

**VARI-RO™ DESALTING PILOT PLANT
TESTING AND EVALUATION**

FINAL TECHNICAL REPORT

**Science Applications International Corporation
16701 West **Bernardo** Drive
San Diego, CA 92127**

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U.S. Department of the Interior Mission Statement

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GLOSSARY

AF	acre-foot = 326,000 U. S. gallons (approximately)
AFY	acre-feet per year
BAR	metric pressure unit = 100 kpa = 14.5 PSI = 0.9869 atmospheres
BEP	best-efficiency-point
BWRO	Brackish Water Reverse Osmosis process
C	Concentrate
CO₂	Carbon Dioxide
CPM	Cycles Per Minute
CP	centrifugal Pump
CRA	Colorado River Aqueduct
CT	Centrifugal pump, Turbine, and variable speed drive; reverse osmosis pumping and energy recovery system (combined system)
dpM	delta pressure (pressure drop) Membranes
e	efficiency
ECU	Electronic Control Unit
ERV	Energy Recovery Valves
F	Feed
FTV	Flow Throttle Valves
FTR	Final Technical Report
FWV	Feed Water Valves
GPD	U. S. Gallons Per Day
GPH	U. S. Gallons Per Hour
GPM	U. S. Gallons Per Minute
HC	Hydraulic Cylinder
HDU	Hydraulic Drive Unit
l/m	liters per minute
kgal	1000 U. S. gallons
kpa	kilopascal =
kwh/kgal	kilowatt hours per 1000 U. S. gallons
kwh/m³	kilowatt hours per cubic meter
m³/d	meters cubed per day
1000m³/d	1000 meters cubed per day
MWD	Metropolitan Water District of Southern California
MED	Multi-Effect Distillation process
MGD	Million U. S. Gallons per Day
MSF	Multi-Stage Flash distillation process
MW	Megawatts of electric power
NPSH	Net Positive Suction Head
P	Product
PC	pressure, Concentrate
PD	pressure, Discharge
PM	pressure, Membrane
PD	Positive Displacement
PP	Plunger Pump
ppm	parts per million

PSI	pounds per square inch
PSID	pounds per square inch differential
PW	Pelton Wheel turbine
q	quantity rate = flow rate
RFP	Reverse Flow Pump turbine
RO	Reverse Osmosis desalting process
ROWPU	Reverse Osmosis Water Purification Unit
RPM	Revolutions Per Minute
RR	Recovery Ratio of reverse osmosis process = Product flow rate / Feed flow rate
SDCWA	San Diego County Water Authority
SDG&E	San Diego Gas & Electric
sec	specific energy consumption = kwh/kgal or kwh/m³
SP	sump Pumping
SWP	California State Water Project
SWP Nth>Sth	California State Water Project from Northern to Southern California
SWRO	Seawater Reverse Osmosis process
TDS	Total Dissolved Solids in parts per million
TWC	Total Water Cost
VFD	Variable Frequency Drive
VARI-RO™	Variable flow pumping and energy recovery technology for RO
VRO	VARI-RO reverse osmosis pumping and energy recovery system
WC	Water Cylinder
WDU	Water Displacement Unit

DEFINITIONS

Existing Methods	=	methods presently being used to desalt seawater, including MSF, MED, and RO. In this report, the existing methods often refer to RO desalting systems using conventional high pressure feed water pumping and energy recovery, consisting of: centrifugal pumps, plunger pumps, energy recovery turbines, and variable frequency drives for electric motors.
Base Case	=	is a case that is used for comparison.

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SI Metric Conversions

From	To	Multiply by
ft	m	3.048 000 E - 01
in	m	2.540 000 E - 02
ft ²	m ²	9.290 304 E - 02
kgal	m ³	3.785 412
Mgal	m ³	3.785 412 E + 3
acre-ft	m ³	1.233 489 E + 3
lb/in ²	kpa	6.894 757
lb/in ²	BAR	6.894 757 E - 02
°F	°C	t°C = (t°F - 32)/1.8

1. INTRODUCTION

1.1 Project Definition and Team

The Pilot Plant project team included a broad coalition of public and private organizations, as listed below. This Final Technical Report (FTR) resulted from the efforts of this team. The Pilot Plant project was sponsored by the Bureau of Reclamation, Water Treatment Technology Program, under Assistance Agreement No. 1425-5-FC-8 1-204 10.

This pilot plant project resulted from the Bureau of Reclamation's program to increase the efficiency of desalting and water treatment plants, toward providing more usable water in the Western United States. This Phase II assistance agreement was awarded for further demonstration and verification of the technology studied under Phase I (the VARI-RO study) (Childs and Dabiri, 1995). The contract requirement was that the offerers, and their cost sharing partners (team members), conduct the pilot plant demonstration so that the test results are applicable to Full-Scale production systems.

The following supplementary reports are included in the appendices:

- A Test Reporting from Naval Seawater Desalination Laboratory (NFESC)
- B Performance Projections of FILMTEC Membranes at Various Recovery Ratios (DOW)
- C Economic Comparison of VARI-RO vs. Conventional Technology (Laughlin Associates)

The following team members provided funding, advisory services, design assistance, manufacturing, and testing assistance for the Pilot **Plant** project:

RESEARCH ORGANIZATIONS

EPRI	Electric Power Research Institute	St. Louis, MO
NFESC	Naval Facilities Engineering Service Center (Seawater Desalination Test Facility)	Port Hueneme, CA
SAIC	Science Applications International Corp.	San Diego, CA
VPC	Vari-Power Company	Encinitas, CA

UTILITIES

LADWP	Los Angeles Department of Water & Power	Los Angeles, CA
MWD	Metropolitan Water Dist. of Southern Calif.	Los Angeles, CA
SDC	San Diego City	San Diego, CA
SDCWA	San Diego County Water Authority	San Diego, CA
SDG&E	San Diego Gas & Electric	San Diego, CA
SBC	Santa Barbara City	Santa Barbara, CA

DESALTING & CONSULTING ENGINEERING FIRMS

CE	Caroll0 Engineers	Phoenix, AZ
LA	Laughlin Associates	Borrego Springs, CA
MSC	Membrane Systems Corporation	Poway, CA

EQUIPMENT SUPPLIERS

c w	Cal-West Machining, Inc.	Orange, CA
PH	Parker Hannifin Corporation	Santa Fe Springs, CA
SW	Shore Western Manufacturing, Inc.	Monrovia, CA
WGI	Wheatley Gaso Incorporated	Tulsa, OK
z c	Zemarc Corporation	Los Angeles, CA

The benefits provided toward this desalting advancement, by the strategic **affiliation** of the team members, includes:

Research Organizations and Utilities:

- Provide seed capital to stimulate the development.
- Provide expertise in system engineering, testing, and project management.
- Participation allows first hand evaluation for future Full-Scale application needs.

Desalting and Consulting Organizations:

- Provide desalting knowledge to the project.
- Provide economic analysis capabilities.
- Gain knowledge of benefits for future projects.

Equipment Suppliers:

- Provide valuable assistance with the design evolution,
- Provide manufacturing knowledge.
- Reduce the capital investment for manufacturing of future Full-Scale products.

1.2 Pilot Plant Objectives and Technical Benefits

The overall objective of the Pilot Plant effort was to perform technology development and testing toward reducing the cost of potable water produced by desalination. More specifically, this Pilot Plant was directed at the use of alternate pumping and energy recovery technologies for the reverse osmosis (RO) desalination process, which are more energy efficient and environmentally attractive than existing RO and thermal methods.

The focus of this Pilot Plant project was toward the validation of a new approach to pumping and energy recovery (the **VARI-RO** technology) for reverse osmosis desalination. This technology offers the potential to substantially reduce energy consumption, and provide other operational benefits, when compared to existing RO methods that are presently being used commercially.

This Pilot Plant project has shown that the technology works, can provide energy savings, and can provide other operational benefits for seawater reverse osmosis desalination (SWRO), and that it can also be configured for brackish water reverse osmosis desalination (BWRO). The project has answered some of the practical questions relative to the implementation of this new approach for large scale desalination. These practical questions included: mechanical design, performance, maintenance, and economic benefits.

1.3 Specific Water Problem Discussion

Presently 90% of the water for the San Diego region is imported, with the remaining 10% coming **from** runoff stored in local reservoirs. Also, other Southern California regions, including Los Angeles, import a high percentage of the water for urban and other needs. A major portion of the water comes from Northern California, via the State Water Project (SWP); or **from** the Colorado River, via the Colorado River Aqueduct (CRA). Population increase, the six year drought (1985 - 1991), projected shortage of water supply **from** the SWP and CRA, and contingency plans for supply disruption (such as earthquakes) have stimulated a search for alternative water supplies for the Southern California region.

The alternative supplies under consideration, or are in process of being implemented, include:

1. Paying farmers to improve conservation methods, thus making agricultural water available for importation to urban regions.
2. Sewage water reclamation for irrigation (freeway landscaping, golf courses, etc.), and industrial uses.
3. Sewage water repurification, which adds additional steps to the reclamation process to allow this water source to be added to the domestic water supply.
4. Seawater desalting, which would be added directly to the domestic water supply.

Of these alternatives, only seawater desalting adds new water to a water supply system that is presently considered to be nearing maximum capacity. Under the combination of increased population, and emergencies such as severe drought, seawater desalination would help to disaster-proof the water supply system.

Previous studies in the San Diego region indicated that seawater desalination was more costly than other water supply alternatives at the time. However, recent proposals for seawater desalination indicate that this may no longer be the case. Recent proposals (December 3, 1997) have shown that seawater desalination can be accomplished at a substantially lower cost than previous estimates for the San Diego region. These proposals were for a facility near Tampa Bay, Florida in the capacity close to 20 MGD (76,000m³/d), about 20,000 acre-feet (AF) per year. At the time of this report, these proposals are being evaluated; however, the preliminary water cost results are shown in FIGURE 1 - 1:

Developer Team No.	Capacity MGD	Feed Source	Desal Type	No. of Trains	Capital Cost \$ Million	Total Water Cost (TWC)		
						\$/kgal	\$/m ³	\$/AF
1	20	Tampa Bay 8 Brackish	MED w/Blend	4	134.80	3.98	1.05	1297
2	20	Gulf of Mexico	RO	7	78.60	2.80	0.74	913
3	20	Tampa Bay	RO & MVC	4 & 1	91.85	3.18	0.84	1037
4	23	Tampa Bay	RO	52	72.17	2.12	0.56	691
5	20	Tampa Bay	RO	6	93.17	2.90	0.77	945

EX11a-Tampa TW Cost 3/8/98

FIGURE 1-1 Preliminary Tampa Region Seawater Desalination Costs

FIGURE 1-1 shows the potential to desalt seawater at a total water cost (TWC) in the range of \$2.12 to \$2.9 per 1000 gallons (\$0.56 to \$0.74 per cubic meter), about \$700 to \$950 per acre-foot. This is substantially less than the present perception in California of \$1200 to \$2000 per AF, as stated in the January 1998 DRAFT of The California Water Plan Update, Bulletin 160-98, Page 6-80. In the past, the water agencies in California have been looking forward to the time when the increasing cost of imported supplies intercepts the decreasing cost of seawater desalting. It is quite possible that this time has been reached.

A 50% increase in California's population is projected by the year 2020. For Southern California, this will likely mean that the existing aqueducts, and other delivery systems, will exceed existing capacity. While the present cost of importing water through the existing

infrastructure is now less than seawater desalting, it is very likely that the construction cost of new aqueducts will be in the billions of dollars, and the TWC could very well be greater than the cost of seawater desalination. Also, the energy required desalt seawater can be lower than the energy required to pump water through the SWP from Northern to Southern California (SWP Nth > Sth) (see FIGURE 3-1). Furthermore, it has been found that the sewage water reclamation and repurification costs are much higher than originally estimated.

The result is that seawater desalination may now be of equal, or in some cases lower, cost than the other alternatives. This lower seawater desalination cost has resulted from advancements in the reverse osmosis technology in general. This advancement is illustrated by the low seawater desalination water cost in the Tampa proposals. The lower energy consumption of the VARI-RO system can provide an additional cost reduction, thus making this source even more competitive with other alternatives.

The reasons that seawater desalination should now be considered as a viable alternative include:

1. new water is added to the water supply system that is reaching maximum capacity;
2. drought and disruption proofing capability;
3. reverse osmosis desalination is a proven method and is in use around the world;
4. energy consumption can now be lower by using the **VARI-RO** system;
5. costs are now competitive to other alternatives; and
6. acceptance by the public can readily be obtained.

These reasons provide ample incentive to continue the development, and improvement, of the VARI-RO system. This will assure that this advanced technology becomes a proven method to supply desalted seawater when it is needed in California, and elsewhere around the world.

1.4 Scope of Work and Methodology

The methodology for conducting the work for the Pilot Plant project was to define the capacity so that the test results would be applicable to Full-Scale production plants. To do this, various capacities of existing small desalination facilities were considered. This was discussed with the other team members at the kickoff meeting, which resulted in a capacity selection of around 30,000 GPD (114 m³/d) at about 30% recovery ratio (RR).

The work for this Pilot Plant project was divided into key tasks as follows:

- TASK 0 Project Management, Reports, and Presentations.
- TASK 1 Defining Pilot Plant.
- TASK 2 Pilot Plant Design.
- TASK 3 Pilot Plant Equipment Manufacture and Shop Testing.
- TASK 4 Evaluation Testing.
- TASK 5 Operational Testing.
- TASK 6 Defining Full-Scale Unit, Preliminary Full Scale Design, Economic Evaluation, and Water Cost Projections.
- TASK 7 Higher Recovery Ratio Design, Manufacture, and Test.

The results of the work from these tasks have been summarized in this report, along with conclusions and recommendations (see SECTION 2.).

2. CONCLUSIONS AND RECOMMENDATIONS

The VARI-RO technology is an integrated pumping and energy recovery system for reverse osmosis desalination. This Pilot Plant project has shown that the technology can significantly reduce the cost of desalted water, primarily by reducing the energy requirements. It has also been shown that the VARI-RO system has installation and operational advantages over commercially available conventional pumping and energy recovery systems. For some site locations, where electric power rates are high, other economic benefits can be provided by operating at lower recovery ratios. The economic and operational benefits over other methods indicate that the technology is suitable for both seawater and brackish water reverse osmosis (SWRO & BWRO) desalting.

From the work performed during this Pilot Plant project, including the technical and economic evaluations, the conclusions and recommendations below were reached about the VARI-RO technology. The economic analysis was based on parameters provided by the contractor for the existing Santa Barbara Seawater Desalination Facility of 7.2 MGD (27,250 m³/d) capacity.

1. The technology is technically viable and is suitable for desalting facilities of low, medium, or high capacity.
2. The Pilot Plant testing has demonstrated that the technology can provide energy savings under seawater operating conditions. The technology can also provide energy savings under brackish water operating conditions, especially for moderate to high salinity brackish water.
3. Because the VARI-RO system is positive displacement, it has particular advantage for desalination systems that operate under variable membrane pressure conditions. The variable membrane pressures result from changes of salinity, feed water pressure, and membrane fouling.
4. The economic analysis has shown energy savings of 26% and 35% for the VARI-RO Pilot Plant and Commercial systems, respectively.
5. Water cost reductions were shown from \$3.14/kgal (\$0.83/m³) for the conventional plant to \$2.97/kgal (\$0.785/m³) and \$2.88/kgal (\$0.761/m³) for the VARI-RO Pilot Plant and Commercial systems, respectively. This is a savings of 5% and 8%.
6. It is recommended that the Pilot Plant development be continued to incorporate some of the improvements that were identified under this project.
7. It is recommended that a full-scale demonstration project be initiated, with a capacity in the 0.3 to 0.6 MGD range. The goals of this project would be to show that the improved efficiencies for a VARI-RO Commercial unit can be achieved, and to show to the desalting professionals and users that the technology is a viable alternative to conventional methods that are now in use.
8. It is further recommended that desalting professionals design desalting facilities so that these facilities can be easily retrofitted to VARI-RO systems, thereby providing the user an easy option to save operating costs in the future.

3. GENERAL COMPARISON TO CONVENTIONAL PUMPING METHODS

3.1 VARI-RO™ System Overview

The VARI-RO system (Patent Pending) is an integrated variable flow, positive displacement, pumping and energy recovery system for seawater and brackish water reverse osmosis (SWRO & BWRO) desalination. This unique system utilizes modern hydraulic power transmission and electronic control to provide the following key features:

- Variable flow control for optimization and start up.
- Positive displacement pumping and energy recovery.
- Low cycle speed, low pulsation.
- High efficiency.

Because the vibrations and accelerations are low, the system does not require special mounting foundations and can be installed on conventional concrete floors. This feature is particularly beneficial for retrofitting of existing installations with more energy efficient pumping and energy recovery equipment. In addition, it is suitable for low, medium, and high capacity desalination plants; with units up to 5 MGD (million gallons per day) per train being feasible.

As compared to conventional systems using centrifugal pumps, reverse flow pump turbines, and variable frequency drives (CP-RFP-VFD), the VARI-RO technology controls flow and recovery ratio independent of the membrane system pressure changes, because it is positive displacement. Also, the technology has a higher BEP (best **efficiency** point) than a centrifugal system, and this higher BEP is maintained over a wider range of flow and pressure operation. This wider range of high efficiency operation assists in optimizing plant operation under variable membrane pressure conditions. For example, the delivery pressure will automatically adjust for changes due to salinity, temperature, fouling, and/or when new membrane improvements become available. To accommodate pressure changes with a centrifugal pump and turbine system, it is necessary to use flow throttle valves, and/or variable frequency drives. With centrifugal pumps, it is sometimes necessary to trim impellers, or reduce pump stages, to provide an efficient match of head characteristics.

