VARI-RO™ DIRECT DRIVE ENGINE STUDY

FINAL TECHNICAL REPORT

Science Applications International Corporation
16701 West Bernardo Drive
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by
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This study was died toward combining the VARI-RO Direct Drive Engine (VRO-DDE) technology with the highly efficient VARI-RO Electric Motor Drive (VRO-EMD) integrated pumping and energy recovery system for reverse osmosis (RO) desalting. The engine technology provides the capability to use diit thermal power to replace more expensive electric power. The ways that the VRO-DDE technology reduces desalting cost, and environmental impact, includes the following: 1) use of RO. the most energy efficient desalination process; 2) use of efficient positive displacement pumping and energy recovery; 3) use of thermal energy sources that are lower cost than electricity; and 4) by the efficient, and clean, use of these thermal energy sources. By reducing desalting costs, this technology will help to make desalting cost effective as a viable method to augment natural water sources, and help to mitigate water shortages in many locations in the U.S. and other regions of the world.

This technology advancement has resulted from the cross-fertilization of the following technologies: modem hydraulic power transmission, computer control, desalting processes, and recuperated Brayton cycle thermal energy conversion.

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We would like to thank the research organizations, consultants, and equipment suppliers that assisted in tbe success of this project. These team members are summarized in the introduction of tbis Fii Technical Report.

Special thanks go to the following individuals for their contributions during the design evolution, technical reviews, and system evaluation: Farrokh Issacci, Ph.D. and Gerald Amarel, Aerospace Equipment Systems, AlliedSignal, Inc.; Orrin Albert, Cal-West Machining, Inc.; Paul C. Hanlon, C. Lee Cook; Helmut Weber, Sc.D., Flow Energy Engineering; and Jeff Carr, K-TECH.

In addition, we would like to extend our appreciation to the Bureau of Reclamation for their support in the implementation of tbis study.

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U.S. Department of the Interior
Mission Statement

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GLOSSARY

AF	acre-foot = 326,000 U. S. gallons (approximately)
AFY	acre-feet per year
BAR	metric pressure unit = 100 kpa = 14.5 PSI = 0.9869 atmospheres
BEP	best-efficiency-point
BTU	British Thermal Unit
BWRO	Brackish Water Reverse Osmosis desalting process
C	Concentrate
CO_2	Carbon Dioxide
CPM	Cycles Per Minute
CP	Centrifugal Pump
CRA	Colorado River Aqueduct
CT	Centrifugal pump, Turbine, and variable speed drive; reverse osmosis pumping and energy recovery system (combined system)
dpM	delta pressure (pressure drop) Membranes
e	efficiency
ECU	Electronic Control Unit
ERV	Energy Recovery Valves
F	Feed
FTR	Final Technical Report
FWV	Feed Water Valves
GDU	Gas Displacement Unit
GPD	U. S. Gallons Per Day
GPM	U. S. Gallons Per Minute
HC	Hydraulic Cylinder
HDU	Hydraulic Drive Unit
HEU	Heat Exchange Unit
HR	Heat Recovery
HSE	Heat Source Exchanger
kBTU	1000 British Thermal Units
kgal	1000 u. S. gallons
kpa	kilopascal
kwh/kgal	kilowatt hours per 1000 U. S. gallons
kwh/m^3	kilowatt hours per cubic meter
m^3/d	cubic meters per day
1000 m^3/d	1000 cubic meters per day
MED	Multi-Effect Distillation process
MGD	Million U. S. Gallons per Day
MSF	Multi-Stage Flash distillation process
MVC	Mechanical Vapor Compression distillation process
MW	Megawatts of electric power
NPSH	Net Positive Suction Head
P	Product
PC	pressure, concentrate
PD	Positive Displacement
pD	pressure, Discharge
PM	pressure, Membrane
PP	Plunger Pump
PR	Performance Ratio

ppm	parts per million
PSI	pounds per square inch
PSID	pounds per square inch differential
PW	Pelton Wheel turbine
q	quantity rate = flow rate
RFP	Reverse Flow Pump turbine
RO	Reverse Osmosis desalting process
RPM	Revolutions Per Minute
RR	Recovery Ratio of reverse osmosis process = Product flow rate /Feed flow rate
sec	specific energy consumption = kwh/kgal or kwh/m^3
SP	Sump Pumping
SWP	California State Water Project
SWP Nth>Sth	California State Water Project from Northern to Southern California
SWRO	Seawater Reverse Osmosis process
TDS	Total Dissolved Solids in parts per million
TWC	Total Water Cost
VFD	Variable Frequency Drive
VARI-RO™	Variable flow pumping and energy recovery technology for RO
VRO	VARI-RO reverse osmosis pumping and energy recovery system
WC	Water Cylinder
WDU	Water Displacement Unit

DEFINITIONS

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

TRADEMARKS

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SI Metric Conversions

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

1. INTRODUCTION

1.1 Project Definition and Team

The study project. team included a coalition of private organizations, as listed below. This Final Technical Report (FIX) resulted from the efforts of this team. The Pilot Plant project was sponsored by the Bureau of Reclamation, Desalting Research and Development (DesalR&D) Program, under Assistance Agreement No. 1425-97-FC-81-30006C.

This tidy project resulted from the Bureau of Reclamation's program to increase the efficiency of desalting and water treatment plants, toward providing more usable water in the Western United States. This Phase I assistance agreement was awarded to determine the feasibility, and efficiency improvement potential, of combining the VARI-RO Direct Drive Engine (VRO-DDE) technology with the highly efficient VARI-RO Electric Motor Drive (VRO-EMD) system for reverse osmosis (RO) desalting. The VRO-EMD system is an integrated pumping and energy recovery system, which was tested under a Phase II Pilot Plant project (Childs and Dabiri, 1998). The engine technology provides the capability to use direct thermal power to replace more expensive electric power for the RO process.

The contract requirement was that the offerers, and their cost sharing partners (team members), conduct the study so that the test results are applicable to full-scale production systems.

The following supplementary reports are included in the appendices:

A VRO-DDE™ Recuperated Brayton Cycle Thermodynamic Analysis (FEE and SAIC)
B VRO-DDE™ Heat Exchanger Performance Projections (AES)
C VRO-DDE™ Mechanical and System Design (VPC and CW)

(NOTE: Because of pending and future patent applications, the Mechanical and System Design is considered confidential to VPC; and this information cannot be released to the general public.).

The following team members provided funding, advisory services, and design assistance for this Study project:

RESEARCH ORGANIZATIONS

SAIC	Science Applications International Corp.	San Diego, CA
VPC	Vari-Power Company	Encinitas, CA

CONSULTING ORGANIZATIONS

FEE	Flow Energy Engineering	San Diego, CA

EQUIPMENT SUPPLIERS

AES	Aerospace Equipment Systems, AlliedSignal	Torrance, CA
CW	Cal-West Machining, Inc.	Orange, CA
COOK	C. Lee Cook	Louisville, KT
K-TECH	K-TECH Surface Engineering	Hot Springs, AR

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

Research Organizations:

Provide seed capital to stimulate the development.

Provide expertise in system engineering and analysis.

Participation allows first hand evaluation for future full-scale application needs.

Consulting Organizations:

Provide thermodynamic energy conversion knowledge to the project.

Equipment Suppliers:

Provide valuable assistance with the design evolution.

Provide manufacturing knowledge.

Reduce the capital investment for manufacturing of future full-scale products

1.2 Study Objectives and Technical Benefiis

The overall objective of the Study effort was to perform technology development and analysis toward reducing the cost of potable water produced by desalination. More specifically, this study was directed at the use of alternate thermal energy conversion technologies to drive pumping and energy recovery systems for the reverse osmosis (RO) desalination process. This included developing of technologies that are more energy efficient and environmentally attractive than existing RO and thermal desalting methods.

The focus of this Study project was toward the validation of a new approach to utilize direct thermal energy to drive positive displacement pumping and energy recovery for reverse osmosis desalination. The technology to be studied is known as the VARI-RO Direct Drive Engine (VRO-DDE) system, which is used in conjunction with the VARI-RO Electric Motor Drive (VRO-EMD) system. This technology offers the potential to substantially reduce energy cost, provide other operational benefits, and reduce environmental impact when compared to existing desalting methods that are presently being used commercially.

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

1.3 Specific Water Problem Discussion

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

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

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

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

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

Developer Team No.	Capacity MGD	Feed Source	Deal Type	No. of Trains	Capital Cost $ Million	Total Water Cost (TWC) $/kgal	$/m3	$/AF
1	20	Tampa Bay & Brackish	MED w/Blend	4	134.80	3.98	1.05	1297
2	20	Gulf of Mexico	RO	7	78.60	2.80	0.74	913
3	20	Tampa Bay	RO & MVC	4 & 1	91.85	3.18	0.84	1037
4	23	Tampa Bay	RO	52	72.17	2.12	0.56	691
5	20	Tampa Bay	RO	6	93.17	**2.90**	**0.77**	**945**

EX11a-Tampa TW Cost 3/8/98

FIGURE 1-1 Preliminary Tampa Region Seawater Desalination Costs

FIGURE 1-1 shows the potential to desalt seawater at a total water cost (TWC) in the range of $2.12 to $2.90 per 1000 gallons ($0.56 to $0.74 per cubic meter), about $700 to $950 per acre-foot. This is substantially less than the present perception in California of $1200 to $2000 per AF, as stated in the January 1998 DRAFT of The California Water Plan Update, Bulletin 160-98, Page 6-80. In the past, the water agencies in California have been looking forward to the time when the increasing cost of imported supplies intercepts the decreasing cost of seawater desalting. It is quite possible that this time has been reached.

A 50% increase in California's population is projected by the year 2020. For Southern California, this will likely mean that the existing aqueducts, and other delivery systems, will exceed existing capacity. While the present cost of importing water through the existing infrastructure is now less than seawater desalting, it is very likely that the construction cost of new aqueducts will be in the billions of dollars, and the TWC could very well be greater than the cost of seawater desalination. Also, the energy required to desalt seawater can be lower than the energy required to pump water through the SWP from Northern to Southern California (SWP Nth > Sth). Furthermore, it has been found that the sewage water reclamation and repurification costs are much higher than originally estimated.

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

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

1. New water is added to the water supply system that is reaching maximum capacity.
2. Drought and disruption proofing capability is provided.
3. Reverse osmosis desalination is a proven method and is in use around the world.
4. Energy consumption can now be lower by using the VARI-RO Electric Motor Drive system.
5. Energy cost, and environmental impact, can be farther improved by using the VARI-RO Direct Drive Engine system.
6. Costs are now competitive to other alternatives; and
7. Acceptance by the public can readily be obtained.

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

1.4 Scope of Work and Methodology

The methodology for conducting the work for the Study project was to utilize thermodynamic experts to verify that the original theoretical approach is sound, and to perform thermodynamic analysis to predict the performance potential of the system as compared to existing methods

From this analysis, preliminary system configurations were devised to implement the theoretical designs The system configurations were then incorporated into preliminary mechanical designs, which included the selection of sealing and wear surface methods for long term operation under a high temperature environment.

2. CONCLUSIONS AND RECOMMENDATIONS

The VARI-RO technology is an integrated pumping and energy recovery system for reverse osmosis desalination. It includes the VARI-RO Electric Motor Drive version, which has been Pilot Plant tested (Childs and Dabiri, 1998); and the VARI-RO Direct Drive Engine version, which is the subject of this Study. This Study project has shown that the technology can significantly reduce the cost of desalted water, primarily by reducing the energy requirements. It has also been shown that the VARI-RO system has installation and operational advantages over conventional, commercially available, systems for thermal energy conversion and reverse osmosis pumping and energy recovery. For some site locations, where electric power rates are high, operating at lower recovery ratios can provide other economic benefits. The economic and operational benefits over other methods indicate that the technology is suitable for both seawater and brackish water reverse osmosis (SWRO & BWRO) desalting.

