VARI-RO^{TM} "Low Energy" DESALTING FOR THE SAN DIEGO REGION

Preliminary Research Study
FINAL TECHNICAL REPORT

SAIC Report No. 01-0868-03-7340

Science Applications International Corporation
4161 Campus Point Court
San Diego, CA 92121

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Contract No. 1425-3-SP-81-19510

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13. ABSTRACT *(Maximum 200 words)*
This Water Treatment Technology Program research study shows the feasibility to reduce the cost of desalting seawater by using the VARI-RO™ system, which is more efficient and environmentally attractive than "Existing Methods".

The VARI-RO™ system is an integrated pumping and energy recovery method for seawater and brackish water reverse osmosis (SWRO) & (BWRO) desalting projects. The study validated that significant electric power reduction is achievable as compared to conventional centrifugal/turbine methods. As compared to these methods, a power reduction of 5.2 MW (a 30% savings) was projected; and as compared to the California State Water Project (SWP) a reduction of 4.2 MW (22% savings) was projected. These savings projections were based on a 30 MGD (113,550 m^3/d) capacity SWRO facility. This means that desalting seawater can be less energy intensive than importing water from Northern California to the San Diego region via the SWP.

The technology is suitable for low, medium, and high capacity facilities, providing the optimal capability to lower energy consumption, reduce membrane related costs, and improve water quality.

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Bureau of Reclamation Mission Statement

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U.S. Department of the Interior Mission Statement

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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	$t_{°C} = (t_{°F} - 32)/1.8$

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GLOSSARY

AF	Acre-Foot = 326,000 U. S. gallons (approximately)
AFY	Acre-Feet per Year
BEP	best-efficiency-point
BWRO	Brackish Water Reverse Osmosis process

GLOSSARY - continued

CENT. EL	same as CT
CPM	Cycles Per Minute
CT	Centrifugal pump, Turbine, and variable speed drive; reverse osmosis pumping and energy recovery system
FTR	Final Technical Report
GPM	U. S. Gallons per minute
l/m	liters per minute
kWh/kGAL	kilowatt hours per 1000 U. S. gallons
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
PD	Positive Displacement
PSI	pounds per square inch
PSID	pounds per square inch differential
RO	Reverse Osmosis desalting process
ROM	Reverse Osmosis with electric Motor drive
ROS	Reverse Osmosis with Steam turbine drive
RPM	Revolutions Per Minute
RR	Recovery Ratio of reverse osmosis process = Product flow rate / Feed flow rate
SDCWA	San Diego County Water Authority
SEC	Specific Energy Consumption = kWh/k GAL = kWh/m^3
SWP	California State Water Project
SWP N > SD	California State Water Project from Northern California to San Diego
SWRO	Seawater Reverse Osmosis process
TDS	Total Dissolved Solids in parts per million
VARI-RO	positive displacement, variable flow pumping and energy recovery technology for the RO desalination using a patented hydraulic drive method
VRO	VARI-RO reverse osmosis pumping and energy recovery system

DEFINITIONS

Existing Methods	=	methods presently being used to desalt seawater, including MSF, MED, and RO. In this report, the existing method used for comparison is a RO desalting system using high pressure feed water pumping consisting of: centrifugal pumps, energy recovery turbines, and variable speed electric motor drives; which has been abbreviated herein as a CT system.
Base Case	=	a CT system at 960 PSI (66.2 BAR) feed water pressure and 45% recovery ratio.

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1. INTRODUCTION

1.1 Study Definition and Team

The Preliminary Research Study team included: SAIC, VARI-POWER Company, Mr. Terry Henshaw, and The Palmyra Group. This Final Technical Report (FTR) resulted from the efforts of this team. The study was sponsored by the U. S. Bureau of Reclamation, Water Treatment Technology Program, under Contract No. 1425-3-SP-81-19510.

One of the contract requirements was to study a specific water problem at a location in the Western United States. A proposed 30 MGD (113,550 m^3/d)[1] seawater desalting facility to be located in the San Diego region was selected as the focus of this study. This desalting facility would be located along the San Diego coastline. The purpose of this study was to determine the feasibility and performance advantages of using the VARI-RO™ reverse osmosis pumping and energy recovery technology for this plant.

The team members for this study were:

Science Applications International Corporation: SAIC, with nearly 16,000 employees, has become one of the largest employee-owned companies in the United States; and one of the foremost R&D centers in the country. SAIC has been able to attract and retain acknowledged experts in all of the nations most significant interest areas: national security, energy, environment, health, and high technology products.

Dr. Ali E. Dabiri, of the Technology Development Group, was the Project Manager for this study.

VARI-POWER Company: VPC has developed and patented a unique power transmission method for efficiently driving energy-efficient positive displacement (PD) pumping and energy recovery systems for a variety of uses. The use of this method for reverse osmosis desalination is known as the VARI-RO system, abbreviated in this report as VRO. This technology provides the capability to make PD pumping feasible for large scale systems and save considerable energy as compared to existing methods using centrifugal pumps, energy recovery turbines, and variable speed drives. The centrifugal/turbine system is identified in this report as the CT system.

Mr. Willard D. Childs was the Principal Investigator for this study, and has built and tested a previous prototype VARI-RO system.

Mr. Terry Henshaw: He has over 30 years experience in the pumping field. He has held responsible positions with major pump manufacturers, and has published a book entitled: *"Reciprocating Pumps,"* copyright 1987; which is an authoritative book on crank type power pumps and direct acting pumps. In addition he has published numerous articles on pumping in major technical magazines. He has advanced the state-of-the-art in pumping with the design of a multistage centrifugal pump for liquid CO_2 and a power pump for 30,000 PSI operation. For many years he was employed by Ingersoll-Rand and Union Pump Company in positions of Sales Engineer, Manager of Reciprocating Pump Division, and Manager of Research and Development.

1. 30 million gallons per day (MGD), or 113,550 cubic meters per day, capacity is equal to water production of about 30,000 acre-feet per year at 90% capacity factor. One acre-foot is sufficient for two average families for one year, according to the Metropolitan Water District of Southern California (MWD).

Mr. Henshaw performed a technical review of the "Direct Acting" pumping method which is used in the VARI-RO system. The report on his findings is included in appendix B (Henshaw, 1993).

The Palmyra Group: Palmyra specializes in water supply consulting engineering, technical review, and project management of large water treatment and energy projects. The group's expertise includes chemical process and mechanical engineering for both the reverse osmosis and the thermal distillation desalination methods. Recent project involvement by the group's principals includes the design, review, and economic analysis of seawater desalination for Pacific Gas & Electric, Metropolitan Water District of Southern California, and San Diego County Water Authority. For the latter project, Jack Laughlin of the Palmyra Group had project management responsibility for the South Bay Desalination Study (Carollo, Laughlin, 1994), including: engineering, economic, and environmental analysis.

Mr. Jack Laughlin and Mr. Tom Wolf performed the economic analysis of the VARI-RO system, and their report is included in appendix C (Palmyra, 1994).

1.2 Study Objectives and Technical Benefits

The overall objective of the study effort was to perform preliminary research studies on how the cost of potable water produced by desalination can be reduced. More specifically, this study 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 methods.

The focus of this study was 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 when compared to existing methods. Energy consumption savings in the range of 25% to 50% have been projected. The range of savings projections depends upon which existing method is being compared to, the system capacity, and the recovery ratio (RR) being considered. In addition, it offers the potential for other operational benefits and cost savings, including the reduction of the number of membrane elements required for a given water production by operating at lower recovery ratios. The primary goal of this study was to determine the feasibility, and the benefits, of using this new approach for the San Diego desalination project; as well as other desalination applications.

This study has answered some of the practical questions relative to the implementation of this new approach for large scale desalination facilities, utilizing commercially available equipment that has been proven in other industries. These practical questions included: mechanical design, performance, maintenance, and economic benefits. This study has satisfactorily answered these practical questions.

1.3 Specific Water Problem and Location

Presently 90% of the water for the San Diego region is imported from Northern California, via the State Water Project (SWP) or from the Colorado River. The remaining 10% comes from runoff stored in local reservoirs. Population increases, the recent six year drought, projected shortages of water to supply the SWP, and contingency plans for emergencies (such as earthquakes) have stimulated a search for alternative water supplies. Seawater desalting is one of the primary alternatives being considered.

Three feasibility studies for seawater desalination sponsored by the San Diego County Water Authority (SDCWA) have been completed in April 1991, March 1992, and the latest in June 1994; (Black & Veatch, 1991), (Black & Veatch, 1992), and (Carollo, Laughlin, 1994) respectively. These studies explored the possibility of using various thermal and membrane desalination technologies, including multi-stage flash (MSF), multi-effect distillation (MED), reverse osmosis powered by electric motors (ROM), reverse osmosis powered by steam turbines (ROS), and hybrid systems using both RO and MED. It was concluded in the March 1992 study that RO would be the most suitable technology for this facility, using either the ROM or the ROS drive method. It was further concluded in the June 1994 study that ROM was the preferred method.

Study results show that the ROM seawater desalting energy consumption can be reduced by 30%, by using the VARI-RO pumping and energy recovery technology instead of conventional centrifugal pumps and energy recovery turbines. These results were based on a recovery ratio of 45%. It also shows possible economic and environmental advantages of operating at recovery ratios lower than 45%, which is feasible because of the flat energy consumption characteristic of the VARI-RO system versus recovery ratio.

1.4 Scope of Work and Methodology

The methodology was to identify the characteristics of a base case system utilizing existing methods for pumping and energy recovery. From these base characteristics a preliminary sizing, and selection of key components, for a VARI-RO system was accomplished. The performance of this system was predicted, and the performance was compared to the base system for energy consumption and environmental emissions. From these performance comparisons, cost savings were projected for a variety of operating scenarios. The results were then summarized on figures and tables, to allow ready interpretation of the conclusions.

In addition to performance comparisons, the study made practical assessments of the technology, including: mechanical design, maintenance, and economic analysis.

The work for this study was divided into key tasks as follows:

TASK 1	Base Case Characteristics Definition
TASK 2	VARI-RO Preliminary System Design
TASK 3	Performance Comparisons
TASK 4	Economic Analysis & Benefits

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

This study has shown that the VARI-RO technology can significantly reduce the cost of desalted water, primarily by reducing the energy requirements. For some sites, other economic benefits can be provided by operating at lower recovery ratios. The lower energy consumption of this technology can *change the perception* that seawater reverse osmosis (SWRO) desalting is energy intensive, as compared to other water supply alternatives. The efficiency improvements over other methods, also indicate that the technology can reduce the energy requirements for brackish water reverse osmosis (BWRO) desalting

From the work performed during this study, including the technical and economic evaluations, the following conclusions and recommendations were reached about the VARI-RO technology:

1. The technology is technically viable and satisfactory service can be obtained for low, medium, or high capacity desalting plants (see SECTION 4.8).

2. Power savings of 5.2 MW (30% system reduction) can be obtained over conventional centrifugal pump and energy recovery turbine methods, for a 30 MGD (113,550 m3/d) SWRO facility designed for the San Diego region (see SECTION 5.3).

3. Energy cost savings of $2.45 million per year were projected for an electric power rate of 6¢/kWh, which would provide a capital cost payback period of about two years (see SECTIONS 7.1.4 and 7.1.6).

   NOTE: It is expected that the cost of the VARI-RO system will be reduced as a result of design improvements and refinement of production techniques. This could significantly reduce the payback period.

4. The cost of water can be reduced from $963 to $897 per acre-foot (AF) [$0.78 to $0.73 per cubic meter ($m^3$)]. This is a substantial $66/AF ($0.054/m^3) or 7% reduction in water cost. The VARI-RO water cost reduction can be increased to $140/AF ($0.114/m^3) or 13%, when compared to systems with lower centrifugal pump efficiency (see SECTION 7.1.3 for the efficiencies used and SECTION 7.1.7 for the cost of water sensitivity).

5. A cost of water reduction of $66/AF ($0.054/m^3) and $140/AF ($10.114/m^3) represents a savings potential of $40 million and $85 million, respectively, over a 20 year operating period.

6. Seawater can be desalted with 4.2 MW (22% total reduction) less power than importing water to the San Diego region from Northern California via the State Water Project (see SECTION 5.3).

7. A membrane related capital cost savings of over $11 million (8.7% reduction from the total capital cost) was estimated for the Reduced Membrane Quantity Option by operating at 25% recovery ratio, instead of 45%. This membrane related cost reduction would further reduce the cost of water to approximately $821/AF, less any additional costs associated with the corresponding higher feed water and concentrate flow (see SECTIONS 5.4 and 7.2.1).

8. The energy cost savings, at 6¢/kWh, can be increased from $2.45 million per year to $3.11 million per year by operating at lower pressures, which can be achieved with the lower recovery ratio option. This option becomes even more attractive for regions with higher electric power rates (see SECTIONS 5.4.2 and 7.2.2).

9. Improved product water quality can be achieved by operating at lower recovery ratios, and still achieve low energy operation (see SECTION 5.4.3).

10. Environmental benefits can be realized through lower air emissions, resulting from higher efficiency operation; and from operating at lower reject brine discharge concentrations (see SECTIONS 5.1.1 and 5.5.2).

11. Future direct drive engine options offer the potential to further reduce energy consumption and the capability to use lower cost energy sources (see SECTION 6.)

12. The assumed capital costs for the VARI-RO system used in this study are expected to decrease as a result of design improvements and improved manufacturing techniques, so the cost of water savings could be even greater than those shown herein (see SECTION 7.1.6).

13. In summary, there is a definite incentive for the commercial development and application of the VARI-RO technology for SWRO desalination plants. Because of the higher efficiency operation shown by this technology; significant benefits can also be realized for BWRO and recycled water facilities. These savings can make desalting a cost effective water supply solution in locations where it is now excluded because of high energy costs.

14. It is recommended by the Palmyra study herein that a program of design refinement, upgraded equipment cost estimating, applications analysis, and pilot testing be initiated. This program would demonstrate the performance, operational features, and reliability of the technology; plus provide familiarization and confidence to water supply professionals that the economic benefits of the VARI-RO technology can be realized.

15. It is further recommended that water supply professionals evaluate the economic benefits of the VARI-RO system for existing, and also for new projects presently under consideration or being designed. In many cases it will be able to reduce costs, and also to improve the cost effectiveness of desalting versus other water supply improvement methods. For new projects, by providing a physical plant layout, that can accommodate this cost saving system, it will be possible to assure that it can be incorporated during initial construction, or retrofitted at a later date.

3. TASK 1 – BASE CASE CHARACTERISTICS DEFINITION

3.1 Cases Selected for Review

TASK 1 was to establish a base case system. The VARI-RO system would then be compared to this base case. To define the base case, three previous studies of existing methods were reviewed, which used centrifugal pumping for reverse osmosis desalination. In this report, these studies have been designated as CASE 1, CASE 2, and CASE 3. The characteristics for these cases were established by obtaining reports from SDCWA and data from other sources; including bulletins and papers by membrane manufacturers, such as DuPont and DOW Chemical Company. The cases reviewed are as follows:

CASE 1 **From SDCWA report dated April 1991** (Black & Veatch 1991)].
For CASE 1, recovery ratios of 30%, 40%, and 50% were used. The performance analysis was based on the same pressure of 1065 PSI (73.5 BAR) for all recovery ratios. However, at 50% recovery ratio it was stated that 1200 PSI (82.8 BAR) would be necessary for the hollow fine fiber membranes.

CASE 2 **From SDG&E and SDCWA report dated March 1992** (Black & Veatch 1992).
For CASE 2, recovery ratios of 40%, 45%, and 50% were used with pressures of 900 PSI (62.1 BAR), 975 PSI (67.2 BAR), and 1040 PSI (71.7 BAR), respectively. The centrifugal pump efficiencies used in CASE 2 were lower than in CASE 1.

CASE 3 **Compiled from SDCWA report dated June 1994**, (Carollo, Laughlin 1994)
For CASE 3 recovery ratios of 25 %, 35%, and 45% were selected at pressures of 940 PSI (64.8 BAR), 940 PSI (64.8 BAR), and 960 PSI (66.2 BAR), respectively. This was compiled from TABLE 3, ROM, Energy Tabulation of the June 1994 report and the DOW FILMTEC letter report dated April 10, 1992 (DOW, 1992) on membrane performance at various recovery ratios.

The characteristics of the three cases were established in a way that would allow direct comparison to the VARI-RO system characteristics. Herein the centrifugal pump, energy recovery turbine, and variable speed drive systems are referred to as: CT 1, CT 2, and CT 3. The VARI-RO systems for operating at the same parameters are referred to as: VARI-RO 1, VARI-RO 2, and VARI-RO 3. In some of the charts and tables, the latter has been shortened to VRO 1, VRO 2, and VRO 3.

For each of the cases, the performance characteristics of the existing methods were determined from the previous studies and from other available literature. The performance characteristics of the VARI-RO system were determined from manufacturers' literature on key components, and experience with the operation of similar equipment; plus a previous prototype that was tested.

3.2 Base Case Selection

The general characteristics of the three cases were similar. In the interest of brevity, only CASE 3 (CT 3 and VRO 3) will be covered in detail in this report. Tabulations of characteristics for CASE 3 are given in SECTION 5.0, and CASE 1 and CASE 2 characteristics are included in appendix D for reference. The overall energy consumption performance, for all three cases, is covered in SECTION 5.2. In all three cases, a 5 MGD RO train capacity was used; which would require six trains for a 30 MGD (113,550 m3/d) facility capacity.

For CASE 3, the following recovery ratios and membrane feed pressures were selected:

			BASE CASE
Recovery Ratio, RR	25%	35%	45%
Pressure (PSI)	940	940	960

The feed pressures were selected based on those used in the FILMTEC letter report (DOW, 1992). A recovery ratio of 45% was selected for the base case because this was used in the latest SDCWA study (Carollo, Laughlin, 1994), and was also used in the existing 6.9 MGD (26,100 m^3/d) facility installed at Santa Barbara in 1992. The Santa Barbara facility uses FILMTEC membranes.

3.3 Existing Methods Description (CT)

The primary existing method, for large capacity RO pumping and energy recovery, is to use centrifugal pumps with energy recovery turbines; usually with variable speed electric motor drives. This method is abbreviated in this report as the CT system[2]. The energy recovery turbine could be a reverse flow centrifugal pump or a Pelton Wheel impulse turbine. The turbine could drive electric power generators, or could assist in driving the feed water pumps directly. Reverse running centrifugal pump turbines, direct driving the feed pumps, were assumed for the CT method in this study.

Components for the CT system must be carefully selected to match the centrifugal pump and turbine performance head curves with the expected variations in RO membrane system pressure requirements over the life of the plant. The CT system differential pressure requirements will vary due to various changes during operation, including: membrane fouling, feed water temperature changes, salinity changes, supply pressure changes, and back pressure changes from brine discharge. To accommodate these changes, the CT system head must be adjusted accordingly to maintain the desired flow (flux) through the membranes, at the desired recovery ratio. The techniques to do this include: throttling valves, using separate variable speed drives, or using multiple pumps which can be started and stopped to approximate the desired conditions. Each of the techniques for adjusting to system pressure variations can result in additional energy losses; either due to the losses directly attributed to the method, or due to the difficulty in predicting and matching the CT system at the best-efficiency-point (BEP) of the system components.

3.4 VARI-RO Method Description Overview (VRO)

"The VARI-RO "Low Energy" desalting technology utilizes modern hydraulic power transmission and control to provide a highly efficient, low cycle speed, low pulsation, variable flow, positive displacement pumping and energy recovery system suitable for low, medium, and high capacity desalination plants. The primary applications would be SWRO and relatively high salinity BWRO; however, it can also provide benefits for low salinity BWRO in some instances."

As compared to the above mentioned CT system, the VARI-RO technology controls flow and recovery ratio independently of the membrane system pressure changes, because it is positive displacement. Also, the technology has a higher BEP 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 the optimizing of plant operation. For example, when lower pressure membranes become available it will automatically accommodate these advancements, and the energy requirements will simply be lower. With a centrifugal pump system, it might be necessary to trim impellers or reduce pump stages. Additional features of the VARI-RO system are covered later in SECTION 4.1.

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2. The CT system was identified as the CENT. EL system in a previous paper about the VARI-RO system (Childs, 1992)

4. TASK 2 --VARI-RO PRELIMINARY SYSTEM DESIGN

TASK 2 was to prepare a preliminary system design for a VARI-RO desalination system. This included selection of the most suitable configuration, plus the selection of equipment sizes for the base case (45% RR). It also included the selection of the key system components.

Particular emphasis was given to providing a reliable design, that would allow for suitable maintenance of the wear parts, such as sleeves, rods, packings, and valves. Performance projections were prepared for comparison to the centrifugal pump systems, as shown on TABLE 5-2.

4.1 Key Features of the VARI-RO System

The VARI-RO method is an integrated positive displacement (PD), variable flow pumping and energy recovery system for reverse osmosis desalination. The complementary piston stroking method results in smooth flow output, similar to the centrifugal pumps that are used in higher capacity RO facilities. This unique capability combines the benefits of both positive displacement pumps and centrifugal pumps with variable speed drives. The result is high efficiency, ability to match system back pressure at any flow rate, smooth flow, and variable output flow to optimize overall desalting system performance.