As compared to conventional **plunger** pumps, the VARI-RO system has low pressure pulsation, low cycle speed, and variable flow; which makes it suitable for higher capacity applications. It does not require pulsation dampeners, and at 15 CPM cycle speed as compared to 300 RPM for a plunger pump, it would take 20 years to equal the same number of cycles that a plunger pump would get in one year. Due to vibration, and high plunger accelerations, plunger pumps require special mounting foundations for facility installation. This results in additional engineering and capital cost for the facility.

As compared to **Pelton** wheel (**PW**) energy recovery turbines, the VARI-RO system can accept full concentrate discharge pressure without an efficiency loss penalty. Since PW turbines must have an unrestricted exhaust, it is often necessary to have sumps to collect the discharge and sump pumps (with associated electric power and control) to deliver the concentrate to the discharge point. This results in an additional capital cost and electric power cost.

In summary, the integrated VARI-RO system provides a unique solution to reverse osmosis desalination and energy recovery. In addition to providing electric power cost savings, it can provide capital cost and operational benefits as compared to conventional systems. These conventional systems are composed of some combination of the following components:

- Centrifugal pumps, variable frequency drives, and/or valves for throttle and start up.
- Plunger pumps, pulsation dampeners, belt drives, and mounting foundations.
- Reverse flow pump turbines, **Pelton** wheel turbines, sumps, and sump pumps.

In addition, the VARI-RO system can provide capital cost savings in the electric power supply to the facility, because the power requirements are lower and the electric motors are started unloaded.

3.2 Conventional Systems Overview

There are several pumping and energy recovery methods that are presently commercially available for RO desalination. In addition to these commercially available methods, the flow work exchanger (FWE) system (sometimes known as the work exchanger system) is being used for BOOT (build-own-operate-transfer) type contracts in the Caribbean region. Presently the FWE system is only being used in locations where the electric power rates are quite high.

The following are general comments about the primary methods presently being used, and the accessories that are used with these methods:

CP-RFP-VFD - Centrifugal Pump, Reverse Flow Pump turbine, and Variable Frequency Drive

COMMENTS	ACCESSORIES
<ul style="list-style-type: none"> • Presently the RFP is the most common energy recovery method being used for high capacity applications. 	<ul style="list-style-type: none"> • <u>Variable frequency drives</u> are needed for the most efficient operation over a range of membrane pressure conditions, to avoid flow throttle valve losses.
<ul style="list-style-type: none"> • It has lower efficiency than some other alternatives. 	<ul style="list-style-type: none"> • <u>High power electric supply</u> and electric motor are rewired.
<ul style="list-style-type: none"> • It is considered to be the most simple method presently in use. 	<ul style="list-style-type: none"> • <u>Substantial concrete foundations</u> are often used for installation of the pump, turbine, and electric motor.
	<ul style="list-style-type: none"> • <u>Separate pump room</u> is often considered to be desirable to minimize noise transmission.

CP-HTC-VFD - - Centrifugal Pump, Hydraulic Turbo Charger, and Variable Frequency Drive, and

PP-HTC-CCV - - Plunger Pump, Hydraulic Turbo Charger, and Concentrate Control Valve

COMMENTS

<ul style="list-style-type: none"> • The HTC development is a relatively recent addition for RO energy recovery. It has evolved over several years. Early problems included bearing failures at the high speed rotors.
<ul style="list-style-type: none"> • Efficiency of the HTC with a CP is similar to that of the RFP turbine. The HTC system efficiency can be improved by using it with the more efficient PP.
<ul style="list-style-type: none"> • The key advantage of the HTC is that it is a compact unit, which results from the very high operating speeds.
<ul style="list-style-type: none"> • In general, the PP operates at around 300 RPM, which means that the suction valves, discharge valves, and plunger packings are cycled 300 times per minute. These items wear during operation, and are considered to be “expendables”. These expendable components are replaced periodically when the pumping performance degrades.

ACCESSORIES

<ul style="list-style-type: none"> • <u>Variable frequency drives</u> are needed for most efficient operation when the HTC is used with a centrifugal pump, to prevent additional losses from flow throttle valves.
<ul style="list-style-type: none"> • <u>Concentrate Control Valves</u> are needed to match the flow and pressure conditions of the membranes and the main pump, which results in additional losses when operating away from maximum design conditions.
<ul style="list-style-type: none"> • <u>Substantial concrete foundations</u> are required for the PP, because of the reaction loads of the high speed plunger and crank accelerations.
<ul style="list-style-type: none"> • <u>Pulsation dampeners</u> are required to attenuate the pressure pulsations, and minimize field piping vibration from the PP.
<ul style="list-style-type: none"> • <u>Sound enclosures</u> are definitely needed to attenuate the high-pitched sound of the HTC high speed impellers.

CP-PW-VFD-SP - - Centrifugal Pump, Pelton Wheel turbine, Variable Frequency Drive, and Sump Pumps

COMMENTS

<ul style="list-style-type: none"> • Development of the PW has evolved over many years. Early problems included impeller fractures and erosion.
<ul style="list-style-type: none"> • The PW has higher efficiency than either the RFP or the HTC turbines, and it can operate efficiently over a wider range of pressure conditions.
<ul style="list-style-type: none"> • Automatic controls can be added to the flow control valve to adjust for varying pressure and pump speed conditions.

ACCESSORIES

<ul style="list-style-type: none"> • <u>Variable frequency drives</u> are needed for most efficient operation of the centrifugal pump, to eliminate the losses that would result if feedwater control valves are used instead.
<ul style="list-style-type: none"> • <u>Sumps and pumping equipment</u> are usually required to discharge the reject concentrate back to the ocean, which will result in an additional electric power loss, and also capital cost. The sumps are needed because the PW must discharge directly to atmospheric pressure.
<ul style="list-style-type: none"> • <u>Concrete foundations</u> are often used for installation of the pump, turbine, and electric motor.
<ul style="list-style-type: none"> • <u>Sound enclosures</u> are generally considered to be desirable.

PP-PW-SP - - Plunger Pump, with Pelton Wheel turbine and Sump Pumps

COMMENTS

<ul style="list-style-type: none"> Development of the PW has evolved over many years. Early problems were impeller fracturing and erosion.
<ul style="list-style-type: none"> The combination of the PP with PW energy recovery provides higher efficiency than systems using CP, RFP, and HTC methods.
<ul style="list-style-type: none"> A manual PW flow control valve can be used to adjust the membrane pressure, since the PP speed and flow is constant.
<ul style="list-style-type: none"> In general, the PP operates at around 300 RPM, which means that the suction valves, discharge valves, and plunger packings are cycled 300 times per minute. These items wear during operation, and are considered to be “expendables”. These expendable components are replaced periodically when the pumping performance degrades.

ACCESSORIES

<ul style="list-style-type: none"> <u>Belt drives</u> are used to match the plunger pump and Pelton wheel speeds to give the proper flow for the application. These belts result in additional losses.
<ul style="list-style-type: none"> <u>Sumps and pumping equipment</u> are usually required to discharge the reject concentrate through degassifiers and back to the ocean. This additional pumping results in an additional electric power loss, and also capital equipment cost for the facility. The need for sumps, and sump pumping, is because the PW must discharge directly to atmospheric pressure.
<ul style="list-style-type: none"> <u>Substantial concrete foundations</u> are required for the PP, because of the reaction loads of the high speed plunger and crank accelerations.
<ul style="list-style-type: none"> <u>Pulsation dampeners</u> are required to attenuate the pressure pulsations, and minimize field piping vibration from the PP.
<ul style="list-style-type: none"> <u>Separate sound enclosures</u> are desirable, however, sound vibration is still transmitted into the field piping, which is difficult to attenuate.

**PP-FWE -CP-VFD - Plunger Pump, Flow Work Exchanger, Centrifugal Pump,
Variable Frequency Drive**

COMMENTS

<ul style="list-style-type: none"> • The use of the FWE has been limited to BOOT contracts in the Caribbean, where electric power rates are relatively high. The organizations that are selling water have their own maintenance staff to keep the systems operating. This extra staffing is justified by the energy cost savinns.
<ul style="list-style-type: none"> • The combination of the PP with FWE energy recovery has energy consumption rates that are lower than the PP-PW system, and is similar to the VARI-RO system. Since the system is positive displacement, except for the centrifugal boost pump, the pressure adjusts automatically to the operating membrane pressure.
<ul style="list-style-type: none"> • The water directional valves for the FWE switch the concentrate (brine) full flow rate to the pressure exchange vessels at the rate of about 1 CPM. Because the valve switching occurs at full flow rate, significant hydraulic shock is created. Field reports indicate that the valves must be frequently maintained.

ACCESSORIES

<ul style="list-style-type: none"> • <u>Variable frequency drives</u> are needed for the centrifugal booster pump, which boosts the pressure from the FWE to the membrane operating pressure.
<ul style="list-style-type: none"> • <u>Additional floor space</u>, and facility volume, is required in the facility to accommodate the large bulk of the pressure exchange vessels.
<ul style="list-style-type: none"> • <u>Substantial concrete foundations</u> are required for the PP, because of the reaction loads of the high speed plunger and crank accelerations.
<ul style="list-style-type: none"> • <u>Pulsation dampeners</u> are required to attenuate the pressure pulsations, and minimize field piping vibration.
<ul style="list-style-type: none"> • <u>Separate sound enclosures</u> are desirable, however, sound vibration is still transmitted into the field piping from the PP and FWE.

3.3 Advantages of the VARI-RO System

There are several advantages of the VARI-RO technology over conventional pumping and energy recovery methods, including: centrifugal pumps, crank type plunger pumps, reverse flow pump turbines, **Pelton** wheel turbines, and variable frequency drives. The inherent advantages are summarized as follows.

A. Variable Flow, Positive Displacement:

1. Higher **efficiency** than centrifugal pumps.
2. Matches system head (back pressure) at any flow rate.
3. Separate variable speed drives are not required.
4. Holds constant flow rate (flux) setting as membrane pressure changes due to temperature, salinity, and fouling variations.
5. Electric motors can be started unloaded, and at zero flow rate.
6. Flow can be increased gradually from zero to maximum setting during startup, and from maximum to zero during shutdown.

B. Smooth Flow (suction and discharge):

1. Low pulsation output flow, similar to centrifugal pumps, minimizing piping vibration.
2. Pulsation dampeners and suction stabilizers are not required, as with conventional crank type piston or plunger pumps.

C. Low Cycle Speed:

1. Reduces wear and operating cycles on expendable parts, such as valves and packings.
2. At 15 CPM, it would take 20 years to equal the number of cycles of a crank type plunger pump operating at 300 RPM for one year.
3. Results in low operating and maintenance cost, as compared to conventional crank type pumps.
4. Low accelerations allow installation on conventional concrete floors, without special mounting foundations.

D. Highly Efficient Energy Recovery Is Integrated:

1. Provides for high efficiency recovery of reject concentrate energy.
2. Does not have the intermediate losses of turbines, centrifugal pumps, generators, and/or electric motors.
3. Energy consumption is relatively flat versus recovery ratio, which assists in the optimization of a desalting system for improved membrane performance, and can reduce membrane related costs.

E. Electric Power Requirements Are Lower, Plus Unloaded Starting and Stopping Minimizes Power Surges:

1. Reduces capital cost of sub-stations, transformers, and other electric power equipment. Also, variable frequency drives are not required.
2. Demand factor can be reduced, providing lower electric rates.
3. Electric power cost is reduced, which is a significant desalting facility operating cost.

HEAD & FLOW MATCHING: One of the inherent advantages of positive displacement pumping is the direct matching of system head at any flow rate. This means that, as there is system head change due to salinity, temperature, and membrane fouling, the pumping pressure will simply follow the system head while maintaining a constant flow rate through the membranes. For example, the pressure will automatically drop back to the initial pressure after the membranes are cleaned, replaced, or new membranes added; without requiring a separate variable frequency drive.

With the selection of centrifugal pumps during initial design, careful matching of the head/flow characteristics of the centrifugal pump with the head characteristics of the system head is needed. The result is that the selection is based on the maximum expected head; however, at start up the clean membrane head (pressure) is usually much lower than the maximum head. To compensate for this discrepancy, throttle valves are needed to maintain the specified flow rates. Another alternative is to use a separate variable frequency drive to adjust the pump speed to give the specified membrane flow rate.

SYSTEM START-UP CHARACTERISTICS: The variable flow feature, and low rotating inertia, of the VARI-RO technology allows for unloaded across-the-line starting of the electric motors. After starting the system flow can be gradually increased to design conditions. With conventional pumps, it is often necessary to over-size the electric motor to provide sufficient power for start-up.

The capability to easily start and stop the system, without large electric power surges, is particularly advantageous to allow operating during periods of low electric power demand (OFF PEAK). This allows the RO plant owner to take advantage of the lower “interruptible load” electric power rate schedule.

The lower power requirement, variable flow capability, and **start/stop** ease, provides the following benefits as compared to conventional pumping methods:

- 1) lower capacity electric power transmission lines to the facility;
- 2) lower capacity sub-station transformers;
- 3) lower electrical switch gear capacity;
- 4) lower installed electric motor capacity;
- 5) no separate variable frequency drives are needed; and
- 6) improved capability for operating at lower electric power rates.

The above benefits can result in lower capital cost for the desalination facility, in addition to electric power cost savings. This can result in a lower total water cost (TWC).

3.4 Energy Conservation and Global Warming Benefits

Currently there are various systems for seawater desalination, which include: multi-stage flash (MSF), multi-effect distillation (**MED**), mechanical vapor compression (MVC), and reverse osmosis (RO). Many of the present facilities (some over 20 years old) use the MSF process, and are located in Middle East countries. In recent years, however, the use of the RO process has been growing, primarily due to its lower energy consumption (about **1/6th** of MSF with conventional RO, and about **1/10th** with the VARI-RO system). In addition, RO popularity is increasing due to its easier implementation. The total energy consumption for seawater desalination is shown on **FIGURE 3-1**. Also, for purposes of reference, the total energy consumption of the California SWP from Northern to Southern California is shown (SWP Nth > Sth). As shown on this figure, the energy conservation of the conventional RO process is quite

substantial as compared to the other desalting processes. It is also shown that additional conservation can be achieved when the VARI-RO system is used.

In addition to the Middle East countries, there are major seawater desalting facilities in other locations around the world, including: Spain, Canary Islands, Malta, Okinawa, and the Caribbean. Many of the desalting system in these locations use RO. The potential applications for the VARI-RO™ system include: the replacement of existing distillation facilities (MSF, MED, and MVC) that have excessive energy consumption and emissions (or are at the end of their useful life); the retrofitting of existing RO facilities with more efficient pumping systems; and providing improved technology for new RO desalting facilities.

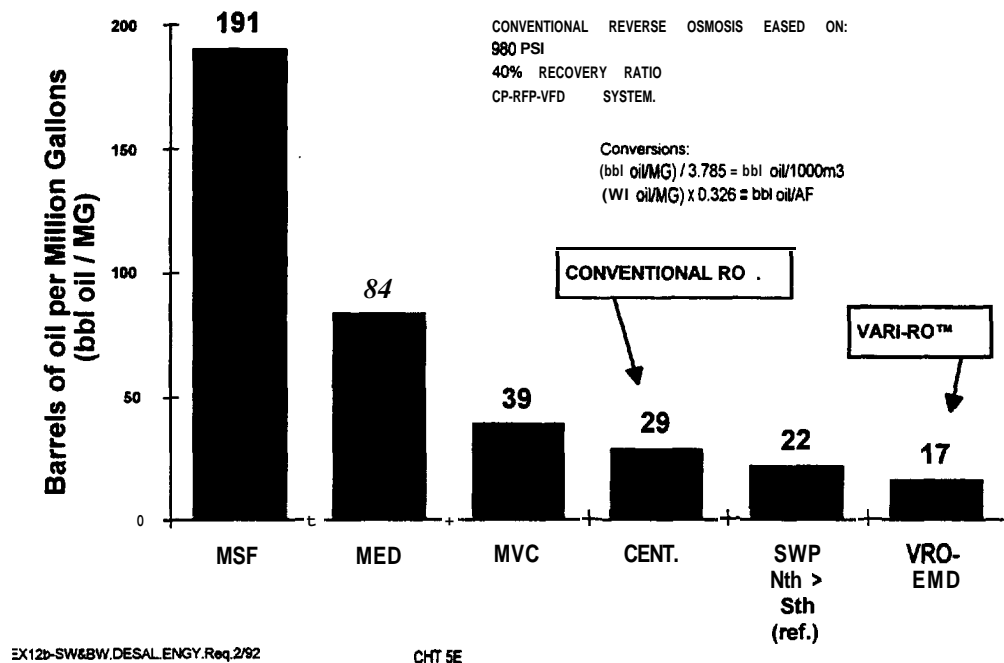


FIGURE 3-1 Total Energy Consumption of Desalting Processes and the SWP

At the 1997 Global Warming Conference, Kyoto, Japan, the proposed treaty emphasized the need to cut carbon dioxide (CO₂) emissions, one of the “greenhouse” gases. In February 1998, the Clinton administration proposed a \$6.3 billion package to “... mobilize cutting-edge technologies in the fight against global warming ...”. The motivation is to: “... overcome the challenge of global climate change and create new avenues of growth for our economy . . .”.

In 1995, the world desalination capacity was 5.4 billion gallons per day (20 million m³/d), which resulted from an average growth rate of 250 MGD (about one million m³/d) per year over the past 10 years. It is projected that the future growth in desalination capacity will be at an even greater rate. The chart in FIGURE 3-1 shows that the use of VARI-RO technology for this new capacity, and the retrofitting of antiquated existing installations, could provide an enormous reduction in CO₂ emissions.

The sale of this technology on a world wide basis would help to meet the Bureau of Reclamation Water Treatment Technology Program objectives, as follows:

- Help United States industry compete in major international markets for desalting systems, by fostering the development and use of new cost-effective and technologically advanced desalting processes.
- Promote partnerships between government and industry in the use of desalting to meet critical water needs.
- Promote technologies that are more energy efficient and environmentally attractive than existing methods.