From the work performed during this Study project, including the technical and economic evaluations, the conclusions and recommendations below were reached about the VARI-RO Direct Drive Engine technology. The economic analysis was based on parameters provided by the contractor for the existing Santa Barbara Seawater Desalination Facility of 7.2 MGD (27,250 m^3/d) capacity.

1. The technology is technically viable and is suitable for desalting facilities of low, medium, or high capacity.
2. The Study analysis and system engineering has shown that the technology can provide energy cost savings under seawater operating conditions. The technology can also provide energy cost savings under brackish water operating conditions, especially for moderate to high salinity brackish water.
3. Because both the engine system and the pumping system of the VARI-RO technology are positive displacement, the technology provides particular advantage for desalination systems that operate under variable membrane pressure conditions. The variable membrane pressures result from changes of salinity, feed water temperature, and membrane fouling.
4. The economic analysis has shown energy cost savings potential of 54% as compared to conventional RO pumping. The total energy savings are much greater when compared to conventional distillation desalination.
5. Water cost reduction was shown from \$3.14/kgal (\$0.83/m^3) for the conventional plant to \$2.77/kgal (\$0.73 l/m') for the VRO-DDE system. This is a saving of 12% over conventional electric powered systems assuming \$0.06/kwh. The cost savings can be even greater at higher electric power rate installations
6. It is recommended that a proof-of-concept Direct Drive Engine system Pilot, Plant project be undertaken to demonstrate the function and performance improvement of the system.
7. It is recommended that a full-scale demonstration project be initiated, with a capacity in the 0.3 to 0.6 MGD range. The primary goal of this project would be to show the energy cost reduction improvement that can be achieved with both the VARI-RO Electric Motor Drive system and the VARI-RO Direct Drive Engine system. Another goal would be to demonstrate to the desalting professionals, and users, that the technology is a viable alternative to the conventional methods that are now in use.
8. It is further recommended that desalting professionals design desalting facilities so that these facilities can be easily retrofitted to VARI-RO systems, thereby providing the user an easy retrofit option to save operating cost in the future.

3. GENERAL COMPARISON TO CONVENTIONAL PUMPING METHODS

3.1 VARI-RO™ Electric Motor Drive System Overview

The VARI-RO Electric Motor Drive (VRO-EMD) system (patent pending) is an integrated variable flow, positive displacement, pumping and energy recovery system for seawater and brackish water reverse osmosis (SWRO & BWRO) desalination.

This unique system utilizes modern hydraulic power transmission and electronic control to provide the following key features:

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

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

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

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

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

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

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

In addition, the VARI-RO system can provide capital cost savings in the electric power supply to the facility, because the power requirements are lower and the electric motors are started unloaded. This w-ill be particularly true for VRO-DDE stand-alone installations.

3.2 VARI-RO Direct Drive Engine System Overview

The VARI-RO Direct Drive engine (VRO-DDE) system is a highly efficient, positive displacement, external combustion, thermal energy conversion method using the closed loop, recuperated Brayton cycle. The Brayton thermodynamic cycle is the same cycle that is used with gas turbines and jet engines. These are continuous born, external combustion, engine systems; which have low emissions as compared to conventional internal combustion diesel. or natural gas engines.

ADDITION TO THE EXISTING VRO-EMD SYSTEMS

The VRO-DDE system is an addition to the VRO-EMD system; which will reduce, or in some cases eliminate, the requirement for electric power to drive the pumping system. Both systems utilize the same hydraulic drive and computer control methods to synchronize piston movement through the power and return strokes.

The addition of the VRO-DDE system will result in an integrated pumping and engine system, which offers the potential to reduce the total water cost (TWC) of reverse osmosis (RO) desalted water in the following ways:

first by having a lower total energy consumption, and

second by using lower cost energy sources as compared to electricity.

In addition, the engine system offers the potential to substantially reduce atmospheric emissions as compared to other desalting technologies, including distillation, due to lower total energy consumption and by using low emission combustion technology.

THERMODYNAMIC CYCLE COMPARISON

The thermodynamic cycle of the engine is not the Otto or Diesel cycle, which are internal combustion engines and have high emissions from burning of the fuel. The VRO-DDE system uses the Brayton cycle, which is the same thermodynamic cycle as gas turbines. Gas turbines are considered external combustion engines and are well known in the industry as having low emissions as compared to internal combustion engines. However, gas turbines must be of large capacity, and used for applications that operate at nearly constant load and speed, in order to achieve high efficiencies. For electric power generation, gas turbines are often used with steam bottoming cycles to achieve high overall plant efficiency.

The VRO-DDE engine system, on the other hand, is positive displacement and has variable cycle speed. This unique design configuration will allow it to be used for both low and high capacity applications, and to operate efficiently over a wide range of operating conditions.

In addition, the technology is well adapted to use the latest “low NOx" combustor technologies to improve efficiency and reduce emissions as compared to conventional engines, and even conventional electric power generation facilities that are now in use. The externally applied thermal energy allows the clean burning of a wide variety of energy sources, including: natural gas, digester gas from wastewater treatment facilities, diesel fuel, hydrogen, and even coal. The combustion process can be carefully controlled to minimize emissions, such as CO, NOx, and particulates. The efficient operation will also reduce CO_2 emissions, one of the greenhouse gases, as compared to conventional desalination methods, including both distillation and reverse osmosis.

The benefits of the VARI-RO Direct Drive engine technology are summarized in the following table:

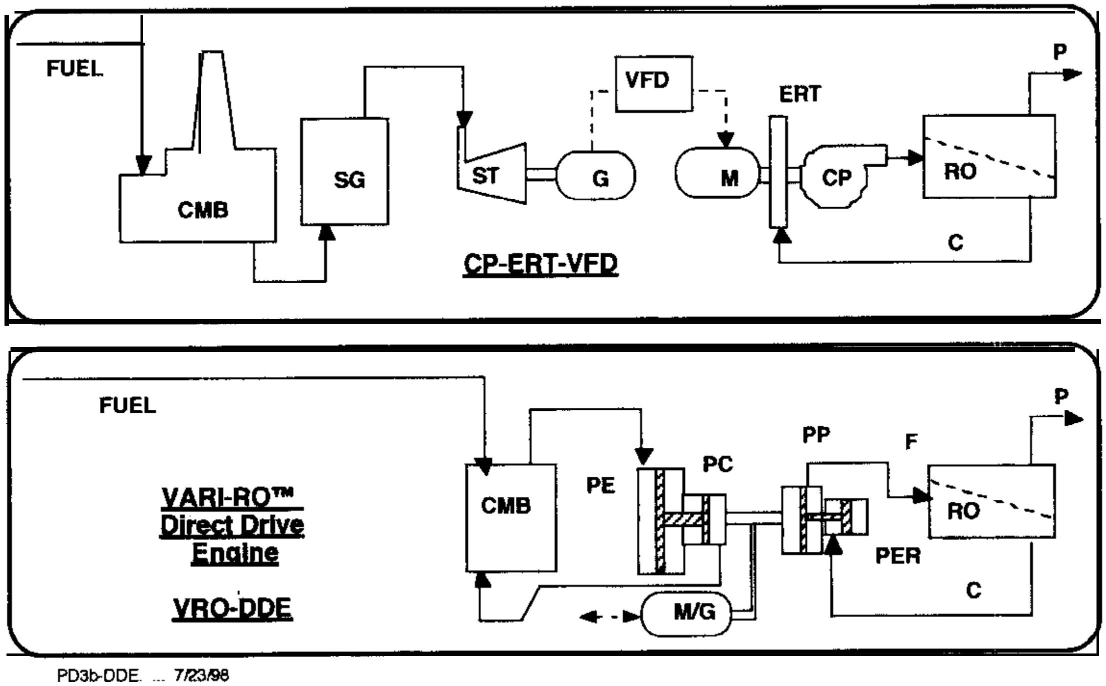
FEATURE	BENEFIT
• Positive Displacement	• High efficiency over a wide operating range.
• External Combustion, combined with the latest combustion technology	• Lower emissions as compared to internal combustion engines, and the potential to be lower than present day electric power plants.
• Low Cycle Speed	• Increased life of working parts, as compared to other positive displacement engines.
• Variable Cycle Speed	• Variable speed or variable power, which provides for excellent load matching capability.
. Proven Components	• Most of the critical components have been proven in other applications.

The benefits of the VARI-RO Direct Drive Engine system complement the benefits of the VARI-RO Electric Motor Drive system.

IMPROVED FUEGTO-WATER EFFICIENCY VERSUS CENTRIFUGAL PUMPING

The system diagrams on FIGURE 3-1 show simplified diagrams of two desalination systems using the reverse osmosis (RO) process. One system is a conventional system using a centrifugal pump, energy recovery turbine, and a variable frequency drive (CP-ERT-VFD) pumping and energy recovery system. The other system is the VARI-RO Direct Drive Engine (VRO-DDE) system.

For the conventional system, the fuel is burned in a combustor to drive steam turbines to generate electric power at high voltage. Transmission lines carry the electric power to the sob-station and voltage transformers at the desalination plant. The variable frequency drive (VFD) provides power to the electric motor to drive the centrifugal feed pomp for the RO system. The energy recovery turbine provides an energy assist to reduce the power requirements of the electric motor. The VFD is used to adjust the output of the centrifugal pomp for system startup; and for membrane pressure variations doe to feed temperature changes, salinity changes, and membrane fouling. The overall fuel-to-water efficiency of the conventional system is relatively low, when you consider all of the intermediate efficiencies (losses).



LEGEND FOR BOTH CENTRIFUGAL PUMP & VARI-RO™ SYSTEM DIAGRAMS:

FUEL = ENERGY SOURCE
CMB = COMBUSTOR
SG = STEAM GENERATOR
ST = STEAM TURBINE
G = GENERATOR
VFD = VARIABLE FREQUENCY DRIVE
M = ELECTRIC MOTOR

ERT = ENERGY RECOVERY TURBINE
CP = CENTRIFUGAL PUMP
F = FEED FLOW
RO = REVERSE OSMOSIS MEMBRANES
P = PRODUCTFLOW
C = CONCENTRATE FLOW

PP = PISTON PUMP
PER = PISTON ENERGY RECOVERY
PE = PISTON EXPANDER
PC = PISTON COMPRESSOR

FIGURE 3-l Facility Diagrams for Conventional and VARI-RO DDE System

For the VRO-DDE system, the fuel is burned in a combustor at the desalination facility to directly drive the pumping pistons for the variable flow, positive displacement pumping and energy recovery system. Because it is positive displacement, it automatically compensates for membrane pressure changes. In addition, because it is variable flow, it can adjust the flow for star&up and optimization of membrane performance. The overall fuel-to-water efficiency of the VRO-DDE system is relatively high, when you consider all of the intermediate efficiencies (losses) that are saved with the Direct Drive Engine method as compared to the conventional method. In addition, the VAFU-RO pumping and energy recovery system is also more efficient than a system using centrifugal pumps and energy recovery turbines.

In summary, the VRO-DDE system offers the potential to significantly reduce the energy consumption, and cost, to desalinate water as compared to conventional methods.

3.3 Water Production and Global Warming Benefits

Currently there arc various systems for seawater desalination, which include: multi-stage flash (MSF), multi-effect distillation (MED), and reverse osmosis (RO). Many of the present facilities (some over 20 years old) use the MSF process, and are located in Middle East countries. To reduce the energy consumption for distillation, the vertical tube evaporator MED (VTE-MED) has been proposed to improve the performance ratio. In recent years, however, the use of the RO process has been growing, primarily due to its lower energy consumption. In addition, RO popularity is increasing due to its easier implementation.