The VARI-RO system is a low speed, direct acting[3], reciprocating pumping method that uses modern hydraulics and controls that have been proven, and used extensively, in other industries. It is not a high speed, crank type power pump, such as conventional triplex and quintuplex plunger pumps commonly used for low and medium capacity RO facilities. With a crank type pump, the sinusoidal plunger motion creates pulsating flow, which must be dampened with pulsation dampeners and suction stabilizers. Because of high cycle speeds, and pulsating pressures, conventional crank type pumps are considered high maintenance items, and are not usually used in high capacity facilities.

The VARI-RO technology, however, minimizes maintenance requirements by operating at low speeds and without pulsating flow. For example, at 15 cycles per minute (CPM) it would take 20 years to equal the cycles of a plunger pump operating at 300 RPM for one year. In addition, the system has been designed for quick and easy replacement of expendable parts, if this becomes necessary to maintain top performance. The cost of expendable parts replacement will be very small in relationship to the energy cost savings, and other cost savings, that the VARI-RO system can provide.

For the VARI-RO method, high performance hydraulic power transmission technology is used as shown in the simplified diagram in FIGURE 4-1. Hydraulic pressure drives three direct acting reciprocating pistons in a patented trapezoidal[4] wave form as shown on FIGURE 4-2. The trapezoidal shape of piston flow rate versus time provides smooth output flow as follows. When the flow from Piston No. 1 has decreased to 1/2 flow, the flow from Piston No. 2 has increased to 1/2 flow. At these half flow positions, the total flow equals the flow of one of the pistons at full flow position. When Piston No. 2 is at full flow, the flow from Piston No. 1 is at zero flow. This flow

3. The book on reciprocating pumps (Henshaw, 1987) and the VARI-RO™ review report (Henshaw, 1993) defines pumping methods as follows: A "direct acting" pump transfers energy from one fluid to another. A "power pump" transfers energy from a rotating driver (such as an electric motor) to a fluid. The power end of a power pump includes a power frame, crank shaft, connecting rods, crossheads, and speed reducers. The direct acting pump has none of these parts.

4 The VARI-RO™ pumping technique allows very low NPSH, because of relatively slow cycle speeds, and also the low piston accelerations that result from the trapezoidal piston velocity wave form. In addition, any brine discharge back pressure is allowable; up to the rated pressure of the discharge piping installed. This means that additional brine discharge pumps are not needed, as are usually required with Pelton wheel energy recovery turbines.

cycle continues for the stroking of Piston No. 3, and then the cycle is repeated. Since the flows from each of the three pistons complement each other in this manner, flow pulsation is minimized. This low pulsation flow capability was proven during the previous prototype testing, which is discussed in SECTION 4.7.

The modern hydraulic components used in the VARI-RO system are commercially available from 5 to 3,000 horsepower (3.7 to 2,238 KW) and have gained wide use in other industries for heavy duty variable speed transmissions, replacing conventional gear shift transmissions in many applications. Key reasons for the use of hydrostatic transmissions include: high power density and the ability to control machine speed precisely, while maintaining efficient operating speeds of the prime movers. Applications that extensively use these hydraulic drives include equipment for: ship steering, large rotary kilns, tunnel boring machines, mining, oil well drilling, construction, agriculture, and general manufacturing industries.

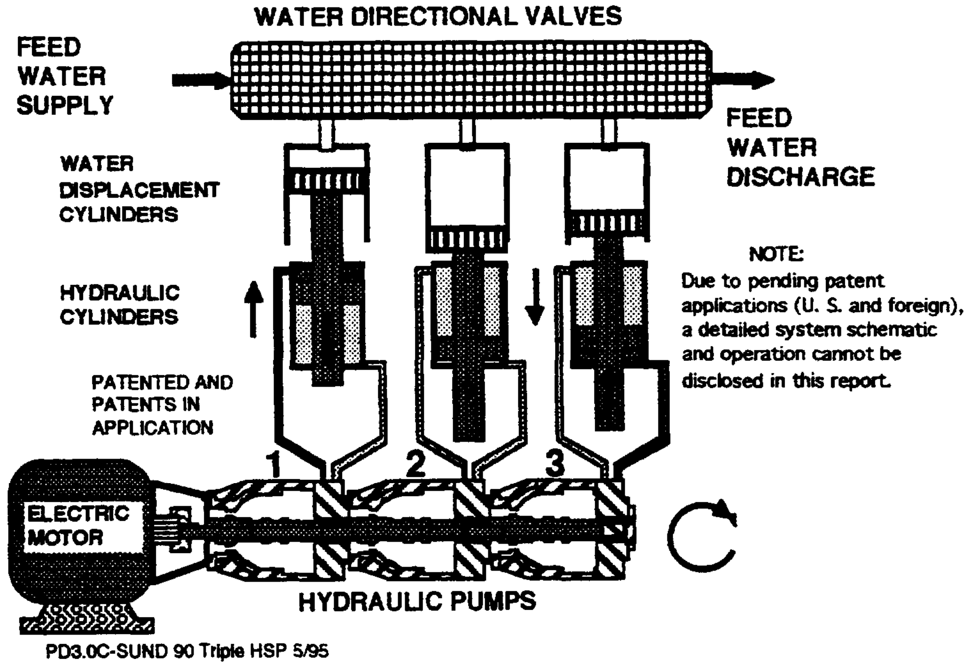


FIGURE 4-1 -- Simplified Schematic of the VARI-RO System

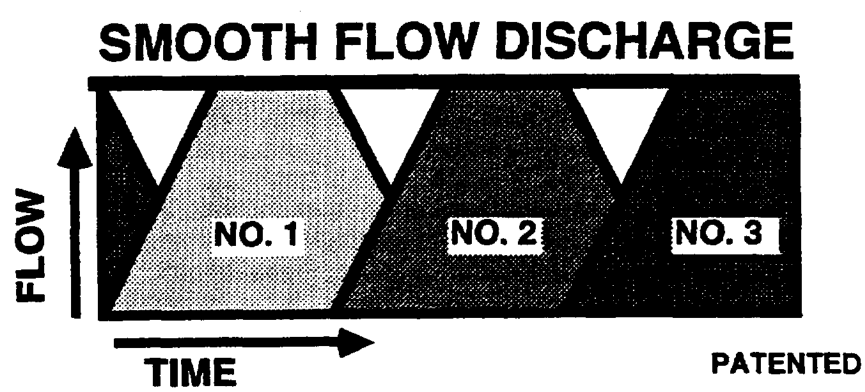


FIGURE 4-2 -- Trapezoidal Piston Flow Profile

4.2 Advantages of the VARI-RO System

There are several significant advantages of the VARI-RO technology over other pumping methods, including crank type plunger pumps and centrifugal pumps. The inherent advantages are summarized as follows.

A. **Variable Flow, Positive Displacement Pumping Method:**

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, at zero flow rate.
6. Flow can be increased gradually from zero to maximum setting during startup.

B. **Smooth Flow Pumping Method:**

1. Non-pulsating 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 Pumping Method:**

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 pump operating at 300 RPM for one year.
3. Results in low operating and maintenance cost, as compared to conventional crank type pumps.

D. **Highly Efficient Energy Recovery Is Integrated:**

1. Provides the lowest specific energy consumption as compared to "Existing Methods".
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 Very Low, 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.

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 membrane fouling, the pressure will simply increase while maintaining a constant flow rate through the membranes. The pressure will automatically drop back to the initial pressure after the membranes are cleaned, replaced, or new membranes added.

Conversely, during initial design selection, careful matching of the head/flow characteristics of the centrifugal pump with the system head is needed with the CT system. In addition, with a centrifugal pump, a separate variable speed drive is needed to adjust the flow and pressure output as the system conditions change. (see SECTION 3.3 for more discussion about the centrifugal pump method).

The variable flow feature of the VARI-RO technology allows for unloaded across-the-line[5] starting, and gradually accelerating flow to design conditions. Also, the flow and pressure can be adjusted during operation to optimize system performance; to compensate for variations of temperature, salinity, or fouling; and/or to compensate for membrane performance advancements in the future. Future membrane advancements could include lower operating pressures.

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). Also, the RO plant owner can take advantage of the lower "interruptible load" rate schedule.

The lower power requirement, and the variable flow capability, of the VARI-RO technology provides the following benefits:

1) lower installed electric motor capacity,
2) less electrical switch gear capacity,
3) lower capacity sub-station transformers,
4) lower capacity electric power transmission lines, and
5) no separate variable speed drives.

4.3 Examples of Variable Speed Drives versus the VARI-RO System

With centrifugal pumps, it is now generally accepted that variable speed drives are preferable to throttling for the pressure and flow adjustments needed to compensate for membrane pressure changes due to fouling and feed temperature changes. For example, variable speed drives were designed into the Santa Barbara seawater facility (SWRO), and were retrofitted into the brackish water facility (BWRO) at Water Factory 21 (Orange County Water District); because the variable flow capability would save energy. In both cases, energy savings resulted from providing a better match of centrifugal pump head to variations in membrane system head.

For either of these examples, the VARI-RO technology would provide additional energy savings without the addition of a separate variable speed drive, because: 1) of higher pumping and energy recovery efficiency; 2) the positive displacement characteristic always matches system head at the set flow rate; and 3) the technology includes variable flow capability, which allows setting the optimum flow conditions.

5. Due to the relatively low inertia of the hydraulic pumps, the starting current of six times rated for the electric motors will be very short. With centrifugal pumps, variable speed drives are necessary to prevent the long duration power and flow surges that would result during across-the-line starting.

4.4 Key Subassemblies of a VARI-RO System

The key subassemblies of a VARI-RO module include:

SUB-ASSEMBLY	CONSISTING OF:
HYDRAULIC POWER SUPPLY (HPS)	Electric Motor (M) Hydraulic Pumps (HP) Electronic Control Unit (ECU).
WATER DISPLACEMENT UNIT (WDU)	Water Displacement Cylinders (WDC) Water Directional Valves (WDV) Hydraulic Cylinders (HC)

A block diagram of the VARI-RO system is shown in FIGURE 4.3.

4.5 Sizing Considerations and Results

For this preliminary design, the philosophy was to select a basic configuration and then vary the key parameters to determine the component sizes that are needed for the module capacity. For the base case, a product water capacity of 5 MGD (18,900 m^3/d) at a recovery ratio of 45% was selected.

The cycle speed selected was 15 cycles per minute (CPM), giving a 4 second period for each complete cycle. This is a conservative cycle speed for this module capacity, which will result in very low piston accelerations and low operating cycles on key components. For lower capacity modules a higher cycle speed can be selected, which would reduce the relative size requirement of the Water Displacement Cylinders.

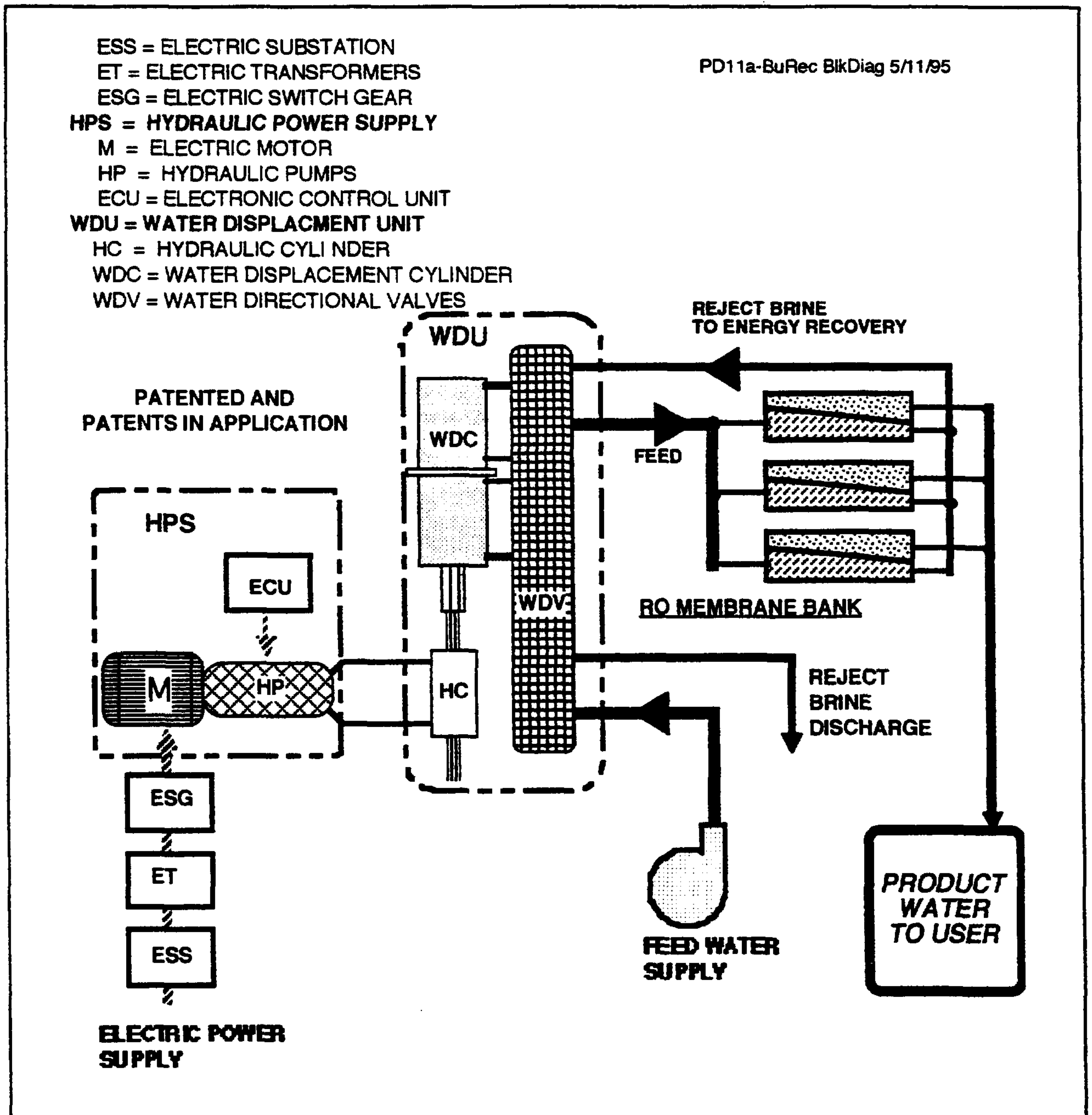
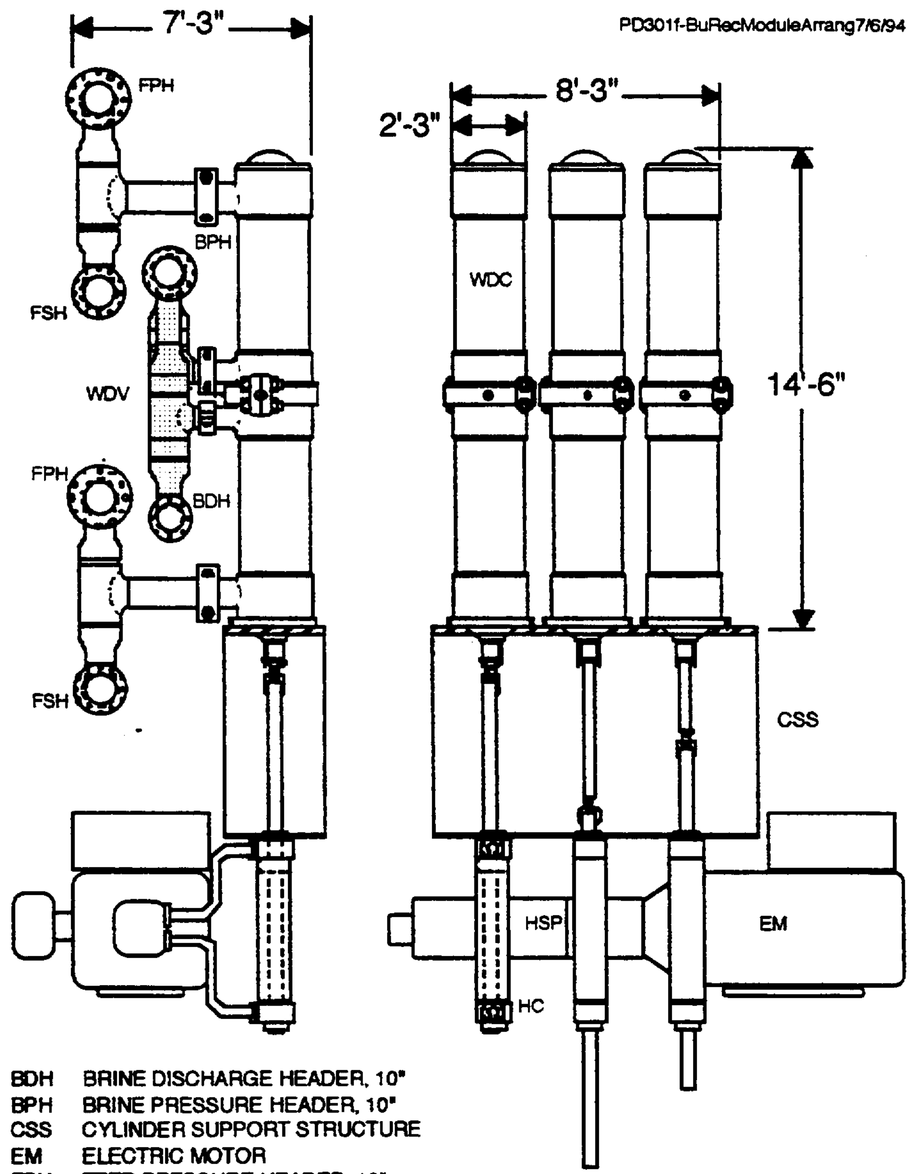


FIGURE 4-3 – VARI-RO Module Block Diagram

4.6 Overall VARI-RO System Configuration

A general arrangement of a VARI-RO module is shown on FIGURE 4-4. The configuration shown is a high capacity unit, in a vertical orientation. However, the cylinders could also operate in a horizontal orientation, if this provides a better utilization of the available space. Also, the physical arrangement and size can be readily revised to suit a particular application, by changing cycle speeds, bore sizes, and strokes.



BDH BRINE DISCHARGE HEADER, 10"
BPH BRINE PRESSURE HEADER, 10"
CSS CYLINDER SUPPORT STRUCTURE
EM ELECTRIC MOTOR
FPH FEED PRESSURE HEADER, 12"
FSH FEED SUPPLY HEADER, 12"
HC HYDRAULIC CYLINDERS
HSP HYDROSTATIC PUMPS
WDC WATER DISPLACEMENT CYLINDERS
WDV WATER DIRECTIONAL VALVES

SEAWATER RO:
5 MGD PRODUCT @ 45 % RR;
2500 HP, 1800 RPM, EM

FIGURE 4-4 – VARI-RO Module General Arrangement

4.7 Previous Prototype Testing

The basic principles and operation of the VARI-RO pumping system were proven with a prototype that was built, tested, and operated in a brackish water application. This pump operated in parallel to an existing centrifugal pump, with only one of the pumps supplying flow at any given time. During the period of operation, the energy consumption was about 60% of the centrifugal pump.

A photograph of the prototype unit is shown in FIGURE 4-5. The rated capacity was 40 GPM (151 l/m) at 470 PSI (32 BAR) with a 15 horsepower (11 kW) electric motor.

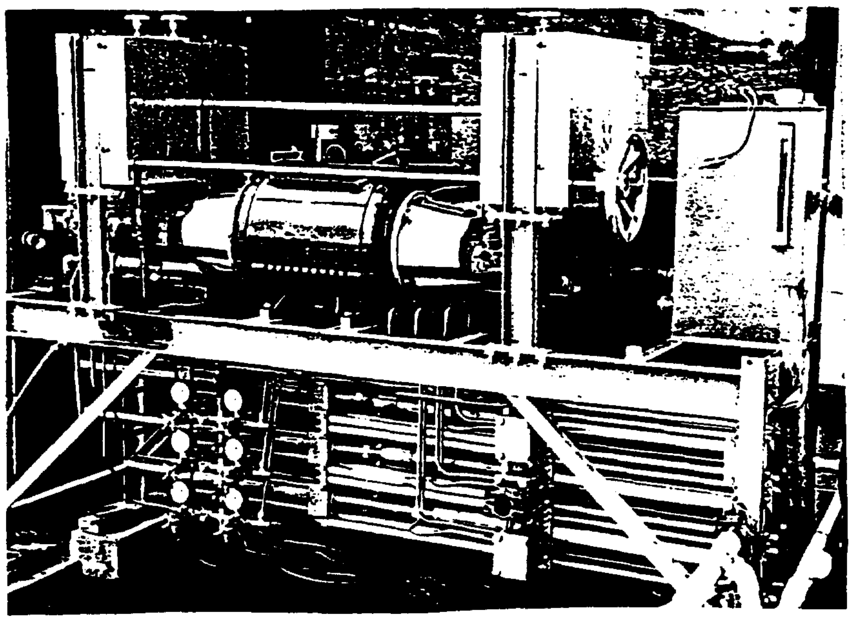


FIGURE 4-5 – Prototype VARI-RO Pumping Unit

The prototype unit was a low budget, proof of concept unit, to prove the basic operating method. The unit was operated over a period of about two years, and proved the following:

1. The basic concept works.
2. Significant energy can be saved.
3. Pressure pulsations are low for a positive displacement pump.
4. Pulsation dampeners and suction stabilizers are not required.
5. Pumping effectiveness is improved over centrifugal pumps and throttle valves.
6. Flow and pressure can be varied to suit optimum membrane conditions.
7. Motors can be started unloaded.
8. System can be brought up to operating conditions smoothly.