The VARI-RO technology developments can also help to meet a key objective of the global warming treaty, which is to reduce CO₂ emissions by a substantial amount by the year 20 10.

4. PILOT PLANT PARAMETERS AND CONFIGURATION

The design for a VARI-RO Pilot Plant included the selection of the most suitable configuration, plus the selection of equipment sizes for the selected capacity and RR. It also included the selection of the key system components and electronic control.

4.1 Pilot Plant System General Parameter Selection

ORIGINAL CAPACITY SELECTION: At the Team Member Kickoff Meeting for the Pilot Plant project, several capacity options were considered. With the consensus from the meeting, and considering the standard components available, the selected capacity for the original unit was 32,000 GPD (113.6 m³/d) and 29% recovery ratio, with a cycle speed of 13.7 CPM. A design pressure range of 800 PSI (55 BAR) to 1000 PSI (69 BAR) was selected.

HIGHER RECOVERY RATIO SELECTION: Later in the program, the unit was modified to see how it would function under higher recovery ratio conditions. The new capacity was projected to be about 49,000 GPD (185 m³/d) and 43% recovery ratio, with a cycle speed of 13.7 CPM.

BENCH MARK TEST PARAMETERS: It was decided to do all of the initial testing at 800 PSI (55 BAR) and 12 CPM. While lower than the original design conditions of 1000 PSI and 13.7 CPM, these parameters provide a “Bench Mark” reference point for comparisons during the system development. During a further testing program, the system will be operated at the higher design condition parameters, after additional system upgrades.

4.2 VARI-RO System Sub-assemblies and Configuration

The sub-assemblies of the VARI-RO system include:

<u>SUB-ASSEMBLY</u>	<u>CONSISTING OF:</u>
ELECTRONIC CONTROL UNIT (ECU)	Computer Servo Controller Instrumentation
HYDRAULIC DRIVE UNIT (HDU)	Electric Motor (EM) Hydraulic Pumps (HP) Hydraulic Accessories
WATER DISPLACEMENT UNIT (WDU)	Hydraulic Cylinders (HC) Water Cylinders (WC) Feed Water Valves (FWV) Energy Recovery Valves
(ERV)	

A block diagram of the VARI-RO integrated pumping and energy recovery system is shown in FIGURE 4-1. This figure also shows the relationship to the other systems in a reverse osmosis desalting facility. The other systems include the electric power supply system, the feed water supply and treatment system, and the reverse osmosis membrane bank system.

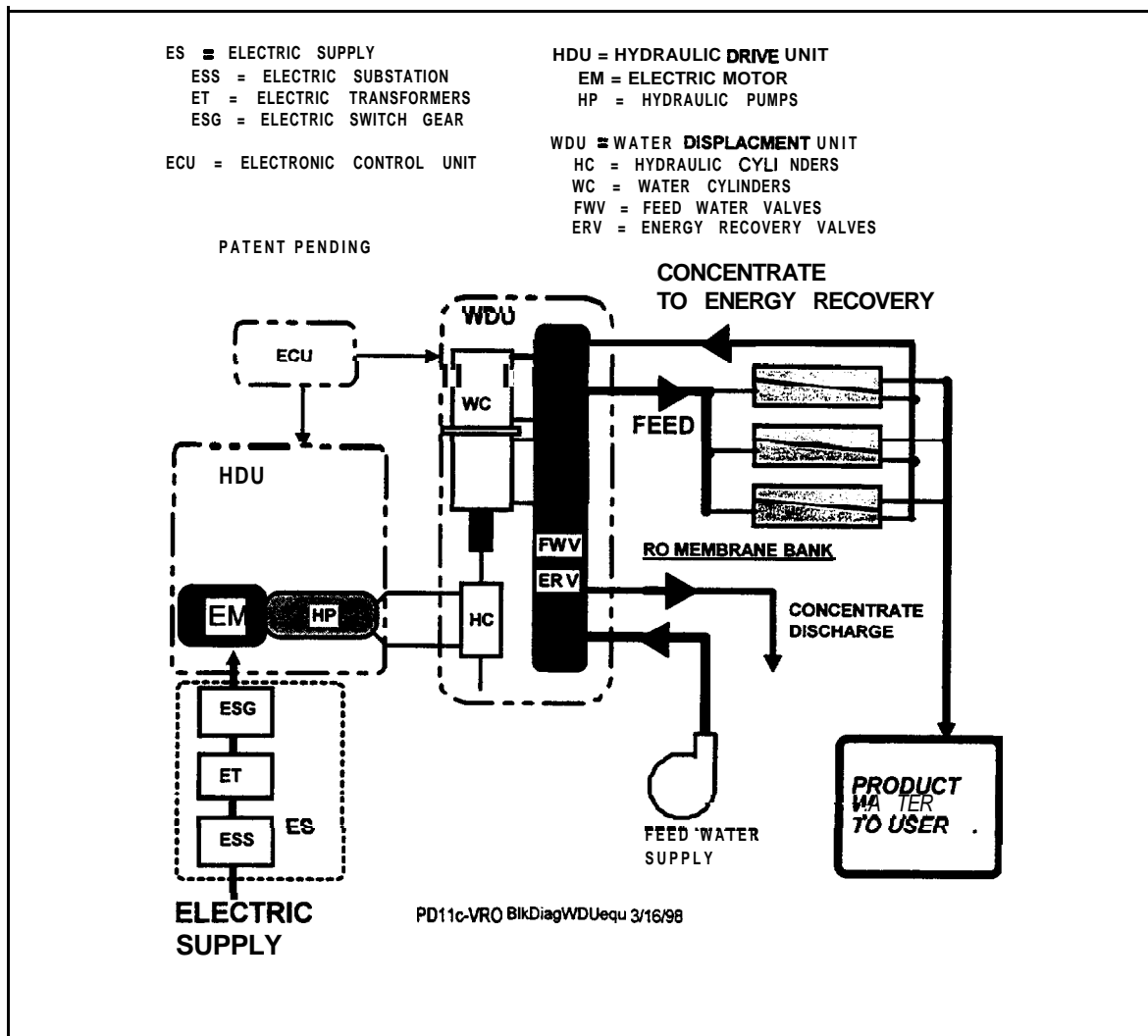


FIGURE 4-i VARI-RO System Block Diagram

A general arrangement of the VARI-RO system is shown in FIGURE 4-2. The configuration shown has a vertical orientation for the water displacement unit (WDU). However, for future full-scale units, the cylinders could also operate in a horizontal orientation; if this provides a more convenient arrangement for the desalting facility. Photographs of the Pilot Plant unit sub-assemblies are shown in FIGURES 4-3, 4-4, and 4-5.