One way to evaluate the various desalination methods is to determine how much water can be produced from a given quantity of thermal power, as shown in FIGURE 3-2. The calculations for this figure are given in FIGURE 3-3. For this illustration, it has been assumed that the equivalent of one megawatt of thermal power is available (1 MWt). This thermal power could be from natural gas, oil, or even solar power. From this quantity of thermal power, the approximate quantity of water that can be produced was calculated, for the following cases (with the input power requirements as noted):

CASE 1: Multi-Stage Flash (PR = 13) Desalting Method (base)

Thermal Energy = 828 kBTU/kgal; Electric Power = 12 kwh/kgal

CASE 2: Multi-Effect Distillation (PR = 23) Desalting Method

Thermal Energy = 468 kBTU/kgal; Electric Power = 7 kwh/kgal

CASE 3: Conventional Reverse Osmosis Centrifugal Pump Desalting Method

Centrifugal Pump, Pelton Wheel turbine, Variable Frequency Drive, with Sump Pumping (CP-PW-VFD-SP). High Pressure Pumping = 12.72 kwh/kgal; Ancillary = 4.5 kwh/kgal

CASE 4: VARI-RO Electric Motor Drive Desalting Method

High Pressure Pumping = 8.27 kwh/kgal; Ancillary = 4 kwh/kgal

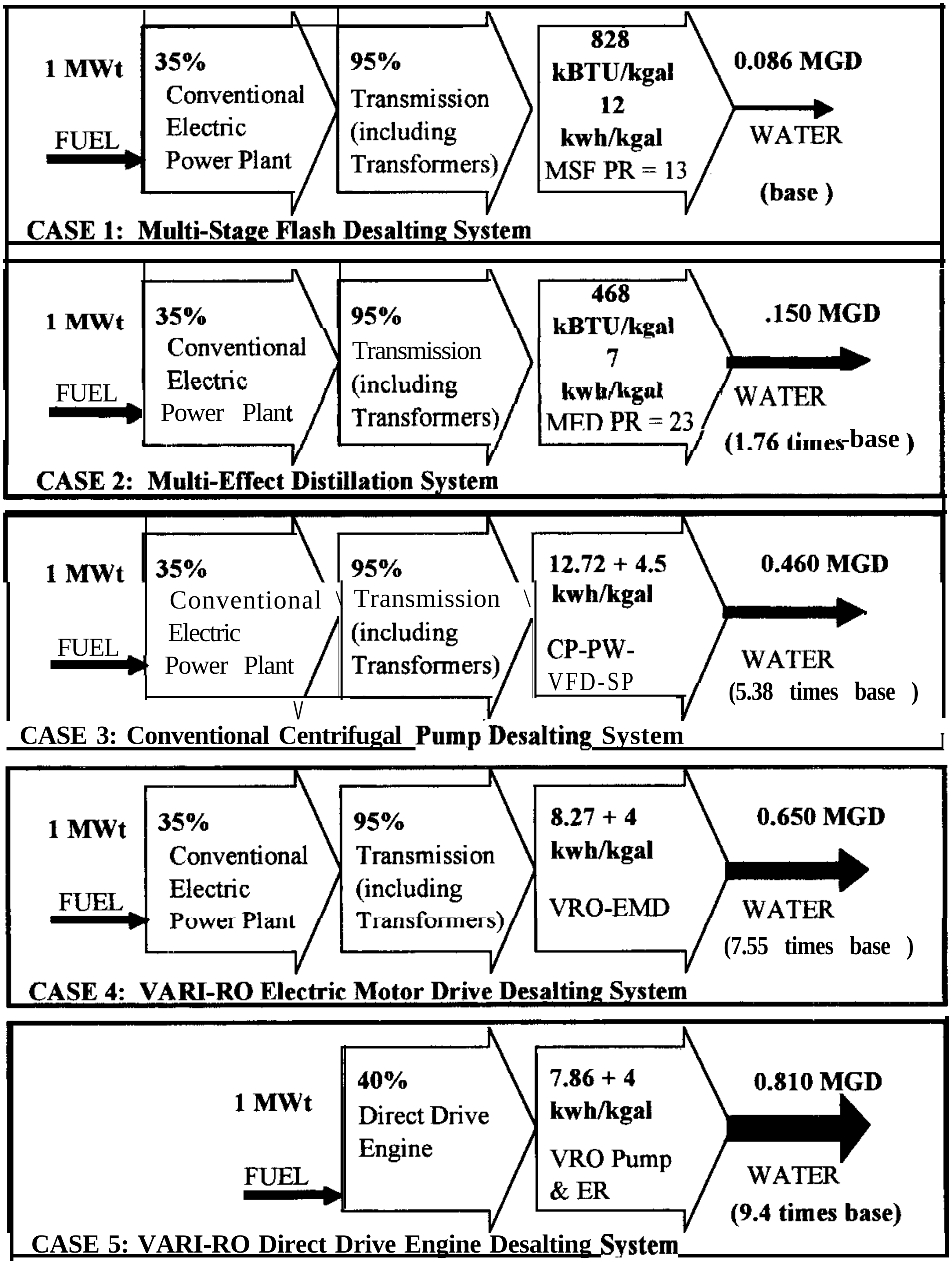
CASE 5: VARI-RO Direct Drive Engine Desalting Method

High Pressure Pumping = 7.86 kwh/kgal; Ancillary = 4 kwh/kgal

Source References: Cases 1 & 2, (Boyle, 1991) and (MWD, 1993); Cases 3, 4, & 5 (Childs and Dabiri, 1998). The energy consumption values shown for these cases have been converted, and extrapolated from these sources to provide a basis for relative water production from a given energy source. For Cases 3, 4, and 5 the ancillary power was reduced from 5.64 kwh/kgal to 4.5 kwh/kgal for the Pelton wheel case (with sump pumping) and 4 kwh/kgal for the VARI-RO cases (without sump pumping). The rationale is that the ancillary power can be reduced with careful design. The VARI-RO system features provide for easier facility optimization.

There may be slight variations from actual performance at any given facility.

As shown on FIGURE 3-2, the water production from the conventional RO process is quite substantial as compared to either of the major distillation processes (MSF & MED). It is also shown that additional water production can be achieved when the VARI-RO Electric Motor Drive (VRO-EMD) system is used, and even more when the VARI-RO Direct Drive Engine (VRO-DDE) system is used.



File No. PD15a-BuRec VRO-DDE Diag 8/6/98   File No. EX15a-BuRec VRO-DDE Calc.8/6/98

FIGURE 3-2 Water **Production** from a Given Power Source

CASE	Total Input Specific Power kwht/kgal	EFFICIENCIES	Thermal Energy Required kBTU/kgal	SEC of Plant Ancillary kwhe/kgal	SEC of RO Pump & ER System kwhe/kgal	Product Water Produced MGD	Multiple of Water Produced
1 MSF PR = 13	279	Power Plant 35% Transmission 95%	828	12.00		0.086	BASE
2 MED PR = 23	158	Power Plant 35% Transmission 95%	468	7.00		0.152	1.76
3 CP-PW-VFD-SP	52	Power Plant 35% Transmission 95%		4.50	12.72	0.463	5.38
4 VRO-EMD	37	Power Plant 35% Transmission 95%		4.00	8.27	0.650	7.55
5 VRO-DDE	30	Engine for VRO-DDE 40%		4.00	VRO-Pump & ER 7.86	0.809	9.40

File No. EX15a-BuRec VRO-DDE Calc.8/6/98

NOTES: Water production based on: 1.00 MWt input power
Transmission includes transformers

FIGURE 3-3 Water Production vs Input Power Calculations

These calculations show the potential for over nine (9) times the water to be produced from a given energy source with the VRO-DDE system as compared to a facility using the MSF PR = 13 distillation process. Most of the world's seawater desalination is presently accomplished with the energy intensive MSF process, and a more efficient process is definitely needed.

In addition to the Middle East countries, there arc major seawater desalting facilities in other locations around the world, including: Spain, Canary Islands, Malta, Okinawa, and the Caribbean Many of the desalting facilities at these locations use the RO process. The potential applications for the VARI-RO™ technology (both the VRO-EMD and the VRO-DDE systems) include: 1) the replacement of existing distillation facilities that have excessive energy consumption and emissions (or are at the end of their useful life); 2) the retrofitting of existing RO facilities with more efficient pumping systems; and 3) providing improved technology for new RO desalting facilities. The VRO-DDE technology will be especially beneficial in regions with high electric power rates.

At the 1997 Global Warming Conference, Kyoto, Japan, the proposed treaty emphasized the need to cut carbon dioxide (CO_2) emissions, one of the "greenhouse" gases. In February 1998, the Clinton administration proposed a $6.3 billion package to "... mobilize *cutting-edge technologies in the fight against global warming* ". The motivation is to "... overcome *the challenge of global climate change and create new avenues of growth for our economy* ".

In 1995, the world desalination capacity was 5.4 billion gallons per day (20 million m^3/d), which resulted from an average growth rate of 250 MGD (about one million m^3/d) per year over the past 10 years. It is projected that the future growth in desalination capacity will be at an even greater rate. The chart in FIGURE 3-2 shows that the use of VARI-RO technology for this new capacity, and the retrofitting of antiquated existing installations, could provide an enormous reduction in CO_2 emissions for a given water production. Conversely, more water could be produced from the energy that is now being used.

The sale of this technology on a worldwide basis would help to meet the Bureau of Reclamation Desalination Research & Development (DesalR&D) Program objectives, as follows:

- Help United States industry compete in major international markets for desalting systems, by fostering the development and use of new cost-effective and technologically advanced desalting processes.

- Promote partnerships between government and industry in the use of desalting to meet critical water needs.

- Promote technologies that are more energy efficient and environmentally attractive than existing methods.

The VARI-RO technology developments can also help to meet a key objective of the global warming treaty, which is to reduce CO_2 emissions by a substantial amount by the year 2010.

4. SYSTEM CONFIGURATION AND OPERATION

The preliminary design for a VARI-RO Direct Drive Engine included the selection of the most suitable configuration. The following describes the system design that was selected It is expected that as the design matures there will be an opportunity to improve upon this initial selection.

4.1 VARI-RO Direct Drive Engine System Description.

The VARI-RO Direct Drive Engine (VRO-DDE) system consists of a highly efficient, positive displacement, external combustion, thermal energy engine system using the closed loop, recuperated Brayton cycle. This engine system drives a highly efficient pumping and energy recovery system for pumping feed water to reverse osmosis membranes, and recovering energy from the reject concentrate A block diagram of the system is shown on FIGURE 4-1.

The Direct Drive Engine (DDE) system consists of the sub-systems, noted below. These subsystems will be integrated with the pumping and energy recovery sob-systems of the previously tested Electric Motor Drive system.

The sub-assemblies of the DDE system include:

SUB-ASSEMBLY	CONSISTING OF:
HEAT EXCHANGE UNIT (HEU)	Combustor (C) Heat Source Exchanger (HSE) Recuperator (RC) Cooler (CL)
GAS DISPLACEMENT UNIT (GDU)	Expander Cylinders (EC) Compressor Cylinders (CC) Expander Valves (EV) Compressor Valves (CV)

This will result in an integrated pumping and engine system, which offers the potential to reduce the total water cost of reverse osmosis (RO) desalted water

In addition, the engine system offers the potential to substantially reduce atmospheric emissions as compared to other desalting technologies, including distillation. These lower emissions result from lower total energy consumption, and from using improved “low emissions” combustion technology.