During the period of operation, there were a number of problems experienced. These were not basic flaws in the design, but were hardware problems that one encounters in any first of a kind development program. The knowledge gained from this prototype unit has resulted in significant design improvements for the present VARI-RO system configuration.

In summary, the prototype unit verified that the VARI-RO pumping system is based on sound technical principles, and that substantial operating advantages and energy savings can be provided by the implementation of this technology.

4.8 VARI-RO Pumping Technique Viability

Two independent technical reviews of the VARI-RO pumping and energy recovery technique were made. The first (Henshaw, 1993) by Mr. Terry Henshaw, a Consulting Engineer specializing in reciprocating pumps and other forms of pumping. The second (Palmyra, 1994) by the Palmyra Group, Inc., specializing in engineering, consulting, and process design. The following are summaries from their reports, which are enclosed in appendices B and C.

4.8.1 *The Direct Acting Pumping Technique*

In Mr. Henshaw's evaluation report, he classifies the VARI-RO pumping technique as a direct acting pump type, rather than as a power pump type. The key differences between these pump types are discussed in his book (Henshaw, 1987) as noted in SECTION 4.1 (Foot Note No. 3).

In both his book and his report, Mr. Henshaw states that direct acting pumps have much lower maintenance requirements than power pumps. The following statement is an excerpt from Mr. Henshaw's report about the maintenance requirements of the direct acting pump type.

> "Since about 1950 power pumps have become more popular than direct acting pumps; however, direct-acting pumps are still used for certain very demanding applications. An illustration of this is the use of direct-acting pumps for hot oil service (up to 4000 PSI & 700 °F) in petroleum refineries *"The inherent low speed of these units also generally leads to less maintenance than power pumps in similar hot services"*. (Henshaw, 1987, pages 57 & 59). [This is an understatement. A direct acting pump usually requires an order of magnitude less maintenance than a power pump in the same service.]"

The primary reason that direct acting pumps have much lower maintenance requirements than power pumps is that the cycle speeds are much lower. Power pumps, that are commonly used for low and medium capacity RO desalination facilities, are usually of the triplex (3 plunger) and the quintuplex (5 plunger) variety. These crank type pumps are usually driven at relatively high speeds, in the range of 300 revolutions per minute (RPM). For comparison, it is planned that the large capacity VARI-RO system would operate at around 15 CPM. This low cycle speed substantially reduces the number of cycles on packings and valves. In the example illustrated, it would take 20 years of operation for a VARI-RO system to equal the number of cycles a power pump would have in one year.

4.8.2 *Technical Viability of the VARI-RO Method*

The technical viability of the VARI-RO method was evaluated by Henshaw and Palmyra in the reports included in appendices B & C.. The following excerpts summarize Palmyra's conclusions:

> "Based on a limited review of the VARI-RO literature, the report by Mr. Terry Henshaw, and their own experience with positive displacement pumps for RO systems, it was concluded that the method is viable. Also, the technology offers a definite potential for reducing energy usage in RO desalination plants."
>
> "The VARI-RO system may require a higher level of operator skill for optimizing and trouble shooting than a centrifugal system, and would likely be more maintenance intensive. However, these drawbacks can be mitigated to a fair degree by conservative design practices addressing slow cycle speeds, valve design, packing design, materials selection, and careful attention to control systems. With a sound design approach, it is likely that equivalent reliability can be achieved."

From these evaluations it can be surmised that the VARI-RO system is more complex than a centrifugal pump system; however, it should be realized that variable speed drives utilized with centrifugal pumps are also quite complex. The question here is not the complexity of the system, but how well it is designed for the intended service and what benefits are provided by the system. There are countless examples of relatively complex devices that perform superbly for long periods of operation. It should also be realized that the key wear parts, such as packings and valve discs can be replaced quite quickly; and at relatively little expense, as compared to the energy cost savings capability of the system. Further, as pointed out in SECTION 8.1, at the slow cycle speed it would take 20 years to equal the same number of cycles of conventional crank type plunger pumps in one year; which are widely used in low to medium capacity RO applications.

4.8.3 *Conclusions for Pumping Technique Viability*

The following statements are extracted from Mr. Henshaw's and Palmyra's reports:

1. Reciprocating pumps are commonly used in demanding services unsuitable for centrifugal pumps.

2. The VARI-RO reciprocating pump is a direct-acting pump type as opposed to a crank type power pump.

3. Direct-acting pumps are used for demanding service, and usually require less maintenance than a power pump in the same service.

4. The low cycle speeds being considered for the VARI-RO system provides the capability to achieve long operating life.

5. The trapezoidal wave form (FIGURE 4-2) seems to be a viable method for reducing pulsations in both the suction and discharge piping; thereby, minimizing the need for discharge pulsations dampeners and suction stabilizers commonly used with crank type power pumps.

6. Reciprocating pumps are in general more efficient than centrifugal pumps, and are more effective under varying operating conditions.

7. An efficiency allowance of 97% for the feed piston and 98% for the reject brine piston appear to be obtainable.

NOTE: These high efficiencies will result in about 96% efficiency for the reject brine energy recovery. This compares to a centrifugal pump and turbine system energy recovery efficiency of about 62%, based on a centrifugal pump efficiency of 83% and a turbine efficiency of 75%.

8. Mr. Henshaw's main concern is with the hydraulic system used to supplement the power from the reject brine. He is not familiarity with this type of power and control system, and suggested that this system should be independently reviewed.

9. Careful attention needs to be given to valve selection, rod packing and piston seal design, and materials for seawater service. With this achieved, there is no reason that the system cannot be designed for satisfactory service for either high or low capacity applications.

NOTE: The VARI-RO system materials of construction will be high grade stainless steels, composites, fiberglass reinforced plastics, ceramics, and other materials that have been proven for seawater and highly concentrated reject brine.

10. It is generally concluded that the method is viable, it can provide significant economic and environmental benefits, and it should be developed for commercial applications.

5. TASK 3 – PERFORMANCE COMPARISON

5.1 VARI-RO System Characteristics

TASK 3 was directed at comparing the preliminary design characteristics of the three cases. For each case, the predicted performance of the VARI-RO system was compared to the centrifugal system. In the interest of brevity, only detail characteristics for CASE 3 will be covered in this report. The performance results for CT 3 as shown in TABLE 5-1, and for VRO 3 in TABLE 5-2. The data for CASE 1 and CASE 2 are shown in appendix D.

The following example from CASE 3 illustrates the performance comparison between a seawater CT system and a VRO system at a recovery ratio of 45%. From TABLES 5-1 and 5-2 it is noted that for a 5 MGD (18,900 m^3/d) module, the flow rates for product, feed and brine are: 3,472 GPM (13,140 l/m); 7,716 GPM (29,200 l/m); and 4,244 GPM (16,100 l/m), respectively. For this example, the membrane feed pressure is 960 PSI (66.2 BAR) and the membrane pressure drop 74 PSI (5.1 BAR), giving a reject brine pressure of 886 PSI (61.1 BAR). Under these conditions, and the indicated efficiencies, the net power input is 2,885 KW for the CT 3 system and 2,018 KW for the VRO 3 system. The VRO 3 system provides a power savings of 867 KW, or a 30 % reduction.

In the above example, at 45% RR, the specific energy consumptions (SEC) for the CT 3 and VRO 3 systems are 13.85 and 9.69 kWh/kGAL (3.66 and 2.56 kWh/m^3), respectively. This is a savings of 4.16 kWh/kGAL (1.1 kWh/m^3), or a 30% reduction.

5.2 Specific Energy Consumption Savings, Cases 1,2, & 3

For each of the cases, the SEC was calculated and plotted versus the recovery ratio. The resulting SEC for both the CT and the VRO systems for CASE 1, CASE 2, and CASE 3 are plotted on FIGURE 5-1. Note that the energy consumption for all of the VRO systems is substantially lower than the CT systems. Also note that the VRO curves are relatively flat versus recovery ratio. This capability will allow the desalting system recovery ratio to be selected that will give the best overall performance, rather than selecting the highest feasible recovery ratio to achieve low energy consumption, as is usually done with a CT system. The benefits of lower recovery ratio options are discussed later in SECTION 5.1.3.

In addition, the percent savings of the VARI-RO systems energy consumption as compared to the base CT systems are plotted in FIGURE 5-2. This percentage savings allows a quick comparison of the savings potential of the VARI-RO system versus existing methods. Note that the savings is in the range of 24% to 49%, except for one data point at 50% RR.

The energy consumption for CASE 3 is shown in FIGURE 5-3, along with the percent savings. The feed pressures are the same as used for the membrane performance projections (DOW, 1992), which had the same feed pressure at 45 % RR as used in the latest SDCWA study (Carollo, Laughlin, 1994). The efficiencies used for the centrifugal system (CT 3) are also the same as the SDCWA study, which included the losses of an electric variable speed drive.

"CT 3" DOW FilmTec Membranes	RECOVERY RATIO (RR) 25%	35%	45%
FLOW RATES			
PRODUCT (MGD)	5	5	5
PRODUCT (GPM)	3,472	3,472	3,472
FEED WATER SUPPLY (GPM)	13,889	9,921	7,716
BRINE DISCHARGE (GPM)	10,417	6,448	4,244
PRESSURES (PSID)			
SUPPLY	20	20	20
MEMBRANE FEED {1}	940	940	960
MEMBRANE PRESSURE DROP	19	30	74
BRINE	921	910	886
BRINE DISCHARGE	20	20	20
EFFICIENCIES (%) {2}			
FEED PUMP	83%	83%	83%
ENERGY RECOVERY TURBINE	75%	75%	75%
ELECTRIC MOTOR	95%	95%	95%
VARIABLE SPEED DRIVE {3}	95%	95%	95%
POWER INPUT (kW)			
FEED PUMPING	7,424	5,303	4,214
ENERGY RECOVERY (pump drive)	3,395	2,076	1,329
NET (FEED - ENERGY RECOVERY)	4,030	3,227	2,885
SPECIFIC ENERGY CONSUMPTION sec = kWh/k GAL for NET Energy Input to RO	19.34	15.49	13.85
MEMBRANE QUANTITY {4}			
No. EL/MGD (FilmTec HR-8040)	304	350	420
NUMBER REQUIRED / TRAIN	1520	1750	2100

NOTES { } "CT 3":

{1} Membrane pressure based on data from (DOW, 1992).
{2} Efficiencies used from (Carollo, Laughlin 1994, TABLE 1 ROM)
{3} Variable speed drive used instead of throttling to adjust flow & pressure
{4} Membrane quantity is based on (DOW, 1992).

EX21a-"BASE"

TABLE 5-1 – "CT 3" Characteristics for CASE 3

VARI-RO™ 3 (Compared to "CT 3") DOW FilmTec Membranes	RECOVERY RATIO 25%	35%	45%
FLOW RATES			
PRODUCT (MGD)	5	5	5
PRODUCT (GPM)	3,472	3,472	3,472
FEED WATER SUPPLY (GPM)	13,889	9,921	7,716
BRINE DISCHARGE (GPM)	10,417	6,448	4,244
PRESSURES (PSID)			
SUPPLY	20	20	20
MEMBRANE FEED {1}	940	940	960
MEMBRANE PRESSURE DROP	19	30	74
BRINE	921	910	886
BRINE DISCHARGE	20	20	20
EFFICIENCIES (%) {2}			
FEED PUMP PISTON	97%	97%	97%
ENERGY RECOVERY PISTON	98%	98%	98%
ELECTRIC MOTOR	95%	95%	95%
HYDRAULIC DRIVE {3}	88%	88%	88%
POWER INPUT (kW)			
FEED PUMPING	6,858	4,899	3,893
ENERGY RECOVERY (pump drive)	4,789	2,928	1,875
NET (FEED - ENERGY RECOVERY)	2,070	1,971	2,018
SPECIFIC ENERGY CONSUMPTION sec = kWh/k GAL for NET Energy Input to RO	9.93	9.46	9.69
MEMBRANE QUANTITY {4}			
No. EL/MGD (FilmTec HR-8040)	304	350	420
NUMBER REQUIRED / TRAIN	1520	1750	2100

NOTES { } "VARI-RO™ 3":

{1} Membrane pressure based on data from (DOW, 1992).
{2} The piston eff. includes packing friction & valve pressure drop.
{3} Hydaulic eff. includes hydraulic pump & cylinder.
{4} Membrane quantity is based on (DOW, 1992).

EX21a-"BASE"

TABLE 5-2 – "VRO 3" Characteristics for CASE 3

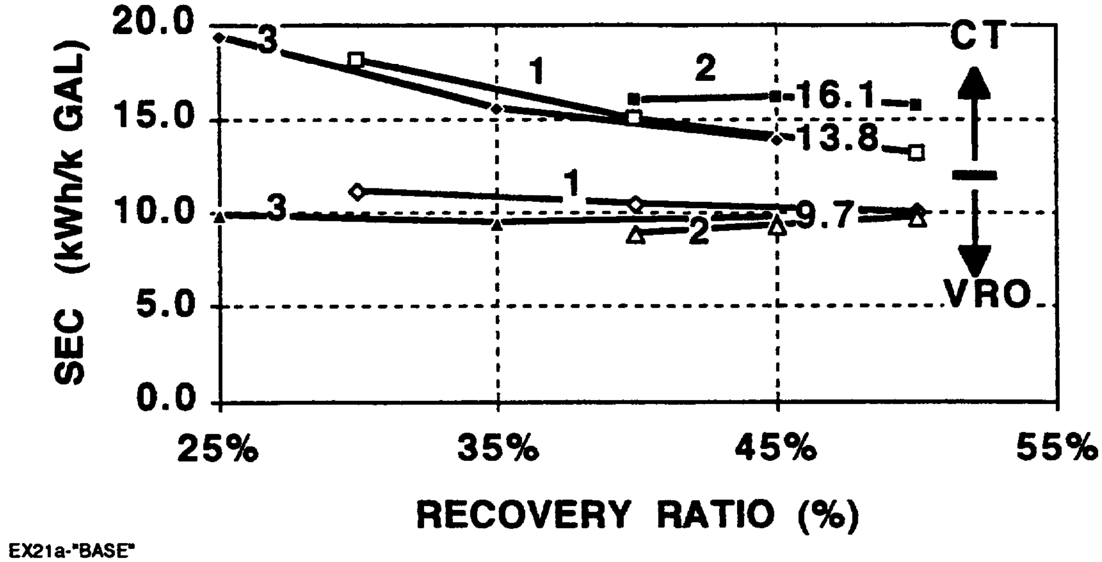


FIGURE 5-1--Specific Energy Consumption vs RR for CASES 1, 2, & 3

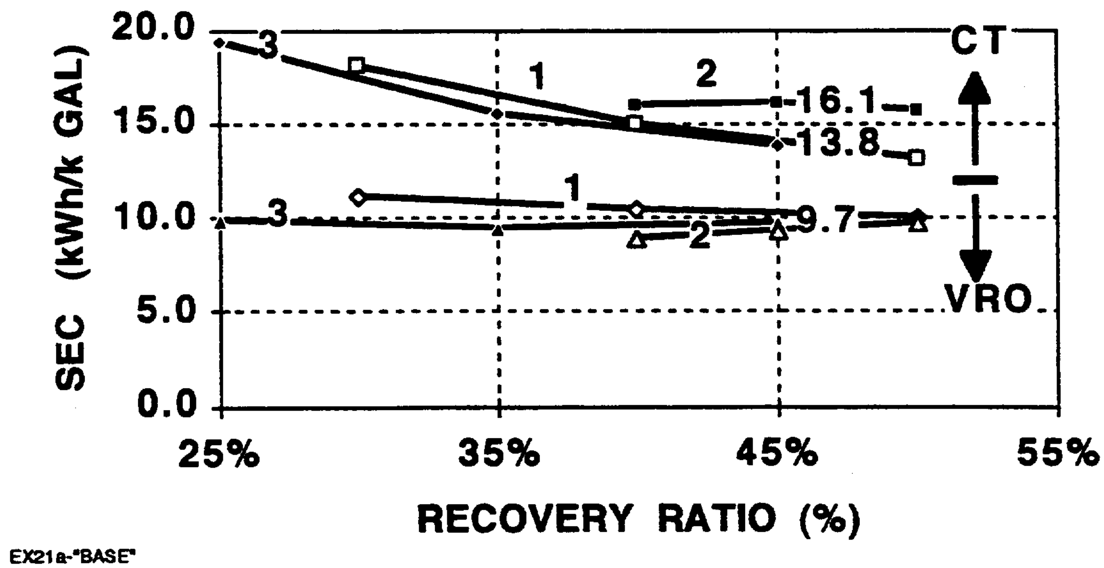


FIGURE 5-2-- % VARI-RO with respect to CT vs RR

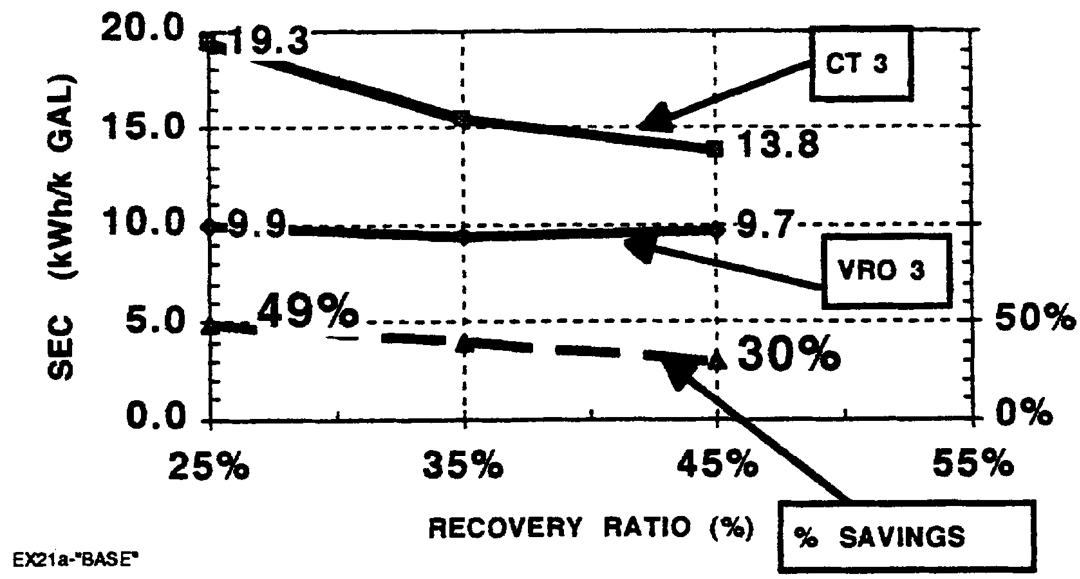


FIGURE 5.3--CASE 3" Specific Energy Consumption (CT & VRO) for RO Pumping

For each of the cases, the SEC predicted for the VARI-RO systems is substantially less than the centrifugal and turbine systems. The values used for the efficiency calculations were established from general experience, and from published manufacturers' literature on key components for both the CT and the VRO systems.

5.3 Power (MW) Comparison of VRO to CT & SWP

The bar chart in FIGURE 5-4 shows the projected relative power requirements to provide 30 MGD (113,550 m3/d) of potable water to the San Diego region. The reverse osmosis energy consumption is based on a recovery ratio of 45%. These projections are based on the systems described below:

SYMBOL	DESCRIPTION	SOURCE OF INFORMATION
CT	Centrifugal/turbine RO	(Carollo, Laughlin, 1994, TABLE 2, ROM), and as shown in TABLE 3-1.
SWP N>SD	State Water Project, Northern California San Diego.	(Boyle, 1991, Page 21, Energy needs of the SWP)
VRO	VARI-RO Electric Drive Pumping & Energy Recovery Method.	(Childs, 1992), and as adjusted to meet the specific requirements shown in TABLE 3-2 .

