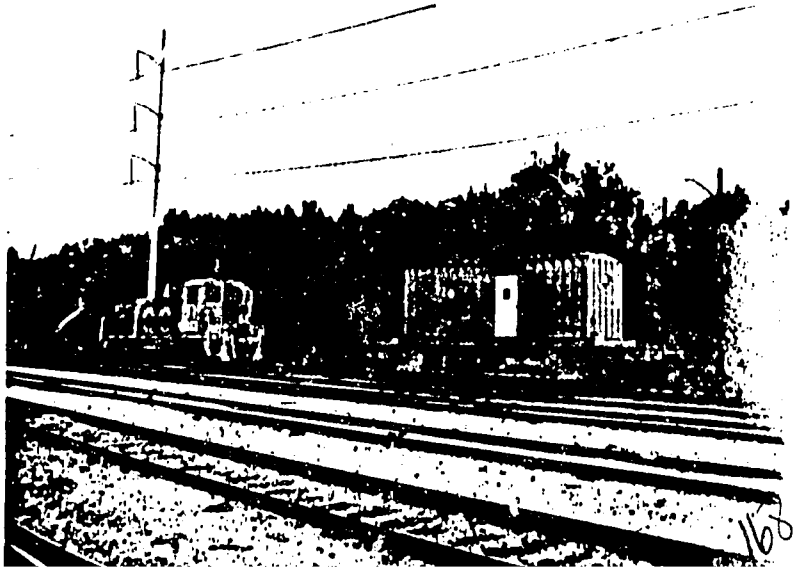
Ultra pure water rinse systems for electronic industry





Compact R.O. SYSTEMS for hospitals and laboratories

Self-contained water purification systems of various sizes

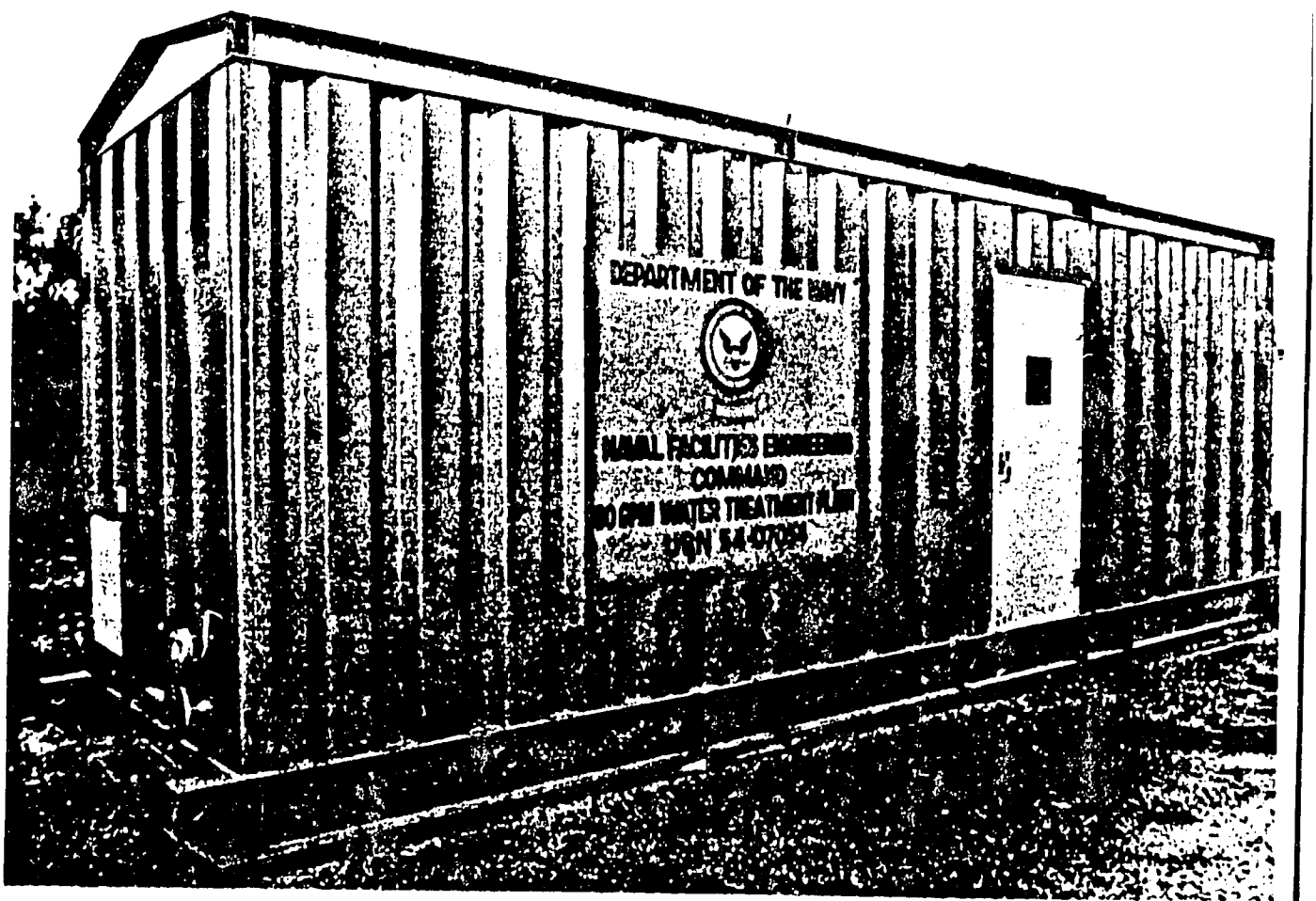


AQUATRON INTERNATIONAL, INC. technology is helping U.S. Navy...

Aquatron International, Inc. is providing the U.S. Navy with sophisticated two pass R.O. SYSTEMS capable of producing 90,000 gallons per day of ultra pure water.

These systems utilize the most advanced technology and engineering techniques in the industry today.

These systems will be deployed at naval support stations located around the world to provide ultra pure water for such uses on nuclear carriers and submarines.



SweetWater®

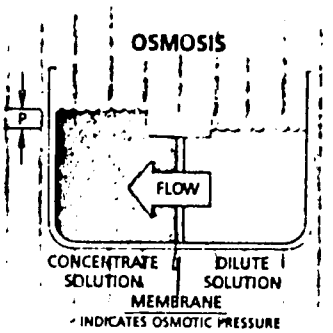
DESIGNED REVERSE OSMOSIS WATER PRODUCTION SYSTEMS

170

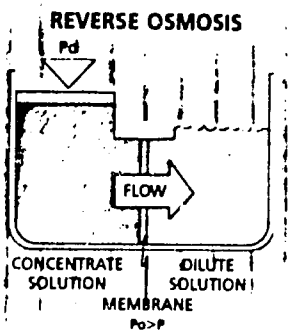
The Osmotic Process

When freshwater and saltwater are allowed to stand side by side, separated only by a semi-permeable membrane, the natural tendency is for the freshwater to flow through the membrane into the saltwater. In nature this equalization is called osmosis.

To reverse this natural tendency, pressure can be applied to the saltier side which forces freshwater through the membrane out of the concentrated saltwater. This process is called REVERSE OSMOSIS (RO) and is the basic reason why SweetWater is able to make good tasting drinkable water from the sea.



Osmosis–normal flow from low-concentration solution to high-concentration solution.

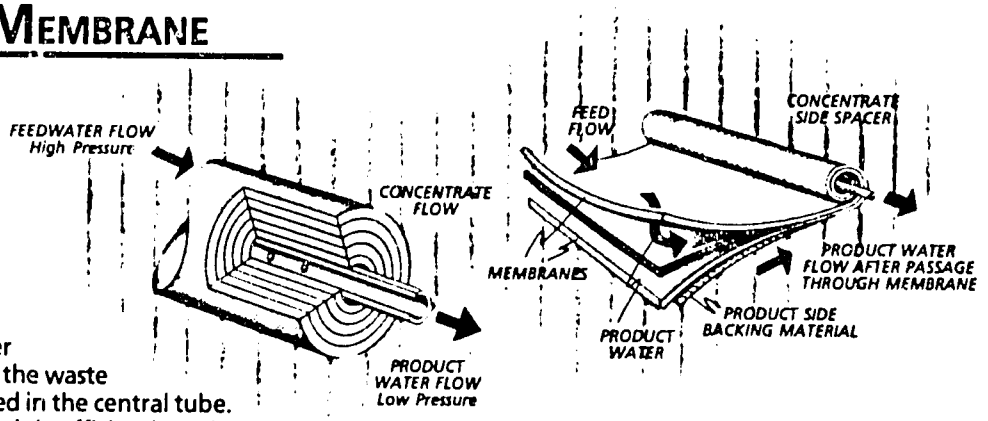


Reverse osmosis–flow reversed by application of pressure (Po) to high-concentration solution.