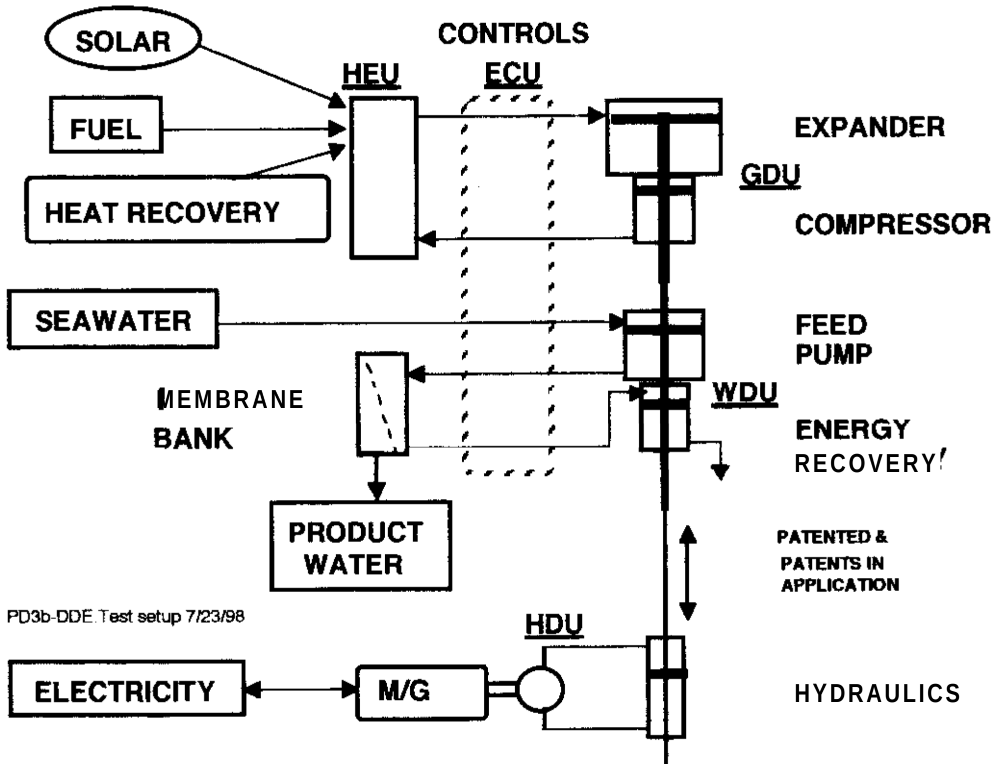


FIGURE 4-1 VARI-RO Direct Drive Engine System Block Diagram

The above block diagram shows how the sub-assemblies of the DDE are integrated with the sub-assemblies of the VARI-RO Pumping and Energy Recovery system, which are described in the next section.

4.2 VARI-RO Pumping and Energy Recovery System

The sub-assemblies of the VARI-RO pumping and energy recovery system are listed below. These are the same sob-systems that are used in the VARI-RO Electric Motor Drive system.

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

A block diagram of the VARI-RO integrated pumping and energy recovery system is shown in FIGURE 4-2. This figure also shows the relationship to the other systems in a reverse osmosis desalting facility. The other systems include the electric power supply system, the feed water supply and treatment system, and the reverse osmosis membrane bank system,

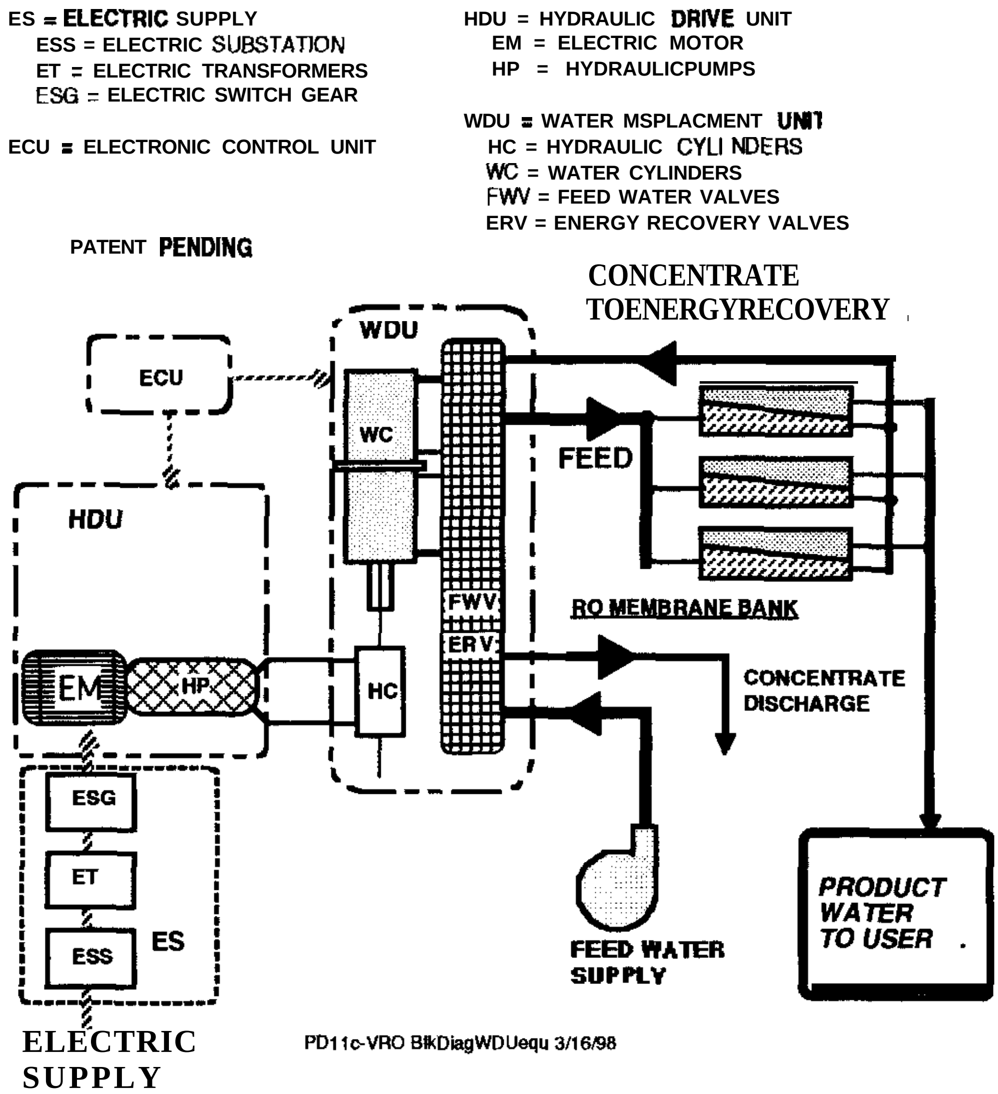


FIGURE 4-Z VARI-RO Pumping and Energy Recovery System Block Diagram

The VARI-RO Pumping and Energy Recovery system, when used with the Direct Drive Engine system, is very similar to the Electric Motor Drive system; except for some key differences. The major key difference is that most of the energy input is from the DDE, rather than the electric motor. In the case of the VRO-DDE system the electric motor function is for system start-up, and to provide a power smoothing effect during the piston stroking. In this case, the electric motor provides a function similar to the flywheel in conventional crank type engines.

The primary power input into the pumping and energy recovery system is from a direct drive shaft; which is connected to the DDE cylinders in the gas displacement unit (GDU), as shown in **FIGURE 4-l.**

4.3 VARI-RO System Operating Scenarios

The technology is applicable to any desalination requirement, including brackish water and seawater. It is also applicable to other applications, such as general pumping and gas compression. An example of general pumping would be the pumping of the product water to a higher elevation for distribution. Tbe technology can, however, provide the greatest savings for seawater desalination; which was the focus of this study.

UNIQUE DUAL-USE CAPABILITY

The VARI-RO technology (both the VRO-EMD and the VRO-DDE versions) can be applied in several ways. One way would be to start off with the EMD version for the facility, and design the install&on for the-future addition of the DDE version. This would provide electric power cost savings for the initial plant start-up with a technology that has been proven with the testing program The decision to implement the DDE version could then be based on increased cost of electric power, shortage of available electric power, and the general desire to lower the operating cost of the desalting facility by using a lower cost energy source.

After the implementation of the DDE version, the dual-use plant can be operated from fuel, or from electric power during lower cost off-peak rates. In addition, the facility could be used to generate electric power, when there is no need for water. In this case, the RO pumping would be bypassed; and the electric motors would be driven as induction generators.

This dual-use capability would add to the cost effectiveness of a desalting facility that was put in place for water supply diversification and drought-proofing. In the dual-use mode, the facility could provide useful electric power when adequate water supply is available from traditional sources; rather than being put on stand-by.

It is expected that the efficiency for electric power generation will be greater than the efficiency of conventional steam powered electric power plants, and the technology will have the potential to be equal to combined cycle electric power plants. Tbe combined cycle plants would include gas turbine generators with steam bottoming cycles. The practicality of operating the VRO-DDE system in the dual-use mode would depend on the need for additional electric power production in the region, when water supply from desalination is not needed. A trade-off analysis will be necessary to determine the economic benefit of this dual-use operation.

STAND-ALONE CAPABILITY

When the Direct Drive Engine technology has sufficiently matured in its design development, then the facility can be designed to implement the DDE technology without first going with the EMD version. The benefit here would be that the cost of a major electrical sub-station, and the associated power equipment, would be saved.

This stand-alone implementation scenario would be particularly applicable for locations that are away from traditional power grids, where electric power rates are high, and where the primary need is water supply augmentation with desalination. This would save the cost of the electric power transmission lines, and/or the additional electric power generating capacity that would be necessary with an electric powered desalting system. It would also be applicable for solar power applications, where the thermal energy is obtained by focusing the sun's rays on a high temperature receiver, which becomes the heat source exchanger.

5. ENGINE THERMODYNAMIC ANALYSIS

5.1 General Theory of Operation

The thermodynamic cycle of the VARI-RO Direct Drive Engine system is a closed loop, recuperated Brayton cycle, as shown in FIGURE 5-1. The Brayton cycle is the same thermodynamic cycle common to jet engines and gas turbines, which are usually open loop, are without the recuperator, use rotary compressors and expanders, and operate at high pressure ratios to get high efficiency. For the VRO-DDE system, the loop is closed to reduce the volume of the working fluid gas, uses a recuperator to recover energy, uses piston compressors and expanders to improve efficiency and transmit force directly to the RO pumping equipment, and will achieve high efficiency at low pressure ratios.

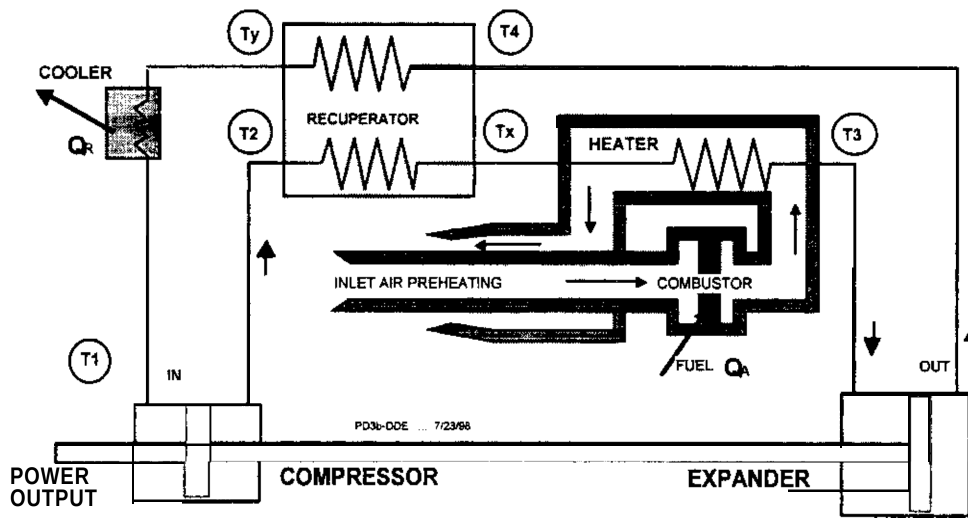


FIGURE. S-l Closed Loop, Recuperated Brayton Cycle Diagram

The P-V and T-S diagrams for this thermodynamic cycle are shown in Figure 1 of Appendix A. In the case of the VRO-DDE system, a significant amount of the expander force output of the engine system is transmitted directly to the RO pumping pistons. The remaining force is used to drive the compressor pistons. A typical force profile is illustrated in FIGURE 5-2.