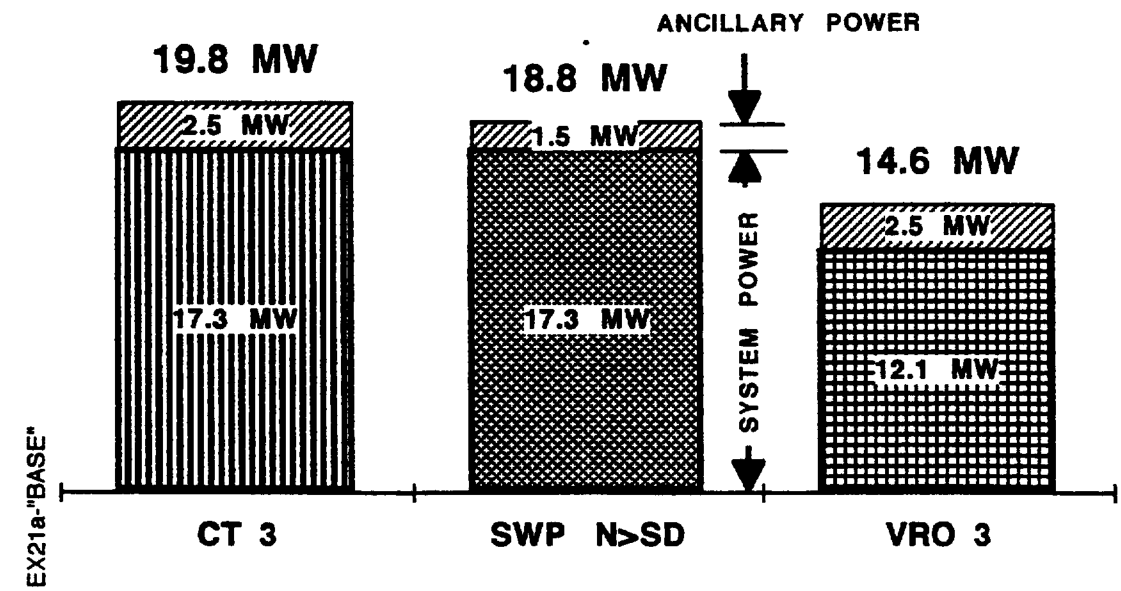


FIGURE 5-4 – Power Comparison of VRO to CT & SWP N > SD for 30 MGD (113,550 m3/d) Supply. (45% RR for RO Systems)

For both the CT and the VRO desalting systems, the ancillary power was calculated as shown in TABLE 5-3. For the State Water Project to San Diego, 17.3 MW pumping power was calculated to move 30 MGD (113,550 m^3/d) of water from Northern California to storage reservoirs near Los Angeles; based on data from (Boyle, 1991). An additional 1.5 MW of ancillary power was estimated to treat the water and pump it from the storage reservoirs to the San Diego region.

The total electric power consumption, system plus ancillary power, for a 30 MGD (113,550 m^3/d) supply is summarized below:

WATER SUPPLY METHOD	POWER (MW) SYSTEM	POWER (MW) TOTAL	VRO MW SAVED	PERCENT VRO SAVED SYSTEM	PERCENT VRO SAVED TOTAL
Centrifugal/Turbine RO (CT)	17.3	19.8	5.2	30%	26%
State Water Project to SD (SWP)	17.3	18.8	4.2	30%	22%
VARI-RO System	12	14.6			

Coincidentally, the power requirement for desalting seawater with the CT method was calculated to be about the same (17.3 MW) as pumping water from Northern California.

The above table shows a total VARI-RO system power reduction of 5.2 MW over the centrifugal / turbine system and 4.2 MW over the State Water Project.

The energy cost savings of the VARI-RO system are discussed in SECTION 7.1.4.

	GPM	PSID	EFF.	POWER
Product Distribution	20,833	100	75%	1.2 MW
Feed Supply {2}	46,296	20	75%	0.5 MW
Brine Discharge {3}	25,463	20	100%	0.3 MW
TOTAL PUMPING POWER				2.0 MW
MISC. FOR CONTROLS, LIGHTING, ETC.				0.5 MW
TOTAL ANCILLARY POWER				2.5 MW

NOTES: Based on: 30 MGD 45% RR

{1} Product delivery assumed for site specific local distribution

{2} Assumes only pressure drop, since any excess would be NPSH to RO pumps.

{3} Assumes back pressure only decreases energy recovery availability.

EX21a-"BASE"

TABLE 5-3 – Ancillary Power for Both CT and VRO Desalting Systems

5.4 Lower Recovery Ratio Operation

As shown previously in FIGURE 5-3, the energy consumption of the VARI-RO system is relatively flat versus recovery ratio for a nearly constant pressure operation. This means that, from an energy requirement point of view, lower recovery ratios can be used. At lower recovery ratios the reject brine concentration is lower, which has a lower osmotic pressure. The result is that less net driving pressure is needed to push the product water through the membranes (Reduced Pressure Option). Conversely, if the same net driving pressure is available, a given membrane can produce a greater quantity of water (Reduced Membrane Quantity Option). The latter option results in a reduced number of membranes for the same plant capacity.

This membrane recovery ratio characteristic provides the option to either reduce the quantity of membranes for a given water production, or to operate at lower pressures. Either option provides the opportunity to improve the desalting system operation, and hence reduce the cost of water produced. These RO membrane characteristics are illustrated in a letter report (see appendix A) on the DOW FILMTEC membrane performance at various recovery ratios (DOW, 1992), which is used for the analysis in this report. This same characteristic is shown in a report on optimizing water costs with DuPont's PERMASEP B-10 TWIN™ membrane elements (DuPont, 1992), and discussed in the ADA paper (Childs, 1994).

5.4.1 *Reduced Membrane Quantity Option (Constant Pressure)*

The reduction of membrane quantity per MGD water production versus recovery ratio at constant membrane pressure is illustrated in FIGURE 5-5.

The following summarizes an example of membrane quantity reduction for a 30 MGD (113,550 m^3/d) desalting facility:

RECOVERY RATIO	No. OF ELEMENTS per MGD	No. OF ELEMENTS for 30 MGD	REDUCTION delta QTY.	REDUCTION %
45%	420	12,600		
25%	304	9,120	3,480	28 %

Assuming 8 elements per pressure vessel (PV), this would reduce the number of PVs by 435. This results in a membrane related cost savings of about $11.7 million, as noted in SECTION 7.2.1. The rack space requirement per PV is approximately 1.5 feet (0.46 m) high, 1.5 feet (0.46 m) wide, and 40 feet (12.2 m) long; plus an additional 12 feet (3.6 m) on each end for servicing (Carollo, Laughlin, 1994, page 4-8). Assuming a rack column with 10 PVs stacked on top of one another, the reduced number of membranes would be equivalent to about 44 columns. The floor space requirement for each column would be 1.5 feet wide by 64 feet (19.5 m) long. For 44 rack columns, the reduced floor space requirement would be about 4,220 square feet (392 m^2) .

In addition to a reduction in the number of elements, pressure vessels, racks, and floor space area; there would also be a reduction in the number of high pressure pipe fittings, associated piping, and installation time. Plus, there would be fewer membranes to clean and replace during the operation of the facility, thereby reducing operating costs.

The capital cost savings of this option are discussed in SECTION 7.2.1.

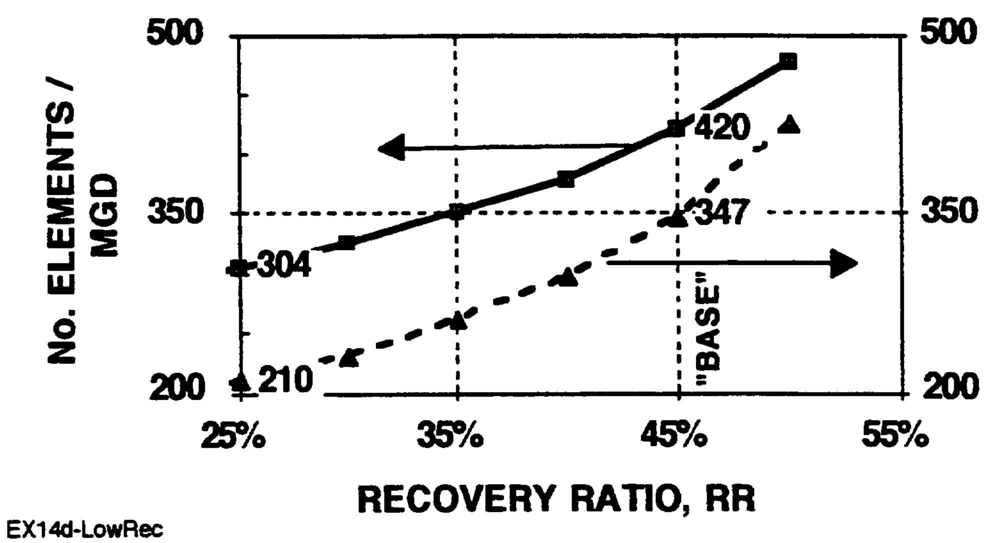


FIGURE 5-5 -- No. of Membrane Elements & Permeate TDS vs RR for Constant Pressure Operation.

5.4.2 *Reduced Pressure Option (Lower Power)*

The reduction of the pressure requirement for water production versus recovery ratio with constant membrane element quantity is illustrated in FIGURE 5-6.

The following summarizes an example of pressure reduction by operating at 25% RR for a 30 MGD (113,550 m3/d) desalting facility, based on a constant membrane quantity equal to that required at 45% RR:

RECOVERY RATIO	PRESSURE REQUIRED PSI	REDUCTION delta PSI	%
45%	960 (66 BAR)		
25%	808 (56 BAR)	152 (10.5 BAR)	16 %

With the VARI-RO system, the power requirement reduces from 12.1 to 10.7 MW at this lower pressure. Referring to FIGURE 5-4, this is a 6.6 MW (38%) reduction from the 17.3 MW requirement of the CT system; instead of the 5.2 MW (30%) reduction shown in SECTION 5.3 for base case operation.

The additional energy cost savings for this option are discussed in SECTION 7.2.2.

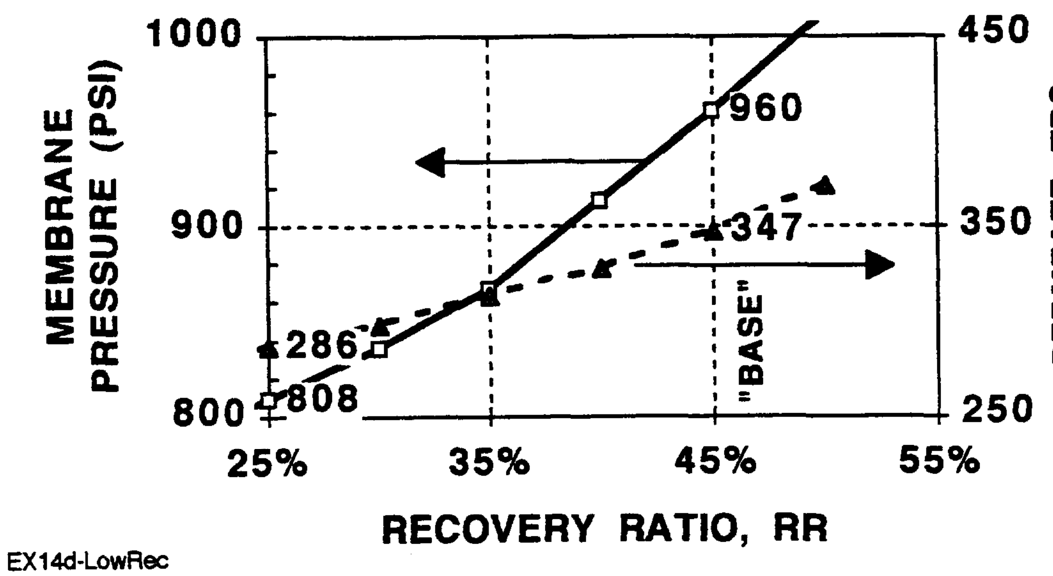


FIGURE 5-6 – Membrane Pressure & Permeate TDS vs RR for Constant No. of Membranes

5.4.3 *Improved Water Quality at Lower Recovery Ratios*

The improvement of water quality (TDS) versus recovery ratio was previously illustrated in FIGURES 5-5 and 5-6. The table below summarizes an example of water quality improvement by operating at 25% RR instead of the base 45% RR.

LOW RECOVERY OPTION	WATER QUALITY (TDS) @ 45% RR	WATER QUALITY (TDS) @ 25% RR	REDUCTION delta TDS	REDUCTION %
Reduced Membranes	347	210	137	39%
Reduced Pressure	347	286	61	18%

This indicates that the Reduced Membrane Quantity Option can provide 39% water quality improvement at 25% RR, which is quite substantial. The Reduced Pressure Option also shows water quality improvement of 18%.

> **NOTE:** With the lower TDS permeate water quality, an opportunity is presented to further reduce the cost of water by blending with other non-seawater sources, while still maintaining the EPA maximum allowable level below 500 mg/l TDS.

5.4.4 *Lower Recovery Ratio Optimization Considerations*

To realize the benefits of the Reduced Membrane Quantity or the Reduced Pressure options, it will be necessary to increase the flow rates for feed water and reject brine. During desalting system design optimization, this increased flow requirement would be traded off against the membrane related cost savings, the reduced power requirements in the case of lower pressure operation, the improved water quality, and the environmental benefits of reduced reject brine discharge concentrations (SECTION 5.5.2).

The evaluation of the savings benefit, resulting from the Reduced Pressure Option versus the Reduced Membrane Quantity Option, would depend upon the assumed electric power rate. At low electric power rates, the membrane savings would likely give the lowest cost of water. At high electric rates, the power savings resulting from the lower pressure operation would likely result in the lowest cost of water.

The cost benefits[6] of the lower recovery ratio option are discussed in SECTION 7.2.

6 In addition to this report, the technical benefits of lower recovery ratios were discussed in a privious paper (Childs, 1992, Section 3.1)

5.5 Environmental Benefits

5.5.1 *Atmospheric Emission Reduction*

Environmental benefits can result from the higher operating efficiency of the VARI-RO technology compared to the CT system for desalination. For a 30 MGD (113,550 m3/d) desalting facility, utilizing electric power as the energy source, the estimated power savings for the VARI-RO system was 5.2 MW; as shown previously in SECTION 5.3

The Environmental Impact Report (EIR) for the 7 MGD Santa Barbara system projected air emissions for an electrical power requirement of 8 MW (Woodward-Clyde, 1990). Based on these projections, an electric power reduction of 5.2 MW would result in a correspondingly lower emissions as noted below:

POLLUTANT		REDUCTION AMOUNT	
SOx	=	16.8	tons/year
NOx	=	24.3	tons/year
CO_2	=	24,726	tons/year

This demonstrates that a substantial 30% air emissions reduction can be realized by utilizing the VARI-RO method instead of the CT method.

5.5.2 *Lower Concentration Ocean Brine Disposal*

The disposal of reject brine has become a significant issue in the permitting of desalting facilities. This is discussed in a paper presented at the IDA conference in Japan (Del Bene, 1993). In this paper it was stated: *"SWRO, with recovery ratios up to 50%, poses a potential problem because the dense brine concentrate sinks to the ocean floor and may threaten the benthic environment."* To minimize this effect various methods of diluting the brine, including diffusers and mixing with sewage water, are being considered.

This could be another advantage of using the VARI-RO system and operating at lower recovery ratios. At lower recovery ratios, the brine concentration is lower, which will tend to minimize the dense brine problem. The benefits of this are illustrated by the following statement: *"For a SWRO brine discharge with a salinity of 70 parts per thousand, a dilution of approximately 35-40 times would be required to achieve an effluent stream salinity of 1 part per thousand above the ambient. For lower discharge salinities lower dilutions would be required."* (Del Bene, 1993, Dispersion Criteria).

At low recovery ratios, it may also be possible to reduce the injection of antiscalant chemicals into the feed water; because lower brine concentrations will have reduced tendency to precipitate in the membranes.

The potential for improved brine disposal, at lower recovery ratios, is beyond the scope of this study; however, it is a subject that should be given additional investigation to determine the potential environmental benefits.

6. FUTURE "Direct Drive" ENGINE OPTION

The consideration of the direct drive VARI-RO NG (natural gas) and the VARI-RO HR (Heat Recovery) engine versions were beyond the scope of this particular study. The engine versions were covered in previous papers on the VARI-RO method (Childs, 1992) and (Childs, 1993). The engine versions are only mentioned here to provide information to the reader that these options could further reduce desalting energy consumption and reduce the cost of water. This is accomplished by cutting out "middle men" losses, such as electric generators and motors; and by using lower cost energy sources, such as natural gas, waste heat, and even solar energy.

It was projected in the previous paper (Childs, 1992), that the equivalent electric specific energy consumption (kWHe/kGAL) at 40% RR could be reduced from 17.1 for the CT method to 9.9 and 6.3 for the EL (electric drive) version, and the NG (natural gas) version, respectively. As compared to the CT system, this NG version would provide a 60% reduction in energy consumption. The cost of water savings would be an even greater percentage, because natural gas costs less than electric power.

The benefits of the direct drive VARI-RO HR (Heat Recovery) engine version were investigated in another previous paper (Childs, 1993). With this HR version, it was estimated that four times the water could be produced as compared to a multi-effect distillation (MED) system, from the same energy source. In this case, the energy source was a 425 °F hot gas stream from the exhaust of an electric power production gas turbine.

The VARI-RO direct drive engine versions offer the potential to combine the energy efficiency of reverse osmosis desalination with the use of thermal energy sources, which have lower cost than electric power. It is recommended that a program be initiated to perform further analytical analysis and design development of the VARI-RO direct drive engine versions. If this further engineering study confirms that the cost benefits are significant, then proceed toward a pilot demonstration project.

7. TASK 4 – ECONOMIC ANALYSIS and BENEFITS

TASK 4 was directed at determining the economic benefits of the VARI-RO system as compared to conventional methods for RO pumping and energy recovery. This discussion on economic analysis and benefits is divided into two sections. SECTION 7.1 covers a comparative economic analysis made and reported by The Palmyra Group (Palmyra, 1994). SECTION 7.2 covers the economic benefits of the low recovery ratio operation options, as discussed in SECTION 5.4.

7.1 Comparative Economic Analysis

7.1.1 *Introduction*

The comparative economic analysis was performed by The Palmyra Group. Their report is enclosed in appendix C. It consisted of two primary tasks, as follows:

TASK 1 - Overview of the VARI-RO technology
TASK 2 - Economic Analysis

The first part of TASK 1 was directed at establishing the base case conditions at the 30 MGD (113,550 m3/d) South Bay Desalination project that is being considered by the San Diego County Water Authority (SDCWA), and corresponds to CASE 3 in this report. From this base case, at 45% recovery ratio, the pumping and energy recovery characteristics of the centrifugal pumps, energy recovery turbines, and variable speed drives were established.

The second part of TASK 1 was to make a general overview of the VARI-RO technology, including: technical viability, operating reliability, energy savings potential, and evaluate sensitivity analysis in the assumptions made on component efficiencies. Palmyra's evaluation of the technical viability was summarized previously in SECTION 4.8.2.

TASK 2 was to prepare an economic analysis of the VARI-RO technology as applied to a large capacity desalination facility such as the 30 MGD (113,550 m3/d) South Bay Desalination Project. This included making assumptions for project economic factors, capital cost, operating and maintenance, and parameters for economic sensitivity calculations.

7.1.2. *Methodology*

The data for use in the comparative economic analysis was developed as follows:

a. **Cost estimates of the VARI-RO system** – This was accomplished by selecting key commercial components and generating preliminary designs of the key system custom components unique to the system. Vendors were contacted for commercial component costs, and layout drawings were sent to qualified equipment manufactures for cost estimates of custom components. Initially, the modules were sized for 2.5 MGD, which would require 12 modules for a 30 MGD (113,550 m3/d) system. This 2.5 MGD cost estimate basis was used for the comparative economic analysis.

Later, the system was resized to 5 MGD modules, requiring 6 modules for the facility. The fewer number of modules, plus a redesign of the Water Displacement Cylinder to reduce material and machining costs, will provide for a substantial decrease in the manufacturing cost of the modules. The resulting cost reduction of the VARI-RO system will further improve its economic benefit, beyond that shown in the Palmyra report, as discussed in SECTION 7.1.6, Payback Period.

b. **Electric power supply system costs** -- Since the VARI-RO system (VRO) will require less power than the centrifugal and turbine system, plus a separate variable speed drive is not required, a large cost reduction for the electric power supply system will result. To obtain estimated costs on this equipment, budgetary quotations were obtained from General Electric, Industrial and Power Systems Sales.

c. **System performance comparisons** -- The efficiencies and other comparative information was determined and summarized for both the CT and the VRO systems, similar to those covered earlier in this report (TABLES 5-1 and 5-2).

d. **General facility costs** -- Capital costs, factors for contractor costs, and factors for operation and maintenance were taken from the South Bay Desalination study (Carollo, Laughlin, 1994), with appropriate modifications as stated in the report (Palmyra, 1994), which corresponds to CASE 3 in this report.

This information was reviewed and used by Palmyra to prepare their comparative economic analysis as covered in their report, which is enclosed in appendix C.