The SweetWater Membrane

The SweetWater module uses a spiral wound design as illustrated to the right. In this type of RO module, the pressurized sea water is constantly flowing past the many membrane surfaces. It is helpful to visualize the module as a unique filter where fresh water passes through the filter (spiral wound membranes), keeping the salts behind in the unfiltered portion of water which are continuously discharged with the waste water. The fresh product water is collected in the central tube.

The SweetWater spiral wound module efficiently and economically reduces high concentration of dissolved minerals and salts.



Sample RO Test Results

The chart shows the content of seawater before and after the RO process.

Comparison of Seawater–Before and After

ELEMENTS	RESULTS BEFORE	RESULTS AFTER	ELEMENTS	RESULTS BEFORE	RESULTS AFTER
TDS at 18°C (mg/l)	36,073	250	Conductivity (michromhos)	45,000	<550
Chloride (mg/l)	17,600	183	pH (units)	7.7	7.4
Sodium (mg/l)	11,000	105	Iron (mg/l)	0.3	<0.1
Calcium (mg/l)	315	0.8	Manganese (mg/l)	<0.1	<0.1
Magnesium (mg/l)	1,300	2.6	Strontium (mg/l)	13.8	0.4
Potassium (mg/l)	418	6.4	Nitrate (mg/l)	<2.0	<2.0
Sulfate (mg/l)	2,346	2.3	Silicon as SiO_2 (mg/l)	10.7	<5.0
Bicarbonate (mg/l)	63	4.9	Turbidity (FTU)	0.28	0.13
Carbonate (mg/l)	None	None	Boron (mg/l)	4.0	0.4
Hydroxide (mg/l)	None	None	Ammonia (mg/l)	None	None
Hardness as $CaCO_3$ (mg/l)	6,140	28	Bromide (mg/l)	85	0.85
P-alkalinity as $CaCO_3$ (mg/l)	0	0	Fluoride (mg/l)	0.8	<0.1
T-alkalinity as $CaCO_3$ (mg/l)	104	8	Total Sulfides (mg/l)	<0.1	<0.1

Note: Mg/l is the same as ppm
Salinities above 45,000 mg/l require special configurations

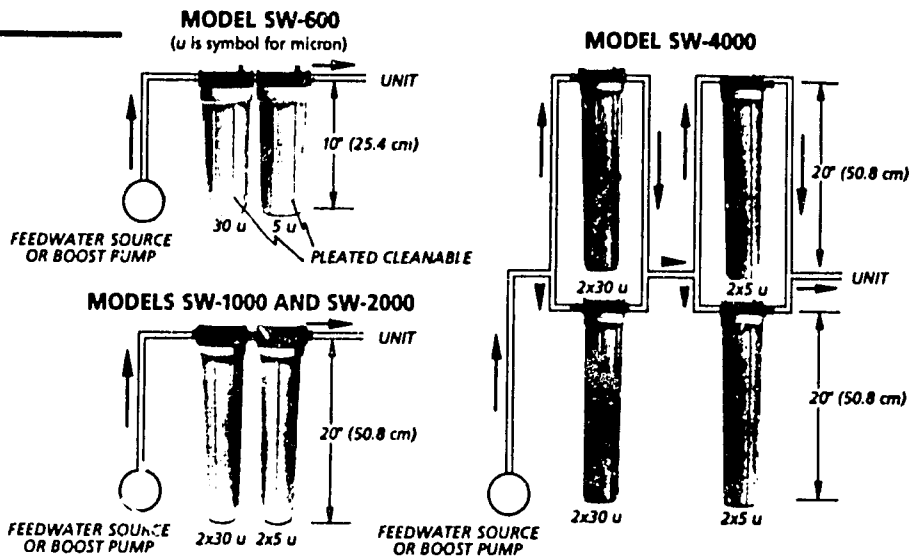
Operation And Maintenance

SweetWater systems require no special knowledge whatsoever to start and operate. Thanks to their simple, yet advanced design, routine maintenance is extremely simple.

Economy is one of SweetWater's strongest points. 1000 gallons (3785 liters) of water, produced by a SweetWater unit would cost U.S. $4.30. In comparison, the same amount of water produced by distillation would cost U.S. $6.65. (Documentation available upon request.)

STANDARD PACKAGES

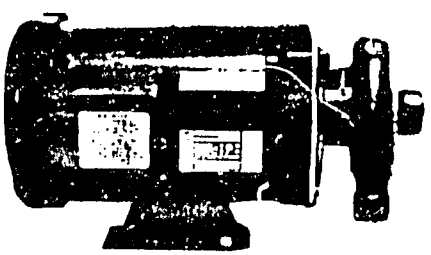
For any reverse osmosis system to function to manufacturer's design standards, the heart of the system (the membranes) must pass water which has been cleaned (filtered) to pre-set standards. All SweetWater systems are equipped with pre-filtration systems that are designed for operating areas where the feedwater contains only minor amounts of contaminants. This presumes the unit will be operating with salt or brackish water where there is low solid material suspended in the feedwater plus *no* oil contamination and *no* chlorine. Shown are the Standard Filtration arrangements shipped with SweetWater RO Systems.



OPTIONAL PACKAGES

BOOST PUMPS

Boost pumps are available from SweetWater to match the flow requirements of your unit. They may also be purchased locally. When adding additional pre-filtration one must take into account the additional pump requirements caused by the pressure drop across the standard filters and any additional pre-filtration that is added. Consult SweetWater for your unit's specific pump requirements.

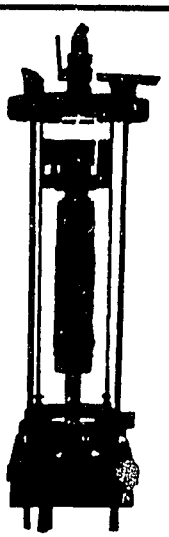


Available in various sizes matched to flow rate of unit. Consult SweetWater for size required. Only centrifugal pumps may be used as feedwater pumps.

PRE-TREATMENT OPTIONS

OIL PRE-FILTRATION

Oil, if present in feedwater, will coat the membrane and cause a decrease in system effectiveness. The system as shipped will not effectively prevent oil from entering the system. If the SweetWater system is to be used in harbors, or other areas known to contain oil in the feedwater, an oil filtration package must be added.



Available in various sizes matched to flow rate of unit. Consult SweetWater for size required.

BACKWASH MEDIA FILTER*

SweetWater's RO water makers will from time to time, be required to operate in adverse conditions which will require other than standard pre-filtration. High suspended solids in many areas will force the use of additional filtration to keep the system in best operating condition. When operating in a high solids area such as river basins where there is high concentration of sand and silt, or in tropical waters where high algae content may be present, a backwash media filter unit is required. The operation of this filter unit is similar to a water softener. To keep it operating efficiently, it must be backflushed periodically. Installation of a backwash media filter option is in the line between the feedwater pump and the filtration package supplied with the SweetWater system.

Available in various sizes matched to flow rate of unit. Consult SweetWater for size required.

*If the optional backwash media filter is used, the 30 micron filter becomes redundant and will not be supplied.