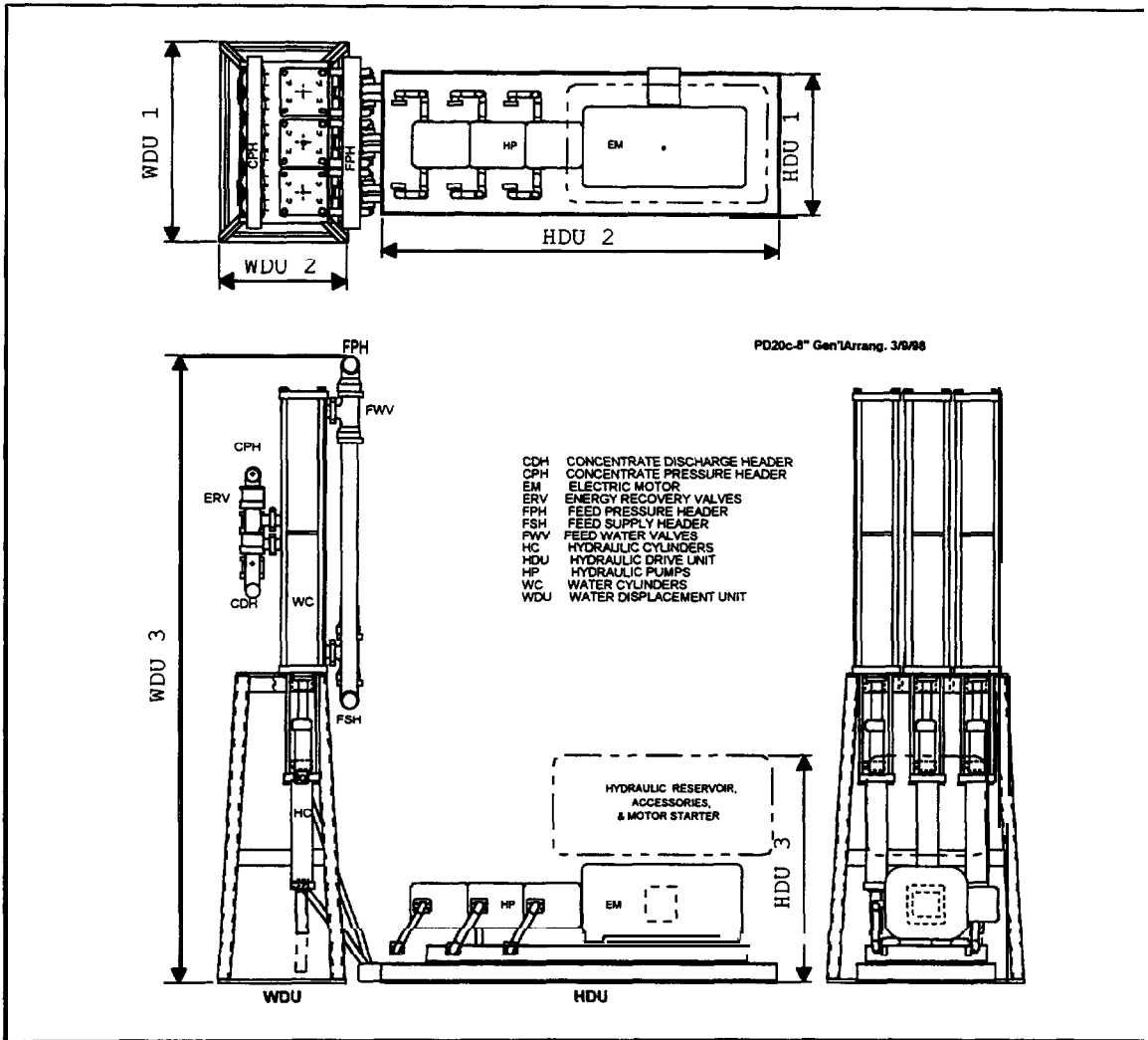


FIGURE 4-2 VARI-RO System General Arrangement

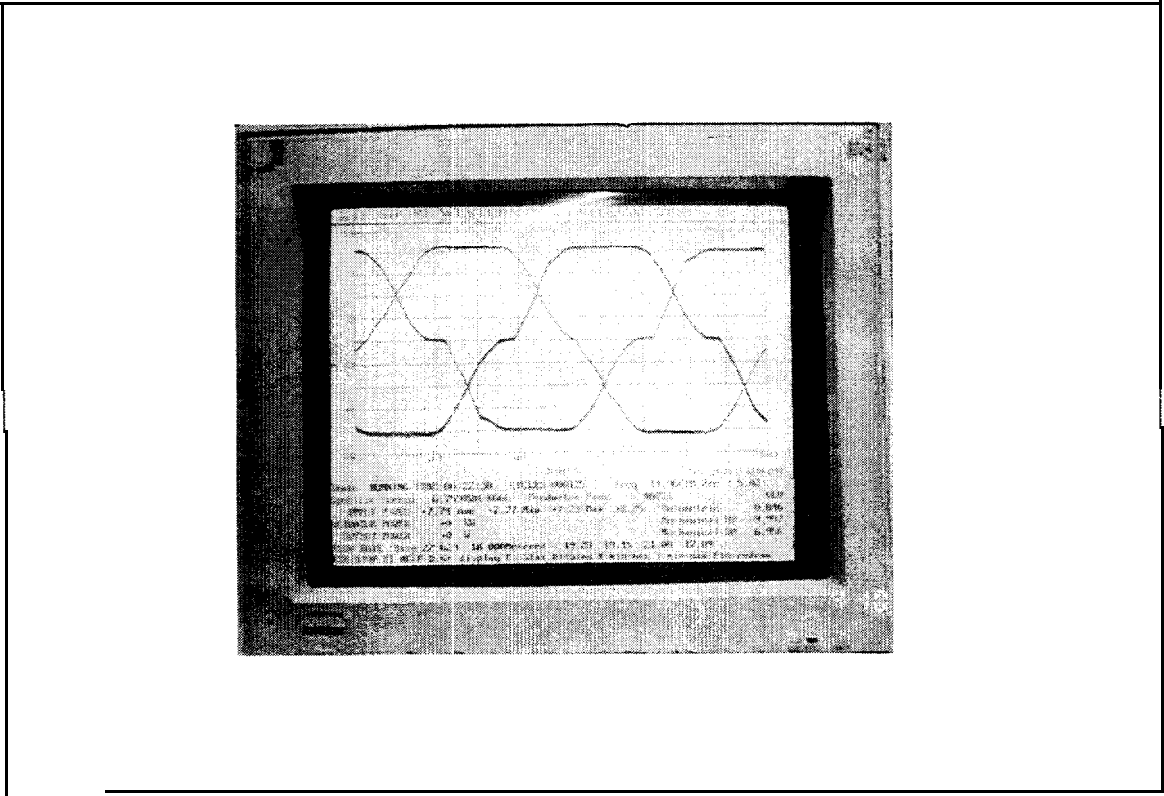


FIGURE 4-3 Pilot Plant, Electronic Control Unit Display

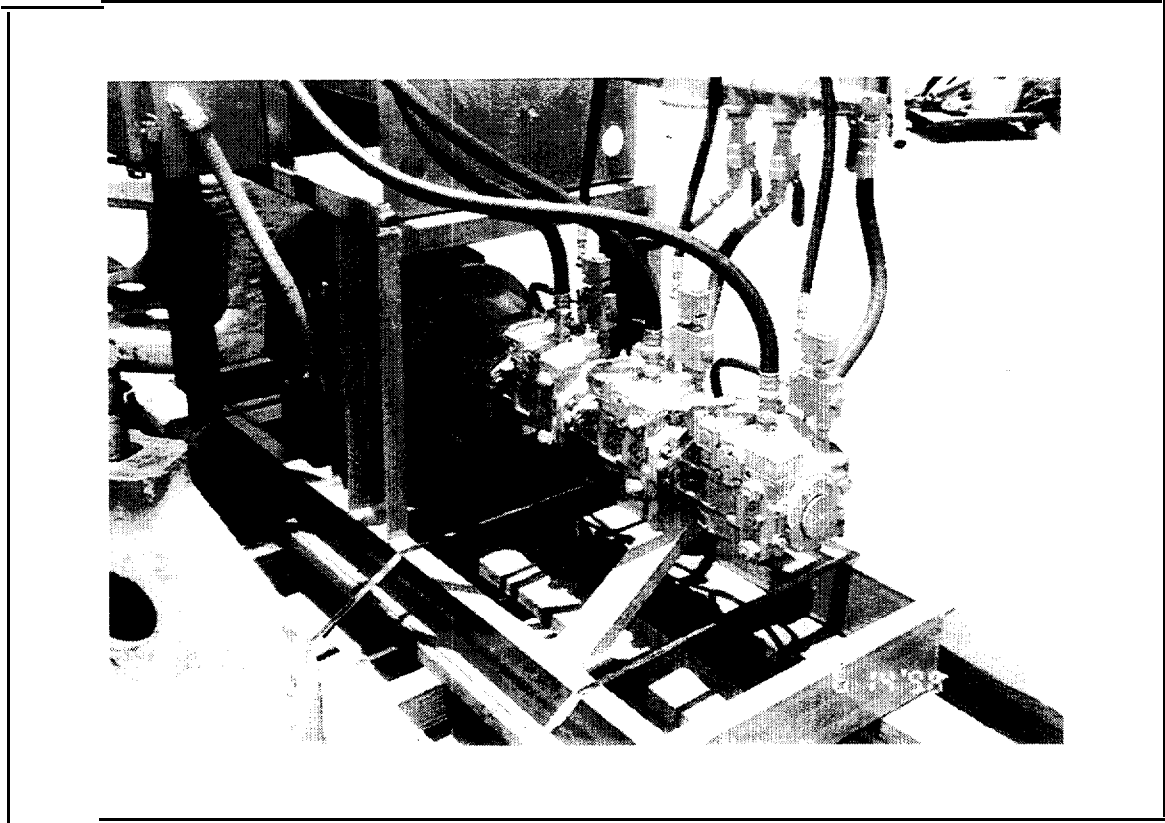


FIGURE 4-4 Pilot Plant, Hydraulic Drive Unit

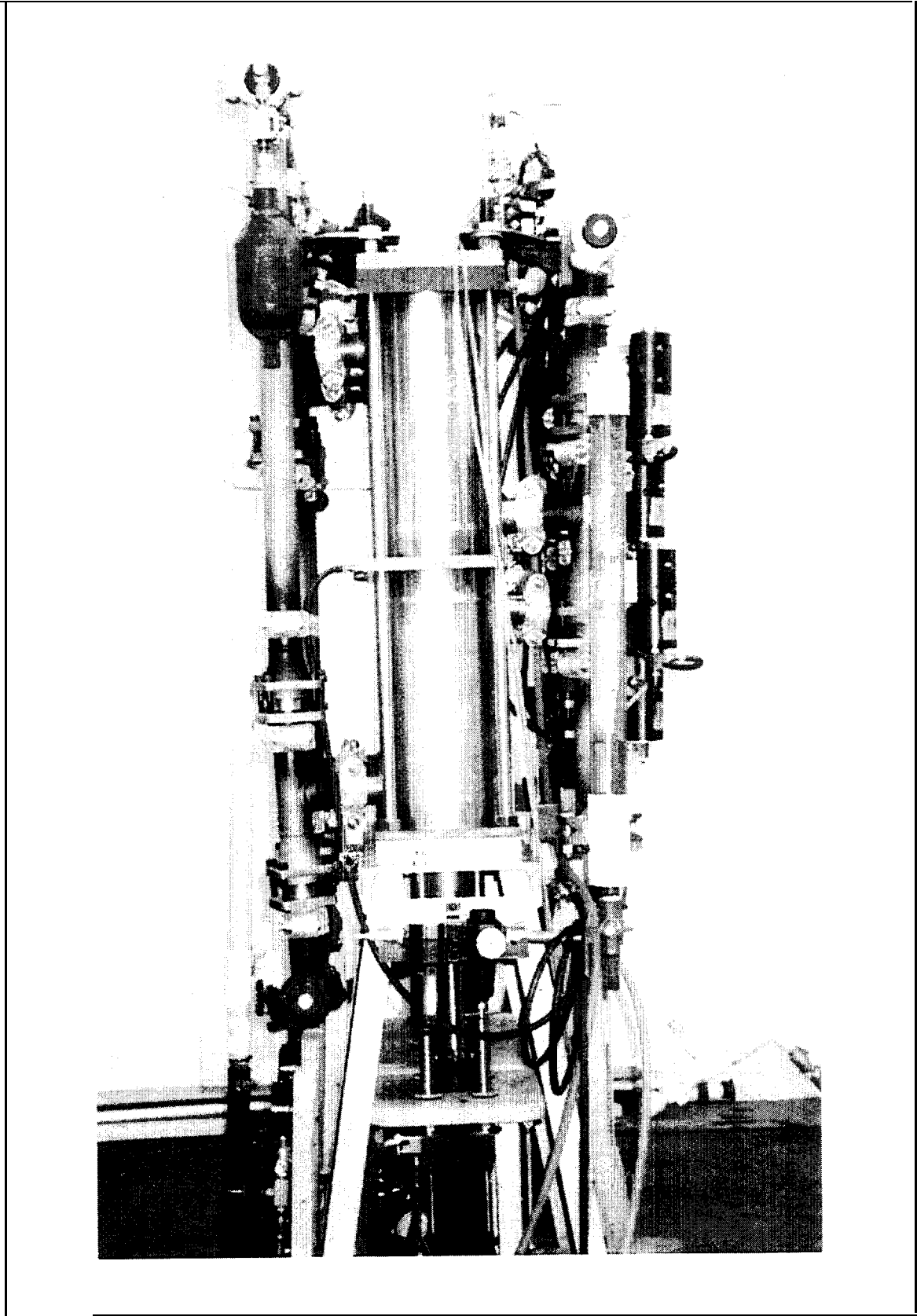


FIGURE 4-5 Pilot Plant, Water Displacement Unit

5. TESTING AND PERFORMANCE RESULTS

The shop testing was performed at Shore Western's facility, Monrovia, California, and the performance testing was performed at San Diego City's San Pasqual Water Reclamation Facility, near Escondido, California.

5.1 Test Setup and Methodology

The VARI-RO system testing was performed under simulated conditions. Fresh water was used as the testing medium for convenience, and to conserve project cost. Since the primary objectives, of this relatively short duration testing program, were to prove function and performance; testing with fresh water provides the same results as testing with seawater. Testing with seawater is only important for long duration testing to determine corrosion effects, which is planned for a subsequent testing program.

The basic test setup simulated the components external to the VARI-RO system shown in FIGURE 6- 1. The feed water supply consisted of a water tank and a pump for supply pressure (pS). The membrane simulator consisted of a throttle needle valve to create membrane back pressure (pM), and a ball valve to simulate concentrate pressure drop (dpM) through the membranes. The concentrate discharge included a pressure gage (pD) and a visual flow meter.

The measurement of product water flow rate was accomplished using three different methods. The general purpose methods were a visual meter to provide a quick indication of product flow rate, and a bucket and stop watch method to give a more accurate flow. For verification, a larger water tank, weighing scale, and stop watch were used for more precise measurement of flow rate over a longer elapsed time period. During test runs, the product flow measurements values were manually input into the computer for recording and performance calculations.

5.2 Electronic Control, Diagnostics, Data Acquisition, and Analysis

The Electronic Control Unit consists of: computer, display screen, servo controller, transducers, and printer for data recording. The computer software capability includes: calculations for cylinder stroking from the hydraulic pumps, data acquisition, and data analysis. The transducers for control and instrumentation include the following:

<u>TRANSDUCERS and MEASUREMENT METHODS</u>	<u>USED FOR THE FOLLOWING FUNCTIONS</u>
Cylinder Position (3)	Position feedback to Servo Controller Position versus cycle period Velocity versus cycle period Cylinder displaced flow rate for volumetric efficiency calculation.
Membrane Pressure (1)	Feed pressure versus cycle period Water Displacement Unit efficiency calculation

Hydraulic Pressure (2)	Hydraulic cylinder pressure versus cycle period Differential cylinder pressure Hydraulic cylinder force calculation Mechanical efficiency Power input to the WDU.
Differential Pressure (1)	Pressure drop measurements, such as membrane simulation (dpM), and energy recovery valves.
Power	Visual power meter Recording of power input Specific energy consumption calculations
Product flow measurement (tank, scale, and stop watch)	Recording of product flow rate, which is manually input into the computer. Volumetric efficiency calculations Specific energy consumption calculations

The computer control, diagnostics, data acquisition, and data analysis system developed for the Pilot Plant unit testing is quite sophisticated. A wide variety of operating parameters (individually or together) can be dynamically displayed on the computer screen for each cycle period, or for multiple periods. This allows the operator to look for variations from one cycle, or test run, to the next for diagnostic purposes. In addition, certain parameters are displayed on the screen in engineering units for monitoring of performance. The dynamic data, and the engineering unit data., can be recorded for subsequent analysis after the test runs have been completed.

The extensive data analysis and recording, that is provided in the computer software, provides the operator information for monitoring the performance of the unit, and the capability to trouble shoot malfunctions.

5.3 Functional Results

The Pilot Plant testing of the **VARI-RO** system has demonstrated the following functional features for startup, shutdown, optimization, and diagnostics:

1. **UNLOADED ELECTRIC MOTOR STARTUP:** The ability to start the electric motors unloaded and under low inertia was demonstrated. This feature avoids high surge electrical currents for long time periods that can occur with conventional pumping methods. This can become an important feature for high capacity facilities that can minimize the electrical power supply requirements.
2. **PRE-PUMPING CHECKOUT:** If desired, the operation of the various sub-systems can be checked out before starting of the main pumping operation. For example, all of the energy recovery valves (ERV) can be set to the "OPEN" position, and the cylinders stroked under low supply pressure. This function is useful for assuring that the air has been bled from the system. In addition, each ERV can be individually operated to check for function, and trouble shooting.

3. **LOW CYCLE SPEED STARTUP:** For the Pilot Plant unit, the typical startup cycle speed was 3 CPM, with the cylinders moving from the “HOME” position to the normal cycling position. After checking that everything was functioning properly, the cycle speed was gradually increased to normal cycle speed, usually 12 CPM; which brought the flow up to normal conditions. Other startup cycle conditions can be readily setup to optimize the facility operation.
4. **VARIABLE CYCLE SPEED:** By varying the cycle speed, the output flow is also varied. This is an important feature for optimization of the desalting operation.
5. **NORMAL OPERATION MONITORING:** By watching the computer display screen, the various operating parameters can be monitored by the operator. The various parameters can be turned on and off, and the screen refreshed to check out individual functions and/or parameters. This capability is particularly important for equipment diagnostics.
6. **PARAMETER MONITORING:** At the end of each cycle, the recorded data is updated and displayed, for example every 5 seconds at 12 CPM. During the system operation, the operator can note deviations of a particular parameter from normal operation. This can provide advanced notice of the possible need for system maintenance.
7. **ENERGY RECOVERY VALVES SHIFTING AT ZERO FLOW:** A key feature of the VARI-RO system is the high efficiency energy recovery. To accomplish this high efficiency, the energy recovery valves (ERV) switch the total flow between the three water cylinders in a complementary fashion. The unique control method provides that the flow to each ERV is brought to zero before it is closed or opened. This eliminates hydraulic shock, and this feature will be particularly important for future high capacity systems. However, while the flow through any individual valve goes **from** zero to maximum in a gradual manner, the total flow from the VARI-RO system is constant and with low pulsation, due to the unique complementary operation.
8. **CONTROLLED SHUTDOWN:** Upon receiving the signal to shutdown, the cylinders sequentially go the “HOME” position and stop. This provides for slow deceleration of the flow during shutdown, and avoids the mechanical shock that can occur with conventional systems. This also is an important feature for high capacity systems that have long intake and discharge piping systems.

In summary, the Pilot Plant testing has demonstrated the unique features of the VARI-RO system that makes this variable flow, positive displacement system suitable for high capacity desalting applications.

5.4 Performance Results at “Bench Mark” Operating Conditions

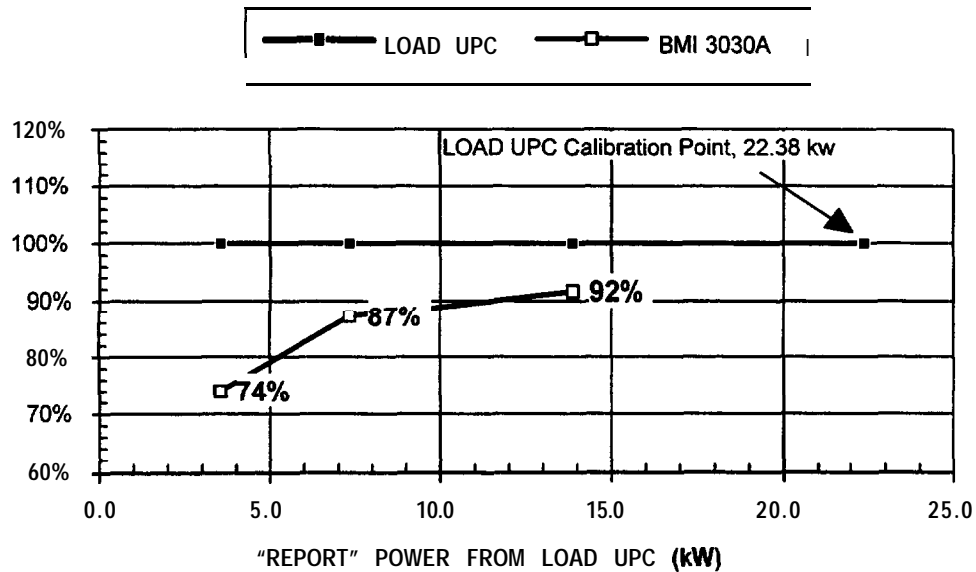
A series of tests were made by Mark Silbernagel of the NFESC. Mark’s trip report is included as Appendix . These tests were run at the “Bench Mark” operating conditions as described in SECTION 4-1, at 800 PSI and 12 CPM.

CALIBRATION CHECKS

For these series of tests, the pressure transducers were calibrated against a master pressure gage. The calibration of the master gage was checked against a dead weight tester. The product and concentrate flow rates were determined using a tank, weigh scale, and stop watch.

The input electrical power was measured using a power meter (LOAD UPC) that is incorporated into the VARI-RO system, which is connected electrically to the ECU computer. The LOAD UPC power meter was calibrated to a setting provided by the manufacturer at 22.38 kW (30 horsepower). The calibration of the power meter was checked by Murray Slater, a power measurement specialist from SDG&E, using a BMI 3030A power profiler. According to Murray, this power profiler is a precision instrument that is returned to the manufacturer for calibration checks once a year. Three power calibration runs were made with the BMI 3030A meter, and the data compared to the LOAD UPC meter, as shown in FIGURE 5- 1.

Each of the power checks were well below the LOAD UPC readings, which indicated that the LOAD UPC meter was reading high at power levels below the calibration set point. The curve indicates that the BMI readings would converge with the LOAD UPC readings at the calibration set point. For the test runs, it was concluded that the BMI readings were correct, and the results taken with the LOAD UPC meter were adjusted accordingly.



EX20a-SDG&E Pwr.Chk.8/20/97

FIGURE S-1 SDG&E Power Meter Calibration Check

TYPICAL TEST RUNS

FIGURE 5-2 summarizes typical test results that were obtained while under the “Bench Mark” parameters. Run No. 807 012 data were taken on August 7, 1997, run ID No. 0 12; as part of a series of tests that were conducted at that time.

Run Number		ORIGINAL RECOVERY RATIO		NEW RECOVERY RATIO
		A	(B-A)/A % % Change	B
		807012		130009
Specific Energy, kwh/kgal	secVRO	11.70	-23%	9.01
Membrane Pressure, PSI	pM	800		800
Cycle Speed, CPM	CPM	12		12
Capacity, GPD	GPD	27,288	59%	43,488
Recovery Ratio, actual flow	RR	27.3%	57%	42.7%
Feed, GPM	qF	69.5	2%	70.7
Concentrate, GPM	qC	50.5	-20%	40.5
Product, GPM	qP	18.95	59%	30.2
Product Internal Leakage, GPM		3.66	-15%	3.12
Electrical Supply, kw	kwES	13.54	23%	16.63
Hydraulic Pumps Eff.	eHP	76.8%	8%	82.6%
Water Displ. Unit Overall Eff.	eWDU	75.7%	11%	84.2%

File No. EX12a-Anal.130009 1/30/98Sensi.

FIGURE 5-2 Performance Change with WDU Improvements

Run No. 807 012 was run with the original recovery ratio configuration, which resulted in a recovery ratio (RR) of about 27%.

Run No. 130 009 was part of a series of tests conducted on January 30, 1998, and this test was Run ID No. 009. This series of runs were made after some modifications to the Pilot Plant unit in late 1997. These modifications included changing to a higher RR of about 43%. Also, during these modifications, a new dynamic sealing method was installed to reduce internal leakage and mechanical friction; which improved the system efficiency.

PERFORMANCE RESULTS IMPROVEMENT

The test results from Run No. 807 012 gave a specific energy consumption of 11.7 **kwh/kgal** (3.09 **kwh/m³**) at 800 PSI (55 BAR), 27% RR, and capacity of about 27,300 GPD (103 **m³/d**). This is actually very good performance for a system of this low capacity and recovery ratio.

The test results from Run No. 130 009 gave a specific energy consumption of 9.01 **kwh/kgal** (2.38 **kwh/m³**) at 800 PSI (55 BAR), 43% RR, and capacity of about 43,500 GPD (165 **m³/d**). This is a substantial improvement over the very good performance for the original system. There are several reasons that explain this performance improvement. One reason is that the capacity increased 59%, while the power input (**kwES**) only increased 23%. One reason for a lower percentage power increase is that the hydraulic pumps were operating at a more efficient higher power level, where the parasitic losses are a smaller percentage of the total power. Other reasons are that the water displacement unit mechanical and volumetric efficiencies improved.

EXPECTED FUTURE PILOT PLANT UNIT PERFORMANCE IMPROVEMENT

As noted above, the test results were taken under the “Bench Mark” conditions (SECTION 4.1). It is expected that the Pilot Plant unit performance will improve when the unit is operated at design operation conditions of 13.7 CPM versus 12 CPM. One reason for the expected future performance improvement is that the hydraulic pumps will be operating at closer to the rated conditions. Another reason is that the product water flow rate is expected to increase about 14% to about 49,000 GPD (185 m³/d), while the mechanical friction and internal leakage losses are expected to remain about the same. If these expectations hold true, the specific energy consumption could decrease from the present 9 kwh/kgal (2.38 kwh/m³) to about 8.5 kwh/kgal (2.25 kwh/m³), about a 5% reduction.

With this improvement to 8.5 kwh/kgal at 800 PSI (55 BAR), then a specific energy consumption of 10.6 kwh/kgal (2.8 kwh/m³) at 1000 PSI (69 BAR) appears to be achievable.

NOTE: As a reference consideration, the present hydraulic drive unit (HDU) has two hydraulic pumps that are of the correct capacity, and one that has excess capacity. This resulted from a component delivery problem when the unit was manufactured. The over capacity hydraulic pump is only operating at about 70% of its design capacity. It has been estimated that if the correct hydraulic pump was installed, the energy consumption would improve another 2%. If this proves to be the case, then the specific energy consumption of about 10.4 kwh/kgal (2.75 kwh/m³), at 1000 PSI (69 BAR), appears to be possible with the Pilot Plant unit.

EXPECTED FUTURE FULL-SCALE UNIT PERFORMANCE

From the knowledge obtained during the Pilot Plant operation, several design improvements have been devised that are expected to improve performance. Also, for higher capacity units, the parasitic losses are expected to be a smaller percentage of the total power. Based on this, it has been projected that the specific energy consumption will improve, perhaps to about 10 kwh/kgal (2.64 kwh/m³) at 1000 PSI (69 BAR) and 45% RR.

EXPECTED FUTURE FULL-SCALE SMOOTH OUTPUT FLOW

During Pilot Plant operation, pressure pulsations were noted during each cycle. This was described in Mark Silbemagel’s report, APPENDIX B, as exceeding the +/- 5% maximum recommend by a pumping manual. This pressure pulsation was reduced when a small dampener was connected to the system. It should be noted that this pressure pulsation was at a low frequency (12 CPM), as compared to conventional positive displacement plunger pumps (typically 300 RPM). Also, this pressure pulsation was a relatively gentle pressure variation during each cycle period, as compared to the higher frequency pulsation of plunger pumps.

The primary reason for this pressure variation, during each cycle of the Pilot Plant unit, was that one of the hydraulic pumps in the hydraulic drive unit is a different capacity than the other two. The reason for this hydraulic pump capacity difference is mentioned in the NOTE above. This resulted in the control system not providing a perfect match of the stroking characteristics of the pump, that was different, with the other two hydraulic pumps. This difference caused a pressure variation during each cycle.