7.1.3 *Energy Savings Comparisons for Efficiency Cases*

For both the centrifugal and the VARI-RO systems, base case efficiencies of components were estimated. These were applied to system equations to calculate the power requirements in megawatts (MW), (Palmyra, 1994, pages 5 & 6). To determine the sensitivity of the estimates, the base case efficiencies were compared to a case with lower VARI-RO system efficiencies and a case with lower centrifugal pump efficiencies[7]. The results of these comparisons are summarized below:

EFFICIENCY CASE		POWER (MW)		VARI-RO REDUCTION	
CT	VARI-RO	CT	VARI-RO	delta MW	%
BASE	BASE	16.9	11.7	5.2	30%
BASE	LOWER	16.9	13.1	3.8	22%
LOWER	BASE	21.6	11.8	9.8	45%
LOWER	LOWER	21.6	13.1	8.5	39%

This comparison indicates an energy savings ranging from 3.8 to 9.8 MW resulting in a percentage savings in the range of 22 to 45 percent. The base case savings were 5.2 MW (30%), which is the same differential projected in SECTION 5.3.

7. For the lower efficiency sensitivity cases, the VARI-RO system efficiencies were reduced as follows: piston from 97% to 95% and hydraulic from 88% to 85%. The centrifugal pump efficiency was reduced from 83% to 75%.

7.1.4 *Energy Cost Savings for the Efficiency Cases*

Assuming an electric power rate of 6¢/kWh, and a 90% capacity factor, the value of the energy savings shown in SECTION 7.1.3 would be as follows:

		ENERGY COST SAVINGS		
CASE	delta MW	per year	5 years	20 years
BASE-BASE	5.2	$2,450,000	$12,250,000	$49,000,000
BASE-LOWER	3.8	1,800,000	9,000,000	36,000,000
LOWER-BASE	9.8	4,600,000	23,000,000	92,000,000
LOWER-LOWER	8.5	4,000,000	20,000,000	80,000,000

This indicates a 5 year energy cost savings in the range of $9 to $23 million. This means that with a VARI-RO system capital cost and maintenance cost differential less than this amount, a break even point can be reached in less than 5 years. Also, if the electric power rate is greater than 6¢/kWh, the break even point would be even shorter, for a given cost differential.

For the BASE-BASE case, an estimate of the payback period has been given in SECTION 7.1.6.

7.1.5 *Capital Cost Differential Estimates*

A comparative preliminary capital cost estimate was prepared for the VARI-RO system (Palmyra, 1994, Tables 3-2 and 3-3). This is summarized as follows:

	CENTRIFUGAL	VARI-RO
Electric Power Equipment	$4,685,000	$1,505,000
Pumping and Energy Recovery	2,953,000	8,444,000
Installation & Startup	8,229,000	8,805,000
Other	74,577,000	74,578,000
TOTAL	$90,444,000	$93,332,000
Direct Capital Cost Differential (base)		**$2,888,000**
Overall Project Economic Factor[8]		1.85
Capital Cost Differential (with Project Economic Factor applied)		**$5,343,000**

8. The overall project economic factor reflects a multiplier applied to the facility capital cost estimate, for items such as: indirect costs, installation, and contingency.

7.1.6 *Payback Period*

For the base case efficiency conditions, an energy cost savings of $2.4 million per year (SECTION 7.1.4) was estimated. Based on this energy cost savings, the payback period would be:

At Direct Capital Cost Differential (base):

$$\textbf{PAY BACK PERIOD} = \frac{\$2{,}888{,}000}{\$2{,}450{,}000/\text{year}} = \text{about 1 YEAR}$$

With Overall Project Economic Factor applied:

$$\textbf{PAY BACK PERIOD} = \frac{\$5{,}343{,}000}{\$2{,}450{,}000/\text{year}} = \text{about 2 YEARS}$$

Basically this indicates that the VARI-RO system can be paid for in about one year for the direct capital cost differential, and about two years with the economic factor applied. After this payback period, the system would then save over $40 million for a 20 year period of operation; as shown in SECTION 7.1.4.

NOTE: Lower VARI-RO system capital costs are expected in the future. As the VARI-RO system design matures, and production techniques are developed, it is expected that the capital costs can be substantially reduced from those used in this report. This will reduce the capital cost differential between the two methods, since the centrifugal pump and energy recovery turbine equipment capital costs were based on production costs of equipment that has reached design maturity. However, even at the cost differential shown, the payback period due to the energy savings is still quite short.

7.1.7 *Cost of Water Sensitivity Analysis*

The cost of water was estimated for both the centrifugal and the VARI-RO systems (Palmyra, 1994, pages 11-14). These estimates were made for the base case conditions and for cases with lower efficiencies for both systems (see SECTION 7.1.3), and higher differential capital cost for the VARI-RO system. The results of this cost of water sensitivity analysis, for an energy cost of 6¢/kWh, are summarized as follows:

CASE[9]	COST OF WATER ($/AF)		VARI-RO REDUCTION	
	CT	VARI-RO	delta	%
BASE	**963**	**897**	**66**	**6.9%**
LOWER VARI-RO EFF.	**963**	**918**	**45**	**4.7%**
LOWER CENT. EFF.	**1037**	**897**	**140**	**13.5%**
HIGHER VARI-RO COST	**963**	**911**	**52**	**5.4%**

This cost of water sensitivity analysis indicates a VARI-RO system cost reduction from $52 to $140 per acre-foot ($0.042 to $0.114 per m^3), giving a savings range from 5 to 13 percent.

9. The parameters for the lower efficiency cases were given in SECTION 7.1.3 (Footnote 7). For the higher VARI-RO system cost, the hydraulic unit was increased 15% and the displacement unit 30%.

7.1.8 *Electric Power Rate Sensitivity*

A graph was prepared to show the effect of different electric power rates (Palmyra, 1994, page 14). The results of this comparison are summarized as follows:

ELECTRIC RATE	COST OF WATER ($/AF)		REDUCTION	
¢/kWh	CT	VARI-RO	delta	%
4	**850**	**820**	**30**	**3.5%**
6	**963**	**897**	**66**	**6.9%**
8	**1075**	**980**	**95**	**8.8%**
10	**1185**	**1070**	**115**	**9.7%**

This shows that, as electric power rate increases, the cost savings resulting from the higher efficiency of the VARI-RO system become more significant. Higher electric power rates will provide an additional incentive to consider the Reduced Pressure Option as discussed in SECTION 7.2.2.

7.1.9 *Conclusions for Comparative Economic Analysis*

The conclusions reached as a result of the comparative economic analysis are:

1. Results of the base case comparison shows a total water cost for the VARI-RO system to be $897/AF, which is a cost advantage of $66/AF, for a savings of about $2.4 million /year. This is about 7% of the total cost of water. (Palmyra, 1994, page 13)

2. The total cost of the desalination plant with the VARI-RO system is only about 3 percent higher than the total capital cost with the conventional pumping and energy recovery system. This indicates that the capital cost impact of the VARI-RO system is small with respect to the total capital cost. (Palmyra, 1994, page 13)

3. The energy cost savings for the VARI-RO system are about $2.5 million per year or about 24% of the total energy cost at an electric power price of $0.06/kWh. This cost advantage is slightly offset by a higher maintenance cost of about $0.1 million/year, producing a total cost advantage for the VARI-RO system of about $2.4 million/year, or about 13 percent of the total O&M cost. (Palmyra, 1994, page 13) It would, therefore, take only about 2 years to payback the added capital cost for the VARI-RO system, including the economic markup factor; as discussed in SECTION 7.1.5.

4. The lower power requirement of the VARI-RO technology resulted in an energy savings of about 30% when compared to a conventional centrifugal system, which is a significant savings. In addition the lower power requirement and the elimination of the variable speed drive reduces the cost of the electric power equipment.

5. Even at the lower efficiency sensitivity cases (for either the centrifugal or the VARI-RO systems) the advantage of the VARI-RO system ranges from 5 to 13% on the total cost of water.

6. The VARI-RO system could allow operating at a lower recovery ratio. Lowering the system recovery would, for example, allow operation with either less membrane elements or at a lower operating pressure. Either option would result in a higher quality (lower TDS) product water. To quantify the benefits of these options would require evaluation and optimization of the facility design and economic analysis.

In summary, there is a definite incentive for commercial development of the VARI-RO technology for desalination plants. To achieve verification, a program to refine the design, improve equipment cost estimates, applications analysis, and pilot testing was recommended (Palmyra, 1994, page 15 & 16).

7.2 Lower Recovery Ratio Cost Benefits

The possibility of reducing membrane related costs, energy costs, and improving water quality by operating at lower recovery ratios was covered in SECTION 5.1.3 of this report. This possibility was also briefly mentioned in the comparative economic analysis (Palmyra, 1994, page 15). The potential environmental benefits of lower reject brine density (concentration) were covered in SECTION 5.1.4.2. The remainder of this section discusses the possible cost benefits of lower recovery ratio operation.

7.2.1 *Reduced Membrane Quantity Option , Capital Cost Savings*

As shown in SECTION 5.1.3.1, a membrane reduction of 3,480 (28%) was shown by operating at a recovery ratio of 25% instead of the base case 45%, which was based on a letter report (DOW, 1992). It w as indicated that this would result in reducing the number of pressure vessels by 435 and the floor space requirement by 4,220 square feet. For the base case, the number of pressure vessels was based on eight elements per pressure vessel (Carollo, Laughlin, 1994, page 4-8).

Cost estimating information was obtained from a DOW FILMTEC representative in an April 1992 meeting. This information, as shown in the tabulation below, was extrapolated to the present base case conditions to provide a general overview of the cost savings potential. The estimated cost obtained for the pressure vessels was $2,500 each, based on six elements per vessel. For this estimate, a pressure vessel cost of $3,000 each was assumed for eight element vessels. The 1992 costs were escalated by 5% to reflect 1994 costs. In addition, the same project economic factor of 1.85 (SECTION 7.1.5) was used to reflect total capital costs for the facility.

ITEM	UNIT COST 1992$	UNIT COST 1994$	REDUCTION QTY.	PROJECT COST REDUCTION w/ ECONOMIC FACTOR
Elements	$1300	$1365	3480	$8,790,000
Vessels	3000	3150	435	2,535,000
Racks/vessel	200	210	435	169,000
Piping/vessel	300	315	435	253,000
TOTAL MEMBRANE RELATED COST REDUCTION				**$11,747,000**

This indicates a membrane related capital cost savings potential of about $11.75 million with the Reduced Membrane Option, neglecting the savings due to the reduction of floor space requirement. This savings could reduce the cost of water from $963/AF to $821/AF. However, some of this savings would be offset by increased costs resulting from increased flow rates in the feed water supply and brine discharge systems, which are site dependent; and were not estimated in this study.

In the comparative economic report (Palmyra, 1994, page 12), the total capital cost was estimated to be $135 million for the standard RO system. The membrane related cost savings represents 8.7% of this capital cost, which is a substantial savings. Also note that this membrane related cost savings is nearly three times the cost differential estimated for the VARI-RO system, as noted in SECTION 7.1.5.

7.2.2 *Reduced Pressure Option , Additional Energy Savings*

As shown in SECTION 5.4.2, a pressure reduction of 152 PSI (10.5 BAR), providing a percentage reduction of 16%, was projected for operating at a recovery ratio of 25% instead of the base case 45%. For this option the membrane quantity was held constant.

Based on this pressure reduction, the power requirement for the VARI-RO system was reduced from 12.1 MW to 10.7 MW. As compared to the 17.3 power requirement for the base case centrifugal system, this is a reduction of 6.6 MW (38%). The value of this additional energy savings is shown below.

		VARI-RO SYSTEM ENERGY COST SAVINGS , @ 6¢/kWh		
OPTION	**delta MW**	**per Year**	**5 years**	**20 years**
Reduced Pressure, 25% RR	6.6	$3,110,000	$15,550,000	$62,200,000
BASE, 45% RR	5.2	2,450,000	12,250,000	49,000,000
ADDITIONAL SAVINGS	**1.4**	**$660,000**	**$3,300,000**	**$13,200,000**

At a higher electric rate of 10 ¢/kWh, the additional 5 year cost savings would increase from $3.3 million to $5.5 million. While this is a significant additional savings, it appears that at this electric power rate, it would be more cost effective to utilize the Reduced Membrane Quantity Option (Constant Pressure), as noted in SECTION 7.2.1, rather than the Reduced Pressure Option (Lower Power). This would likely change for locations with high electric power rates, such as facilities located on remote islands in the Caribbean.

7.2.3 *Economic Value of Improved Water Quality and Economic Benefits*

As shown in SECTION 5.4.3, water quality can be improved by operating at lower recovery ratios. Improved water quality can have economic benefits for some locations, by not requiring additional water treatment and/or by increasing the supply of potable water by blending with other water sources. Also, as discussed in SECTION 5.5, environmental benefits could result from using a VARI-RO system.

> NOTE: The evaluation of the potential economic benefits for operating at a lower recovery ratios is very site dependent. It could be influenced by the availability of a blending source of water, or the cost of equipment to further improve the water quality. This capability of the VARI-RO system is only pointed out here to provide another tool for reducing the cost of water produced by desalting. Determining the value of these benefits was beyond the scope of this study.

8. VARI-RO SYSTEM PILOT PROJECT

This section of the report discusses application selection for a low capacity pilot project and provides a comparative performance analysis for several candidates. It also covers the key tasks involved in the design, construction, and installation of a VARI-RO system to prove the overall concept and viability in a reverse osmosis application.

The need for a pilot project is illustrated from the following statement from Palmyra's report (Palmyra, 1994, page 15)

> *"In summary, there is a definite incentive for commercial development of the VARI-RO method for seawater desalination plants if the performance and cost assumptions used in the study are verified. To achieve this verification, we recommend that a program of design refinement, equipment cost estimating, applications analysis, and pilot testing be conducted on a sequential basis to confirm the performance and cost advantages of the technology."*

The following was stated earlier in this report, SECTION 3.4. *"The VARI-RO "Low Energy" desalting technology utilizes modern hydraulic power transmission and control to provide a highly efficient, low cycle speed, low pulsation, variable flow, positive displacement pumping and energy recovery system suitable for small, medium, and high capacity desalination plants. The primary applications would be SWRO and relatively high salinity BWRO; however, it can also provide benefits for low salinity BWRO in some instances."*

The goal of the Pilot Project will be to verify the viability of the VARI-RO system and confirm the hardware performance for the desalting applications mentioned. The key tasks for the Pilot Project are as follows:

1. **Form a project team to implement the program.**
2. **Select a low capacity application.**
3. **Determine the performance criteria for the application.**
4. **Perform sizing analysis to determine specifications for the key components.**
5. **Select and purchase key components.**
6. **Design the equipment.**
7. **Manufacture and shop functional test.**
8. **Install and startup at the job site.**
9. **Operate the system.**
10. **Evaluate and report the performance.**

During the implementation of this low capacity Pilot Project, consideration will be given to assure the capability to extrapolate the results to other higher capacity applications. This would be done by selecting a suitable application for actual testing. Then using the results of this testing, the performance can be projected for a variety of other applications. For example, it would be possible to prove the general function and performance on a brackish water application. These results could then be extrapolated to a seawater application, with proper consideration of the materials of construction and differences in operating pressures.

8.1 Lower Capacity Module Considerations, and Objective

The "BASE CASE" for this particular study was a high capacity seawater application with a module capacity of 5 MGD (18,900 m^3/d) at 1000 PSI (69 BAR) and 45% RR (recovery ratio). This unit would require about 2500 shaft horsepower (HP) (1900 KW). This compares to a centrifugal / turbine and variable speed drive system requirement of about 3500 shaft horsepower (2600 KW).

This is a saving of 1000 horsepower (746 KW) per module, or about a 30% saving. The hydraulic drive components for this high capacity module are commercially available, and have been proven in other applications.

In addition to this high capacity application, a number of modules for low and medium capacity seawater applications have been analyzed, ranging from 0.036 MGD (136 m^3/d) to 0.66 MGD (2500 m^3/d). Also, a number of module capacities for brackish water applications have been analyzed. For the lower capacity seawater modules, it has been noted that the specific energy consumption is about the same as it is for the higher capacity modules. The reason for this is that positive displacement components for either low or high capacity modules have about the same efficiencies under similar operating conditions. This means that the performance of a high capacity VARI-RO system can be predicted by testing a low capacity module. The specific energy consumption will be a function of the efficiency of the components selected. From the testing of this low capacity module, it will then be possible to project the performance that can be attained in a high capacity application by comparing the relative efficiencies of the components.

At the present time, for existing and planned facilities, centrifugal pumps and turbines are always selected for high capacity applications and are sometimes selected for medium capacity applications. For low to medium capacity applications, crank type triplex or quintuplex plunger pumps are usually selected, especially in regions where electric power rates are relatively high. For low capacity applications, energy recovery is seldom used. For medium capacity applications, various forms of energy recovery are sometimes used, especially for locations with high electric power rates.

The reason that plunger pumps are used for lower capacity applications is that the efficiencies of centrifugal pumps drop off considerably at lower capacities. Also, the efficiencies of turbines and electric variable frequency drives (VFD) usually are lower at lower capacities. VFDs are often needed with centrifugal pumps to minimize the throttling losses that can result from variations in membrane pressure requirements.

Pilot Project Objective: The objective of the VARI-RO system Pilot Project will be to demonstrate the implementation feasibility, and the benefits that can be provided, for a wide range of reverse osmosis desalting applications. This would include applications that presently use plunger pumps, centrifugal pumps, energy recovery turbines, and variable frequency drives.

8.2 Lower Capacity Application Candidates

Several applications have been identified and analyzed as possible candidates for a Pilot Project. For reference convenience, these are referred to as APP-1, APP-2, APP-3, APP-4, and APP-5. The first three applications are existing, and use plunger pumps (PP) without energy recovery. The last two applications are proposed new installations. For these proposed installations, it has been assumed that the competing system would be a CT system (centrifugal pump, energy recovery turbine, and a variable speed drive system). For APP-4, two pressure and recovery ratio conditions are being evaluated by the desalting system engineering firm. These have been identified as LR for "low recovery" and HR for "high recovery" ratios.

TABLE 8-1 shows the performance criteria for these applications, along with the projected energy cost savings that can be provided by the VARI-RO system. The energy cost saving projections are based on 8¢/kWh, 100% use factor, and 92% electric motor efficiency. An electric rate of 8¢/kWh was selected because this is a reasonable average commercial rate. The savings for other conditions can be approximated with a direct ratio to the factors used in the calculations.

The prime candidate for a Pilot Project is application No. 2 (APP-2). This application presently has three 140 horsepower pumping units, which have been in operation for about 8 years. The value of the energy cost savings is about $48,000 per year per unit (at 8¢/kWh), with a 55 horsepower requirement for each VARI-RO unit. This is a saving of 85 horsepower for each unit, providing a savings potential of about 250 horsepower at this facility. For an additional 8 years of operation, the potential value of the energy savings would be over $1 million, at the assumed commercial electric rate. This facility presently makes its own power at about 1/2 the commercial rate. Even at this lower electric power rate, the savings potential is around 1/2 million dollars for this period of operation.

> NOTE: At the time of writing this report, the operator of the APP-2 facility is considering participation in the Pilot Project, but has not made a commitment. If this facility cannot be used as the pilot site, then an alternative plan will be developed.

8.3 Lower Recovery Operation Benefit

As covered in SECTION 5.4, the VARI-RO system has a relatively flat energy consumption versus recovery ratio at a constant pressure. It was also illustrated in SECTION 5.4.2 that, at lower recovery ratios, the pressure can be lowered to provide energy savings. These unique characteristics of the VARI-RO system make the possibility of operating at lower recovery ratios a viable option.

For application No. 4 (APP-4), which is in the planning stages, various recovery ratio and membrane pressure options are being evaluated. One consideration is a high recovery ratio of 55% to reduce the feed water flow, which may require an operating pressure as high as 1200 PSI (83 BAR). Another alternative being considered is to operate at a lower recovery ratio of 40%, which could allow the pressure to be as low as 800 PSI (55 BAR). From TABLE 8-1 (APP-4LR & APP-4HR) it is shown that at either recovery ratio or pressure condition, the VARI-RO system can provide substantial energy cost savings of $27,000 and $26,000 per year, respectively.

It is further shown that $40,000 per year can be saved, if the VARI-RO system is used at the low recovery ratio and low pressure condition versus a conventional centrifugal system at the high recovery ratio and high pressure condition. The flat energy consumption versus recovery ratio characteristic of the VARI-RO system is the primary reason that this option can provide the projected energy cost savings.

APP-4 is planned to be constructed in three phases. Phase 1 would have three units of the capacity shown, giving a total capacity of 0.432 MGD. At the completion of Phase 3, the total facility capacity would be 1.15 MGD. For the complete facility, the VARI-RO system has the potential to provide a total saving of about $320,000 per year, or over $1.5 million savings for a 5 year period of operation. These savings depend upon which set of operating conditions are evaluated; however, under any set of comparative conditions, the savings that can be provided are quite substantial.