CHLORINE PRE-FILTERS

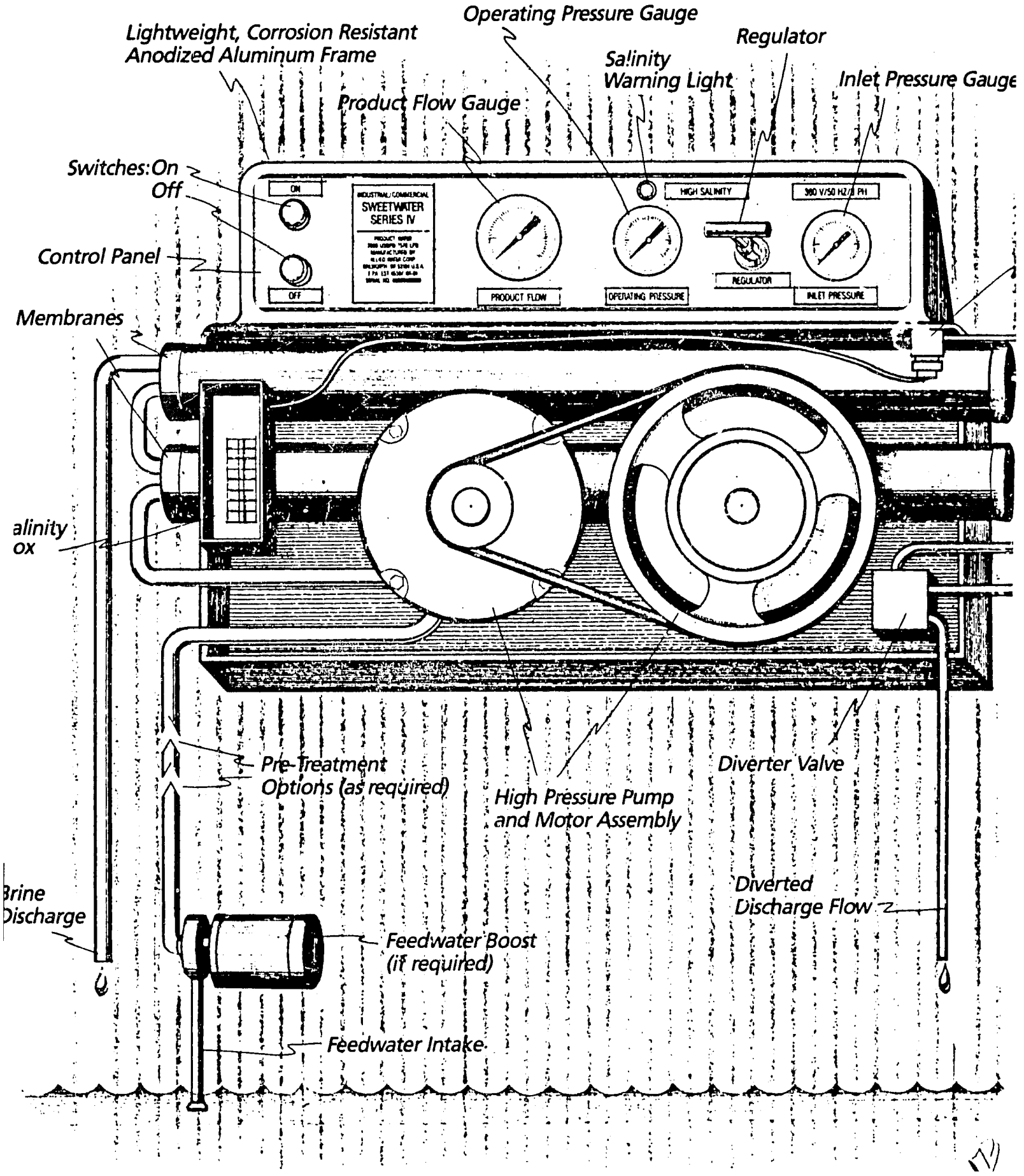
When operating a SweetWater unit where chlorine is present in the water, a chlorine filter must be used. Chlorine will permanently damage the membranes. Consult SweetWater if chlorine is present in the feedwater.

IRON (RUST) PRE-FILTER

Iron (rust) in the feedwater is detrimental to the membranes and to the operation of a reverse osmosis system. Therefore, any iron in the feedwater must be removed.

If it is impractical to use stainless steel, copper, Cu-Ni or plastics in the feedwater pumps or piping, or if a sea chest is used, an iron pre-filter or a Green Sand Filter must be used. SweetWater makes them available in various sizes to suit your specific need. Contact your local distributor or the factory for further information.

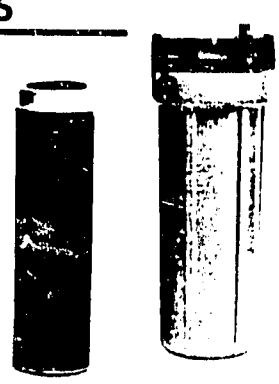
TYPICAL FLOW DIAGRAM



POST-TREATMENT OPTIONS

POST CARBON FILTER

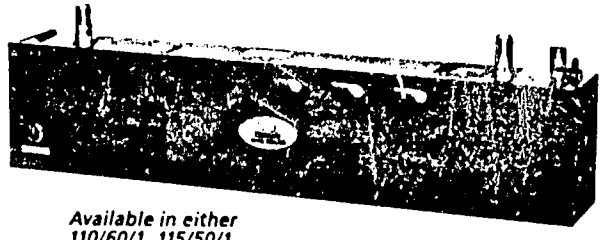
In extreme cases, water which has passed through a SweetWater system may still contain odor or taste from the original feedwater source. While this is a harmless condition, the use of a charcoal filter will help to eliminate this problem. A charcoal filter is placed in the product water line after the storage tank.



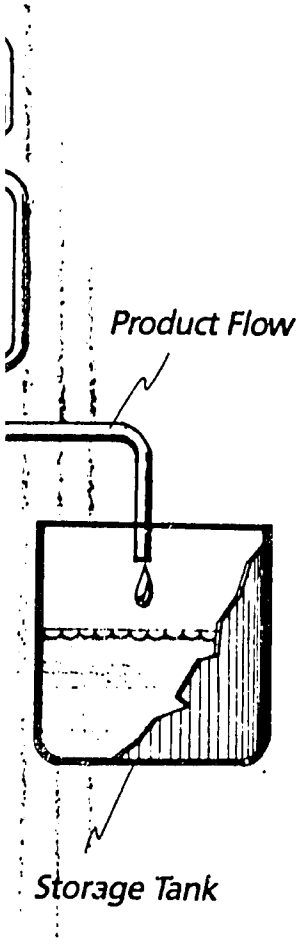
Available in various sizes matched to flow rate of unit. Consult SweetWater for size required.

ULTRAVIOLET UNIT

SweetWater RO systems produce safe, pure potable water, however, the water may be contaminated in the storage tank. To insure cleanliness an ultraviolet system may be added to the discharge line from the storage tank beyond the carbon filter. SweetWater offers one size capable of processing 3-10 gpm (11-38 lpm).

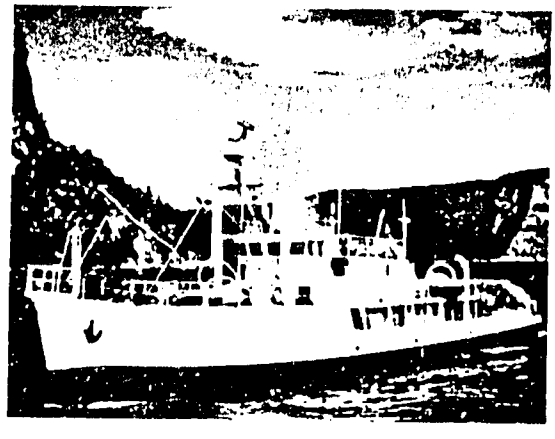


Available in either 110/60/1, 115/50/1, 220/50/1 or 230/60/1.



ON BOARD COUSTEAU'S R/V CALYPSO

SweetWater systems, standard or custom, deliver a continuous supply of pure, clean water from any ocean in the world. Starting and maintenance require no special knowledge whatsoever. Advice, answers and service are always available from SweetWater's dependable, worldwide sales/service network.