In future full-scale units, all of the hydraulic drive pumps will be identical; and the control system will be more precise. It is expected that these measures will provide smooth output flow, with low pressure pulsations, as compared to conventional positive displacement pumping equipment.

6. PERFORMANCE COMPARISONS TO CONVENTIONAL METHODS

A general comparison of the VARI-RO system to conventional pumping and energy recovery methods was given in SECTION 3. This section provides a performance comparison to typical conventional systems that are presently being used for reverse osmosis desalination facilities.

For these comparisons, equations were derived for both the VARI-RO system and the conventional system, as shown in SECTIONS 6.1 and 6.2

6.1 VARI-RO System, Specific Energy Consumption Equations

The VARI-RO system is an integrated pumping and energy recovery method for reverse osmosis desalination. Because of the integrated functions, the usual specific energy consumption equations used for conventional pumping and energy recovery systems do not apply. New equations have been derived for the VARI-RO system, which are shown in FIGURE 6-1.

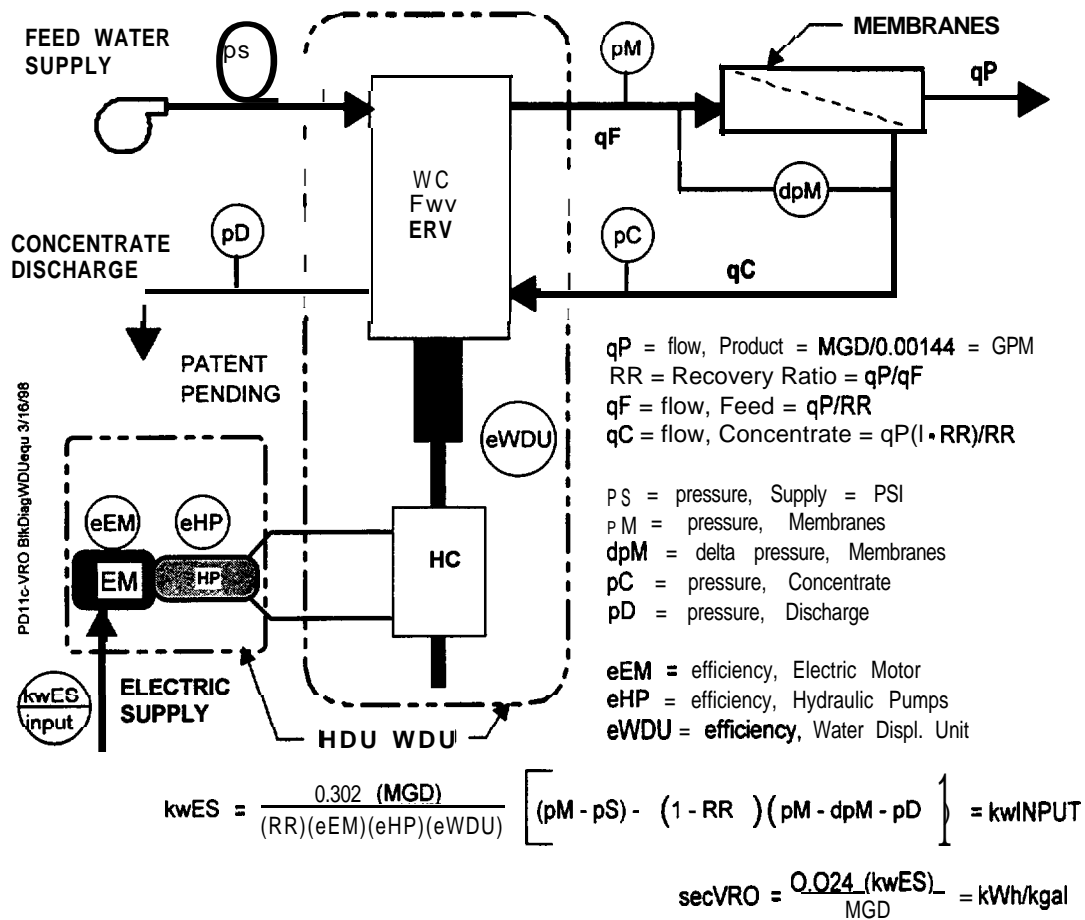


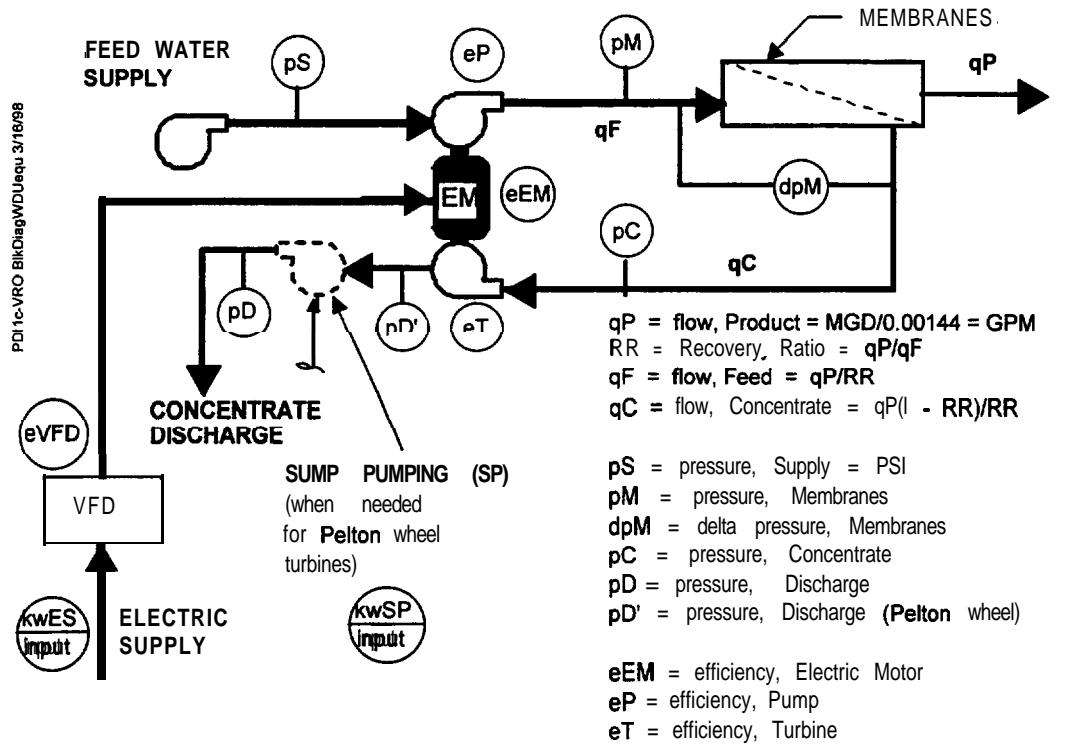
FIGURE 6-1 VARI-RO System, Diagram and Equations

In these new equations, the power input from the electrical supply ($kwES$) is defined in terms of the efficiencies of the electric motor (eEM), the hydraulic pumps (eHP), and the integrated water displacement unit ($eWDU$). The system characteristic is defined in terms of the product water produced (MGD), the recovery ratio (RR), and the system pressures as shown. The specific energy consumption of the VARI-RO system ($secVRO$) is then the input power ($kwES$) divided by the product water production (MGD), giving the result in kilowatt hours per 1000 gallons ($kwh/kgal$).

6.2 Conventional System, Specific Energy Consumption Equations

Specific energy consumption equations that apply to conventional pumping and energy recovery systems are shown in FIGURE 6-2. The equations are for conventional systems composed of a centrifugal pump, reverse flow pump turbine, and variable frequency drive (CP-RFP-VFD). With slight variations, these equations also apply to **Pelton** wheel turbine systems with centrifugal pumps (CP-PW-VFD-SP), and systems with plunger pumps and **Pelton** wheel turbines (**PP-PW-SP**). Since **Pelton** wheel turbines must exhaust to atmospheric pressure, additional energy consumption needs to be added for sump pumping, when this is needed to move the water to the point of discharge. For plunger pump systems, the efficiencies used would also need to include the drive belts. As an example, for a plunger pump with 90% efficiency and a belt drive with 95% efficiency, the efficiency (**ePP**) would be for the combined components, or 85.5%.

NOTE: The variable frequency drives would not be used for the plunger pump systems. Also, if these are not used with the centrifugal pump systems, then appropriate flow throttle valve (FTV) losses need to be added to the analysis,



$$kwES = \frac{0.302 \text{ (MGD)}}{(RR)(eVFD)(eEM)} \left[\frac{(pM - pS)}{eP} - eT (1 - RR) (pM - dpM - pD) \right] = \text{kwINPUT}$$

$$kwSP = \frac{0.302 \text{ (MGD)} (1 - RR) (pD)}{(RR)(eVFD)(eEM)(eP)}$$

$$secCONVEN. = \frac{0.024 (kwES + kwSP)}{\text{MGD}} = \text{kWh/kgal}$$

FIGURE 6-2 Conventional System, Diagram and Equations

The electric supply power input (**kwES**) of the system is the power of the pump less the power of the turbine, divided by the efficiencies of the variable frequency drive (**eVFD**) and the electric motor (**eEM**). If the system includes sump pumping, then this power (**kwSP**) would need to be added to the **kwES** power before calculating the specific energy consumption (**secCONVEN.**) of the conventional system.

6.3 Performance of Pilot Plant Unit, Actual and Projected

FIGURE 6-3 is based on the equations shown in FIGURES 6-1 and 6-2 for the VARI-RO system and Conventional systems for reverse osmosis pumping and energy recovery. The data and results shown in this figure are based on the “Bench Mark” Pilot Plant testing described previously in SECTION 5.4, for Cases ID: Run No. 807 012 and Run No. 130 009.

CASE ID	Run 807 012	Run 130 009	VRO Pilot Plant	VRO Commercial
DESCRIPTION	Original Recovery Ratio at 800 PSI	New Recovery Ratio at 800 PSI	Higher Recovery Ratio at 800 PSI	Higher Capacity at 800 PSI
Constant Pressure Conditions				
PUMP & ENERGY RECOV. TYPE versus VARI-RO Elect. Mtr. Drive	PP-none VRO-EMD	PP-none VRO-EMD	PP-none VRO-EMD	CP-PW-VFD-SP VRO-EMD
CAPACITY/TRAIN (MGD)	0.0273	0.0435	0.0500	0.5000
RECOVERY RATIO RR	27.3 %	42.7%	45.0%	45.0%
Number of trains	1	1	1	1
Total Capacity (reference) MGD m3/d	0.027 103	0.043 165	0.050 189	0.600 2,271
FLDW RATES/TRAIN. GPM				
FEED, GPM nF	69.4	70.7	77.2	925.9
CONCENTRATE qC	50.5	40.5	42.4	509.3
PRODUCT qP	19.0	30.2	34.7	416.7
PRESSURES (PSI)				
Supply pS	30	30	30	30
Membrane Pressure (reference) P M (PSI) pM (BAR)	800 55.2	000 55.2	800 55.2	800 55.2
Membrane Pressure drop dpM	52	40	50	50
Concentrate to ER PC	746	760	750	750
Discharge from ER (ii PW) pD'	0	0	0	0
Discharge from RFP,VRO,SP pD	17	15	20	20
NOTE: for PW, box = 1	1			
EFFICIENCIES, OVERALL	(100% = not included). Also VFD not applicable to VARI-RO.			
Variable Freq. Drive eVFD	100.0%	100.0%	100.0%	97.0%
Electric Motor eEM	93.0%	93.0%	93.0%	95.0%
CONVENTIONAL SYSTEM:	PP-none	PP-none	PP-none	CP-PW-VFD-SP
Cent. or Plunger Pump eCP or ePP	85.5%	85.5%	85.5%	76.0%
Turbines ePW, eRFP	0.0%	0.0%	0.0%	83.0%
specific energy consumption secPW+SP	26.22	16.66	15.87	12.00
VARI-RO SYSTEM:	VRO-EMD	VRO-EMD	VRO-EMD	VRO-EMD
Hydraulic Pumps eHP	76.8%	82.6%	84.0%	88.0%
Water Displacement Unit eWDU	75.7%	84.2%	85.0%	92.0%
specific energy consumption secVRO	11.71	9.00	8.94	7.72
% Savings saveVRO(%)	55 %	46%	44 %	36 %

EX2a-FTR VROvsConv.Anal 3/17/98

FIGURE 6-3 Pilot Plant Performance Based on Derived Equations

The “VRO Pilot Plant” & “VRO Commercial” columns show lower specific energy consumption projections at higher efficiencies for the hydraulic pumps (eHP) and the water displacement unit (eWDU). This is after improvements have been made for higher cycle speed operation (Pilot Plant), and higher capacity (Commercial).

As a point of reference, for the low capacity operation, the specific energy consumption of a plunger pump without energy recovery is shown. In general low capacity systems usually do not have energy recovery. This method is presently used in U. S. Army/Marines ROWPU (reverse osmosis water purification units). For the VRO Commercial unit, the conventional system is a centrifugal pump with Pelton wheel energy recovery, variable frequency drive, and sump pumping (CP-PW-VFD-SP).

6.4 Performance comparisons for the Santa Barbara Application

For the Economic Analysis, the existing Santa Barbara Seawater Desalination Facility is being used as the reference plant to predict the cost of water. The facility has 12 trains of 0.6 MGD (2,270 m³/d) capacity. The pumping and energy recovery system for this facility incorporates centrifugal pumps, Pelton wheel turbines, variable frequency drives, and also sump pumps to discharge the concentrate. FIGURE 6-4 provides a comparison of performance, using the equations in FIGURES 6-1 and 6-2.

CASE ID	VRO Pilot Plant vs Conven.				VRO Commercial vs Conven.			
	DESCRIPTION		Santa Barbara Seawater RO		Santa Barbara Seawater RO		Santa Barbara Seawater RO	
			Start-up at 865 PSI	Design at 955 PSI	Start-up at 865 PSI	Design at 955 PSI		
PUMP & ENERGY RECOV. TYPE	CP-PW-VFD-SP	CP-PW-VFDSP	CP-PW-VFDSP	CP-PW-VFDSP	VRO-EMD	VRO-EMD	VRO-EMD	VRO-EMD
versus VARCRO Elect. Mtr. Drive	VRO-EMD	VRO-EMD	VRO-EMD	VRO-EMD	VRO-EMD	VRO-EMD	VRO-EMD	VRO-EMD
CAPACITY/TRAIN (MGD)		0.600	0.600	0.666	0.600			
RECOVERY RATIO	R R	45.0%	45.0%	45.0%	45.0%			
Number of trains		12	12	12	12			
Total Capacity (reference)	M G D	7.2	7.2	7.2	7.2			
	m ³ /d	27,252	21,252	27,252	27,252			
FLOW RATES/TRAIN, GPM								
FEED, GPM	qF	926	926	926	926			
CONCENTRATE	qC	509	509	509	509			
PRODUCT	qP	417	417	417	417			
PRESSURES (PSI)								
Supply	pS	30	30	30	30			
Membrane Pressure	PM (PSI)	665	965	865	955			
(reference)	pM (BAR)	59.7	65.9	59.7	65.9			
Membrane Pressure drop	dpM	64	64	94	64			
Discharge from ER (if PW)	pd'	0	0	0	0			
Discharge from RFP, VRO, SP	pd	0	0	0	0			
NOTE: for PW, box = 1		1						
EFFICIENCIES, OVERALL	(100% = not included). Also MD not applicable to VARI-RO.							
Variable Freq. Drive	eVFD	97.4%	97.5%	97.5%	97.5%			
Electric Motor	eEM	95.0%	95.0%	94.9%	95.0%			
CONVENTIONAL SYSTEM:		CP-PW-VFD-SP	CP-PW-VFD-SP	CP-PW-VFD-SP	CP-PW-VFD-SP			
Cent or Plunger Pump	eCP or ePP	76.0%	76.0%	76.0%	76.0%			
Turbines	ePW, eRFP	83.5%	83.5%	83.5%	83.5%			
specific energy consumption	secCONVEN.	12.72	14.05	12.72	14.05			
VARI-RO SYSTEM:		VRO-EMD	VRO-EMD	VRO-EMD	VRO-EMD			
Hydraulic Pumps	eHP	84.0%	84.0%	88.0%	88.0%			
Water Displacement Unit	eWDU	85.0%	85.0%	92.0%	92.0%			
specific energy consumption	secVRO	9.37	10.33	8.27	9.11			
% savings	saveVRO(%)	26%	26%	35%	35%			

EX4a-FTR SantaBarb.Orig 3/18/98

FIGURE 6-4 VARI-RO System versus Method used at Santa Barbara

For this facility, the start-up membrane pressure was 865 PSI (60 BAR); and the design pressure was 955 PSI (66 BAR). The higher design pressure provides a margin for membrane pressure variation due to salinity, temperature, and fouling. For the assumed efficiencies, VARI-RO system energy consumption savings of 26% and 35% have been projected, for the VRO Pilot Plant and VRO Commercial versus Conventional cases, respectively.

The efficiencies used for the centrifugal pumps, Pelton wheel turbines, variable frequency drives, and electric motors were provided by the facility contractor. The efficiencies for the VARI-RO system are based on extrapolations from the Pilot Plant test data, and data from equipment manufacturers for higher capacity units. The VRO Pilot Plant case is based on the lowest expected efficiencies, and the VRO Commercial case is based on efficiencies that can reasonably be expected for VARI-RO systems of higher capacity, in the 0.3 to 5 MGD (1,135 to 18,925 m³/d) capacity range.