APPLICATION	METHOD	MGD	RR	PSI	HP	kWh/kGAL
APP-1	PP VRO	0.036	36%	1000	46 20	24.9 10.8
	SAVINGS (APP-1), HP & PERCENT				26	57%
	VARI-RO ELECTRIC COST SAVINGS, $1000/YEAR					$15
APP-2	PP VRO	0.122	35%	900	140 55	22.3 8.8
	SAVINGS (APP-2), HP & PERCENT				85	61%
	VARI-RO ELECTRIC COST SAVINGS, $1000/YEAR					$48
APP-3	PP VRO	0.144	42%	980	155 69	20.9 9.4
	SAVINGS (APP-3), HP & PERCENT				86	55%
	VARI-RO ELECTRIC COST SAVINGS, $1000/YEAR					$49
APP-4LR Low Recovery	CT VRO	0.144	40%	800	105 58	14.2 7.8
	SAVINGS (APP-4LR), HP & PERCENT				47	45%
	VARI-RO ELECTRIC COST SAVINGS, $1000/YEAR					$27
APP-4HR High Recovery	CT VRO	0.144	55%	1200	129 84	17.4 11.4
	SAVINGS (APP-4HR), HP & PERCENT				45	35%
	VARI-RO ELECTRIC COST SAVINGS, $1000/YEAR					$26
VRO SAVINGS POTENTIAL (APP-4LR VRO vs APP-4HR CT)					71	85%
VARI-RO ELECTRIC COST SAVINGS, $1000/YEAR						$40
APP-5	CT VRO	0.3	45%	850	194 122	12.6 7.9
	SAVINGS (APP-5), HP & PERCENT				72	37%
	VARI-RO ELECTRIC COST SAVINGS, $1000/YEAR					$41

TABLE 8-1 – Potential Pilot Project Applications

8.4 Pilot Project Program

The Pilot Project program will consist of putting together a project team, identifying a target application, designing a VARI-RO system for the application, building the system, shop functional testing, field installation, startup, and operation.

The project team would consist of SAIC as the program manager and the VARI-POWER Company for system design and project engineering. Other members of the team would likely include: 1) a company engaged in the supplying of hydraulic power and control equipment, 2) a company engaged in the manufacturing of pump parts for reverse osmosis applications, 3) a desalting engineering or system integration company, 4) an end user with the targeted application, and 5) a research organization.

The primary system design tasks include:

Overall System:	Defining performance criteria Sizing and selection of key components
Hydraulic Power Supply (HPS)	General arrangement and vibration isolation Piping design and interface Electronic control unit (ECU) design and programming
Water Displacement Unit (WDU)	Hydraulic cylinder interface Water displacement cylinder design Water directional valves design ECU interface to the energy recovery valves

A preliminary general arrangement of the Pilot Project module is shown on FIGURE 8-1. The critical technical issues in the development of this technology includes: dynamic packing selection and design, energy recovery pilot valve interface and timing, and WDU materials selection.

After manufacture, the system will be shop tested to verify function of the various components and that the unit will perform as expected. It will then be moved to the job site for installation and startup.

During the testing phase a report of operation and function will be prepared.

8.5 Pilot Project Estimated Costs

The estimated costs for the Pilot Project are as follows:

Design & Subsystem Development	$160,000
Manufacture and Shop Testing	130,000
Field Testing	210,000
Evaluation and Reporting	25,000
TOTAL	$525,000

This estimate is provided for budgetary purposes. A more detailed breakdown will be provided by the project team members for the Pilot Project program.

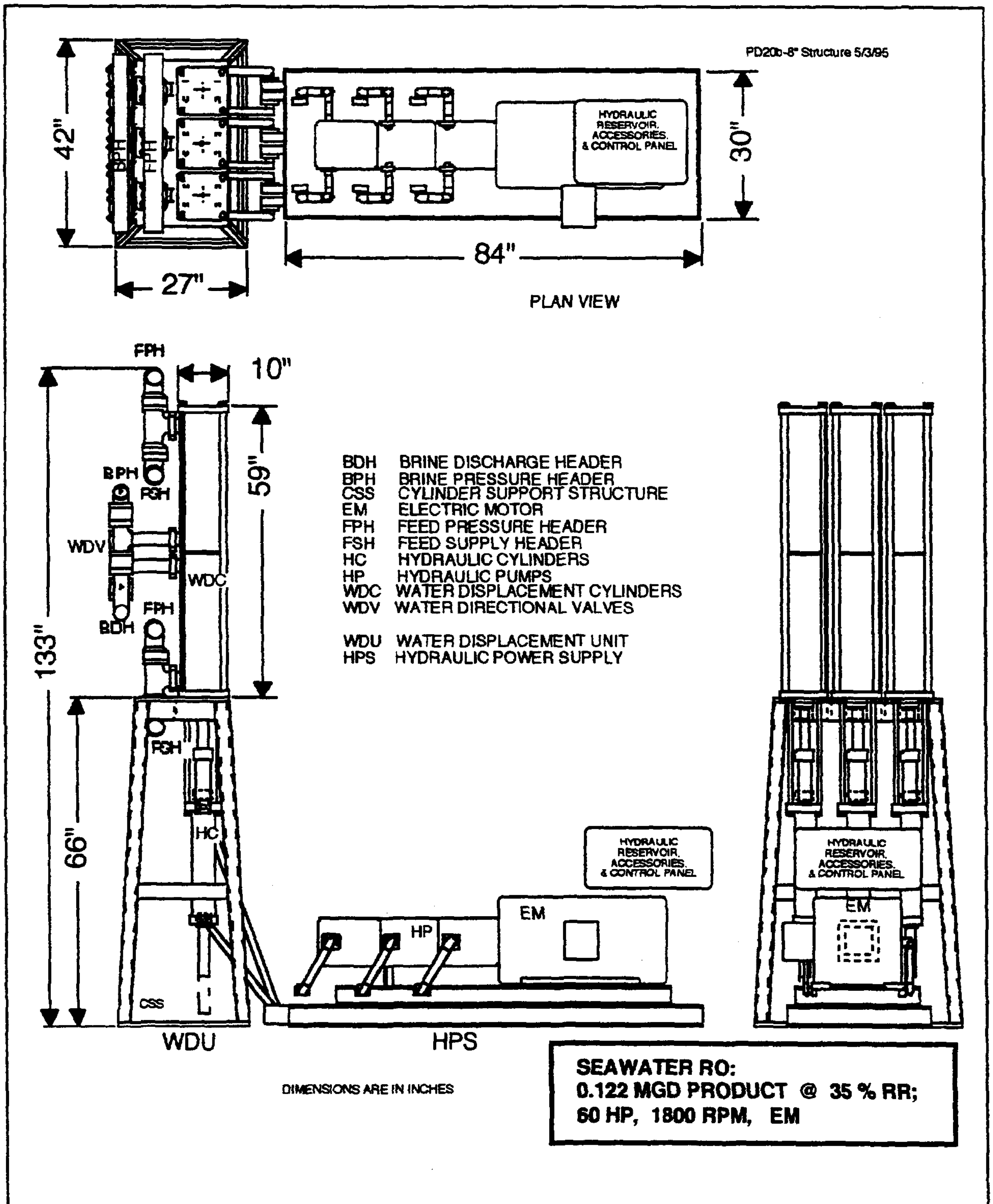


FIGURE 8-1 – VARI-RO Pilot Project Module General Arrangement

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Appendix A

"Performance Projections of FILMTEC Membranes at Various Recovery Ratios"

DOW Chemical Company

DOW

Dow U.S.A.

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

April 10, 1992

Willard Childs
SAIC
4161 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 an 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, 2/2

J. F. Loos

John F. Loos

Appendix B

"Report,
"The VARI-RO™ System,
Preliminary Evaluation"

Henshaw, Terry L.,
Pump Consultant

Terry L. Henshaw, P.E.
Consulting Engineer

2 August 1993

REPORT

Prepared for:
Willard D Childs
582 Rancho Santa Fe Rd
Encinitas CA 92024

Subject: Reverse Osmosis (RO) Desalination Project
Direct-Acting Pump with Energy Recovery
The VARI-RO™ System,
Preliminary Evaluation

The following comments have been prepared after a review of the June 20, 1993, Rev. B 30-page report, describing the VARI-RO™ system; and our meeting at the San Francisco Airport Hilton on July 28, 1993. These comments provide a general impression of the viability of the pumping and energy recovery system, and a suggestion for possible improvement. The time constraint precluded a detailed analysis.

To obtain additional detail about some of my comments, please refer to my book entitled **"RECIPROCATING PUMPS"**, Von Nostrand Reinhold Company, 1987. Page number references to this book have been noted, for example, as [RP-10].

TYPE OF PUMP

The VARI-RO™ reciprocating pump is what is known in the industry as a direct-acting pump (as distinguished from a power pump) [RP-1,2,3,4]. A **direct-acting** pump transfers energy from one fluid to another. A **power pump** transfers energy from a rotating driver (such as an electric motor) to a fluid. The power end of a power pump includes a power frame, crankshaft (or camshaft), connecting rods, and crossheads. A direct-acting pump contains none of these parts.

Since about 1950 power pumps have become more popular than direct-acting pumps; however, direct-acting pumps are still used for certain very demanding applications. An illustration of this is the use of direct-acting pumps for hot oil service (up to 4000 psi & 700 °F) in petroleum refineries [RP-57]. *"The inherent low speed of these units also generally leads to less maintenance than power pumps in similar hot services."* [RP-59]. [This is actually an understatement. A D-A pump usually requires an order of magnitude less maintenance than a power pump in the same service.]

Common driving fluids for direct-acting pumps include: steam, compressed air, or other fluids under pressure available at a process plant. This also includes hydraulic fluids to drive intensifiers for high pressure water jet cutting of concrete, metals, leather, cloth, and other materials.

With respect to reciprocating positive displacement (PD) pumps, the following comments are made:

1. Numerous direct-acting pumps have been built for demanding services.

2. The direct-acting pump, when driven by a liquid and designed for minimal pressure drops through the valves, is a very efficient machine. It is the most efficient method I'm aware of for transfering energy between two liquids. The only losses are the packing friction and the pressure drops through the valves and fluid passages. With careful attention to these factors, efficiencies above 90%, and possibly 95%, are achievable.

3. Direct-acting pumps have been built for RO systems to transfer energy from the high pressure brine to the feed water, although I know of no commercial applications.

NOTE: During our meeting you described a system known as the flow work exchanger (FWE), which is presently being used for production and sale of desalted water, but the system is not presently being offered for sale to other users.

4. Electric motor driven power pumps (crank type) are commonly used as feed pumps in smaller RO systems. (Larger

systems typically use centrifugal pumps). These power pumps typically have efficiencies in the range of 85% to 92%, and operate at speeds up to 400 RPM. Most of the efficiency loss is in the power end (crossheads and bearings), with the remaining losses in the packing friction and valve pressure drops. Additional losses occur in the speed reducer (belts or gearing); and from variable speed drives, if used.

5. Power pumps are more efficient than centrifugal pumps, but typically require more maintenance, leak more, and contribute to system pulsation. The higher maintenance is one of the reasons that careful attention is given to the capability to replace fluid end wear parts, such as valves, packing, plungers, and liners. Higher maintenance is partially attributed to operating at higher speeds to reduce the size of the equipment. The lives of power pump components are significantly extended by operating at lower speeds.

NOTE: You have pointed out that the VARI-RO™ system would operate at low cycle speeds, typically 20 CPM, as compared to the 100 to 400 RPM that is typical for power pumps. My personal experience, and the referenced papers on slurry pumping referred to on Page 12 of your 6/20/93B document, indicate that the VARI-RO™ system can be designed to provide long operating life for clean seawater service.

6. Direct-acting pumps, because of their lower speeds, typically require less maintenance, and pulse less, than power pumps; although pulsation is normally more than a centrifugal. (However, the standard gas driven, duplex [2 pistons], direct-acting pump produces a negligible pulse if the valves are in good condition and properly set.)

NOTE: In your 6/20/93B report, the trapezoidal wave form, as illustrated in Figures 4 and 11, seems to be a viable method for reducing pulsations in both the suction and the discharge lines, thereby minimizing the need for discharge pulsation dampeners and suction stabilizers [RP-261] commonly use with power pumps.

In the case of power pumps, the sinusoidal flow pulsation [RP-144] can be be reduced (but not eliminated) by using more pistons or plungers (ie., triplex {3}, quintuplex {5}, or septuplex {7}) [RP-143].

EXPERIENCE

You had reported that a prototype of the VARI-RO™ system has been built and operated; however, this experience was not covered in the 6/20/93B report. The photos you showed me in the 7/28/93 meeting were helpful in understanding the system, and the description of your experiences during the four, or so, years of operation were enlightening.

I suggest that a summary report of this experience be written to supplement the 6/20/93B report. Problems encountered should be described. They were not basic flaws, but hardware problems as encountered in any development program.

MAIN CONCERN

The VARI-RO™ system utilizes a hydraulic system (electric motor driven) to supplement the power from the reject brine. The advantages are that it eliminates the need for a main charging pump (centrifugal or power) and provides for recovery of all energy from the reject. However, it introduces additional equipment and additional cost over the direct-acting method discussed in Type of Pump comment #3.

> NOTE: After our 7/28/93 meeting, I now have a better understanding of the VARI-RO™ hydraulic system and some of its benefits. The capability to precisely control piston speed, and stop the piston (dwell) before shifting the energy recovery valves seems to be beneficial. Without controlled acceleration and deceleration, there can be significant shock.

The hydraulic system seems to have merit; however, I suggest that its design and application be thoroughly reviewed as outlined in TASK 4 in the 6/20/93B report PREFACE.

EFFICIENCIES

The 99% and 98% efficiencies stated in Figure 1 seem high. I would expect these values to be closer to 95%; however, this depends on the factors covered previously in comment #2.

> **NOTE:** As discussed during our meeting, the low differential pressure across the piston, see Figure 7, in the "concentric" configuration may give a higher efficiency than the "in line" configuration shown on Figure 1. This depends on the materials and finishes selected for the "outboard" packing gland seals and the recovery ratio rod. It appears that changing this configuration as suggested in Miscellaneous Comment #8 would increase efficiency.

An overall efficiency of 95% for both the feed water and the reject brine pistons may be obtainable. This is an allowance of 97% for the feed water and 98% for the reject brine. In any case, the efficiency will be significantly higher than centrifugal pumps.

Testing will be needed to verify the specific energy consumption (SEC) values given in TABLE 1.

MISCELLANEOUS COMMENTS

1. (Pg. 1) - For fairness, it would seem that efficiency comparisons should also be made to power pumps with Pelton Wheel energy recovery, and also to direct-acting pumps without the hydraulics, ie the flow work exchanger (FWE).

2. (Pgs 8 & 9) - It was unclear as to what was meant by the statements that the *"...centrifugal pump ...must provide the full flow and pressure to the system..."*. and *"...the hydraulic pump ... only needs to provide differential power..."*. This needs clarification.

3. (Pg 9) - What happens to the recovery ratio when the membrane fouls?

> **NOTE:** Your reply was that with the VARI-RO™ system the recovery ratio remains constant because it is determined by the piston areas. In the case of a centrifugal system, the recovery ratio is controlled as membranes foul by a combination of adjusting pump speed with the variable speed drive, and throttling the brine flow.

4. (Pg 10) - Zero pulsations - Although possibly attainable when all valves are functioning properly, pulses will be present if the valves malfunction. (For instance, a leaky suction or discharge valve on the pump will produce a pulse.)

5. (Pg 10) - Pulsation Dampeners - "Large" pulsation dampeners are not normally required with power pumps. The size is a function of the number of pistons and displacement per stroke. [RP-262]

6. (Pg 11) - Concentric Displacement unit versus the inline version. It is not clear why only the latter design is "concentric".

NOTE: Your reply was that, with the concentric arrangement, the brine flow is in the same cylinder barrel as the feed flow, and thus is "concentric". This is a term coined to distinguish this from the inline arrangement, where the feed and reject flows are into separate cylinder barrels as shown on Figure 1.

7. (Pg 11) - Is the unit going to be designed to run vertically? If so, what provisions will be made to vent air from the cylinders?

8. (Pg 11) - Figure 7 and 8 illustrates a unit with two outboard high pressure seals. It appears that one of these seals could be eliminated if the sleeve was in the center, and the reject fed into the center of the unit, with the feed water on the outboard ends. This configuration would reduce seal friction and increase efficiency.

9. (Pg 11) - Hydraulic Drive Unit - Why supercharging pumps? These will consume more power and result in more equipment to maintain. If the system is so efficient, why is a cooler required?

NOTE: Your reply was that, hydrostatic pump systems are closed loop systems and require a supercharge pump of sufficient capacity to makeup for internal leakage and to assure that the hydraulic pump (at say 1800 RPM) has sufficient NPSH (net positive suction head). Usually the supercharge pump is integral to the hydrostatic pump unit.

The cooler is necessary because the case size is much smaller than a power pump of similar power and efficiency, and as a result does not have sufficient surface area to dissipate the 10% energy loss of this device.

10. (Pg 12, 6.1) - Why do the proposed cycle speeds compare to 100 RPM? As written, it is not clear to the reader that the lower cycle speed (20 CPM) of the VARI-RO™ unit will provide longer life than conventional power pumps that operate at over 100 RPM.

11 (Pg 18, Figure 10) - These look like PD pump check valves. How can they control the flow of the high pressure reject?

NOTE: In our meeting, you explained how the pilot method functions to control the opening and closing of these valves. In fact, the priciple of operation is the same as that of a high-pressure valve that I recently designed for one of my clients.

RECIPROCATING PUMPS versus CENTRIFUGAL PUMPS

Centrifugal pumps are typically selected for applications with higher capacities and lower heads.

Reciprocating pumps are selected for applications for which centrifugal pumps are unsuitable. The severity of these services contribute to the higher maintenance requirements of reciprocating pumps. Other reasons for higher maintenance include: (1) power pumps selected at high speeds in order to reduce the size of the pumps and speed reducers. (This imposes high cyclic stresses on pump and system components.), and (2) systems not designed to compensate for the high-frequency pulsing flow.

Reciprocating pumps are, however, used satisfactorily for a wide range of applications [RP-53], including high capacity applications discussed in the references quoted in the 6/20/93B report, page 12. These high capacity applications include oil well drilling mud, secondary recovery, salt water disposal, and well servicing. As an example, Wilson-Snyder Pump Company has built reciprocating pumps with capacities to 4000 GPM.

Reasons for using reciprocating pumps include: higher efficiency, ability to adapt to a wide range of system conditions, and severe service unsuitable for centrifugal pumps.

Higher efficiency operation of reciprocating power pumps is covered in the case study by Barry W. Brown, USN (Retired), entitled **"SAVING ENERGY WITH POWER PUMPS"** [RP-318].

CONCLUDING COMMENTS ON THE VARI-RO™ SYSTEM

In my brief review of the VARI-RO™ system from the 6/20/93B report and our 7/28/93 meeting, I found the system to be well conceived. I see no reason that the system cannot be designed to provide satisfactory service in either high or low capacity applications. Careful attention, of course, will be necessary in valve selection [RP-23], rod packing gland and piston seal designs [RP-34, & 76-136], and the selection of materials for seawater service.

The slow cycle speeds and the trapezoidal piston velocity profile should solve major problems of crank type power pumps.

My primary concern is with the hydraulic drive system. I am not familiar with the detail design of this type of power and control system. I suggest it be reviewed as outlined in TASK 4. Also, I did not attempt to evaluate the value of the energy savings, and other benefits, as outlined for TASKS 1 and 2.

Appendix C

"Comparative Economic Analysis
of
VARI-RO Technology
for
Large Seawater RO Plants"

Palmyra Group, Inc.

COMPARATIVE ECONOMIC ANALYSIS OF VARI-RO TECHNOLOGY FOR LARGE SEAWATER RO PLANTS

Prepared for
Science Applications International Corporation

Prepared by
Palmyra Group Inc.

June 1994

Table of Contents

COMPARATIVE ECONOMIC ANALYSIS OF VARI-RO TECHNOLOGY FOR LARGE SEAWATER RO PLANTS

1.0 INTRODUCTION

The purpose of this study is to provide a brief technical overview of VARI-RO technology for large seawater reverse osmosis (RO) desalination plants and to develop cost comparisons of VARI-RO technology vs. conventional high pressure feed pump and energy recovery systems for a 30 MGD seawater reverse osmosis (RO) plant located in the San Diego region.