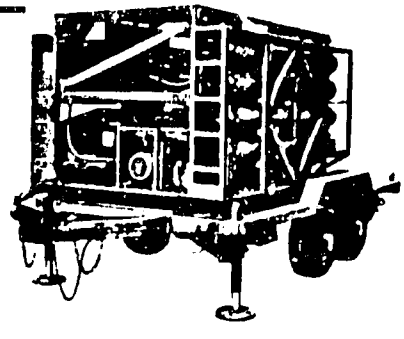


R/V Calypso
© Cousteau Society, Inc.

SWEETWATER MIL-SPEC SERIES

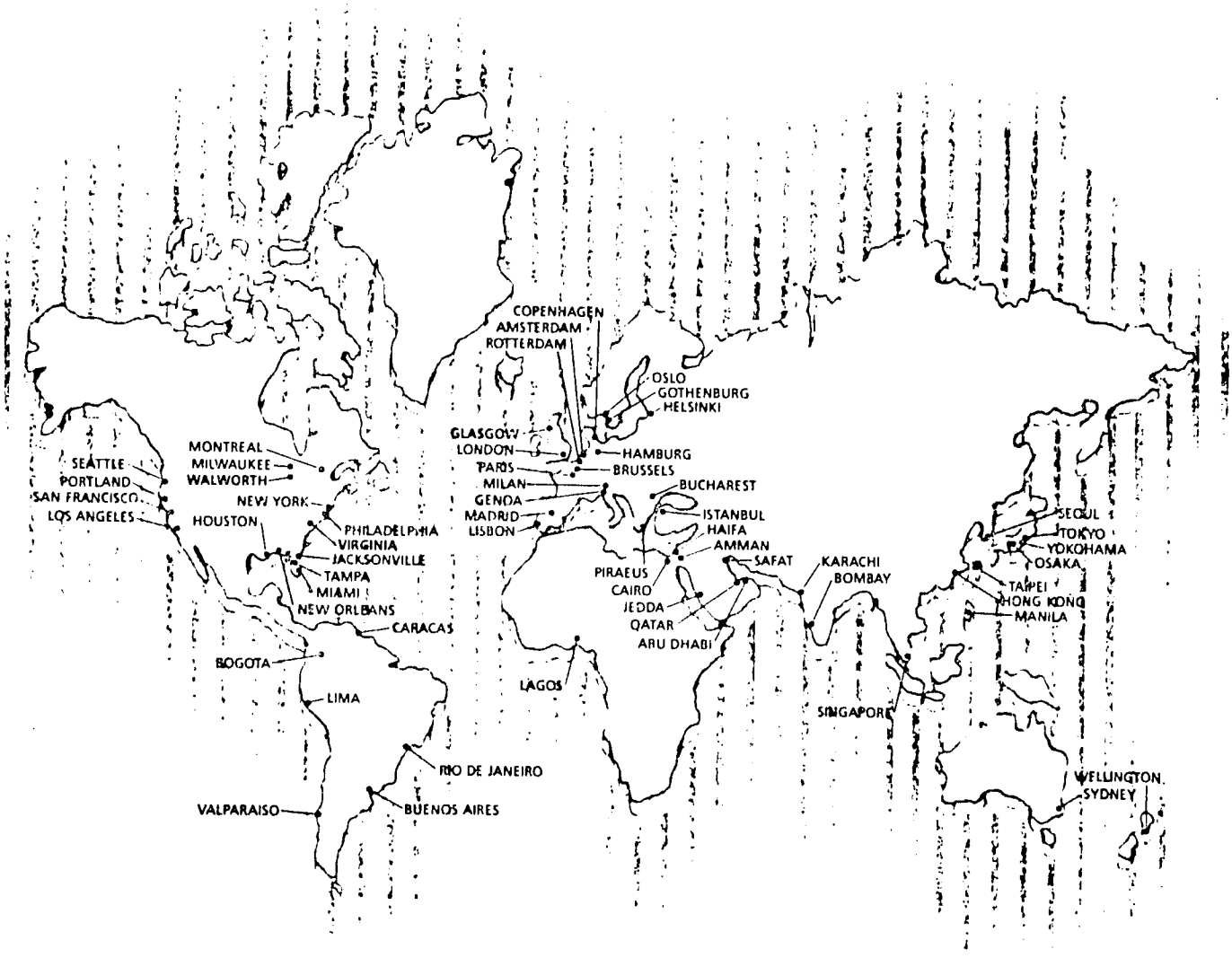
SweetWater's engineering expertise is available to the world's military markets with NBC (Nuclear, Biological, Chemical), Anti-Mag (Naval), heavy duty and lightweight, military-style, trailer-mount systems.

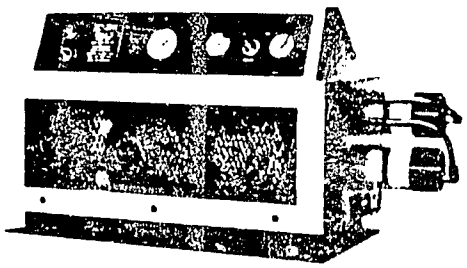
Built and certified to military specifications, they are field deployable, mobile, self contained, rugged, reliable and can withstand aerial drops. Call or write for additional free literature.



SweetWater. Superior RO systems that back you up every step of the way.

WORLDWIDE SALES AND SERVICE





SweetWater®

Manufactured by Allied Water Corp.

A subsidiary of MARLAND Environmental Systems, Inc.

P.O. Box 501, Great Falls, Virginia 22066 U.S.A.

Telephone: (703) 759-5244 • Telex: 287014 MARL UR

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SweetWater Features

STANDARD

- Lightweight fiberglass enclosure (SW100–SW4000)
- Corrosion resistant, anodized aluminum frame
- Corrosion resistant gauges: low pressure gauge, operating pressure gauge and product flow gauge
- Energy efficient TEFC motors
- Pre-filter package
- Adjustable pressure regulator
- Low pressure and high pressure safety devices
- Water quality sensor (salinity monitor and diverter valve)
- Chemical injection package (Brackish Models)

OPTIONS

- Ultraviolet sterilizer with monitor
- Carbon pre-filter for chlorine removal
- Carbon post-filtration for taste and odor
- Feedwater boost pumps
- Additional pre-filtration packages for virtually all feedwater conditions
- Pre-filter package–custom designed
- SweetWater 4000 seawater unit is available in an Intrinsically Safe version
- Chemical injection package

Feedwater Flow Rates*

Models	Nominal
SW-600	3.0 gpm (11 lpm) @ 35 psi
SW-1000	7.0 gpm (26 lpm) @ 35 psi
SW-2000	10.0 gpm (38 lpm) @ 35 psi
SW-4000	20.0 gpm (76 lpm) @ 35 psi
SW-6500	28.0 gpm (106 lpm) @ 35 psi
SW-13500	56.0 gpm (212 lpm) @ 35 psi

*The flow rates indicated are rated prior to standard pre-filters.

Control Box Dimension*

SW600, SW1000, SW2000, SW4000:
14.5" L x 12.5" W x 7.6" H–8.5 lbs.
36.8 cm x 31.8 cm x 19.3 cm–3.9 kg.
SW6500, SW13500
(Integral – Built in)

*All control boxes are prewired to the units with 9' (2.7m) of cable.

Standard Capacities* (Seawater)

Model No.	Gallons per day	Liters per day	Tons per day
SW-600	600	2,271	2.27
SW-1000	1,000	3,785	3.79
SW-2000	2,000	7,570	7.57
SW-4000**	4,000	15,140	15.14
SW-6500	6,600	24,983	25.00
SW-13500	13,500	51,102	50.00

*Rated flow ± 15% capacities @ 25°C – 35,000 mg/l seawater. Larger capacities on request. Designed to order.
**SweetWater 4000 Seawater Unit is available in an Intrinsically Safe version, SWE-4000. Other capacities in this configuration available on request.

Standard Capacities* (Brackish Water)

Model No.	Gallons per day	Liters per day
SWB-600	600	2,271
SWB-1000	1,000	3,785
SWB-2000	3,640	13,777
SWB-4000	7,200	27,252
SWB-6500	11,000	41,635
SWB-13500	23,000	87,055

*Rated flow ± 15% capacities @ 25°C – 10,000 mg/l seawater. Larger capacities on request. Designed to order.