7. FACILITY OPTIMIZATION WITH THE VARI-RO SYSTEM

With conventional pumping and energy recovery systems, the energy consumption is higher at lower recovery ratios. Because of this higher energy consumption at lower recovery ratios, and other factors, it is presently the usual case for the RO system designer to select as high a recovery ratio as the membrane system will allow before having fouling problems under normal operating conditions. The VARI-RO system, however, has a relatively flat energy consumption versus recovery ratio at a constant membrane pressure. As a result of this flat energy consumption characteristic, it is possible to have lower energy consumption at lower recovery ratios than would normally be done with conventional pumping. This feature provides the RO system designer a new tool for the optimization of the facility for lowest total water cost (TWC).

Advantages of lower recovery ratios include:

1. Lower membrane pressure for the same membrane quantity.
2. Conversely, fewer membranes can be used if the pressure is kept the same.
3. The water quality is improved at lower recovery ratios.
4. The salinity of the concentrate is lower, which reduces the fouling potential.
5. At lower concentrate salinities, it may be possible to improve the chemical pretreatment for lower cost or less environmental impact.
6. With a lower salinity concentrate, the environmental issues related to ocean brine disposal may be improved (Del Bene, et al, 1993). For example, less mixing for dilution of the concentrate may be possible.

Disadvantages of lower recovery ratios include:

1. The feedwater flow is higher for a given product water production.
2. Higher capacity intake and discharge piping are needed.
3. More feedwater needs to be pumped and pretreated.
4. The chemical costs could be higher, if some modification of the chemical pretreatment is not made to take advantage of the lower concentrate salinity.

A tradeoff study is needed to determine if the lower pressure operation is cost effective as compared to the higher flow rates of the feedwater and concentrate. As a part of this tradeoff study, the electric power rates need to be considered. In regions with high electric rates, such as the Caribbean or the Canary Islands: the advantage of operating at lower recovery ratios, and pressures, will be greater.

This section outlines a possible scenario for the Santa Barbara Seawater Desalination Facility directed toward reducing the energy consumption by operating at lower recovery ratios and at lower membrane pressures. This scenario considers that the intake and discharge piping for this facility was designed for a capacity of 9.6 MGD (36,340 m³/d), whereas the membrane system has a capacity of 7.2 MGD (27,250 m³/d). This would allow the recovery ratio to be decreased to about 35% while maintaining the present water production capability.

NOTE: At lower recovery ratios, the possibility of operating at lower pressures was discussed in the VARI-RO study (Childs and Dabiri, 1995), page 27. This possibility of operating at lower recovery ratios is based on membrane characteristic data (DOW, 1992) provided by DOW FILMTEC, who manufactured the membranes for this facility. This membrane characteristic data also shows that the water quality is improved at lower recovery ratios. The lower energy characteristic of the VARI-RO system, at lower recovery ratios, can provide the RO systems engineer another tool to optimize the facility for the lowest total water cost (TWC).

7.1 Lower Energy Consumption at Low Recovery Ratio Characteristic

Due to the high energy recovery efficiency of the VARI-RO system, the specific energy consumption (**sec**) can be lower at low recovery ratios for the same membrane system. This is illustrated by the calculations shown in FIGURE 7-1. The “Base Case” conditions are based on a start-up pressure of 865 PSI at 45% RR. The other cases are for the membrane pressure changing with recovery ratio according the membrane characteristics provided by the manufacturer (DOW, 1992 Appendix B). For these calculations, the same efficiencies given in FIGURE 6-4 for VRO Commercial versus Conventional were used.

CASE ID DESCRIPTION	VRO Commercial (versus Recovery Ratio)			
	Santa Barbara			
	Still lower RR at 35% RR at 780 PSI	Lower RR at 40% RR at 823 PSI	Base Case at 45% RR at 865 PSI	Higher RR at 50% RR at 910 PSI
Start-up Pressure				
PUMP & ENERGY RECOV. TYPE versus VARI-RO Elect. Mtr. Drive	CP-PW-VFD-SP VRO-EMD	CP-PW-VFD-SP VRO-EMD	CP-PW-VFD-SP VRO-EMD	CP-PW-VFD-SP VRO-EMD
CAPACITY/TRAIN (MGD)	0.600	0.600	0.600	0.600
RECOVERY RATIO R R	36%	40%	46%	60%
Number of trains	12	12	12	12
Total Capacity MGD (reference) m3/d	7.2 27,252	7.2 27,252	7.2 27,252	7.2 27,252
FLOW RATES/TRAIN: GPM				
FEED, GPM qF	1,190	1,042	926	633
CONCENTRATE qC	774	625	509	417
PRODUCT qP	417	417	417	417
PRESSURES (PSI)				
Supply pS	30	30	30	30
Membrane Pressure pM (PSI) (reference) pM (BAR)	780 53.8	823 56.8	865 59.7	910 62.8
Membrane Pressure drop dpM	64	64	64	64
Discharge from ER (if PW) pD	0	0	0	0
Discharge from RFP,VRO,SP pD	0	0	0	0
NOTE: for PW, box = 1	1			
EFFICIENCIES: OVERALL	(100% = not included). Also VFD not appliile to VARCRO.			
Variable Freq. Drive eVFD	97.6%	97.6%	97.6%	97.6%
Electric Motor eEM	96.0%	96.0%	94.9%	96.0%
CONVENTIONAL SYSTEM: Cent. or Plunger Pump Turbines (0% = none) specific energy consumption	eCP or ePP ePW, eRFP secCONVEN.	CP-PW-VFDSP 76.0% 83.6% 13.37	CP-PW-VFDSP 76.0% 83.5% 12.97	CP-PW-VFD-SP 76.0% 83.6% 12.72
VARI-RO SYSTEM: Hydraulic Pumps Water Displacement Unit specific energy consumption	eHP eWDU secVRO	VRO-EMD 88.0% 92.0% 7.66	VRO-EMD 188.0% 92.0% 7.95	VRO-EMD 88.0% 92.0% 8.27
% Savings saveVRO(%)	43%	39%	35%	32%

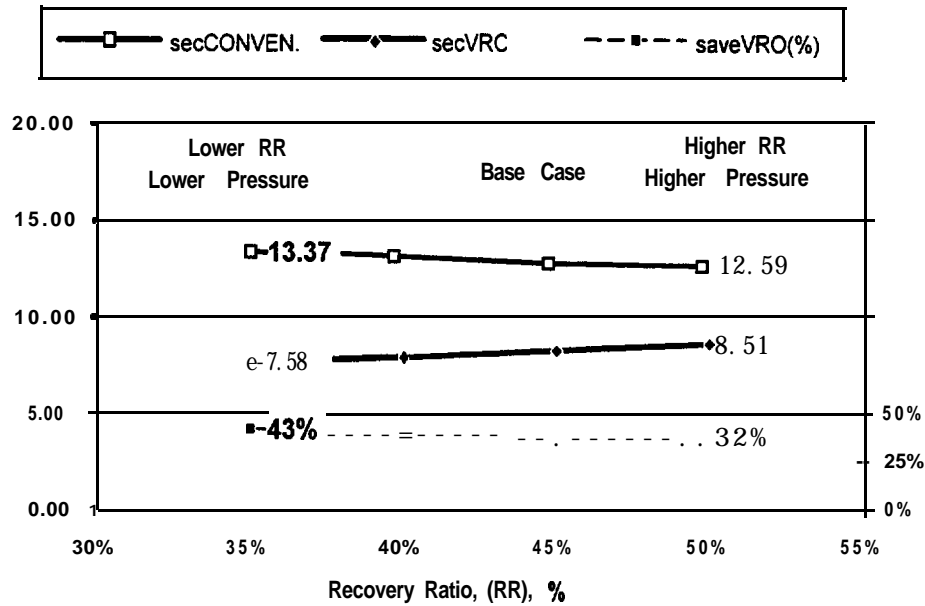
EX5a-FTR Flat sec VS RR 3/18/98

FIGURE 7-1 Lower Specific Energy Consumption at Lower Recovery Ratio

Even though the feed water flow rate at 35% RR is increased as compared to 45% RR, it is still less than the design capacity of the intake system at 9.6 MGD (36,340 m³/d). This means that operation at 35% RR is physically feasible for this facility, and could be a design consideration for improving the facility operation with the VARI-RO system.

This also illustrates the applicability of this optimization consideration for other applications.

As shown in FIGURE 7-2, with the conventional system the specific energy consumption increases from 12.72 to 13.37 kwh/kgal (3.36 to 3.53 kwh/m^3) with a RR decrease from 45% to 35%, respectively. Whereas, with the VARI-RO system the energy consumption decreases from 8.27 to 7.66 kwh/kgal (2.18 to 2.02 kwh/m^3) under the same conditions. The result is that the energy consumption can actually be lower with the VARI-RO system at lower recovery ratios.



EX5a-FTR Flat sec vs RR 3/18/98

FIGURE 7-2 VARI-RO System, Lower Energy Use at Lower Recovery Ratios

In addition to saving energy, operation at lower recovery ratios could provide additional advantages, such as improved water quality, reduced membrane fouling potential, and lower salinity in the discharge concentrate. The latter could reduce the need for further dilution prior to discharging the concentrate back to the source.

Operating at lower recovery ratios requires a tradeoff study to determine the most economical operation. In regions with higher electric power rates, the operation at lower recovery ratios may be of particular advantage, and show a savings in total water cost (TWC).

For inland brackish water reverse osmosis (BWRO) applications, the disposal of the concentrate can be costly. This usually results in the use of high recovery ratios for the total facility. This can be accomplished with lower recovery ratios for the first stages, and using subsequent stages for further concentration of the concentrate. A tradeoff study would be necessary to determine in the high energy recovery efficiency of the VARI-RO system would provide operational advantages for these types of applications.

8. ECONOMIC ANALYSIS

A report by Laughlin Associates is included as Appendix C, entitled: “*Economic Comparison of VARI-RO vs. Conventional High Pressure Pumping and Energy Recovery Technology*” (Laughlin, 1998). This report uses as the base case the 7.2 MGD (27,250 m³/d) seawater desalination facility at Santa Barbara, California. The present pumping system consists of 12 trains of 0.6 MGD (2,270 m³/d) each at 45% recovery ratio. The initial operating pressure was 865 PSI (59.6 BAR), and the design operating pressure for the facility is 955 PSI (65.8 BAR). The initial operating pressure is used for the comparative analysis of the VARI-RO system versus the conventional system.

The conventional pumping and energy recovery system consists of centrifugal pumps, Pelton wheel energy recovery turbines, variable speed drives, and sump pumping to discharge the concentrate back to the ocean (CP-PW-VFD-SP). The efficiencies for these components, used in this comparison, were provided by the facility contractor. The method for calculating specific energy consumption for the conventional system is given in FIGURE 6-2.

For the VARI-RO system, two cases are considered, which are identified as VARI-RO Pilot Plant and VARI-RO Commercial. The efficiencies for the hydraulic pumps and the water displacement units were determined as follows. The Pilot Plant efficiencies are based on extrapolations from the Pilot Plant testing. The Commercial efficiencies are based on higher capacity units and a more mature design, where higher efficiencies are expected. The method for calculating specific energy consumption for the VARI-RO system is given in FIGURE 6-1.

A comparative summary of the relative energy consumption between the VARI-RO systems and the conventional system are shown in FIGURE 8-1. This information has been extracted from the Laughlin report. This shows an energy consumption savings of 26% and 35% for the VARI-RO Pilot Plant and Commercial systems, respectively. At an electric power rate of \$0.06/kwh, this is an annual savings of \$0.486 and \$0.646 million per year, respectively. The savings would be even greater at higher electric power rates, and when the facility is operating at higher operating pressures. The higher operating pressures can result from changes in salinity, feed water temperature, and membrane fouling.

It should be noted that this analysis did not consider the losses attributed to the sump pumping. These losses would result from the efficiency of the electrical supply, electric motors, pumping equipment, and flow throttling valves (if any). The sump pumping for the Santa Barbara facility was required to discharge the concentrate from the Pelton wheel energy recovery back to the ocean. The VARI-RO system can take full discharge back pressure, and does not require a separate sump pumping system.

The total water cost considers the capital cost of the facility, amortized over the expected life of the facility. In the case of this facility, the intake and outfall structures were sized for 9.6 MGD (36,300 m³/d) capacity, while the balance of the facility was sized for 7.2 MGD (27,250 m³/d). It is expected that the total water cost would reduce if the facility was upgraded to full capacity.

Based on the system parameters for the 7.2 MGD (27,250 m³/d) capacity, the total water cost is given in FIGURE 8-1, which shows a savings of 5% and 8% for the VARI-RO Pilot Plant and Commercial units, respectively.

	VARI-RO Pilot Plant	VARI-RO Commercial	Conventional Plant
FACILITY PARAMETERS			
Capacity, MGD	7.2	7.2	7.2
Recovery Ratio, %	45%	45%	45%
Membrane Pressure, PSI	865	865	865
Plant Availability Factor, %	92%	92%	92%
EFFICIENCIES, %			
Variable Frequency Drive Electric Motor			97.5%
Centrifugal Pump			95%
Pelton Wheel			76%
Sump Pump	(not considered in this comparison)		
Hydraulic Pumps	64%	86%	
Water Displacement Unit	85%	92%	
SPECIFIC ENERGY CONSUMPTION, sec			
High Pressure Pumping (HPP), kwh/kgal	9.37	8.27	12.72
VARI-RO Savings, %	26%	35%	
ECONOMIC COMPARISON			
Electric Power Rate, \$/kwh	0.06	0.06	0.06
Annual Energy Cost for HPP, \$million/year	1.359	1.200	1.845
VARI-RO Savings, \$million/year	0.486	0.646	
Total Water Cost, \$/AF	967	939	1,024
Total Water Cost, \$/m ³	0.785	0.761	0.830
Total Water Cost, \$/kgal	2.97	2.68	3.14
VARI-RO Savings, %	5%	8%	

EX7a-FTR EconAnalSum 4/2/98

FIGURE 8-1 Economic Analysis Comparative Summary

A key consideration in the selection of high pressure pumping equipment is that after the desalting facility has been placed in operation, the saving of operating expenses is of particular importance. This analysis indicates that the VARI-RO system would save about \$0.6 million per year, which would be a saving of \$6 million over a 10 year operating period for the 7.2 MGD (27,250 m³/d) facility. These savings would be even greater at higher electric power rates, and at higher operating pressures.

Another consideration is the potential to provide additional energy savings by operating at lower recovery ratios as discussed in Section 7.1. A tradeoff study would be needed to determine if this would result in lower total water cost. A desalting system design that operates at lower recovery ratios, and lower membrane pressures, would likely show water cost savings for regions with high electric power rates.

9. CONTINUED TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

9.1 Pilot Plant Unit

There have been two primary goals for the present Pilot Plant unit, as follows:

1. To prove the function and operational benefits of the VARI-RO system.
2. To prove the energy consumption potential with a low capacity unit, and project the energy consumption to higher capacity units.

With respect to these two goals, the project has been very successful. As the project progressed through the development phase certain items were identified for improvement. Some of these improvements have been incorporated, including:

- **Electronic Controls and Data Acquisition Enhancements:** Some improvements were made to the computer software, which improved the data acquisition and analysis.
- **New energy recovery valves:** Four out of 12 of a new design were manufactured and installed. These valves have proven that the new design is a substantial improvement over the original design. Not only does this design improve reliability, it also improves the appearance of the system.
- **Recovery ratio and internal dynamic seals:** As part of the energy performance improvement, some water cylinder internal parts were changed. These changes included increasing the recovery ratio, using a ceramic ratio rod, and going to a special segmented ratio rod seal. These changes made a substantial improvement to the volumetric and mechanical **efficiency**, which resulted in the specific energy consumption improvement from 11.7 to 9.0 1 kwh/kgal (see Section 5.4).

The planned future improvements include improving the functionality of the system, and reducing manufacturing cost for full-scale units. It would be desirable to test these improvements on a pilot scale basis before proceeding with a full-scale demonstration capacity unit. Some of these improvements include the following:

- **Fiberglass reinforced plastic (FRP) barrels, and other design improvements:** For the Pilot Plant unit, and future full-scale units, conceptual design improvements have been made. These design improvements indicate that manufacturing costs can be reduced, and improvements made in reliability and maintainability for the corrosive seawater environment. One improvement would be using FRP barrels in place of stainless steel. The implementation of this change requires changes to the cylinder heads, porting, and valve interfaces, as mentioned below.
- **Electronic Controls and Hydraulic Drive Unit:** Update the performance analysis computations to agree with the latest methodology. Improve the control response of the hydraulic pumps to assure that the pressure control will be suitable for higher capacity units.

- **New energy recovery valves:** Incorporate into the design the latest configuration that evolved from the full-scale design effort, and incorporate a design interface suitable for the change to FRP barrels.
- **Recovery ratio and internal dynamic seals:** Make necessary changes, and improvements, to allow the FRP barrel change.

It is recommended that a program to continue the VARI-RO system development be undertaken.

9.2 Demonstration of Full-Scale Capacity Unit

It is recommended that a demonstration project be implemented to **design**, manufacture, and test a full-scale unit in the 300,000 to 600,000 GPD (1135 to 2,270 m^3/d) capacity range. The objectives for this project include the following:

- Show that the efficiency projections for a Commercial capacity unit can be achieved.
- Demonstrate to the desalting industry that the technology is viable and should be considered as a preferred method for future desalting plants, and as a retrofit for existing facilities.
- Put the VARI-RO system side-by-side with a conventional system to show the installation, operational, and energy saving features of the technology.

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Appendix A

Test Reporting **from**
Naval Seawater Desalination Laboratory

Naval Facilities Engineering Service Center (NFESC)

31 August 1997

TO: **Will Childs**, VARI-RO Power Co.
FROM: Mark A. Silbemagef, U.S. Naval Facilities **Engineering Service Center**
Seawater Desalination Test Facility
1100 **23rd** Ave
Port **Hueneme**, CA 93043

SUBJ: Trip report San Pasqual Water Reclamation **Facility** to observe testing of the VARI-RO **prototype** pump.