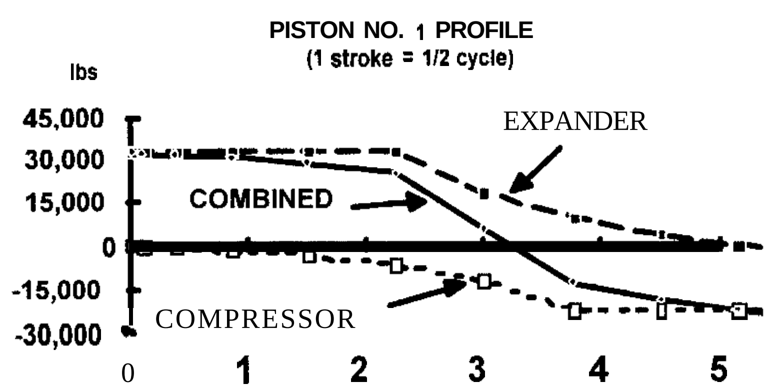


FIGURE 5-2 Piston Force versus Stroke Profile

The efficiency of the recuperated Brayton cycle can approach that of the Stirling cycle, when high efficiency compressors and expanders arc used, which reduces the back work of the cycle for gas compression. The VRO-DDE system accomplishes this by using positive displacement in a unique way. Previously, positive displacement application of the Brayton cycle has been limited by the use of conventional cranks to convert linear motion into rotary motion. The limitation of conventional cranks for the Brayton cycle include the bulky machinery that is required to handle the large displacement of the working fluid, and the resulting geometric side loads of the piston on the cylinder walls. The unique VRO-DDE system design eliminates geometrically induced side loads.

5.2 Operating Characteristics

An efficiency projection for the engine versus pressure ratio is shown **on FIGURE 5-3.** This projection has been made based on a heat source temperature of 1500 “F and a cooling water temperature of 70 °F. At a pressure ratio of 2.5 it shows a thermal efficiency of 55% and a system efficiency of 4 1%. These projections have been made based on estimated efficiencies and effectivenesses of the key components, including: heat source exchanger, recuperator, cooler, expander, compressor, and hydraulic power transmission. For comparison, the efficiency of a conventional electric power plant is in the range of 35% To get higher efficiencies of say 50%, it has been necessary to go to gas turbines with a steam bottoming cycle to extract the energy from the exhaust. This is only feasible for high capacity, base load power plants; not load following power plants

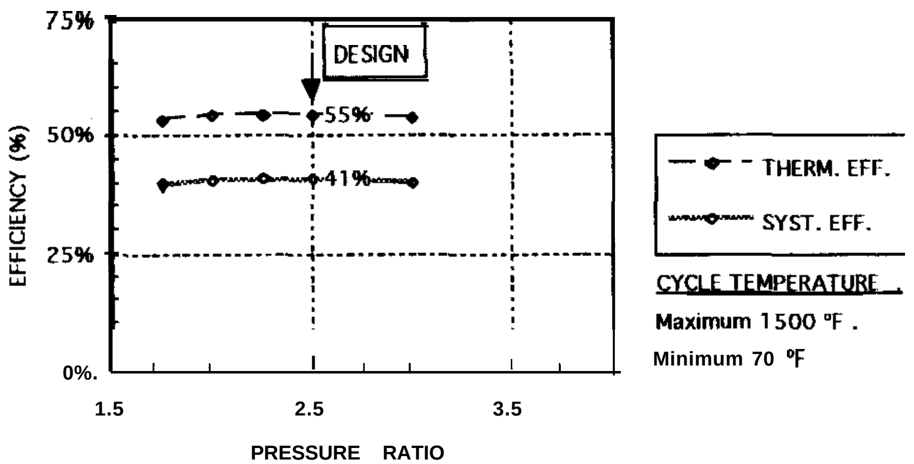


FIGURE 5-3 Engine Efficiency Projection versus Pressure Ratio

During the Study, the design team reviewed the selection of operating pressures and temperatures versus available materials and design configurations. For the proof-of-concept Pilot Plant testing lower pressures and temperatures will be used, which will result in lower efficiencies than is projected for full-scale applications. The analysis performed for this Study is in APPENDIX A (Weber and Dabiri, 1998).

With the computer models, it will be possible to compare the actual results to the predicted results. Based on the test information, it will then be possible to project the operating performance that can be expected at higher pressures and temperatures in a mature design From these predictions, a projection of “equivalent” kwh/1000 GAL (kwh/m^3) product water will be made for comparison with conventional RO pumping systems using conventional electric power generation.

6. COMBUSTOR AND HEAT EXCHANGERS

6.1 Combustor

The Direct Drive Engine technology is well adapted to use the latest “low NOx" combustor technologies to improve efficiency and reduce emissions as compared to conventional engines, and even conventional electric power generation facilities that are now in use. There have been substantial improvements in burner technologies over the past decade, as a result of the drive to reduce atmospheric pollution. The externally applied thermal energy allows the clean burning of a wide variety of energy sources, including: natural gas, digester gas from wastewater treatment facilities, diesel fuel, hydrogen, and even coal. The combustion process can be carefully controlled to minimize emissions, such as CO, NOx, and particulates. The efficient operation, and the lower fuel requirements per volume of water produced, will also reduce CO2 emissions, one of the greenhouse gases.

6.2 Heat Source Exchanger

The heat source exchanger (HSE) provides a similar function that the steam generator, or boiler, and superheater performs in a steam power plant. The design principles for the HSE are a well known science. The design challenge will be to optimize the thermal transfer effectiveness in a cost effective configuration. Once through steam generators have been built and tested for gas turbine exhaust heat recovery systems. These steam generators were designed to ASME Boiler Code to operate at 1500 °F (8 15 °C) and 1500 PSI (103 BAR). Presently, it is expected that the full-scale VRO-DDE HSE operating requirements will be at a similar temperature, but at a lower pressure of 500 PSI (34 BAR). Another part of the HSE is the combustion air pre-heater. This heat exchanger recovers some of the energy from the combustion gas before it goes up the exhaust stack.

6.3 Recuperator

The recuperator (RC) heat exchanger is a key component in performance of the VRO-DDE system. The RC recovers thermal energy from the hot exhaust gas of the expander, which reduces the energy input requirements of the combustor and the heater. This improves the overall thermal efficiency of the system. There are several configurations of recuperators that are possible from simple tube and shell heat exchangers to plate-fin heat exchangers. The latter are more compact, lighter, use less material, and have higher effectiveness than other configurations. For the preliminary design plate-fin heat exchangers have been selected. The design parameters and general characteristics are given in APPENDIX B (Issacci, 1998).

6.4 Cooler

The cooler (CL) rejects thermal energy from the engine system. The design requirements are much less severe than the other heat exchangers. The material selection will depend on the cooling medium. The coolant could be air, fresh water, or seawater, for example. One possibility that will be examined for full-scale designs will be to use the feedwater as the coolant before going to the high pressure pumps and the RO membranes. This would be a form of energy recovery, because the increased temperature of the feedwater will result in a lower membrane pressure requirement. A tradeoff analysis would be necessary to determine the cost effectiveness of this alternative. A preliminary sizing of a plate-fin heat exchanger is given in APPENDIX B.

7. FACILITY OPTIMIZATION WITH THE VARI-RO SYSTEM

7.1 Recovery Ratio Optimization with VARI-RO Pumping

The VARI-RO pumping and energy recovery system has a relatively flat specific energy consumption versus recovery ratio at a constant membrane pressure. As a result of this flat energy consumption characteristic, it is possible to have lower energy consumption at lower recovery ratios than can be accomplished with conventional pumping, by operating at lower pressures. The capability to operate at lower pressures results from the lower osmotic pressure of the lower salinity concentrate. This feature of the VARI-RO system provides the RO system designer a new tool for the optimization of the facility for lowest total water cost (TWC).

With conventional pumping and energy recovery systems, the energy consumption is higher at lower recovery ratios, due to the lower efficiencies. Because of this higher energy consumption at. lower recovery ratios, and other factors, it is presently the usual case for the RO system designer to select a high recovery ratio. The recovery ratio selected is often a.5 high as the membrane system will allow before having scaling problems, leaving very little margin for abnormal conditions. This high recovery ratio can create operational problems if there is a change in the feed water, or if an error is made in the control of the recovery ratio or the chemical pretreatment.

Advantages of lower recovery ratios include:

1. Lower membrane pressure for the same membrane quantity, resulting in lower energy consumption when the VARI-RO system is used.
2. Conversely, fewer membranes can be used if the pressure is kept the same.
3. The water quality is improved at lower recovery ratios.
4. The salinity of the concentrate is lower, which reduces the scaling potential.
5. At lower concentrate salinities, it may be possible to improve the chemical pretreatment for lower cost or less environmental impact.
6. With a lower salinity concentrate, the environmental issues related to ocean brine disposal may be improved. For example, less mixing for dilution of tbe concentrate may be possible.

Disadvantages of lower recovery ratios include:

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

In many cases, it may be more advantageous to operate at a lower recovery ratio to save energy, improve the product water quality, and reduce the potential for membrane fouling by providing a greater safety margin. To evaluate these factors, a tradeoff study is needed.

The potential benefits, for facility optimization and lower recovery ratio operation for seawater desalination, were covered in a previous report (Childs and Dabiri, 1998).

7.2 Optimizing Energy Use with VARCRO Engine

As mentioned in a previous paper (Childs and Dabiri, 1992), there are several versions of the VARI-RO technology that are feasible, including the Electric Motor Drive and the Direct Drive Engine. The following briefly describes a few of the possible versions, and summarizes how the engine versions can be applied to optimize the energy use at a desalination facility.

<u>**VARI-RO™** Electric Motor Drive **(VRO-EMD):**</u> This is an integrated pumping and energy recovery system for reverse osmosis desalination. This integrated system competes directly with conventional systems composed of centrifugal and plunger pumps, reverse flow pump and Pelton wheel turbines, throttle valves, variable frequency drives, sumps and sump pumping, and the associated mounting foundations and piping necessary for installing this equipment.

The VRO-EMD system can also be driven by other prime movers, such as steam turbines or diesel engines. In fact, the low inertia, and zero flow, start-up makes it ideal for saving wear and tear on diesel engine clutches. Field reports have shown that there have been clutch problems when driving conventional plunger pumps for high pressure RO systems.

<u>**VARI-RO™ Direct Drive Engine (VRO-DDE-NG and VRO-DDE-HR):**</u> The energy source for these versions is natural gas (NG) or thermal energy heat recovery (HR). These versions are similar to the VRO-EMD, except that they are driven directly by a heat engine from a thermal energy source. In the case of the natural gas version, this fuel source would be burned in a combustor and the thermal energy transferred to the engine system by means of a heat source exchanger (HSE).

In the case of the heat recovery version, this could be the hot exhaust gas from a gas turbine electric power plant. A possible scenario would be to use some, or all, of the thermal energy in the exhaust gas to direct drive the RO pumping system to provide increased water production. This would be more efficient than using this energy directly for MSF or MED distillation. Also, it would also be more efficient than first converting this thermal energy to steam in a heat recovery boiler, generating electricity, and using this electricity to drive the RO pumps.