Dimensions And Weights*

SW600	51" L x 25" D x 23" H 130 cm x 63.5 cm x 58.4 cm	255 lbs. 116 kg
SW1000	51" L x 27" D x 23" H 130 cm x 69 cm x 58.4 cm	265 lbs. 120.5 kg
SW2000	53" L x 27" D x 23" H 135 cm x 69 cm x 58.4 cm	340 lbs. 154.5 kg
SW4000	59" L x 41" D x 24.5" H 150 cm x 104 cm x 62 cm	610 lbs. 277.3 kg
SW6500	90" L x 48" D x 66" H 228.6 cm x 121.9 cm x 167.6 cm	1500 lbs. 680.4 kg
SW13500	96" L x 60" D x 66" H 243.8 cm x 152.4 cm x 167.6 cm	2500 lbs. 1134 kg

*Add 10% for shipping weights.
Above are all dry weights.

Water Connections

Models	Feed Inlet	Product Outlet	Brine Outlet	Product to drain
SW-600	1" FNPT (2.54 cm)	¼" FNPT (.635 cm)	½" FNPT (1.27 cm)	¼" FNPT (.635 cm)
SW-1000	1" FNPT (2.54 cm)	¼" FNPT (.635 cm)	¾" FNPT (1.9 cm)	¼" FNPT (.635 cm)
SW-2000	1" FNPT (2.54 cm)	⅜" FNPT (.95 cm)	¾" FNPT (1.9 cm)	⅜" FNPT (.95 cm)
SW-4000	1½" FNPT (3.81 cm)	½" FNPT (1.27 cm)	1" FNPT (2.54 cm)	½" FNPT (1.27 cm)
SW-6500	2" FNPT (5.08 cm)	¾" FNPT (1.9 cm)	1½" FNPT (3.81 cm)	¾" FNPT (1.9 cm)
SW-13500	3" FNPT (7.62 cm)	1" FNPT (2.54 cm)	2" FNPT (5.08 cm)	1" FNPT (2.54 cm)

Above FNPT specifications will accommodate standard piping.

All specifications are subject to change without notice.

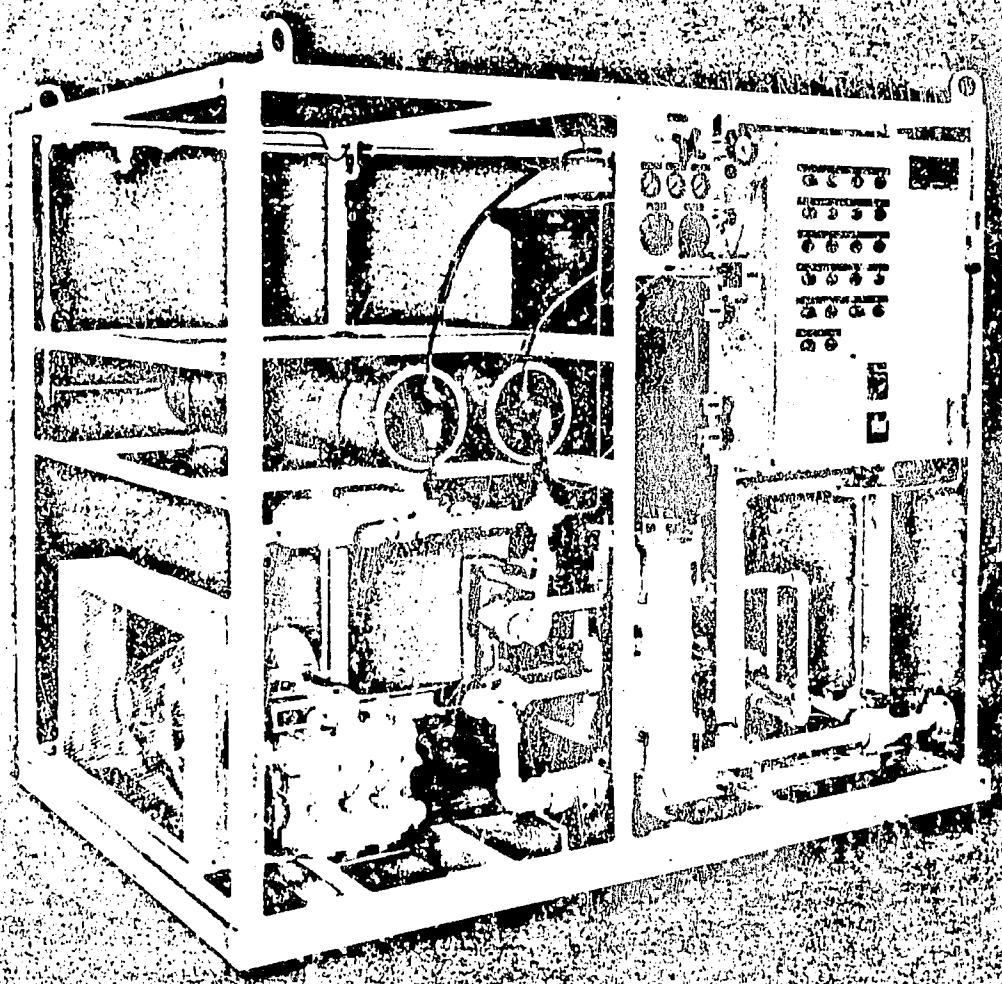
Culligan®

aqua-cleer®

SERIES SWL

SEAWATER CONVERSION SYSTEMS

FRESH WATER FROM SEAWATER



DESIGNED TO MEET EVERY APPLICATION

WATER TREATMENT WORLDWIDE™

177

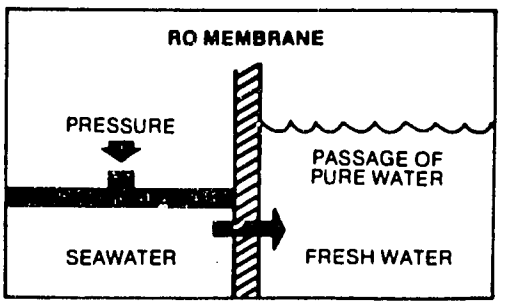
Culligan® aqua-cleer® SERIES SWL SEAWATER CONVERSION BY REVERSE OSMOSIS

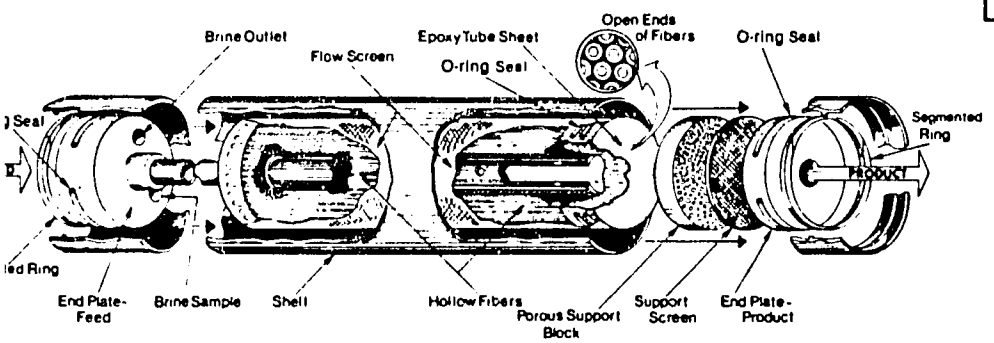
PRODUCT FEATURES

- Compact pre-engineered sizes from 1,600 to 72,000 gallons per day available. Units can be duplexed for larger capacities.
- Designed for simple operation and easy access for servicing.
- All controls and instrumentation conveniently located on front.
- Built-in failsafe features for system protection.
- Individual visual and audible alarms for ease of system monitoring.
- High efficiency positive displacement type pump.
- Optional energy recovery available.
- Complete with module maintenance equipment.
- Rugged construction. Heavy steel frame is blasted, primed and epoxy coated. Suitable for single point lift.