The **following report summarizes NFESC's** evaluation of the VARI-RO pump for reverse osmosis systems. The report is in chronological order with specific recommendations and overall test summary provided at the end.

17 July 1997 **Pre-test** Trip to Inspect Pump and **Test Setup**:

On **17 July 1997** a **trip** was **made** to the San **Pasqual** Water Reclamation **Facility** to observe testing of the **VARI-RO** prototype pump. The purpose of the trip was to become familiar **with the** design and **operation** of the pump and to evaluate the test setup. Based **on this trip**, an additional trip was scheduled for 6 to 8 August 1997 **to** assist in a performance evaluation **Of** the pump. The following suggestions were made in order to conduct the performance evaluation:

- Prepare a means of timing *and* weighing the concentrate and **permeate flow** rates in order to **verify** volumetric **efficiencies**. A 55 gallon capacity **drum** and 1000 **lb.** range **scale** was judged to be adequate **which** should give a **flow** measurement accuracy of less than 0.2%.
- **Install a new** concentrate pressure gauge to measure the pressure of the de-pressurized concentrate.
- Install vacuum gauge in the suction line for the hydrostatic pumps to verify adequate suction pressure to the hydrostatic pumps.
- Check high pressure **relief** valve located in **the** feed pressure header to verify that it is not relieving during normal operation.
- **NFESC** would provide a dead weight tester to verify transducer calibration.
- Get **SDG&E** to provide an additional **means** of verifying the power measurement **since** this measurement is critical to the evaluation.
- Conduct tests with the gas charged dampener located in the feed pressure header *valved on* in order to reduce pulsation. Peak to peak pulsations' were measured for test run 717014 at 844 psi operating pressure without the dampener and 822 psi operating pressure with the dampener. The peak

to peak values were approximately 155 psi without the dampener and 69 psi with the dampener. This test showed that the pulsation levels of the prototype pump without the dampener definitely exceed the recommended +/- 5% of operating pressure (*Pumping Manual*, by R.H. Warring, 7th Edition, pg. 303.). In some cases, the manual recommends a +/- 2% criteria be used. On typical plunger pump tests we conducted at NFESC we were measuring peak to peak pressures of less than 50 psi with dampeners installed.

- It was also noticed that significant pulsations were present in the suction header based on the oscillations observed on the suction header pressure gauge. These should be measured to verify that they are not causing a low NPSH condition in the suction header.
- Re-check the range of the power meter installed to see if better accuracy could be obtainable through multiple wraps through the current transformers.

6 August 1997 Review of Test Setup and Transducer Calibration:

On 6 August the pressure transducer calibration was checked using a dead weight tester by first calibrating the test gauge over a range of 338 to 964 psi and then the transducers were calibrated according to the test gauge. This method was performed to avoid getting oil from the dead weight tester in the transducers and the transducer manifold. The test gauge showed an accuracy of approximately 0.8% over the calibration range compared to the dead weight tester. The transducers were then calibrated according to the test gauge.

The Load Controls power meter installed on the VARI-RO unit is a 30 hp range unit so additional wraps through the CT were not necessary to obtain any more accurate measurements.

The tank and scale for flow rate measurements were inspected and judged to be more than adequate for getting accurate flow measurements to within 0.3%.

Two software configurations were setup on the pump control and data collection program. One configuration would utilize the differential pressure transducer and the second or default configuration would utilize the hydraulic cylinder transducers.

A 0-100 psi range pressure gauge was installed in the de-pressurized concentrate line.

The equations for calculating the efficiencies were reviewed.

A performance evaluation plan was developed which would include test runs at 800 and 600 psi for cycle speeds of 12, 6, and 9 cycles per minute (cpm). The performance evaluation would include:

- Stroke and cycle speed would be verified.
- Flow rates would be measured by weighing the water (converting to gallons assuming a density of 8.34 lb./gal) and timing the flow.

- The ball valve for simulating membrane pressure drop would be set to give a 50 psi differential when operating at 800 psi and 12 cpm. The differential pressure would then be measured for • & same valve setting at 800 psi and speeds of 6 and 9 cpm.
- Comparisons of power measurements would be made between the meter supplied by SDG&E and the Load Controls power meter installed on the unit.
- After the performance measurements, leakage tests on the cylinders would be performed by closing the ER valves manually and stroking the hydraulic cylinders individually.

7 - 8 August 1997 Performance Testing:

In the differential pressure software configuration, the valve for simulating membrane pressure drop was adjusted to give a 52 psi differential at 12 cpm speed and 800 psi (test run 807002 and 807003). The valve was then left in the same position and the pressure drop was measured at 31 psi at 9 cpm (test run 807005), and 14.5 psi at 6 cpm (test run 807004). These values would be manually entered into the data analysis spreadsheet. The software configuration was then changed to the default configuration with transducers located on the hydraulic cylinders.

The measured cycle speed was verified by timing and counting the strokes and was found to be within 0.5%. The measured stroke was verified and was found to be within 1% (test run 807001). The measured stroke by the position sensors is probably more accurate than what we could verify through a manual measurement

The SDG&E power meter was installed. The power meter was a Synergistic Control Systems Model C120E meter/recorder. Since the unit was equipped with 100 amp current transducers (CT), three turns of wire were routed through the CTs to improve the accuracy of the measurement. Power measurements from the meter were then divided by 3 for comparison to the Load Controls meter. The SDG&E meter consistently read higher than the Load Controls meter by about 4.1% in the 14.5 kW range and 7.1% in the 7 kW range. The relationship was very linear with the load controls meter reading = $-0.9832 \cdot \text{SDGE meter} - 0.3695$ $R^2 = 1.0$
 An additional meter was installed after the 7-8 August test period with calibration curves provided by VARI-RO. The third meter readings have been used in the analyses as it was felt that this meter was the more accurate of the three meters installed. (see note on power measurement recommendations)

The performance testing was then started with test runs at 800 and 600 psi for 12.6, and 9 cpm.

Results of Performance Tests:

The results of the performance tests labeled run numbers 807006 through 807072 have been summarized in detail by VARI-RO in the various spreadsheets entitled *HYDRAULIC POWER SUPPLY (HPS) AND WATER DISPLACEMENT UNIT (WDU) EFFICIENCY EVALUATION AND PROJECTIONS FOR THE VARI-RO SYSTEM*. The

most recent analyses are on the sheets for 8/22/97. An additional analyses was performed 8/23/97 to analyze the Sensitivity of the specific power consumption to leakage flow, reduced friction forces, and increased hydraulic pump efficiency (for larger units where parasitic losses are a smaller percentage of the overall power consumption).

The table below summarizes the results for the test runs conducted:

Test Run No.	Feed Flow (gpm)	RO Feed Pressure (psi)	800 psi Feed Volumetric Efficiency	800 psi Product Volumetric Efficiency	800 psi Hydraulic Pump Efficiency
807006B	69.75	801	98.1	84.5	77.7
807012	69.47	814	97.7	83.8	76.8
808001	70.12	832	97.8	83.5	75.3
807008	35.8	827	100	74.6	62.6
807010	53.03	815	98.7	81	72.8
			600 psi Feed Volumetric Efficiency	600 psi Product Volumetric Efficiency	600 psi Hydraulic Pump Efficiency
807011	53.45	607	98.6	84	69.3
807009	35.96	609	99.8	78	57.4
807007	70.7	594	98.2	87.1	80.4

The main performance factors that are critical are the feed and product volumetric efficiencies. If these efficiencies are greater than 98%, then the pump is operating correctly. However, during the testing there were dramatic differences between the feed and product volumetric efficiencies. The feed volumetric efficiency of 97.7% to 97.8% (test run 807012, 808001) is typical for positive displacement pumps, but the product volumetric efficiency of 83.8% to 83.5% which is determined by the energy recovery portion of the WDU is much lower than the 98% expected. This difference shows that there is significant leakage in the ER section of the WDU. While at San Pasqual, some manual stroking tests were conducted which showed significant leakage across the ER ratio rod seals for pistons 2 and 3. This would account for some of the loss in volumetric efficiency. In addition the automatic air bleeds installed in the bulkheads for cylinders 2 and 3 can also contribute to the Leakage since there is full differential pressure (822-52-17=753 psi) across the air bleeds. These bulkheads could be easily manually vented with valves since the bulkhead is not a moving part like the piston. These changes could significantly improve the ER section volumetric efficiency as shown in the 8/23/97 sensitivity analysis which resulted in a drop in the specific energy consumption from 11.7 kWhr/kgal to 9.86 kWhr/kgal.

When looking at the effect of operating speed and pressure, feed volumetric efficiencies are within the expected range over the range of pressures and cycle speeds tested. Product volumetric efficiencies are higher at lower pressures and higher cycle speeds indicating leakage flow on the ER side as discussed earlier. Hydraulic pump efficiencies are higher at higher cycle speeds possibly indicating a lower percentage of parasitic losses due to the charge and servo pumps. However at

the **12 cpm speed (70 gpm flow) the hydraulic pump efficiency** is lower at **600 psi versus 800 psi** which **could** indicate some leakage **flow** for the hydraulic cylinders at the higher pressures.

Additional measurements were made on **8/8/97** to determine the idle power in the **HPS** system, This power is due **to** the charge pumps and the servo pump. Assuming an **80% motor efficiency** at **15% of full load** the parasitic losses are approximately **2.52 kW**. At normal operating pressure of **800 psi and 12 cpm** this parasitic loss is approximately **17%** of the power. This **loss** measurement has also been incorporated into the **spreadsheet**.

Overall Summary of Test Results:

Then overall results of the testing have shown a specific power consumption of **11.7 kWhr/kgal** at **800 psi operating pressure**. This is as low as any commercially **available** system. With projected improvements in the **ER** volumetric efficiency, there is no reason that the specific power consumption **should** not **fall** into the **8 to 10 kWhr/kgal**.

VARI-RO Pump Recommendations:

It would be better if all the hydraulic pumps were identical since **one** of the pumps is not operating at maximum displacement and is probably causing some efficiency losses

Eliminate automatic **air bleeds** wherever **possible**.

Power Measurement Recommendations:

Power measurements are critical to evaluating the performance and concern me **because there** is significant variability between the three meters. I have had some discussions with **electrical** engineers at NFESC who **are** experts in power measurement. They see no reason why a \$500 to \$1000 meter should not give an accuracy of 0.5%. This cost **range** is typical of power meters installed by utilities. Utility power meters must meet a minimum of **1%** accuracy with **OS%** the typical **accuracy** of meters installed. The critical factor in power measurement is calibration **of the** power meter with the CT's that **are** used with the meter. The CT's are **the** main source of error in power measurement. **Examining** the numbers you took for the latest meter where you averaged them, the standard deviations are too high to be able to say that meter is more accurate than the Load Controls meter. At this **point** I tend to **believe** the Load Controls meter since I know **it** was calibrated with the **CTs** and that the averaging technique of the computer is **probably** better than **manually** recording numbers and averaging them. One other suggestion our **experts** had was **to install** a **kWhr** meter like is used for residential use and then monitor **kWhr** over a reasonable time period and then back out the power.

Test Setup Recommendations:

It seemed obvious that **no money** was invested **into** the test setup. This was one of the reasons the pump was going to **be** tested at **NFESC** to assure that the test setup was adequate. Before any future testing, **I would** recommend that the test setup be completely redone.

The overall test set-up should conform to standard guidelines for the installation of positive **displacement** plunger pumps. The **Hydraulic** Institute Standards or the **Wheatley** Green Book (**3rd** edition) provide some excellent guidelines. **I** think we need a test setup that represents a standard installation. The benefits of a **proper installation cannot be** quantified at this **time** other than **that** when equipment is tested and performance data is being relied upon for *evaluation the test* setup should **conform** to some standard. In addition if pulsation levels are reduced the equipment **will** be more reliable.

Some suggestions in order of importance:

- Install a correct sized dampener in the feed header since current pulsation levels are greater than recommended- This should increase system **reliability** and may allow operation **at** higher **cycle** speeds and pressures.
- Increase suction line size from tank to boost pump to **2-1/2"**. **Currently 1-1/2"** is installed.
- Increase boost pump discharge hose size to **2-1/2"** diameter, one size larger than suction header piping. **Currently 1-1/2"** is installed.
- Install a correct sized suction stabilizer in the suction header. If the larger hose diameter, reduces suction pulsation levels it may **not** be necessary to install the suction stabilizer.
- **Use** a larger feed tank (**>1000** gallons) or two tanks connected in series and configure inlet and outlet flaws to reduce the **possibility** of recirculating air in the system.

In terms of new instrumentation:

- **The** bucket and stopwatch method is fine, and since its accuracy is unquestionable **I believe** in sticking with the method.
- The differential pressure transducer should be permanently installed across the membrane valve.
- A vacuum gauge should be put on the hydraulic pump suction to monitor filter differential.
- A **residential/industrial** type power meter should be installed for monitoring **kWhr**.

Appendix B

Performance Projections of FILMTEC Membranes
at Various Recovery Ratios

DOW Chemical Company



Dow U.S.A.

The Dow Chemical Company
10919 Technology Place
San Diego, CA 92127
619 . 485-7840

April 10, 1992

Willard Childs
SAIC
14161 **Campus** Point Court
San Diego, CA 92121

Performance Projections
of **FILMTEC** Membranes
at Various Recovery Ratios

Dear Will,

Attached are **computer performance** projections for various reverse osmosis configurations operating on normal seawater (36143 mg/l TDS) at 17°C. I arbitrarily chose to size a **1.0 MGD** system operating over a recovery range of 50 to 20% recovery.

To determine the amount of membrane required, using a fouling factor = 0.80, I varied the amount of membrane until the **projected** operating pressure was as near to 1,000 psi as possible. With this membrane/pressure vessel configuration thus defined, I then ran the system with a fouling factor = 0.90 and calculated the projected operating pressures. All of these calculations are based on using, **FilmTec** model **SW30HR-8040** membrane elements.

Computer print-out pages 1-28 show these calculations. The following lists the various parameters as a function of **recovery**:

REDUCED MEMBRANE QUANTITY OPTION

Recovery %	No. of Elements	Type of P.V.	No. of P.V.	Permeate TDS	Permeate Flux-GFD
50	476	7 Elem.	68	425	7.1
45	420	7 Elem.	60	347	8.1
40	378	7 Elem.	54	298	9.0
35	350	7 Elem.	50	261	9.7
30	324	6 Elem.	54	230	10.5
25	304	4 Elem.	76	210	11.1
20	288	4 Elem.	72	190	11.7

For the **second** group of calculations I selected the amount of membrane used in the 45% recovery case above, i.e., 420 **FilmTec** model **SW30HR-8040** membrane elements. With this kept constant, I varied the projected **operating** pressure to produce 1.0 **MGD** of permeate at the various recoveries. The projected performance print-outs are shown on attached pages 29-42 and summarized below.

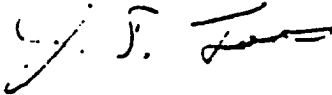
REDUCED PRESSURE OPTION

Recovery %	No. of Elements	Type of P.V.	No. of P.V.	Permeate TDS	Projected Press. PSI
50	420	7M	60	372	1,010
45	420	7M	60	347	960
40	420	6M	70	327	914
35	420	7M	60	314	866
30	420	7M	60	298	836
25	420	6M	70	286	808
20	420	4M	105	275	786

For all of the above configurations and operating conditions with fouling factor = 0.90, I have calculated energy consumption in kw-hrs/k gal. These values are shown in the attached table.

I hope this information is useful for you to complete your studies. Call if you have any questions.

Regards,



John F. Loos

2/2

Appendix C

Economic Comparison of **VARI-RO** vs.
Conventional Technology
for
High Pressure Pumping and Energy Recovery
Laughlin Associates

ECONOMIC COMPARISON OF VARI-RO vs. CONVENTIONAL HIGH PRESSURE PUMPING AND ENERGY RECOVERY TECHNOLOGY

1.0 INTRODUCTION

This report summarizes an economic comparison of VARI-RO versus conventional high pressure pumping and energy recovery technology in a full-scale seawater reverse osmosis desalting plant. The comparison is based on capital cost and performance data **from** the 7.2 MGD Santa Barbara Desalting Plant which is located in Santa Barbara, California. The financing assumptions for the original Santa Barbara plant were modified to reflect 1997 dollars and a 30 year plant financial life.

Performance assumptions for the VARI-RO system were developed through a pilot plant testing program conducted at the City of San Diego's San Pasqual Water Reclamation Plant. These assumptions were confirmed by U.S. Navy participants in the project. Capital cost data for **VARI-RO** equipment were provided by VARI-RO, based on estimates by participating suppliers. The analysis of VARI-RO performance and cost factors was conducted over a two year period involving several stages of component and pilot plant testing and economic modeling.

2.0 REFERENCE DESALTING PLANT DESCRIPTION

The 7.2 MGD Santa Barbara Desalting Plant was chosen as a reference for this study because it represents the largest operational seawater RO desalting plant on the West Coast of the United States. The plant was designed and installed by **Ionics** Incorporated for the City of Santa Barbara. The plant was operated for a brief period of time, then shutdown because the drought in California diminished and lower cost water supplies became available. The plant has been incorporated as a permanent part of Santa Barbara's water supply and will be operated if future water supply shortages are encountered.

The reference desalting plant includes the following major components

- Seawater supply system
- Pretreatment system
- High pressure pumping and energy recovery system
- Seawater RO plant
- Product water treatment and storage system
- Concentrate disposal system

The plant was designed for a total product water capacity of 9.6 MGD at a recovery ratio of 45%. The initial phase of construction provided full capacity systems for the seawater supply system, the product treatment and storage system and the concentrate disposal system. The other systems were designed for the initial capacity of 7.2 MGD.

The seawater supply system includes an offshore intake with submersible pumps which pump water to the pretreatment system. The pretreatment system includes chemical addition and horizontal pressure filters. Filter backwash is treated in a clarifier, then routed to the

concentrate discharge system for ocean disposal. From the pressure filters, feedwater at approximately 30 psi is routed to twelve RO trains each with a product water capacity of 600,000 gallons per day (**gpd**).