Tasks completed for the study included::

- Review of VARI-RO documents provided by SAIC
- Meeting with Will Childs to develop study assumptions
- Technical overview of VARI-RO technology
- Base case economic modeling
- Economic sensitivity analysis

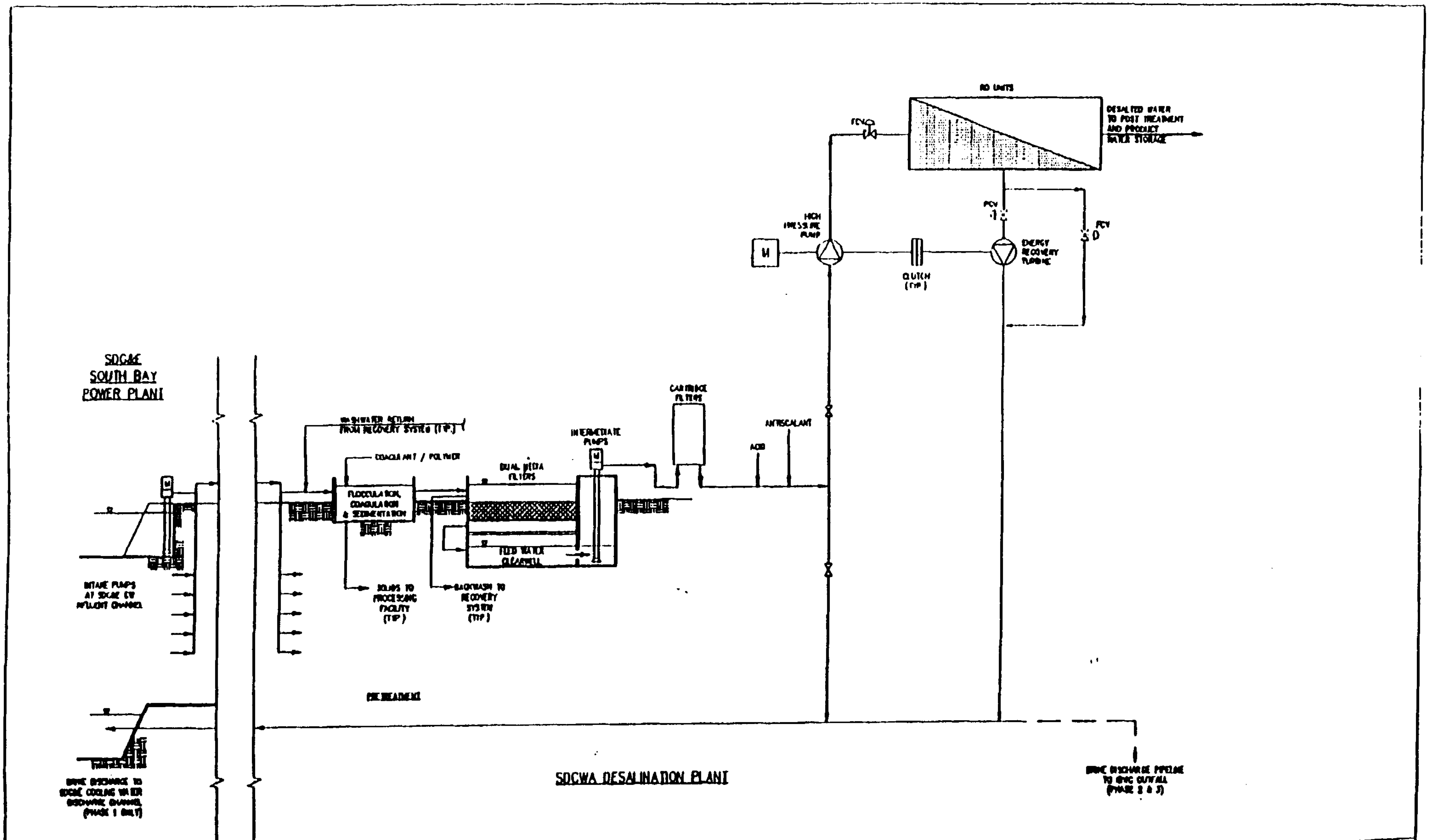
The results of the study are summarized in the following sections.

2.0 TASK 1 - OVERVIEW OF VARI-RO TECHNOLOGY

A technical overview of VARI-RO systems applied to large seawater RO plants located in the San Diego region was performed to develop a perspective of basic concept viability and specific energy savings for the desalination plant.

2.1 Reference Plant Design

The San Diego County Water Authority's South Bay Desalination Project was selected as a reference design for the 30 MGD seawater RO plant. The South Bay Desalination Plant would be located on San Diego Gas & Electric Company's (SDG&E) South Bay Power Plant site in Chula Vista, California. A schematic of the plant is shown on Figure 2-1. Major design features of the plant are shown on Table 2-1.



JOB NO. 3701A.00
DESIGN: K. FRANK 3/94
DRAWN: D. JENSEN 3/94
CHECKED: K. FRANK 3/94

JOHN CAROLLO ENGINEERS

SAN DIEGO COUNTY WATER AUTHORITY

SOUTH BAY DESALINATION STUDY

FIGURE NO. 2-1

TYPICAL RO TRAIN PROCESS SCHEMATIC

The overall facility includes a seawater intake system, pretreatment system, RO plant, product water system and a brine disposal system . The seawater intake is located in the power plant intake channel and provides approximately 67 MGD of flow to the pretreatment plant. The pretreatment plant includes coagulation, flocculation, sedimentation and media filtration. From the pretreatment plant, seawater is pumped to RO plant which is configured into six 5 MGD unit trains each with a high pressure feed pump and energy recovery unit. The high pressure feed pumps are conventional centrifugal units with a rated efficiency of 82.9%. The pumps are driven by electric motors with variable speed drives (VSD) with a combined rated efficiency of 92%. Energy is recovered through the use of reverse-running centrifugal pumps operating at an efficiency of 75% which return mechanical energy to the high pressure feed pump drives.

Table 2-1 **Reference Desalination Plant** **Design Factors**	
RO Plant Product Water Capacity (MGD)	30
RO Plant Recovery (%)	45
Average Seawater Salinity (mg/l)	34,500
Design Feedwater Temperature (Deg F)	68
Brine Discharge Flow (MGD)	37
Installed Electric Power (MW)	28
RO Feed Pump Head (psi)	960
Brine Pressure at Energy Recovery Unit (psi)	931
Number of 5 MGD RO Unit Trains	6
Number of Spiral RO Membrane Elements	10,416

Product water, at a flow of 30 MGD is treated with lime and sodium hydroxide, then stored in an on-site tank. The product water distribution system includes a 48 inch diameter pipleline extending approximately 10 miles from the desalination plant to the Water Authority's aqueduct east of Chula Vista. Brine from the desalination plant is pumped through a 36 inch diameter pipeline from the desalination plant to the International Wastewater Treatment Plant located at the International Border. There the brine is mixed with treated sewage from the wastewater treatment plant and discharged through a 12 foot diameter pipeline and tunnel system which extends 3.5 miles to sea just north of the U.S./Mexico border.

The total power usage of the RO system is 32.4 megawatts (MW). However, the total installed electric power for the desalination plant reflects the use of the energy recovery system and is 27.8 MW including the RO plant, miscellaneous on-site pumping the pumping for the product water and brine discharge pipelines. Of this, 16.9 MW of net electric power are required for the high pressure RO feed pump drives, based on 24.6 MW of high pressure feed pump power minus 7.7 MW recovered through the energy recovery units. The ancillary equipment associated with the desalination plant, excluding the product water distribution system pumping and brine disposal pumping, adds 4.6 MW to the overall power. This gives a net power requirement for economic comparison purposes of 21.5 MW. For technical comparison purposes, only the 16.9 MW associated with the high pressure pumps is considered. The distribution is summarized below.

COMPARISON	Technical Analysis	Economic Analysis
System Power (MW)	35.52	35.52
Less Energy Recovery System	-7.72	-7.72
Installed Electric Power	27.8	27.8
Less Distribution/Brine Disposal	-6.26	-6.3
Less Ancillary Equipment	-4.59	included
NET MW FOR COMPARISON	16.95	21.54

Operation of the desalination plant is assumed to be steady-state at a average capacity/availability factor of 90%.

2.2 *Overview of VARI-RO Technology*

The VARI-RO system, using positive displacement high pressure RO feed pumps and energy recovery units, offers potential energy savings over the conventional centrifugal pumping and energy recovery systems assumed in the reference plant design. Key technical questions which need to be addressed in considering a choice of VARI-RO technology for such a project include:

- Is the VARI-RO concept basically sound?
- Will VARI-RO have equivalent reliability to centrifugal pumping systems?
- What are the actual energy savings for the reference desalination plant?
- What are the uncertainty factors for predicting energy usage?

Technical Viability of the VARI-RO Method

Based on a limited review of VARI-RO literature including the report prepared by Mr. Terry Henshaw plus our own experiences with the specification and operation of high pressure positive displacement reciprocating pumps for RO systems, we conclude that the VARI-RO concept is viable. The specific performance factors for the technology, such as component efficiencies, will need verification through testing. The technology offers a definite potential for reducing energy usage in RO desalination plants.

Operating Reliability

From a practical operating standpoint, the VARI-RO system has considerably more mechanical parts than a comparable centrifugal pumping system and may require higher operator skills for optimizing system performance and trouble-shooting problems. The system would also be more maintenance-intensive.

The potential operating and maintenance drawbacks of the VARI-RO system can be mitigated to a fair degree by conservative design practices addressing slow cycle speeds, valve design, packing design, materials selection and careful attention to control systems. With a sound design approach, it is likely that equivalent reliability can be achieved. However, the operator skills and maintenance costs to achieve this level of reliability are likely to be greater than those of comparable centrifugal pumping and energy recovery systems.

Energy Savings for the South Bay Desalination Plant

A comparison of energy efficiency of the conventional RO high pressure feed pump system vs. the VARI-RO system is shown on Table 2-2. VARI-RO efficiency figures are from Terry Henshaw and Will Childs. Conventional system efficiency figures are from the South Bay Desalination Project Final Report.

Table 2-2
Base Case
Component Efficiency

Component	Conventional System Efficiency (%)	VARI-RO System Efficiency (%)
Electric Motor		95
Electric Motor/VSD	92	
Hydraulic Drive		88
High Pressure Pump	83	97
Energy Recovery Unit	75	98

The total RO plant electric power requirement for the VARI-RO system is given by equation 1. Equation 2 gives the same formula for the conventional RO system. The equation power relates only to the actual high pressure RO pump power, and does not include ancillary power requirements, such as seawater pumping, filter air, and so on.

Equation 1

$$Megawatts = \left(\frac{746}{1714 * 10^6 * e_M * e_H}\right) * \left(\frac{q_F * p_F}{e_{FP}} - \frac{q_B * p_B * e_{BP}}{1}\right)$$

Equation 2

$$Megawatts = \left(\frac{746}{1714 * 10^6 * e_{M/VSD}}\right) * \left(\frac{q_F * p_F}{e_{FP}} - \frac{q_B * p_B * e_{BP}}{1}\right)$$

Where:

q_F = feedwater flow, gpm
q_B = brine flow, gpm
p_F = feedwater pressure, psi
p_B = brine pressure, psi
e_{FP} = feed pump efficiency, fraction
e_M = electric motor efficiency, fraction
e_H = hydraulic drive efficiency, fraction
e_{BP} = energy recovery unit efficiency, fraction
$e_{M/VSD}$ = electric motor/variable speed drive efficiency

The estimated total power requirement using the VARI-RO system for the South Bay Desalination Plant can be calculated as follows:

$$Megawatts = \left(\frac{746}{1714 * 10^6 * 0.95 * 0.88}\right) * \left(\frac{46296 * 960}{0.97} - \frac{25463 * 931 * 0.98}{1}\right)$$

$$Megawatts = 11.76$$

This compares to the estimated total RO system power requirement for the conventional system, using equation 2, of 16.9 MW. Thus, the VARI-RO system produces an electric power reduction of 31% based on the standard RO power.

Impact of Energy Use Assumptions

Based on VARI-RO's design analysis, the lower limits for energy efficiency of the VARI-RO system components are:

- Hydraulic Drive System: 85%
- High Pressure Feed Pump: 95%
- Energy Recovery Unit: 95%

Applying these figures to the reference desalination plant produces an installed power requirement for the reverse osmosis system itself of 13.1 megawatts as compared with 16.9 megawatts for the conventional system. This results in a 22.8% energy use reduction for the desalination plant under assumed worst-case efficiencies for the VARI-RO system.

Effect of Variable Operating Parameters

To investigate the sensitivity of the system to changing parameters and changing performance variables, a rudimentary model was constructed. Figures 2-2, 2-3, and 2-4 illustrate.

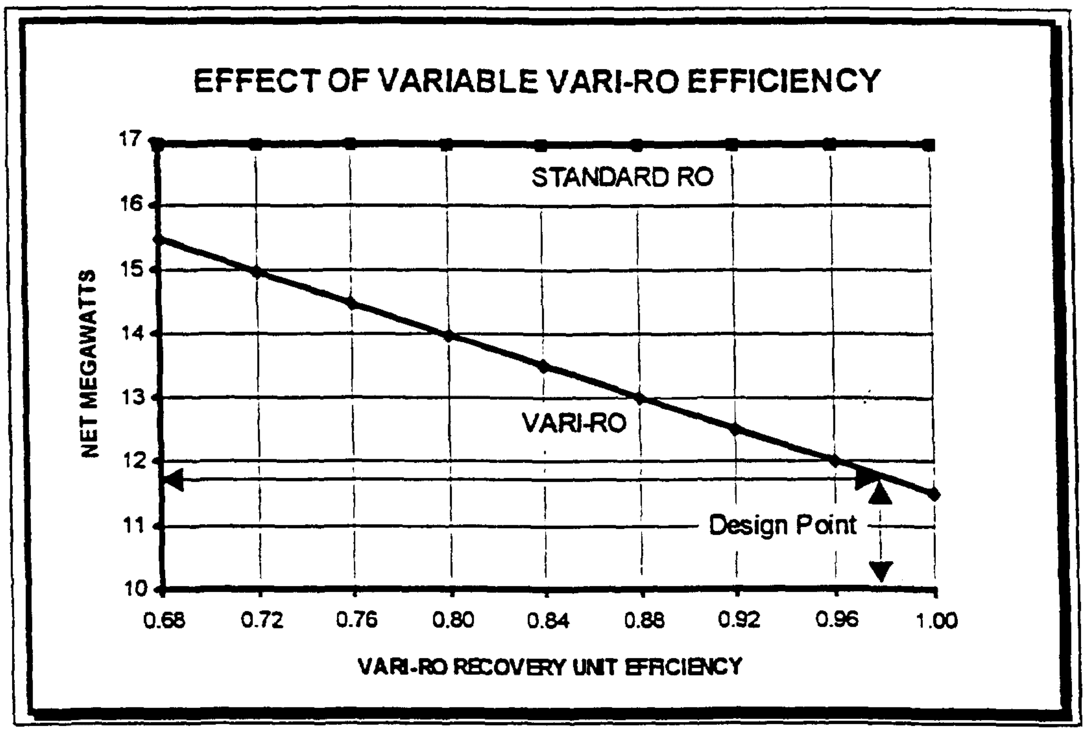


Figure 2-2

Note that the greatest effects come with variable RO feed pump efficiency. Some seawater RO systems do in fact use high efficiency piston type pumps so the high range of efficiency is over 90%. However, the vast majority use centrifugal pumps, with efficiencies as low as 65%. Note however, that even at 100% pump efficiency, the VARI-RO system still offers an energy advantage over the conventional RO system.

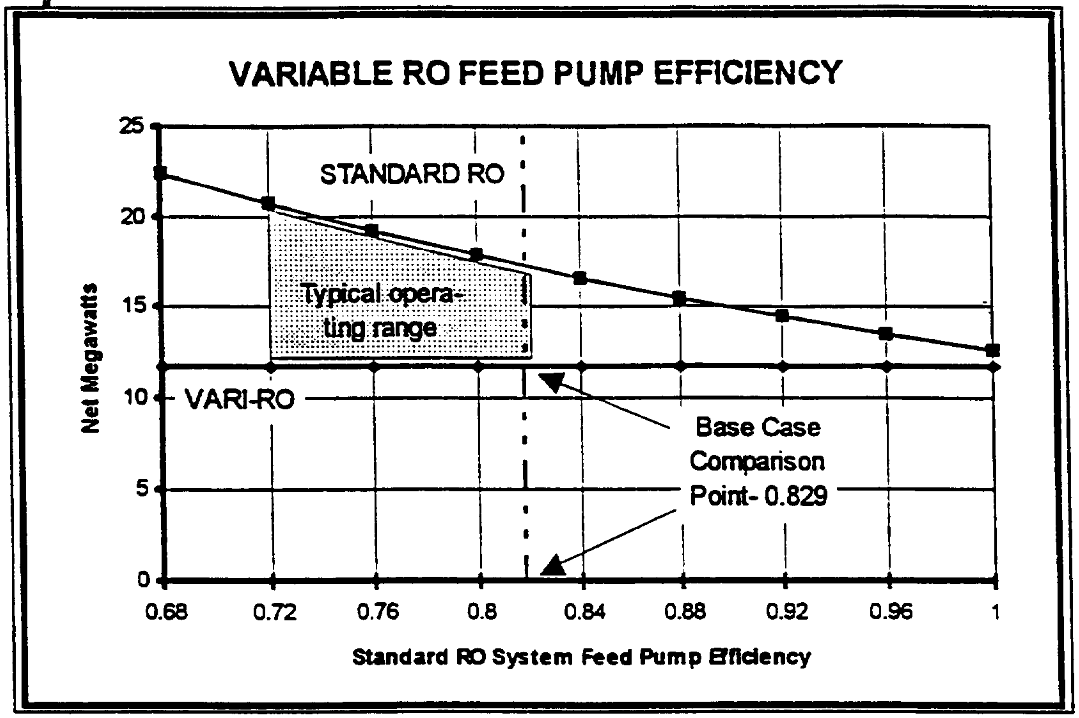


Figure 2-3

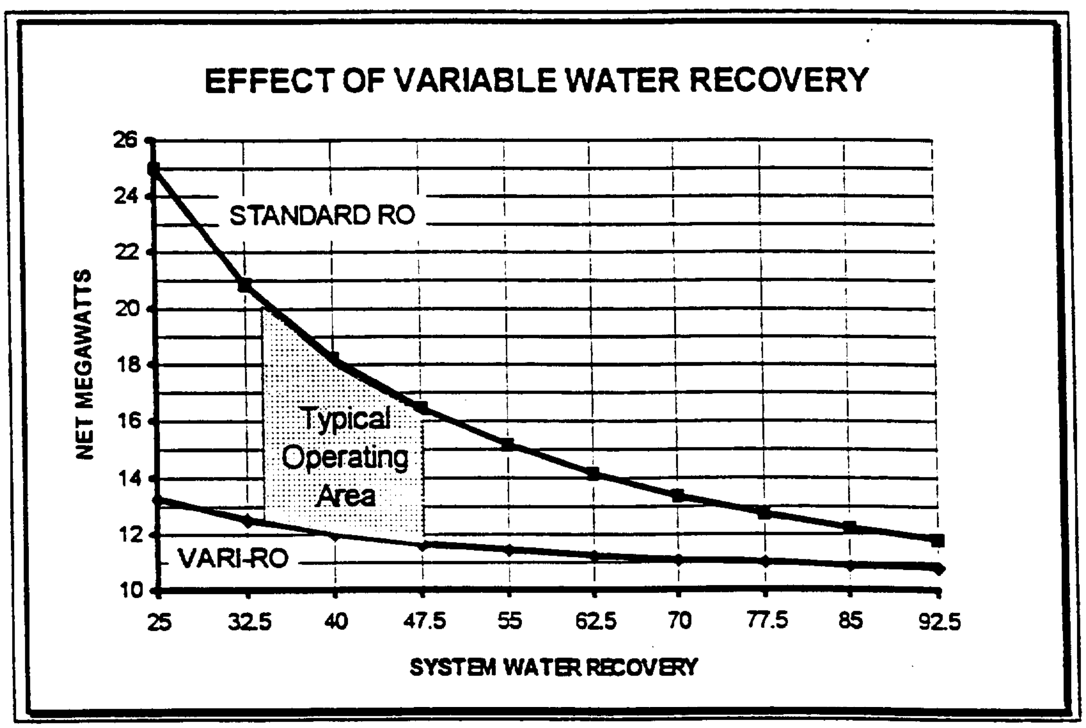


Figure 2-4

3.0 TASK 2 - ECONOMIC ANALYSIS

Economic analysis tasks included:

- Development of economic assumptions
- Capital cost estimates of pumping and energy recovery equipment
- Base case economic modeling
- Sensitivity analysis of energy efficiency, capital cost and electricity price

3.1 Economic Assumptions

Project Economic Factors

Project economic factors to be applied in the economic analysis were derived from the South Bay Desalination Project Final Report. These are shown on Table 3-1.

Capital Cost Assumptions

Economic comparisons of VARI-RO vs. conventional systems were based on the capital, operating and maintenance cost differences for the electric motor drives, high pressure feed pumps, energy recovery units and associated power supply and controls equipment. Capital costs for conventional equipment were derived from the South Bay Desalination Project Final Report and supplier quotations. Capital cost estimates for VARI-RO equipment were provided by Will Childs and derived from estimates of electrical equipment provided by the General Electric Company.

The capital cost assumptions used in the economic analysis are shown on Table 3-2.

Operating and Maintenance Cost Assumptions

Operating labor costs for the VARI-RO system were assumed to be the same as the conventional system. While specialized operator training may be required for the VARI-RO system, long-term operating labor costs shouldn't differ significantly between the two systems. Maintenance costs for the VARI-RO system were assumed as 1.6% of the installed equipment cost , or double the 0.08% factor assumed for the conventional system.