HOW REVERSE OSMOSIS WORKS

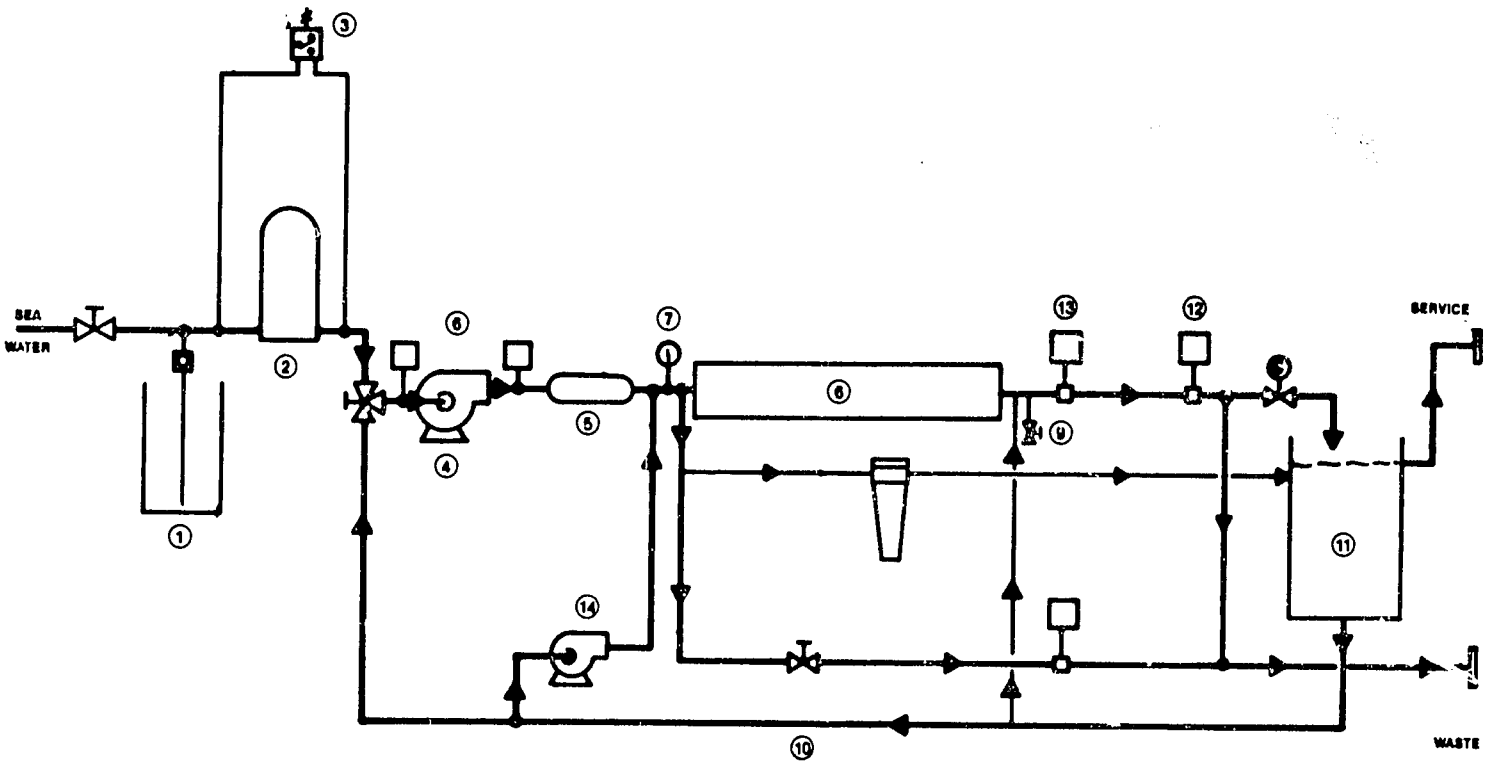
Reverse osmosis is the reverse of the osmosis process that occurs in plants and animals in nature. Pressure is used to force a flow of pure water through a semi-permeable membrane. Using a reverse osmosis system, pure water is forced from concentrated seawater to make fresh water, with the salts and other impurities being rejected to waste and over-board.





DuPont® hollow fiber modules are used in our system. The simplicity of design, operation and long life of this module is your assurance of high quality water with minimum operating difficulties.

SYSTEM OPERATION



1. Automatic pH control system.

2. Cartridge-type polishing filter. All-plastic housing with replaceable elements ensures particle removal.

3. Differential pressure switch senses when filters need changing and sends alarm.

4. High pressure pump boosts seawater to 800-1000 psi for efficient mineral removal.

5. Flow through pulse dampener provides smooth operation.

6. Pressure switches monitor pump suction and discharge. Both high or low pressure will cause system shutdown and activate alarms.

7. Panel mounted 316 SS liquid filled pressure gauges allow operator to easily monitor system operation.

8. DuPont B-10 hollow fiber modules reject 98.5% of all dissolved minerals.

9. Sample valves are provided on the product water side of each module. Permits checking state of individual modules.

10. Product water flush of wetted parts minimizes corrosion during system shut down.

11. Flush/Clean tank stores product water for system flush, module maintenance and to prevent module dehydration in case of power failure.

12. Water quality monitor and divert valve system. Monitor automatically diverts low quality water to waste...allows only high quality water to service.

13. Direct reading flow meters show product and waste flows at a glance.

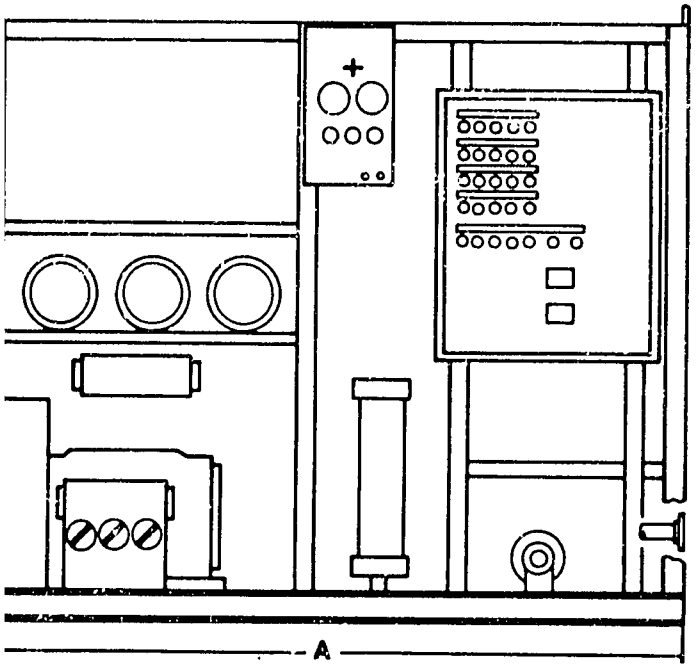
14. Module maintenance system allows simple periodic membrane treatment. Circulation of conditioning solution maintains high salt rejection capability.