<u>**VARI-RO™** Direct Drive **Engine (VRO-DDE-DUAL):**</u> This is a dual-use version, which is similar to the "NG" or "HR" versions except that a huger electric motor is used, which can also be driven as an induction generator to produce electric power at high efficiency. In its simplest form, the electric power generation would be similar to the methods used for generating electricity from wind power, which utilizes the main grid to control electric power frequency. It would also be possible to add the necessary speed controls for stand-alone operation. A solar powered installation would be a possible stand-alone application.

This power generation capability can be used instead of, or in conjunction with, pumping feed water to the reverse osmosis membranes. With the "DUAL" version, excess engine power can go to generate electricity, or the pumping can be bypassed and all of the engine power can go to drive the generator. This electric power generation capability can help offset facility costs when desalination is not needed. This could be particularly cost effective for locations where the desalination facility is only put in place for drought protection, emergency use, and/or to augment natural water sources during times of peak demand. When the facility is not needed to produce water, it can be quickly switched over to produce electricity, by simply bypassing the water pumping function. A possible operating scenario would be to produce electricity during peak demand (say air-conditioning load), and produce water for storage during off-peak electric power demand.

8. ECONOMIC AND ENVIRONMENTAL ANALYSIS

In a **previous** report (Childs and Dabiri, 1998), a report by Laughlin Associates is included as Appendix C, entitled: *"Economic Comparison of VARI-RO vs. Conventional High Pressure Pumping and Energy Recovery Technology."* This report uses as the base case the 7.2 MGD (27,250 m^3/d) seawater desalination facility at Santa Barbara, California. The present pumping system consists of 12 trains of 0.6 MGD (2,270 m^3/d) each at 45% recovery ratio. The initial operating pressure was 865 PSI (59.6 BAR), and the design operating pressure for the facility is 955 PSI (65.8 BAR). The initial operating pressure is used for the comparative analysis of the VARI-RO system versus the conventional system.

The conventional pumping and energy recovery system consists of centrifugal pumps, Pelton wheel energy recovery turbines, variable speed drives, **and** sump pumping to discharge the concentrate back to the ocean (CP-PW-VFD-SP). The facility contractor provided the efficiencies for the components used in this comparison.

For the VARI-RO Direct Drive Engine system, a preliminary estimate of projected capital, O&M, and total water cost (TWC) per 1000 gallons are shown in **FIGURE 8-l.**

	Conventional Plant	VARI-RO DDE
Plant Capacity, MGD	7.20	7.20
Plant Availability Factor, %	92%	92%
Annual Water Production, MGD	6.62	6.62
Annual Water Production, Mgal.	2,418	2,416
Electric Power Rate, $/kWh	0.06	0.06
Installed Capital Cost, U. S. $	38,126,000	39,326,000
High Pressure Pumping Cost, $/yr	1,845,000	645,000
VARI-RO DDE Savings of Energy Cost		54%
Balance of Plant Power Cost	616,000	616.000
Total Annual Power Cost	2,663,000	1,663,000
Other O&M Cost	2,013,000	2,013,000
Total Annual O&M Cost	4.676.000	3,676,000
Annualized Cost of Capital	2.920.000	3,011,906
Total First Year Cost	7,596,000	6,687,906
Total Water Cost, $/AF	1,024	902
Total water Cost, $/m³	0.630	0.731
Total Water Cost (TWC), $/1000 gallon	3.14	2.77
VARI-RO DDE Savings of TWC, %		12%

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FIGURE 8-l Projected Total Water Cost for Full-Scale Plant

For this estimate, the starting point was the Santa Barbara Seawater Desalination facility, as reported in the previous VARI-RO Desalting Pilot Plant Testing and Evaluation Final Technical Report. The total cost of water for the conventional plant is taken from the previous report.

ECONOMIC SAVINGS

For this preliminary economic evaluation, it was assumed that the capital cost for the pumping equipment would increase from about $3 million to about $4.2 million, which is a 40% increase. By using lower cost natural gas, in place of electricity, it was estimated that the high pressure pumping energy cost would be reduced about $1 million per year; or about a 54% reduction. Based on these estimates, the water cost would decrease about 12%, for the base case facility.

Based on the results from the Tampa Bay proposals, see FIGURE l-l, it is expected that for a modem higher capacity facility, the water cost for a conventional facility would be lower than that shown in FIGURE 8-1. By using the VRO-DDE system there would be a further lowering of the total water cost.

There are several arrangement options that are feasible with the VARI-RO Direct Drive Engine system full-scale applications For example, it would be possible to have one high capacity heat exchange unit (HEU) that would supply high temperature gas to several gas displacement units (GDUs), that are supplying water pumping energy to individual RO trains. This is one of the many options that can be reviewed to optimize the energy cost saving capability versus the capital cost of the method.

ENVIRONMENTAL SAVINGS

Environmental savings were discussed in SECTION 3.3. As compared to conventional distillation facilities (MSF and MED) and conventional RO facilities the potential energy savings is quite substantial as shown in FIGURE 3.2. This figure shows that over 9 times the water can be produced as compared to the MSF PR = 13 desalting system. Conversely, this means that for a given quantity of water, the energy requirement is 1/9th.

The energy savings will result in lower emissions, especially CO_2. In addition, low emission combustors would be used, as discussed in SECTION 6.1. This would provide additional environmental savings.

9. CONTINUED TECHNOLOGY DEVELOPMENT

9.1 Study Accomplishments

The primary objectives for the present VARI-RO Direct Drive Engine Study were as follows:

1. To verify the theoretical analysis of the proposed Direct Drive Engine to show the technical validity of the approach.
2. To identify key equipment areas that arc likely to create problems, and implement design efforts to minimize these problems.
3. To show how the cost of water desalination can be reduced with the use of thermal energy in conjunction with the energy efficient reverse osmosis process.

With respect to these objectives, the project has been very successful. A very capable technical team has reviewed and analyzed the technology, and found that it is based on sound technical principles. Some of the technical findings and accomplishments include the following:

- **Thermodynamic cycle analysis:** The closed loop, recuperated Brayton thermodynamic cycle was carefully analyzed to determine the characteristics, and the application of this cycle in a positive displacement engine. This analysis verified that the theoretical approach is valid, and the expected performance is very close to the original predictions

- Heat exchangers: The closed loop, recuperated Brayton cycle depends on three heat exchangers, which include the Heat Source Exchanger (HSE), the Recuperator, and the Cooler. The HSE performs a similar function that a steam generator performs in a steam power plant. The key difference is that in the Direct Drive Engine, the working fluid is always a gas, rather than water and water vapor, as in the case of a steam power plant. In the case of a steam power plant, the pressures and temperatures are limited by the thermodynamic characteristics of water.

  In the case of the DDE system, there is not a thermodynamic pressure and temperature limitation, because the working fluid can be any gas, including: air, carbon dioxide, helium, hydrogen, nitrogen, and xenon. The limits arc a result of the availability of materials to withstand the design pressures and temperatures. Air or nitrogen is the likely first choice for the working fluid; however, helium or hydrogen are likely candidates for advanced engines because of better heat transfer characteristics.

- Mechanical design and internal dynamic seals: With the Direct Drive Engine there arc no geometrically induced side loads, as is the case with conventional crank type engines. Also, the cycle and stroking speeds are very slow by comparison. Because of this design feature, the need for lubrication is greatly minimized. In place of conventional lubricants, carbon graphite guide bushings and dynamic seals are planned, which have been successfully used in high performance positive displacement oil-free air compressors, and also in engine applications.

  These. carbon graphite components would operate against surfaces that have been coated with a smooth, and very hard, chemically deposited ceramic. This ceramic coating has been tested in diesel track engine sleeves, and the life expectancy of these sleeves has been projected to give over a million miles of service.

- **Expander inlet and exhaust valves:** The function of the expander inlet and exhaust valves is similar to a conventional engine The key difference is much slower cycle speed (say up to 20 CPM versus around 2000 RPM). This means that it would take over 100 years to get the same number of cycles that a conventional engine would experience in one year. The opening and closing of these valves would be controlled from the same computer that controls the energy recovery valves of the VARI-RO pumping and energy recovery system. However, the timing would be optimized to get the best possible performance for the operating conditions of temperature, pressure, and cycle speed.

The mechanical and system design, for this unique approach to energy conversion, is covered in APPENDIX C (Childs and Albert, 1998).

9.2 Pilot Plant Testing

The Study has shown that the theoretical approach is sound, and that the major implementation hurdles appear to be solved, or are solvable. Based on this, it is recommended that a program be initiated to test a proof-of-concept Pilot Plant unit, with a power capacity in the 5 to 10 horsepower range.

This DDE Pilot Plant unit could be incorporated into the present VARI-RO Desalting Pilot Plant unit (Childs and Dabiri, 1998). This previous Pilot Plant project tested, and verified the performance capability, of the VARI-RO Electric Motor Drive system.

The planned test set up is shown in FIGURE 9-1. The VARI-RO Direct Drive Engine (VRO-DDE) system is an addition to the present VRO-EMD system. The piston movement (expander and compressor) in the gas displacement unit (GDU) is controlled in the same way that piston movement (energy recovery and pumping) is controlled in the present water displacement unit (WDU). Also, the computer controls the opening and closing of the expander valves in a manner similar to the energy recovery valves of the present unit.

In the case of the expander, power input is by means of hot gas under pressure from an electric heater in the heat exchange unit (HEU). In the case of the energy recovery function in the present unit, the power input is from the high pressure water flow from the membrane simulator. For this proof-of-concept testing, the combustor will be simulated by using an electric heater. For this low capacity testing, it will be easier to control, and measure, the power input in this way.

To conduct the tests, the Electric Motor Drive (VRO-EMD) system will be placed in operation, with the GDU de-coupled from the WDU. The VRO-EMD system will be operated through a prescribed set of test runs; and the power input to the electric motor carefully recorded, which will provide a baseline performance measurement.

The GDU will then be coupled to the WDU, and the system set up for running tbe same set of runs that were previously run with the VRO-EMD unit alone. For this set of runs, the input power to both the electric heater and the electric motor will be recorded. As the power input from the electric heater is increased, the power requirement from the electric motor will decrease under the constant pumping conditions. This data will be used to provide a measurement of the engine performance.