Table 3-1 Economic Factors 30 MGD Desalination Plant	
Desalination Plant Discount Rate (%)	7.5
Equipment Escalation Rate (%)	5.5
O&M Escalation Rate (%)	5.5
Capital Recovery Factor (Based on Startup Year)	0.0847
Cost Basis	1994 dollars
Startup Year	1996
Contingency (% of Direct Installed Costs)	20.0
Installation (% of Equipment Cost)	25.0
Basis for Indirect Costs (% Total Direct Capital Cost)	
Engineering	15.0
Permitting & EIR	1.0
Interest During Construction, % total	2.0
Labor Cost ($/Year Including 45% Overhead)	
Operators and Maintenance Personnel	68,575
Administrative Staff	80,707
Land Lease Cost ($/Acre/Year)	31,650
Wastewater Disposal Cost ($/kgal)	4.84
Sanitary Waste Disposal Cost ($/kgal)	1.12
Chemical Cleaning Waste Disposal ($/kgal)	1,113
Electric Energy ($/kwh)	0.06
Chemical Costs ($/LB)	
Ferric Chloride	0.26
Sodium Hexametaphosphate	0.97
Sodium Bisulfite	0.47
Polyelectrolyte	0.34
Sulfuric Acid	0.07
Lime	0.09
Chlorine	0.16
Carbon Dioxide	0.16
Sodium Hypochlorite	0.50
Ammonia Hydroxide	0.26
Membrane Replacement Cost ($/Membrane Element)	1,300

Table 3-2 Pumping System Equipment Costs 30 MGD Desalination Plant		
Equipment Item	Conventional System	VARI-RO System
HV Circuit Breaker	$40,000	$80,000
15/20 MVA Transformers		$450,000
30/40 MVA Transformer	$330,000	
Secondary Circuit Breakers	$25,000	$50,000
1200 A Feeder Circ. Breaker	$240,000	
Isolation Transformers	$600,000	
Tie Circuit Breaker		$25,000
Limit Amp Motor Starter		$180,000
Induction Motor Drives	$2,400,000	
Induction Motors	$1,050,000	$720,000
Hydraulic Drive Units		$2,400,000
High Pressure Pumps	$1,440,000	$6,040,000
Energy Recovery Units	$1,513,000	Included
Total Equipment Cost	**$7,638,000**	**$9,945,000**
Differential Cost		**$2,307,000**

3.2 Base Case Economic Comparisons

Base case economic comparisons of VARI-RO vs. conventional systems were run on an economic model developed for the reference desalination plant. The desalination plant design configuration assumed in the analysis included the intake system, pretreatment system, RO plant, product water treatment and storage system and the waste treatment and disposal system. The equipment and O&M costs for the VARI-RO and conventional systems were assigned as described in Tables 2.2, 3.2 and Section 3.2. All other desalination plant capital and O&M costs were considered the same for both concepts and were derived from the South Bay Desalination Project Final Report.

The results of the base case economic comparisons are shown on Table 3.3.

Table 3-3 Base Case Economic Comparison		
PRODUCT WATER CAPACITY, MGD	30	30
SYSTEM DESCRIPTION	STANDARD RO	VARI-RO
Base Year	1994	1994
Direct Installed Costs		
Seawater Supply System	$2,737,411	$2,737,411
Pretreatment Equipment	$32,204,977	$32,204,977
Desalination Equipment	$19,378,855	$19,378,855
RO Membrane Elements	$13,536,069	$13,536,069
VARI-RO EQUIPMENT DIFFERENTIAL	$0	$2,307,000
Product Water Treatment & Storage	$2,615,289	$2,615,289
Civil Works	$11,742,978	$11,742,978
Installation & Startup	$8,228,731	$8,805,481
Total Direct Installed Cost	$90,444,310	$93,328,059
Indirect Costs		
Engineering	$13,566,646	$13,999,209
Permitting/EIR	$904,443	$933,281
Interest During Construction	$1,808,886	$1,866,561
Environmental Mitigation	$4,522,215	$4,666,403
Administration, Legal & Fiscal	$4,522,215	$4,666,403
Contingency	$18,088,862	$18,665,612
Waste Disposal (1 time charge)	$706,839	$706,839
Total Indirect Cost	$44,120,108	$45,504,308
Total Capital	$134,564,418	$138,832,367
Power Usage		
System Operating Power, MW	21.54	16.35
KWH/yr	169,821,360	128,903,400
1994 O&M Costs		
VARI-RO Differential Maintenance @1.6%	$0	$68,287
Electricity Cost	$10,189,282	$7,734,204
Chemical Cost	$2,525,726	$2,525,726
Labor Cost	$952,687	$952,687
Maintenance and Replacement	$1,076,515	$1,076,515
Membrane Replacement Cost	$1,624,328	$1,624,328
Insurance	$672,822	$694,162
Filter Sludge Disposal	$617,431	$617,431
Land Lease	$76,726	$76,726
Total 1994 O&M Cost	$17,735,517	$15,370,066
Cost Summary Data		
30 Year Levelized Capital COW, $/AF	$377	$389
1994 O&M Cost, $/AF	$587	$508
1994 Total COW, $/AF	**$963**	**$897**

The VARI-RO system shows a total water cost advantage of approximately $66/acre-foot, or about $2.4 million per year. This is about 7% of the total cost of water.

The total capital cost of the desalination plant with the VARI-RO system is about 3% higher than the total capital cost with the conventional pumping and energy recovery system. This indicates that the capital cost impact of the VARI-RO system is small with respect to the total capital cost.

Energy cost savings for the VARI-RO system are about $2.5 million per year, or about 24% of total energy cost at at an electric power price of $0.06/kwh. This cost advantage is slightly offset by a higher maintenance cost of about $0.1 million per year, producing a total cost advantage for the VARI-RO system of $2.4 million per year, or about 13% of the total O&M cost.

3.3 Economic Sensitivity Analysis

An economic sensitivity analysis was performed to determine the comparative costs of conventional vs. VARI-RO systems for the following variables:

- **Reducing energy efficiency in the VARI-RO system to 85% for the hydraulic unit, 95% for the high pressure pumping unit and 95% for the energy recovery unit.** This raises the VARI-RO energy to 13.1 MW and the total system energy to 17.7 MW for the VARI-RO system versus 21.5 MW for the conventional system. The net effect on the overall cost of water is to raise the VARI-RO system cost to $918/acre-foot, versus $897/acre-foot at the base case efficiency assumptions.

- **Increasing capital cost of the hydraulic unit by 15% and the displacement unit (high pressure pumping and energy recovery system) by 30%.** This raises the net differential capital cost of the VARI-RO system from $2,307,000 to $4,479,000.

  $$\$4{,}479{,}000 = \$2{,}307{,}000 + \$6{,}040{,}000 * 0.30 + \$2{,}400{,}000 * 0.15$$

  The impact on the cost of water is to raise the overall cost from $897/acre-foot to $911/acre-foot. The relatively small effect is due the small percentage of capital cost made up by the VARI-RO system. This effect has important implications for developing a price strategy for the finished product.

- **Decreasing high pressure centrifugal feed pump efficiency to 75%.** This raises the conventional system energy from 16.9 MW to 21.6 MW. The overall conventional system power is therefore raised to 26.2 MW. This raises the conventional system cost of water from $963/acre-foot to

$1,037/acre-foot. The VARI-RO system advantage in this case rises to 13.5% versus 7% at the design conditions.

- **Varying electricity price.** Figure 3-1 illustrates the effect of varying electricity price on the total cost of water.

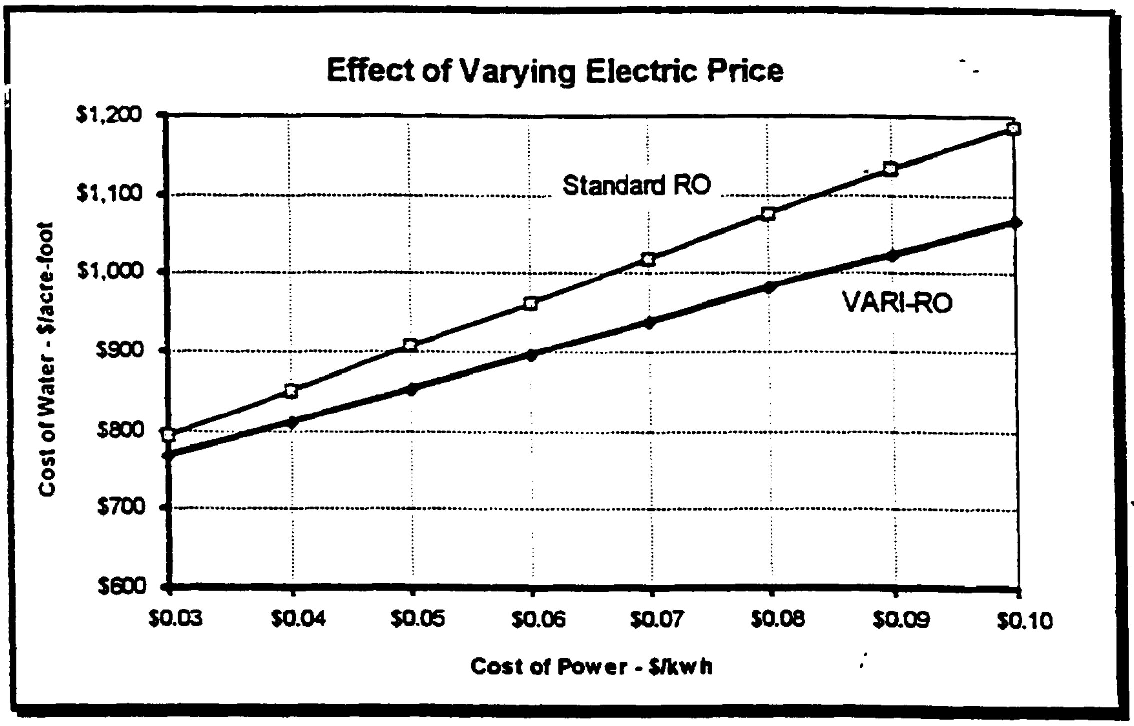


Figure 3-1

The curve is less steep for the VARI-RO system since the higher energy efficiency of the VARI-RO system damps the effect of increasing power costs.

4.0 CONCLUSIONS

- For the assumed base case conditions for a 30 MGD seawater reverse osmosis plant located in the San Diego region, the VARI-RO system produces a total water cost savings of approximately 7% and an annual cost savings of about $2.4 million at an electricity price of $0.06/kwh. The savings result almost entirely from a reduction in energy usage. With an estimated $4.3 million in increased capital cost for the VARI-RO system, the payback on the investment would be about two years.

- At the development state of the VARI-RO process, the accuracy of capital cost estimates may be uncertain. In the sensitivity analysis, an increase of 15% in the capital cost of the hydraulic unit and 30% in the capital cost of the displacement unit reduced the overall cost of water advantage for VARI-RO from about 7% to 5%. On one hand, the capital cost difference for the VARI-RO system, at about 3% of total project capital cost is relatively insignificant. On the other hand, project decisions are often made on a capital cost basis, therefore, the capital cost of VARI-RO equipment must be minimized to ensure a competitive position.

- At base case VARI-RO efficiencies of 88% for the hydraulic drive, 97% for the high pressure feed pump and 98% for the energy recovery unit, the VARI-RO system produced an energy savings of 31%, which is significant. In addition, the VARI-RO system eliminates the need for the variable speed drives, thus reducing the capital cost associated with the drives and the power supply equipment.

- Reducing the energy efficiency assumptions for the VARI-RO system to 85% for the hydraulic drive, 95% for the high pressure feed pump and 95% for the energy recovery unit produces an energy use advantage of 23% as compared with 31% for the base case conditions. This advantage remains significant with respect to total annual cost savings.

- Because of reduced energy usage, the VARI-RO system has greater water cost savings as the price of electricity increases. These potential savings range from about $50/acre-ft at $0.05/kwh to $100/acre-ft at $0.08/kwh for assumed base case conditions.

- Reducing the assumed efficiency of the conventional centrifugal pumping system from the base case of 82.9% to 75% would raise the total water cost advantage of the VARI-RO system from 7% to 13.5%. Because many centrifugal pumping systems operate with efficiencies close to 75%, such an advantage may be possible.

- The VARI-RO system could potentially allow a lower recovery rate to be selected without a major energy use impact on the overall desalination facility. Lowering the system recovery would, for example, allow operation with either less membrane elements or at lower operating pressures. The reduced osmotic pressure (feed/reject log mean average) would also result in higher quality (lower TDS) product water for a given set of operating conditions. On the other hand, changing the recovery rate would affect the plant layout, the number of RO pressure vessels, brine pumping system, brine pipeline sizes and chemical consumption of the entire system. To effectively evaluate and re-optimize the desalination plant for VARI-RO equipment would require a total facility design and economic analysis.

In summary, there is a definite incentive for commercial development of the VARI-RO method for seawater desalination plants if the performance and cost assumptions used in the study are verified. To achieve verification, we recommend that a program of design refinement, equipment cost estimating, applications analysis and pilot testing be conducted on a sequential basis to confirm the performance and cost advantages of the technology.

Appendix D

Supplementary Data

"CT 1" SPIRAL WOUND MEMBRANES	RECOVERY RATIO (RR) 30%	40%	50%
FLOW RATES			
PRODUCT (MGD)	5	5	5
PRODUCT (GPM)	3,472	3,472	3,472
FEED WATER SUPPLY (GPM)	11,574	8,681	6,944
BRINE DISCHARGE (GPM)	8,102	5,208	3,472
PRESSURES (PSID)			
SUPPLY	20	20	20
MEMBRANE FEED	1,065	1,065	1,065
MEMBRANE PRESSURE DROP	50	50	50
BRINE	1,015	1,015	1,015
BRINE DISCHARGE	20	20	20
EFFICIENCIES (%) [1]			
FEED PUMP [2]	84%	84%	84%
ENERGY RECOVERY TURBINE [2]	85%	85%	85%
ELECTRIC MOTOR	95%	95%	95%
GENERATOR [3]	95%	95%	95%
POWER INPUT (kW)			
FEED PUMPING	6,597	4,948	3,958
ENERGY RECOVERY (generator)	2,833	1,821	1,214
NET (FEED - ENERGY RECOVERY)	3,764	3,126	2,744
RO SPECIFIC ENERGY CONSUMPTION kWh/kGAL for NET energy input	18.06	15.01	13.17
MEMBRANE QUANTITY [4]			
HOLLOW FINE FIBER (HFF) [5]	850	892	970
SPIRAL WOUND (SW)	1824	1986	2250

NOTES [ ] "CT 1":

[1] Eff. were assumed to give the energy consumption stated in the report.

[2] The centrifugal pump & turbine efficiencies seem high.

[3] Generator for systems generating electric power.

[4] Less membrane quantity is required at lower RR at same pressure.

[5] The HFF qty. is based on 1200 psi, which was not used in energy calcs.

EX21a-"BASE"

VARI-RO™ 1 (Compared to "CT 1") SPIRAL WOUND MEMBRANES	RECOVERY RATIO 30%	 40%	 50%
FLOW RATES			
PRODUCT (MGD)	5	5	5
PRODUCT (GPM)	3,472	3,472	3,472
FEED WATER SUPPLY (GPM)	11,574	8,681	6,944
BRINE DISCHARGE (GPM)	8,102	5,208	3,472
PRESSURES (PSID) [1]			
SUPPLY	20	20	20
MEMBRANE FEED	1,065	1,065	1,065
MEMBRANE PRESSURE DROP	50	50	50
BRINE	1,015	1,015	1,015
BRINE DISCHARGE	20	20	20
EFFICIENCIES (%)			
FEED PUMP PISTON [2]	98%	98%	98%
ENERGY RECOVERY PISTON [2]	98%	98%	98%
ELECTRIC MOTOR	95%	95%	95%
HYDRAULIC DRIVE [3]	88%	88%	88%
POWER INPUT (kW)			
FEED PUMPING	6,425	4,819	3,855
ENERGY RECOVERY (pump drive)	4,113	2,644	1,763
NET (FEED - ENERGY RECOVERY)	2,312	2,175	2,093
RO SPECIFIC ENERGY CONSUMPTION kWh/kGAL for NET energy input	11.10	10.44	10.04
MEMBRANE QUANTITY [1], [4]			
HOLLOW FINE FIBER (HFF) [5]	850	892	970
SPIRAL WOUND (SW)	1824	1986	2250

NOTES [ ] "VARI-RO™ 1":

[1] Pressures and membrane qty. the same as "CT 1".

[2] The piston eff. includes packing friction & valve pressure drop.

[3] Hydaulic eff. includes hydraulic pump & cylinder.

[4] Less membrane quantity is required at lower RR at same pressure.

[5] The HFF qty. is based on 1200 psi, which was not used in energy calcs.

EX21a-"BASE"

"CT 2" SPIRAL & HFF MEMBRANES		RECOVERY RATIO 40%	45%	50%
FLOW RATES				
PRODUCT (MGD)	MGD	5	5	5
PRODUCT (GPM)		3,472	3,472	3,472
FEED WATER SUPPLY (GPM)		8,681	7,716	6,944
BRINE DISCHARGE (GPM)		5,208	4,244	3,472
PRESSURES (PSID)				
SUPPLY		20	20	20
MEMBRANE FEED		900	975	1,040
MEMBRANE PRESSURE DROP		50	50	50
BRINE		850	925	990
BRINE DISCHARGE		20	20	20
EFFICIENCIES (%) [1]				
FEED PUMP [2]		74%	74%	75%
ENERGY RECOVERY TURBINE [2]		70%	69%	69%
ELECTRIC MOTOR		95%	95%	95%
GENERATOR (not applicable)				
POWER INPUT (kW)				
MISC. ELECTRICAL [3]		28%	27%	26%
MISC. ELECTRICAL		936	904	848
FEED PUMPING		4,729	4,562	4,327
ENERGY RECOVERY (pump drive)		1,386	1,214	1,065
NET FEED - ENERGY RECOVERY		3,343	3,348	3,262
TOTAL FOR FACILITY (for 6 5 MGD modules		25.674	25.512	24,662
SPECIFIC ENERGY CONSUMPTION		16.05	16.07	15.66
SEC = kWh/kGAL for NET Energy Input to RO				
MEMBRANE QUANTITY [4], [5]				
HOLLOW FINE FIBER (HFF)		NA	NA	5,520
SPIRAL WOUND (SW)		9,504	9,360	NA

NOTES [ ] "CT 2":

[1] Eff. were assumed to give the energy consumption stated in the report.

[2] The cent. pump & turbine eff. are more reasonable than "BASE 1".

[3] Misc. electrical kW as % of NET kW.

[4] The greater membrane qty. at lower RR is due to lower pressure.

[5] The membrane quantities are much greater than shown for "BASE 1".

EX21a-"BASE"

VARI-RO™ 2 (Compared to "CT 2") SPIRAL & HFF MEMBRANES		RECOVERY RATIO 40%	45%	50%
FLOW RATES				
PRODUCT (MGD)	MGD	5	5	5
PRODUCT (GPM)		3,472	3,472	3,472
FEED WATER SUPPLY (GPM)		8,681	7,716	6,944
BRINE DISCHARGE (GPM)		5,208	4,244	3,472
PRESSURES (PSID)				
SUPPLY		20	20	20
MEMBRANE FEED [1]		900	975	1,040
MEMBRANE PRESSURE DROP		50	50	50
BRINE		850	925	990
BRINE DISCHARGE		20	20	20
EFFICIENCIES (%)				
FEED PUMP PISTON [2]		98%	98%	98%
ENERGY RECOVERY PISTON [2]		98%	98%	98%
ELECTRIC MOTOR		95%	95%	95%
HYDRAULIC DRIVE [3]		88%	88%	88%
POWER INPUT (kW)				
MISC. ELECTRICAL (MISC/NET)		51%	46%	41%
MISC. ELECTRICAL ("BASE 2") [1]		936	904	848
FEED PUMPING		4,058	3,915	3,763
ENERGY RECOVERY (pump drive)		2,206	1,960	1,718
NET (FEED - ENERGY RECOVERY)		1,853	1,955	2,045
TOTAL FOR FACILITY (for (6) 5 MGD module:		16,731	17,155	17,357
SPECIFIC ENERGY CONSUMPTION		8.89	9.38	9.81
SEC = kWh/kGAL for NET Energy Input to RO				
MEMBRANE QUANTITY [1], [4], [5]				
HOLLOW FINE FIBER (HFF)		NA	NA	5,520
SPIRAL WOUND (SW)		9,504	9,360	NA

NOTES [ ] "VARI-RO™ 2":

[1] Pressures, misc. elect. kW, & membrane qty. the same as "CT 2".
[2] The piston eff. includes packing friction & valve pressure drop.
[3] Hydaulic eff. includes hydraulic pump & cylinder.
[4] The greater membrane qty. at lower RR is due to lower pressure.
[5] The membrane quantities are much greater than shown for "CT 1".

EX21a-"BASE"