Culligan® aqua-cleer® REVERSE OSMOSIS

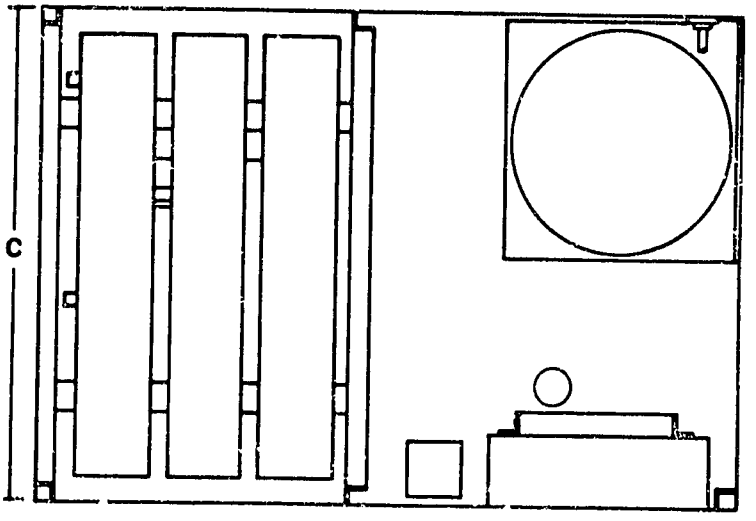
SYSTEM SPECIFICATIONS

SWL SERIES																
MODEL		041	042	043	061	062	063	064	065	066	067	068	069	610	611	612
Nominal Design Capacity	GPD	1600	3200	4800	6000	12000	18000	24000	30000	36000	42000	48000	54000	60000	66000	72000
	m³/d	6.1	12.1	18.2	22.7	45.4	68.1	90.8	113.6	136.2	159.0	181.7	204.4	227.1	249.8	275.2
Operating Seawater Flow	GPM	8	15	22	13	24	36	48	60	72	84	96	108	120	132	144
	m³/h	1.8	3.4	5.0	3.0	5.5	8.2	11.0	13.6	16.4	19.1	21.8	24.5	27.3	30.0	32.7
No. of DuPont B-10 Modules		1-4"	2-4"	3-4"	1-8"	2-8"	3-8"	4-8"	5-8"	6-8"	7-8"	8-8"	9-8"	10-8"	11-8"	12-8"
Motor Horsepower		7.5	10	15	10	20	30	40	50	50	60	75	75	75	100	100
Average Power	KW	3.7	7.2	10.4	6.3	11.2	16.7	22	27	31	36	41	46	51	56	61
Length A	ft	4'-10"			6'-8"			8'-0"								
	m	1.47			2.03			2.44								
Height B	ft	4'-7"			6'-0"			6'-8"						7'-8"		
	m	1.4			1.8			2.03						2.35		
Depth C	ft	2'-9"			4'-6"			6'-0"								
	m	.84			1.4			1.83								
Dry Weight	lb	1220	1300	1450	2450	2850	3100	5100	5470	6100	6650	7300	7950	8225	8900	10700
	kg	550	590	660	1110	1290	1410	2310	2475	2760	3010	3300	3600	3720	4030	4840

Note: Nominal rated capacity is based on standard seawater of 35000 PPM TDS at 77°F temperature. Capacity will vary with temperature and operating pressure.



FRONT VIEW



TOP VIEW

Culligan®

WORLDWIDE SERVICE CAPABILITY

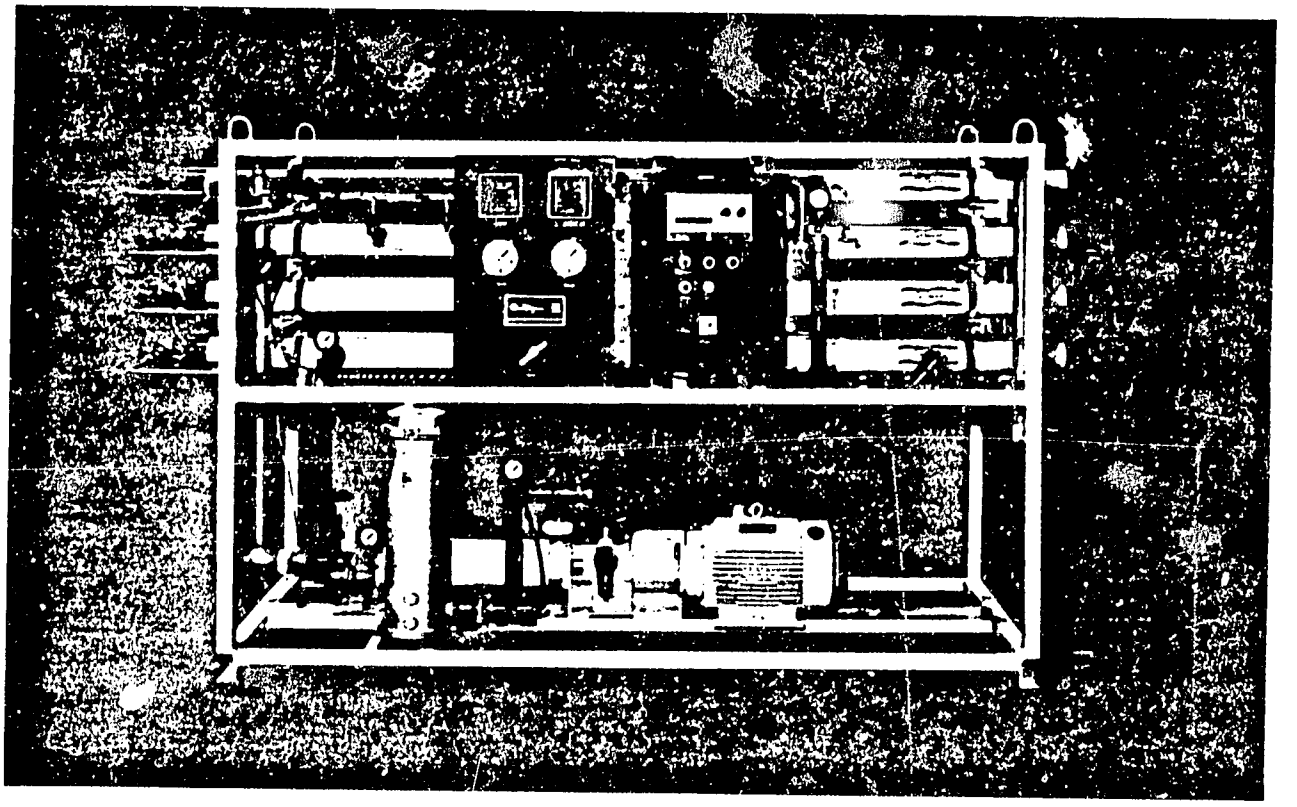
For the right answer to your water treatment problems, turn to the people who offer the efficient, dependable systems approach. Technical service is available worldwide. Call or telex Northbrook for dispatch of serviceman nearest your location.

Culligan USA
1 Culligan Parkway
Northbrook, IL 60062
Tel: 312-498-2000
Telex: 910-686-0005
Cable: Culliinc

6/82 Printed in U.S.A.

THE FUTURE CALLS FOR
Culligan.

SERIES K
REVERSE OSMOSIS SYSTEMS



Culligan Series K Reverse Osmosis Systems are designed for rugged industrial duty to offer the utmost in performance, durability and reliability. Standard models are available to provide water that is nearly free of dissolved solids, bacteria, virus and pyrogenic contaminants in quantities of from 26,000 to over 100,000 gallons per day.

K Series models are available with a choice of membranes and module configurations. The KS models use the conventional spiral wound cellulose acetate modules, the KP models have spiral wound thin-film composite membrane modules, while the KD models incorporate the DuPont hollow fiber modules. This choice allows for the best selection of module configuration and membrane type for the characteristics of the incoming water and operating parameter.

All K Series systems come with standard features that include a prefiltration system with replaceable elements to remove turbidity to extend component life; panel mounted flow meters, in-line temperature and pressure gauges to monitor system performance; conductivity monitor with selector switch for constant product/feed water TDS or percent rejection readings; and low feed water pressure shutdown control to protect the stainless steel pumping system. A full range of optional components and custom capacity designs are available to tailor the K Series to your exact requirements today, or allow for future expansion needs.

The Culligan K Series Reverse Osmosis systems represent the highest level of design, engineering excellence and performance available today.