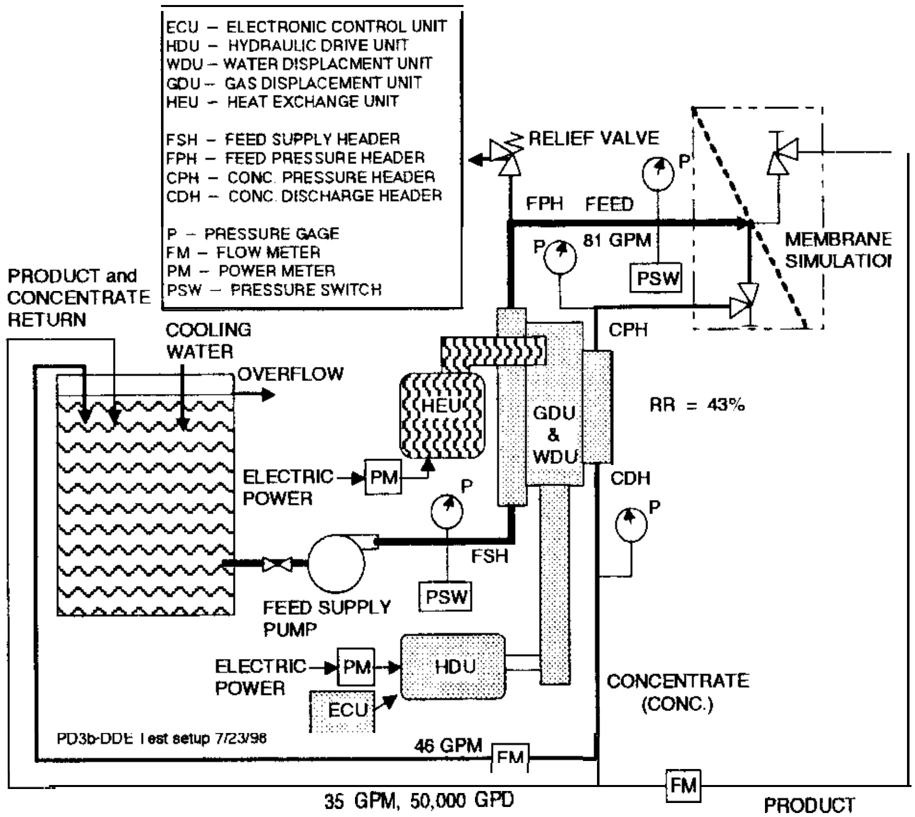

FIGURE 9-1 DDE Pilot Plant Test Schematic

9.3 Demonstration of Full-Scale Capacity Unit

It is recommended that a demonstration project be implemented to design, manufacture, and test a full-scale unit in the 300,000 to 600,000 GPD (1135 to 2270 m^3/d) capacity range. The objectives for this project include the following:

- Show that the efficiency projections for a commercial capacity unit can be achieved

- Demonstrate to the desalting industry that the technology is viable and should be considered as a preferred method for future desalting plants, and as a retrofit for existing facilities.

- Put the VARI-RO system side-by-side with a conventional system to show the installation, operational, and energy saving features of the technology.

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Appendix A

VRO-DDE™ Recuperated Brayton Cycle Thermodynamic Analysis

Flow Energy Engineering
and
Science Applications International Corporation

VRO-DDE™ Recuperated Brayton Cycle Thermodynamic Analysis

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August 1998

1. Introduction

A reciprocating engine operating on a modified recuperated Brayton cycle (referred to as simply the Brayton cycle in this report) is proposed to directly drive reverse osmosis desalination pumps, known as the VARI-RO™ system. The combined system is called the VARI-RO™ Direct Drive Engine (VRO-DDE™) system. The pump incorporates three reciprocating pistons operating 120 degrees out of phase with each other. These pistons provide a uniform flow rate and resulting system pressure; which permits effective operation of the reverse osmosis desalination unit.

Because of the reciprocating pumping pistons, it is convenient to also design the engine in the form of three sets of reciprocating pistons. These pistons are coupled directly to hydraulic pistons. The hydraulic pistons are, in turn, connected to the desalination pump pistons. Thus, there are no intervening gears or linkages. The hydraulic system is used so that it absorbs power from, or provides power to, the system to maintain the prescribed relatively constant flow rate. Thus the hydraulic system provides a power compensating function, because the power from the engine is non-uniform over the cycle period.

The Brayton cycle is used because the top pressure is nearly constant with no pressure peaks, which permits uniform piping and flange use at the maximum pressure of the Brayton cycle. It should be noted that the engine and its associated equipment size decreases with increasing pressure, which decreases the working fluid volume. However, there is a trade-off with cost, which could increase with higher design pressures. Most of the equipment for the proof-of-concept Pilot Plant unit is designed for a maximum pressure of 150 psig. Increasing the design pressure to 300 psi, or higher, could increase the equipment cost for the Pilot Plant unit. Future full-scale designs may use peak pressures of 300 psig, or higher. For the present project recuperators and other heat exchangers are readily available. For a recuperator effectiveness of 90%, the maximum cycle efficiency occurs at a pressure ratio of 3 as found in the thermodynamic analysis of the Brayton cycle. Thus, the low pressure of the Brayton cycle is set at 54.9 psia (3.79 BAR), which is one-third that of the high absolute pressure of 164.7 psia (11.35 BAR).

2. Cycle Operation

The Bmyton cycle is shown in Figure 1, and the engine schematic is shown in Figure 2. The compression and expansion cylinders are shown on the left and right respectively of Figure 2. As the compression piston moves to the right beginning at the left side of the cylinder, the gas to the right of the piston is compressed. The exit valve at the outlet, state 2, remains closed until the volume becomes sufficiently small to result in a pressure ratio of 3. Meanwhile gas at state 1 flows into the cylinder behind the left side of the piston.

When the pressure to the right of the piston becomes equal to p_2 the valve at 2 opens and the gas flows out of the cylinder at constant pressure and through the exhaust valve until the piston reaches the right end of the cylinder. This outflow process is also at constant enthalpy, as will be shown later. Thus, state 2 on the Brayton cycle represents this process. The ratio of the compressed gas cylinder volume at the point of the valve opening to the total cylinder volume is V_2/V_1 and is termed the cut-off ratio for compression.

While the compression cylinder moves to the right, gas at state 3 flows into the expansion cylinder at constant pressure. This filling process continues until the volume V_3 at closing of the inlet valve yields the specified p_4/p_3 when the piston expands isentropically to V_4. The total expansion cylinder volume is V_4 and the inlet valve closes when the cylinder volume of the in *flowing gas* is V,. The ratio of this cylinder volume to the total cylinder **volume** is V_3/V_4 and is termed the cut-off ratio for expansion. The gas continues to expand until it reaches pressure p_4 at the right end of the cylinder gas. Meanwhile, the gas on the right of the expansion piston has been flowing out the exhaust valve at p_4.

The same processes as described above occur on the opposite side of the pistons as they go from right to left on the return stroke. Thus, the pistons are double acting. When the pistons return to the left side of the cylinder, one cycle has been completed. The cycles per minute are adjustable, and with the length of the piston stroke its velocity is determined for a given cycle speed. The compression inlet and outlet valves open and close automatically when the pressure differential increases above the cracking pressure, to allow flow through the appropriate valve. In the expansion cylinder a computer controls the inlet and **outlet** valves and the optimum cut-off ratio.

3. Brayton Cycle Analysis

Note that the cycle has been termed the Brayton cycle, although the processes in the cylinders are a combination of isentropic and constant pressure processes. There is isentropic compression and constant pressure emptying in the compression cylinder and constant pressure filling and isentropic expansion in the expansion cylinder. The expansion filling and compression emptying of the cylinders is at constant pressure and also at constant enthalpy (constant temperature for a perfect gas).

To show that the constant pressure filling of the expansion cylinder and emptying of the compression cylinder is a constant enthalpy process, the time-dependent energy equation for a control volume is used. It is written as

$$dU/dt = dQ/dt \; dW/dt - dW_x/dt - (hw)_{in} + (hw)_{,,}$$

Where U is the total internal energy of the gas in the control volume, h_{in} and h_{out} the specific enthalpy of the gas flowing into or out of the control volume and w_{in} and w_{out} the mass flow of gas into or out of the control volume. W is the work done by the control volume at its boundaries (exclusive of flow work), W_x is the work done by any shaft protruding from the control volume (positive if work is done by the shaft), and Q is the heat transfer to the gas in the control volume. Q , W_x and w_{out} are zero.

The time dependent continuity equation is written

$$dm/dt = w_{in} - w_{out}$$

where m is the mass of gas in the control volume and w, is zero. These equations may be combined and multiplied by dt to obtain

$$dU = - dW + h_{in} dm$$

where $dW = pdV$, which is the work done by the gas on the piston.

This equation may be integrated from the beginning of gas filling (where m = 0 and V = 0) to any later state which results in

$$mu + pmv = h_{in} m$$

or $$h_{cont. vol.} = h_{in} = h_3$$

The same procedure may be used to show that the compression cylinder emptying process is also a constant enthalpy process.

Because two properties determine a state and enthalpy and pressure remain constant, states 2 and 3 are fixed during the compression emptying and expansion filling processes. Thus, the cycle looks like the Brayton cycle shown in Figure 1. It is noted that with a relatively low pressure ratio of 3, the constant pressure portion of the stroke is relatively long, or about 60% of the total stroke. This results in a high mean-effective-pressure (mep) as compared to the maximum pressure P_2. This will be an important design benefit for full-scale engines.

4. Is-entropic Processes in the Cycle in the Compression and Expansion Processes

The isentropic processes in the Bmyton Cycle are essentially isentropic, because the boundary layers are thin compared with the dimensions of the cylinder and there are virtually no eddies which would result in fluid flow losses. Thus the heat transfer and fluid friction are essentially zero. The processes shown between the two constant pressure processes in Figure 1 are truly isentropic for the gas. There are, however, friction losses between pistons and their cylinders. These losses range between 2.5% to 5.0% of the isentropic expansion or compression power. For design purposes 5.0% will be used.

5. Losses in the Nearly Constant Pressure Processes

Between isentropic compression and expansion the gas flows through pipes, heat exchangers and the furnace. The loss in the process is assumed to be 10 psi from the end of compression through the recuperator and furnace to the expansion process. The loss is taken to be 5 psi from the end of the expansion process through the recuperator and cooler to the compression process.

6. Thermodynamic Performance and Engine Size

Thermodynamic properties and component efficiencies will determine the work per pound of mass in the cycle. Then for a specified engine horsepower the flow rate is determined. The gas piston rods are directly coupled to the hydraulic pistons, which in turn are connected to the pistons of the reverse osmosis pumps. Thus, for a specified number of pump cycles per unit time and piston stroke length, the piston velocity is determined. The flow rate, piston velocity, and gas density determine the cross-sectional area of the pistons. Of course, the piston velocity is the same for both the expansion and compression pistons.

The following conditions are specified for determining engine size for the proof-of-concept unit, using air as the working fluid; and assuming it to be a perfect gas:

specific heat of gas, $Cp = 0.24$ Btu/lb-F
specific heat ratio, $k = 1.4$
recuperator effectiveness, $e = 0.9$
cycle pressure ratio, $PR = 3$ (3 yields maximum cycle efficiency)
pressure drop from 2 to 3 , $dp_{23} = 10$ psi
pressure drop from 4 to 1 , $dp_{41} = 5$ psi
inlet gas temperature, $T_1 = 90$ F
hot gas temperature, $T_3 = 1175$ F(limited by available component strength by a good margin)
$P_1 = 54.9$ psia
$P_2 = 54.9 \times PR$ psia
$P_3 = P_2 - dp$, psia
$P_4 = P_1 + dp_{41}$ psia
piston velocity, $Vp = 3.1$ in/s
piston stroke , $S = 4.651$ in
horse power (3 pistons) $= 10$ HP

With these specifications all other properties in the cycle are calculated as well as the working fluid flow rate, work per pound, heat added per pound, piston velocity, piston area, cut-off ratios and cycle efficiency.

With a recuperator effectiveness of 90% it may be shown that a pressure ratio of 3 maximizes the cycle efficiency. Hence, in the following analysis a PR of 3 will be utilized. The process from state 1 to state 2 is isentropic. Thus, the temperature at state 2 may be calculated from the isentropic relation,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}} = PR^{\frac{K-1}{K}}$$

Thus, the temperature at state 2 becomes 753 R (293 F). From the assumed pressure drops from 2 to 3 and 4 to 1, we find

P_2 = 164.7 psia
P_3 = 154.7 psia
P_4 = 59.9 psia

The specifications given above yields the temperature at state 4, which is the temperature obtained from the isentropic process between states 3 and 4, or

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{K-1}{K}}$$

Thus, the temperature at state 4 becomes 1247 R (787 F).