Each seawater RO train is supplied by a high pressure feed pump with a **Pelton** wheel for energy recovery. The RO plant includes banks of thin film composite spiral membrane elements operating at a design feedwater pressure of 955 psi.

Product water is transferred to a holding tank where chemicals are added prior to transfer to a nearby water main. Concentrate **from** the energy recovery units is routed to a local sewage treatment plant where it is combined with sewage effluent and discharged through an ocean outfall.

3.0 ECONOMIC ANALYSIS

The process and economic comparisons of VARI-RO versus conventional pumping and energy recovery technology are shown on Tables 3-1 and 3.2 and summarized on Table 3.3. The comparisons include two cases for VARI-RO performance: (1) "Pilot Plant" and (2) "Commercial", The Pilot Plant case is based directly on pilot plant performance data, with capital cost for VARI-RO estimated in manufacturing lots of ten. The Commercial case assumes design and production improvements in full-scale units which result in higher energy efficiencies and lower capital costs. Reference desalting plant costs are based on 1992 project data, escalated to 1997 dollars.

3.1 Process Design Assumptions and Data Sources

The process assumptions for the reference desalting plant were provided by the turnkey equipment supplier, **Ionics** Incorporated of Watertown, Massachusetts. The process design reflects equipment and RO membrane element technology which was state-of-the-art when the plant was commissioned in 1992.

The process design assumptions for VARI-RO equipment were provided by Vari-Power Company and confirmed by Navy participants in the pilot plant test program.

3.1.1 Conventional Pumping and Energy Recovery System Assumptions

The high pressure pumping and energy recovery system for each train includes an electric motor sized for the net energy of the high pressure pump and **Pelton** wheel, a variable frequency drive (VFD), a high pressure pump and a **Pelton** wheel. The high pressure pumps are horizontal multistage centrifugal units provided by Dresser Industries. The motor, VFD, pump and **Pelton** wheel are mounted as an integral assembly. The pumps have a design pressure of 955 psi and an initial operating pressure of approximately 865 psi. The pump efficiency at rated design conditions is 76%. The **Pelton** wheel efficiency is rated at 83%. The combined specific energy of the high pressure pumping and energy recovery system is rated at 12.72 kilowatt hours per 1,000 gallons of product (**kwh/kgal**) at a feedwater pressure of 865 psi.

3.1.2 VARI-RO Pumping and Energy Recovery System Assumptions

VARI-RO technology is assumed to operate at the same flow and pressure conditions as the conventional pumping and energy recovery system technology. Efficiencies assumed for VARI-RO equipment for the Pilot Plant and Commercial cases are shown on Table 3.1. The hydraulic drive efficiency is 84% for the Pilot Plant case and 88% for the Commercial case. The improvement in hydraulic unit efficiency for the Commercial case is based on specific improvements in hydraulic system design and scale-up to larger units.

The efficiencies assumed for the water displacement unit are 85% for the Pilot Plant case and 92% for the Commercial case. The Pilot Plant case efficiency was calculated from pilot test results. The efficiencies assumed for the Commercial case were estimated based on improvements in internal leakage rate and other design factors.

The specific energy factor of 9.37 **kwh/kgal** for the Pilot Plant case was calculated by VARI-RO based on pilot plant results, assuming a **feedwater** pressure of 865 psi and an RO system recovery of 45%. The specific energy value of 8.27 **kwh/kgal** for the commercial case was calculated by VARI-RO, based on efficiency improvements in the hydraulic drive system and the water displacement unit.

3.2 Economic Assumptions and Data Sources

Economic assumptions and comparative results are shown on Table 3.2. The installed capital cost of major components for the reference desalting plant was provided by Ionics based on the original 1992 project costs. These costs were escalated at an average CPI rate of 2.7% per year to 1997 dollars for the study. The capital costs of VARI-RO high pressure pumping and energy recovery equipment for the Pilot Plant case were estimated by the equipment suppliers involved in the pilot test program, assuming manufacturing lots of ten. These costs were reduced by 15% for the Commercial case, assuming improved production methods and increased production quantities.

Engineering, environmental and permitting costs were provided by Ionics in 1992 dollars and escalated to 1997 dollars. The cost of electricity was assumed as **\$0.06/kwh**. A sensitivity analysis was conducted to determine the effect of power costs ranging from **\$0.04/kgal** to **\$0.16/kgal**. The cost of chemicals, insurance and miscellaneous, solid waste disposal and operating labor were estimated from typical values for operating seawater desalting plants. The maintenance factor of 2% of the installed capital cost was provided by Ionics, along with the membrane replacement cost. Operating labor and maintenance factors were assumed to be the same for VARI-RO equipment and conventional equipment.

Total water cost in **\$/acre-ft** was calculated on a basis of annualized capital cost plus first year operating and maintenance cost. The annualized capital cost calculation assumed a cost of capital of 6.5% and a 30 year plant life. These economic assumptions differ from the original Santa Barbara project, which started with a five year water purchase contract with Ionics and followed with a purchase of the system by the City of Santa Barbara.

**Table: 3.1
Process Assumption and Energy Calculations**

DESCRIPTION	VARI-RO Pilot Plant	VARI-RO Commercial	Conventional Plant
Basic Process Factors			
Type of Service	Seawater	Seawater	Seawater
Feedwater Salinity, ppm TDS	34,000	34,000	34,000
Feedwater Temperature Range, deg C	11 to 19	11 to 19	11 to 19
Type of RO Element	Spiral TFC	Spiral TFC	Spiral TFC
Recovery Ratio, %	45	45	45
Total Product Water Capacity, mgd	7.2	7.2	7.2
No. of RO Trains	12	12	12
Product Water Capacity Per Train, mgd	0.6	0.6	0.6
Plant Availability Factor, %	92	92	92
Annual Water Production Rate, mgd	6.6	6.6	6.6
Annual Water Production, mgal	2,418	2,418	2,418
HP Pumping and Energy Recovery System Power			
HP Pump Inlet Pressure, psi	30	30	30
HP Pump Design Discharge Pressure, psi	955	955	955
HP Pump Operating Pressure, psi	865	865	865
RO Unit Differential Pressure, psid	64	64	64
HR Unit Inlet Pressure, psi	801	801	801
HR Unit Discharge Pressure, psi	0	0	0
Electric Motor Efficiency,%	95.0	95.0	95.0
SARI-RO HP Pumping and ER System			
VARI-RO Hydraulic Drive Efficiency,%	84.0	88.0	
VARI-RO Water Displacement Unit Efficiency,%	85.0	92.0	
VARI-RO Net Power Per Train, kw	234	207	
Total VARI-RO System Power, kw	2,811	2,481	
VARI-RO Specific Energy, kwh/kgal	9.37	8.27	
Conventional HP Pumping and ER System			
Variable Frequency Drive Efficiency,%			97.5
Centrifugal Pump Efficiency,%			76.0
Energy Recovery Unit Efficiency,%			83.5
Centrifugal Pump Net Power Per Train, kw			318
Centrifugal Pump Total Power, kw			3,816
Centrifugal Pump Specific Energy, kwh/kgal			12.72
Ancillary Power			
Seawater Supply Pumps Total Power, kw	705	705	705
Product Water and Concentrate Transfer Pumps Total Power, kw	987	987	987
Total Ancillary Power, kw	1,692	1,692	1,692
Ancillary Specific Energy, kwh/1000 gal	5.64	5.64	5.64
Total Power			
Total Power, kw	4,503	4,173	5,508
Total Specific Energy, kwh/1000 gal	15.01	13.91	18.36

**Table 3.2
Economic Comparison**

COST CALCULATION	VARI-RO Pilot Plant	VARI-RO Commercial	Conventional Plant
Installed Capital Cost			
Seawater Supply System (9.6 mgd product capacity)	\$ 3,857,981	\$ 3,857,981	\$ 3,857,981
Retreatment Equipment (7.2 mgd product capacity)	\$ 8,396,791	\$ 8,396,791	\$ 8,396,791
Desalination Equipment (exclusive of HP pumping and ER)	\$ 12,931,061	\$ 12,931,061	\$ 12,931,061
Product Delivery System (9.6 mgd product capacity)	\$ 1,361,641	\$ 1,361,641	\$ 1,361,641
Concentrate Disposal System (9.6 mgd product capacity)	\$ 2,950,221	\$ 2,950,221	\$ 2,950,221
VARI-RO High Pressure Pumping and Energy Recovery System			
Electric Power Supply Components for HP Pumps			
Electronic Control Units	\$ 240,000	\$ 204,000	
Hydraulic Drive Unit Electric Motors		inc	
Hydraulic Drive Unit Motor Starters		inc	
Hydraulic Drive Units	\$ 1,020,000	\$ 867,000	
Water Displacement Unit Cylinders	\$ 1,500,000	\$ 1,275,000	
Water Piping Headers and Couplings	\$ 240,000	\$ 204,000	
Hydraulic Piping	\$ 24,000	\$ 20,400	
Miscellaneous	\$ 60,000	\$ 51,000	
VARI-RO HP Pumping and ER System Cost Per Train	\$ 3,084,000	\$ 2,621,400	
Engineering and Assembly	\$ 577,600	\$ 490,960	
Total VARI-RO HP Pumping and ER System Cost	\$ 3,661,600	\$ 3,112,360	
Conventional High Pressure Pumping and Energy Recovery System			
Electric Power Supply Components for HP Pumps			inc
High Pressure Pump Motors			inc
High Pressure Pump Variable Frequency Drives			inc
Energy Recovery Units			inc
Skids, Interconnections and Shop Checkout			inc
Total Conventional HP Pumping and ER System Cost			\$ 2,954,761
Total Equipment Cost	\$ 33,159,321	\$ 32,610,081	\$ 32,452,481
Engineering	\$ 4,765,751	\$ 4,765,751	\$ 4,765,751
Environmental and Permitting	\$ 907,761	\$ 907,761	\$ 907,761
Total Installed Capital Cost	\$ 38,832,831	\$ 38,283,591	\$ 38,125,991

Table 3.2
Economic Comparison
(Continued)

COST CALCULATION	VARI-RO Pilot Plant	VARI-RO Commercial	Conventional Plant
Operating and Maintenance Cost			
Cost of electricity, \$/kwh	0.060	0.060	0.060
Annual Cost of Power for HP Pumping and ER Systems	\$ 1,359,265	\$ 1,199,693	\$ 1,845,234
Annual Cost of Power for Balance of Plant	\$ 818,170	\$ 818,170	\$ 818,170
Total Annual Power Cost	\$ 2,177,435	\$ 2,017,862	\$ 2,663,404
Annual Cost of Chemicals	\$ 687,827	\$	\$
Annual Cost of Membrane Replacement	\$ 168,144 65,000	\$ 687,827 65,000	\$ 687,827 65,000
Annual Cost of Solid Waste Disposal	\$	\$	\$
Annual Cost of Insurance and Miscellaneous	\$ 183,229	\$ 168,144 183,229	\$ 168,144 183,229
Annual Cost of Operating Labor	\$	\$	\$
Annual Cost of Maintenance for HP Pump and ER Systems @ 2.0%	\$ 259,444 73,232	\$ 259,444 62,247	\$ 259,444 59,095
Annual Cost of Maintenance for Balance of Plant @ 2.0%	\$ 589,954	\$ 589,954	\$ 589,954
Total Annual O&M Cost	\$ 4,204,265	\$ 4,033,708	\$ 4,676,098
Cost of Water			
Annualized Cost of Capital at 6.5% and 30 Year Plant Life	\$ 2,973,719	\$ 2,931,660	\$ 2,919,591
Total Annual O&M Cost	\$ 4,204,265	\$ 4,033,708	\$ 4,676,098
Total First Year Cost	\$ 7,177,984	\$ 6,965,368	\$ 7,595,690
Cost of Water, \$/Acre-Ft	\$	\$	\$
Cost of Water, \$/kgal	\$ 2.97 967	\$ 2.88 939	\$ 3.14 314

3.3 Economic Analysis Results

The results of the economic comparisons are summarized on Table 3.3.

**Table 3.3
Summary of Economic Analysis Results**

Description	VARI-RO Pilot Plant	VARI-RO Commercial	Conventio nal Plant
Capital Cost			
Capital Cost of HP Pump/ER Systems(\$)	3,661,600	3,112,360	2,954,765
Capital Cost of Other Equipment (\$)	35,171,233	35,171,233	35,171,233
Capital Cost of Total Desalting Plant (\$)	38,832,833	38,283,593	38,125,998
O&M cost			
Specific Energy of HP Pump/ER Syst (kwh/kgal)	9.37	8.27	12.72
Annual Power Cost of HP Pump/ER Syst (\$)	1,359,265	1,199,693	1,845,234
Annual Cost of Other O&M (\$)	2,845,000	2,834,015	2,830,864
Annual O&M Cost of Total Desalting Plant (\$)	4,204,265	4,033,708	4,676,098
Water Cost			
Annualized Capital Cost (\$)	2,973,719	2,931,660	2,919,591
First Year O&M Cost (\$)	4,204,265	4,033,708	4,676,098
First Year Cost of Water (\$/Acre-Foot)	967	939	1,024
First Year Cost of Water (\$/kgal)	2.97	2.88	3.14

33.1 Capital Cost

The estimated installed capital cost of the Pilot Plant case for the VARI-RO high pressure pumping and energy recovery system is **\$3,661,600** as compared with a cost of **\$2,954,765** for the conventional system -- a difference of about 24%. For the Commercial VARI-RO case the difference is lowered to about 5%. The total **VARI-RO** desalting plant cost for the Pilot Plant VARI-RO case is 1.8% higher than the reference plant. For the Commercial VARI-RO case, the difference is less than 0.5%.

3.3.2 Operation and Maintenance Cost

The cost of electric power for the VARI-RO high pressure pumping and energy recovery systems for the Pilot Plant case is about 26% less than the conventional system. For the Commercial case, **VARI-RO's** power cost advantage increases to about 35%.

The total O&M cost advantage with VARI-RO equipment is about 10% for the Pilot Plant case and about 14% for the Commercial case. The **O&M** cost comparisons assume that VARI-RO has the same labor and maintenance factors as the conventional plant.

3.3.3 Total Water Cost

The calculated total water cost for the conventional plant is **\$1,024/Acre-Foot**, or **\$3.14/ kgal**. These water costs are lower than past reported figures for the Santa Barbara Desalting Plant because of the differences in financial assumptions.

Calculated total water costs using VARI-RO equipment ranged from **\$967/Acre-Foot** for the Pilot Plant case to **\$939/Acre-Foot** for the Commercial scenario. These values would result in an advantage of 6 to 8% over the conventional system for the total cost of water.

3.4 Sensitivity to Price of Electricity

The impact of varying electric power price on total water cost is shown on Table 3.4.

Table 3.4
Sensitivity of Water Cost to Variations in Power Price

Electricity Price (Dollars per kwh)	VARI-RO Pilot Plant (\$/Acre-Ft)	VARI-RO Commercial (\$/Acre-Ft)	Conventional Plant (\$/Acre-Ft)
0.04	870	848	904
0.06	967	939	1,024
0.08	1,065	1,029	1,143
0.12	1,261	1,211	1,383
0.16	1,457	1,392	1,622

The potential water cost advantage of VARI-RO through this range of power costs varies from a minimum of 4% to a maximum of about 14%.

4.0 CONCLUSIONS

Based on the performance and cost information provided by VARI-RO and the results of the economic analysis, the following conclusions are made:

1. The capital cost of VARI-RO equipment is 24% higher than the cost of the conventional high pressure pumping and energy recovery system equipment, but may be reduced to 5% higher through commercial development.
2. The energy requirements for VARI-RO, based on direct pilot plant test results for 865 psi feedwater pressure and 45% recovery (Pilot Plant case), are approximately 26% less than the conventional high pressure pumping and energy recovery system. For improved VARI-RO efficiencies, as shown for the Commercial case, the advantage increases to a maximum of 35%.
3. The first year water cost advantage of VARI-RO, assuming a 30 year plant life, a cost of capital of 6.5% and a price of electricity of **\$0.06/kwh**, is about 6% for initial development, increasing to about 8% through commercial development.
4. The water cost advantage of VARI-RO technology is sensitive to the price of electricity. Lowering the price of electricity from **\$0.06/kwh** to **\$0.04/kwh** reduces the VARI-RO water cost advantage from 6% to 4% for the Pilot Plant case. Increasing the price of electricity from \$0.06 to **\$0.16/kwh** increases the VARI-RO water cost advantage to 14% for the best case.

The reference desalination plant assumed 1992 technology and did not account for improvements which have occurred in commercially available high pressure pumping and energy recovery equipment and in seawater RO membrane element performance. Improvements in commercial pumping and energy recovery systems would reduce the advantage shown for VARI-RO technology. Improvements in seawater RO membrane element performance, along with improvements in overall desalting plant design, would reduce the total cost of water.

The cost of water, as calculated in the economic analysis, is site specific and highly dependent on the cost of peripheral systems such as seawater supply, product delivery and concentrate disposal. It is also highly dependent on the financing assumptions and the cost of electricity. The water costs shown in the study, while lower than some previously reported costs for the Santa Barbara plant, are consistent with current large RO projects under evaluation in the United States.

The results of the pilot test program, especially the final phase, basically confirmed the performance predictions made by SAIC and Vari-Power Company and validated the calculation methodology used to predict the performance of larger-scale units. The VARI-RO equipment costs were developed by qualified suppliers with long-term experience in their respective areas of expertise. The combination of these factors provides confidence that the economic comparisons are reasonable for the current level of technology development.

Full validation of VARI-RO technology will require the development of larger-scale VARI-RO systems, improvements in design details and long-term demonstration plant operation to **confirm** operating labor and maintenance requirements.