Product Applications

- Electronics—Rinse Waters Low in Colloidal, Organic & Ionic Impurities
- Pharmaceutical—Water for Still Pre-Treatment
- Manufacturing—Process & Make-Up Water Treatment
- Food & Beverage—Reduced Sodium Process Water
- Cosmetics—Production of USP Water
- Boilers—Reduced Scaling & Improved Energy Efficiency
- Laboratories—Water for Reagent Make-Up & Glassware Washing
- Plating—Spot-Free Rinse & Solution Make-Up Water
- Drinking Water—Reduced TDS & Improved Taste
- Humidification—Reduced Scaling & Dusting
- Ice Production—Improved Taste & Clarity
- Floriculture—Reduced Leaf Spotting & Mineral Build-Up in Planting Soils

Model Descriptions

Model	Nominal Capacity GPD	Module Type	Element Qty. & Size	Approx. Recovery %	Max. Operating Temp.	Pipe Size (in) Feed	Product	Waste	Motor HP	Approx. Operating Wt.
KS-27	27,000	Spiral C.A.	15-4x40	75	104°F	1½	1½	¾	25	2150
KS-38	37,800	Spiral C.A.	21-4x40	75	104°F	2	1½	¾	25	2200
KS-43	43,000	Spiral C.A.	24-4x40	75	104°F	2	1½	¾	30	2450
KS-54	54,000	Spiral C.A.	30-4x40	75	104°F	2	1½	¾	30	2750
KS-65	64,800	Spiral C.A.	36-4x40	75	104°F	2½	2	1	40	2900
KS-76	75,600	Spiral C.A.	42-4x40	75	104°F	2½	2	1	40	3100
KS-86	86,400	Spiral C.A.	48-4x40	75	104°F	2½	2	1	40	3250
KS-97	97,200	Spiral C.A.	54-4x40	75	104°F	2½	2	1½	40	3500
KP-27	27,000	Spiral TFC	15-4x40	75	110°F	1½	1½	¾	15	2150
KP-38	37,800	Spiral TFC	21-4x40	75	110°F	2	1½	¾	25	2200
KP-43	43,000	Spiral TFC	24-4x40	75	110°F	2	1½	¾	25	2450
KP-54	54,000	Spiral TFC	30-4x40	75	110°F	2	1½	¾	25	2750
KP-65	64,800	Spiral TFC	36-4x40	75	110°F	2½	2	1	30	2900
KP-76	75,600	Spiral TFC	42-4x40	75	110°F	2½	2	1	30	3100
KP-86	86,400	Spiral TFC	48-4x40	75	110°F	2½	2	1	30	3250
KP-97	97,200	Spiral TFC	54-4x40	75	110°F	2½	2	1½	30	3500
KD-26*	26,000	DuPont B-9	2-9½x48	75	95°F	1½	1½	¾	25	1850
KD-39*	39,000	DuPont B-9	3-9½x48	75	95°F	2	1½	1	25	2200
KD-52*	52,000	DuPont B-9	4-9½x48	75	95°F	2	1½	1	30	2500
KD-65*	65,000	DuPont B-9	5-9½x48	75	95°F	2½	2	1½	30	2750
KD-78*	78,000	DuPont B-9	6-9½x48	75	95°F	2½	2	1½	40	3000
KD-91*	91,000	DuPont B-9	7-9½x48	75	95°F	2½	2	1½	40	3250
KD-104*	104,000	DuPont B-9	8-9½x48	75	95°F	2½	2	1½	40	3500

*DuPont moduled systems not recommended for medical or surgical applications.

System Specifications

Nominal Capacity
Approximate initial capacity based on properly pretreated feed water of 1500 PPM TDS as $CaCO_3$ & 77° F, plus operating pressure of 400 psi (225 psi-KP Series)

Operating Conditions
Feed Pressure: 20 psi min (flowing)/75 psi max
Max. Pump Pressure: KS 500 psi
KP 300 psi
KD 400 psi

Power Requirements
460 VOLT/3 PHASE/60 HZ

Overall Dimensions
Depth 48" Width 169" Height 72"

Available Options
Feedwater pH Monitor/Control System
Chemical Feed System
Alternate Electrical Voltage & Controls
High Temperature Shutdown with Alarm
Product Water Relief/Control System
Alternate Capacities

NOTE: This product produces high quality water which can be contaminated by or corrode the plumbing system following the unit. The purchaser is responsible to supply system components of inert material that are compatible with the application.

THE FUTURE CALLS FOR Culligan®

Cat. No. 8194-18

Culligan International Company

Printed in U.S.A. 9/85

APPENDIX D

INSTRUMENTATION SYSTEM SPECIFICATIONS AND DATA REQUIREMENTS FOR A PHOTOVOLTAIC POWER DESALINATION SYSTEM

SPECIFICATIONS FOR A FIELD TEST INSTRUMENTATION SYSTEM

The Renewable Energy Field Test instrumentation system will be used to monitor IPH, PV and wind energy system installations at urban and remote desert locations in Egypt. These energy systems include main power sources (solar collectors, PV arrays and wind turbines) as well as ancillary subsystems depending on specific field test applications. These subsystems include ice-making equipment, desalination systems, a variety of load characteristics ranging from small DC loads to grid-connected applications and back-up power systems (diesel engines and batteries).

The instrumentation system must be a stand-alone system. Failure of the instrumentation system must not affect the performance of the field test system that is being monitored. The instrumentation system must have an on-site data storage system that is non-volatile and capable of easy physical removal and transport to another location for data removal and long-term storage. One form of non-volatile storage system must be a microchip/EPROM or CMOSRAM - Type system that can be "milked" on site easily and without danger of loss of data.

The instrumentation system must be a microcomputer based data logger with programmable input channels and output formats. The user must have control over sampling frequency and output period for each channel. Primary design objectives for the instrumentation system should be reliability, simplicity, small size, low power and the ability to operate in enviornmental extremes (especially high temperature, sand/dust and tropical/sea coast). The unit must be capable of stand-alone battery operation for a period of at least two monts.

The following minimum specifications are required for the instrumentation system. If an exception must be taken to one or more of these requirements, the exception shall be noted and a clear explaination given as to why the

bidder believes that the exception should be acceptable to the purchaser.

Physical Specifications

- o Small, stand-alonge, self-contained system in an environmental enclosure
- o Desired weight: less than 10 pounds
- o Desired size: less than 10 inches x 10 inches x 6 inches

System Power Requirements

- o Capable of operation using self-contained batteries
- o Capability for the use of an external power source to allow continued data collection while changing batteries or the use of a non-battery external power source is desirable.
- o Capable of transient protection from spurious electrical charges or lighting.

Environmental Specifications

- o Ambient Temperature: -25 deg. C to +50 deg. C
- o Relative Humidity: 0 to 90 percent non-condensing
- o Impervious to a tropical, oceanside environment with occasional high airborne sand/dust and/or sulphur levels

Analog Inputs

Number of Channels: At least 16 channels with 20 channels desirable

Volatage Measurement Types: Differential or single-ended

Accuracy of Measurements: at least ± 0.5 percent

Range and Resolution: Selectable for any input channel from microvolts to several volts full scale

Sample Rates: At lease once per second for each channel

Pulse Inputs

Number of Pulse Counter Channels: at least 4 channels with 6 channels desired

Analog and Digital Control Outputs: a total of three resettable channels each is desired with a range of 0 to ± 5 volts with a 0.5 volt resolution

Output Signal Interface

Memory: Capable of storing at least 3000 data points per day for a period of one month (two months desirable)

Display: A visual display of stored data is required on-site for data verification before data removal

Peripheral Interface: Downloading of data at the site should be by physical removal of the data storage device or simple, reliable data downloading to a non-volatile storage device. Storage data files shall be IBM-PC compatible on floppy disc either directly from the data logger or through a simple, fast, reformatting technique.

Field Test #8 (PV Desalination) Data Requirements

Item	Channel Type	Sampling Frequency	Output Interval	Priority Want	Priority Must
Array Power	P	1 sec.	10 min.		x
Array Current	A		" "	x	
Array Voltage	A		" "	x	
Insolation	A		" "		x
Load (kilowatts)	A		" "		x
Load Voltage	A		" "	x	
Load Current	A		" "	x	
Battery Charge Current	A		" "		x
Battery Discharge Current	A		" "		x
Battery Voltage	A		" "	x	
Ambient Temp.	A		" "		x
Ref. Cell Temp.	A		" "		x
Battery Temp.	A		" "		x
Diesel Power	P		10 min		x
Feedwater Conductivity	P		30 min		x
Product Conductivity	P		30 min		x
pH Feedwater	?		30 min		x
Feedwater Temp.	A		30 min		x
Feedwater Pressure	A		10 min		x
Product Water Flow	P		10 min		x
Product Water Flow	P	(Totalized)	daily		x
Brine Outlet Pressure	A		10 min		x

12 ("musts") x 6 samples x 24 hours = 1728
4 ("musts") x 2 samples x 24 hours = 192
1 ("must") x 1 day = 1
Time mark (6 x 24) = 144

Total = 2065 data points per day

17 channels
- o 6 pulse
- o 11 analog