The definition of recuperator effectiveness yields the temperature rise from state 2 to the exit of the recuperator or

$$Tx = T_2 + e\,(T_4 - T_2)$$

Similarly the temperature of the hot gas leaving the recuperator is obtained from the definition of recuperator effectiveness or

$$Ty = T_4 - e\,(T_4 - T_2)$$

It should be noted that the temperature rise of the cold compressed air is the same as the temperature drop of the hot exhaust gas.

Since the pressures and temperatures at the various states of the cycle are known, the densities at these states may be calculated from the perfect gas law. The cut-off ratios for expansion and compression may be calculated from the densities as

expansion cut-off $X_{cut\text{-}off} = V_3/V_4 = \rho_4/\rho_3$
compression cut-off: $X_{cut\text{-}off} = 1 - V_2/V_1 = 1 - \rho_1/\rho_2$

where X is the fraction of the stroke

$$We = Cp\ (T_3 - T_4)\ ;\ Wc = Cp\ (T_2 - T_1)$$

5% of the expansion power and 5% of the compression power are added for friction losses. The heat added (Qadd) in the cycle is also obtained from the energy equation as

$$Qadd = Cp\ (T_3 - Tx)$$

Thus, the cycle efficiency may be calculated with the above equations as

$$\eta = (We - Wc)\ /\ Qadd$$

For the specified horsepower, HP, the flow rate is determined as

$$W = POWER\ /(We - Wc\text{-}LOSS)$$

The piston velocity (Vp) is obtained from the piston stroke S, and the cycles per minute as

$$Vp = 2 \times S \times cpm$$

The cross-sectional area of the expansion (Ae) and compression (Ac) pistons are obtained from the continuity equation as

$$Ae = W / \rho_4\ Vp\ ;\ Ac = W / \rho_1\ Vp$$

All the above calculations provide typical force and power results as shown on Figures 5 and 6.

7. Force and Power Produced by the Pistons

The volumetric flow rate is a steady state value for constant velocity of the piston. The velocity of the pistons varies due to acceleration and deceleration at each end of the stroke. The design velocity is shown in Figure 3. Since the distance that the piston travels is the time integral of the velocity, the velocity of Figure 3 integrates to the distance X shown in Figure 4, which is the fraction of maximum total stroke S. The force produced by the engine pistons is the net pressure times the area of the expansion and compression pistons respectively, or

$$F = \left(\frac{Pexrp}{P_4}\right) P_4 Ae + \left(1 - \frac{Pcomp}{P1}\right) P_1 Ac$$

$$\frac{Pexp}{P_4} = \frac{1}{0x}^{k}\ 0.508 < x \leq 1\ ;\ \frac{Pexp}{P_4} = \frac{P_3}{P_4}\ 0 \leq x \leq 0.508$$

$$\frac{Pcomp}{PI} = \left(\frac{1}{1-X_1}\right)^k \quad 0 \le x < 0.544; \frac{Pcomp}{P_1} = \frac{P_2}{P_1} \quad 0.544 \le x \le 1 .$$

From an inspection of Figure 1,

$$X = V / V_4 = (V_1 - V) / V_1 = 1 - V / V_1$$

The pressures and the resulting forces are shown in Figures 4 and 5, respectively. Note that the force produced by a piston becomes negative because the pressure times the respective area of expansion becomes less than that of compression, as shown in Figure 5. When this occurs, the hydraulic system must provide power to maintain the piston velocity, drawing power from the pistons that have positive power available. Fexp, Fcomp, and Fnet shown in Figure 5 are the expansion force, compression force, and net force respectively. Net force is the difference between the expansion force and the compression force.

To maintain a relatively constant flow rate from the reverse osmosis pump, three pistons are utilized. Each piston is 120 degrees out of phase with the others in a complete forward and return cycle of the piston, as shown in Figure 3. In the example, the stroke is 4.651 in., and the cycle speed is 13.33 cpm. The resultant power from a single piston, which is the product of the velocity shown in Figure 3 and the force shown in Figure 5, is plotted in Figure 6. For the 13.33 cpm, the three pistons are displaced in time from each other by 1.5 sec. The sum of the power from the three pistons is shown in Figure 6. Although one or two of the pistons are sometime moving in opposite directions to the third, the power.is always positive in the first part of the motion and negative at the end of the piston travel, as described above and shown in Figure 6.

The power profile for 1/2 cycle of Piston No. 1 is shown on Figure 6. For three double acting pistons, there are six power strokes like this per cycle. As it is shown in this figure, the instantaneous power varies from the average power by some percentage. The amount of this deviation depends on rise time, ta, constant velocity period, tb, and dwell time, td; and also the variation of compression and expansion pressures. The thermodynamic analysis computer code has been used to look at these parameters with respect to the theoretical power swings. Typical results are shown on Figure 6. The maximum power swing is about 80% of the average power and this corresponds to rise time of 0.45 sec., tb = 1.05 sec., and td = 0.3 sec. The minimum power swing is about 34% and this corresponds to rise time of 0.65 sec. and tb = 0.85 sec. and td = 0.1 sec. Figures 4, 5, and 6 are based on times of: ta = 0.65 sec., tb = 0.85 sec. and td = 0.1 sec.

In the proof-of-concept engine, the actual power swing will be determined for various operating conditions. During this testing the power flow will be added or absorbed by the electric motor to maintain the desired piston velocity, and hence the pumping flow rate. In a full-scale application there are other ways to minimize the effect of the power swings. Some options include phasing six pistons at 60 degrees out of phase, using a flywheel similar to conventional crank type engines, and varying the power profile with computer compensation. For the latter, one option could be to adjust the expander cut-off ratio, lead or lag, to provide part of the compensation.

8. Relations for Piston Velocity Profile, Stroke and Cycle Time

An inspection of the piston velocity profile of Figure 3, stroke, S; and the cycle time, T, yield the following relations

$$T = 2S/Vp\ (avg.)$$

$$cpm = 1/T$$

$$Vp\ (avg.) = [(ta/2 + tc/2)Vp\ (max) + tb\ Vp\ (max)]\ I\ (T/2)$$

$$ta = tc\ , \qquad tb = T/2 - 2ta - td$$

so that

$$(ta + tb)Vp\ (max) = T\ Vp\ (avg.)/2 = S$$

also

$$T/2 = 2ta + tb - td$$

and

$$S / Vp\ (max) = T/2 - ta - td$$

The above equations may be used to solve for the quantities desired. In the examples calculated herein various values of cpm were selected, the stroke, was taken as 4.651 in and the dwell time, td, was taken as 0.3 seconds and 0.1 seconds.

The present Pilot Plant pumping system design is based on a maximum piston velocity, Vp(max), of 3.10 in./s. The power vs. displacement or time of Figure 6 has a positive lobe near the beginning of the piston displacement and a negative lobe near the end. After superposition of the power from the three pistons, there remains a swing between maximum and minimum power. The power is the product of the piston force and velocity, and it will always integrate to the designed horsepower of 3.33 for each piston. Therefore, the maximum and minimum power lobes can be reduced or flattened by slowing the velocity in the regions of highest and lowest power. Reduction of the velocity is accomplished by increasing the rise and drop times ta and tc as shown in the velocity profile of Figure 3. The final result is a reduction of the percent of the power swing between maximum and minimum. This procedure also results in an increase of the cycle time or decrease of the cpm; however, this is another alternative for smoothing the power flow.

9. Clearances Between Piston and Cylinder at the End of the Travel

If there is a clearance between the end wall of the compression cylinder and the end of the piston stroke, the piston must reverse and return a distance C_1 before flow at p_1 can enter the cylinder. The gas trapped in clearance C_2 is at p_2 and the return motion of the piston to clearance C_1 permits the air to return to pressure p_1. To provide the same flow in compression as in expansion, the cross-sectional area of the compression piston must be increased to accommodate the effectively shortened piston stroke, which is s-2 C_1, assuming that the clearance is the same at both ends of the cylinder. Thus to maintain the same volumetric displacement in the compression cylinder the change in cross-sectional area must be increased from A, to A,. To maintain the same volume for the decreased stroke we may write

$$A_1 S = A_2[S-2(C_1-C_2)]$$

For expansion of the gas trapped in the clearance space from C_2 at state 2 to C_1 at state 1 we may write

$$C_1/C_2 = V_1/V_2 = \rho_2/\rho_1$$

For zero clearance between cylinder end wall and the piston C_1 is zero as is C_2. The results for various clearances are shown in the Table below.

Clearance Each End (inches)	A_2/A_1	d_2/d_1
0.125	1.068	1.033
0.25	1.147	1.070
0.375	1.238	1.111

10. Summary and Conclusions

The thermodynamic analysis shows that the maximum cycle efficiency can be attained with pressure ratio of 3 when the recuperator effectiveness is 90% or higher.

While the expansion cylinder is filling with hot gas at constant enthalpy, the compression cylinder is isentropically compressing the gas from state 1 to state 2. This process results in the pressure distribution shown in Figure 4, where the expander pressure goes from high to low and the compressor pressure goes from low to high as time increases. This pressure distribution results in positive power produced by a compression and expansion cylinder for the initial part of the stroke and a negative power for the later part of the stroke. Of course, the positive power is greater than the negative power and three sets of expander and compressor cylinders can be superimposed each operating 120 degrees out of phase with the others.

The superposition of power from three pistons results in power swings from maximum to minimum of up to almost 80% and as low as 34% of the average power depending upon the velocity profile. Reducing dwell time reduces the power sting and its effect was significant when reduced from 0.3 seconds to 0.1 seconds. The power swing was also reduced by increasing the rise and fall times, while maintaining the maximum velocity constant over the constant velocity period. This procedure flattens the maximum and minimum power lobes over each half-cycle of piston travel. In full-scale applications there are other methods available to flatten the power profile. In a full-scale design, there are various other techniques that can be used to smooth the power flow to within acceptable limits.

The diameters of the expansion and compression cylinders arc not much affected over the range of cpm analyzed. For the case of no end clearance on the pistons, this yields a preliminary sizing for the Pilot Plant unit of an expansion cylinder diameter of 22.8 in., and a compression cylinder diameter of 15.9 in. For full-scale designs, the sizing will be optimized by using longer strokes, higher pressures, and perhaps higher operating temperatures.

The following figures arc referred to in this report

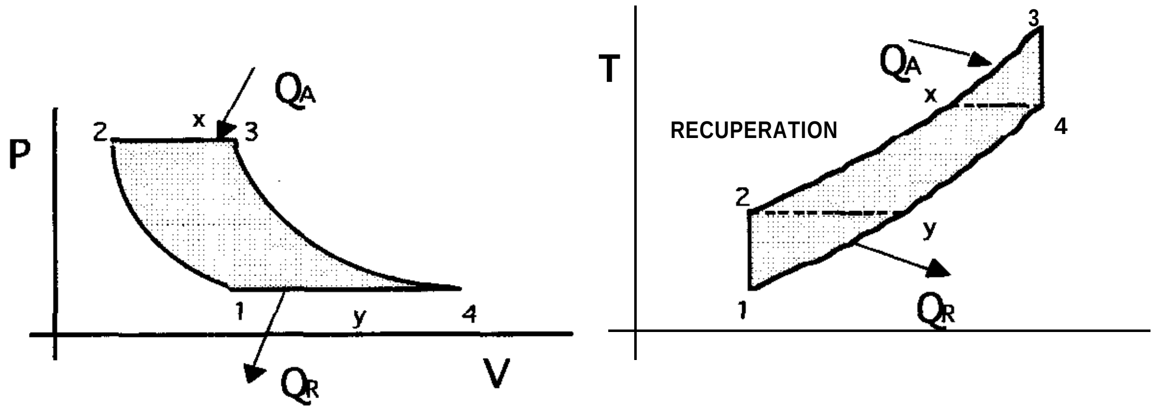

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Figure 1 Recuperated Brayton Cycle, PV and TS Diagrams

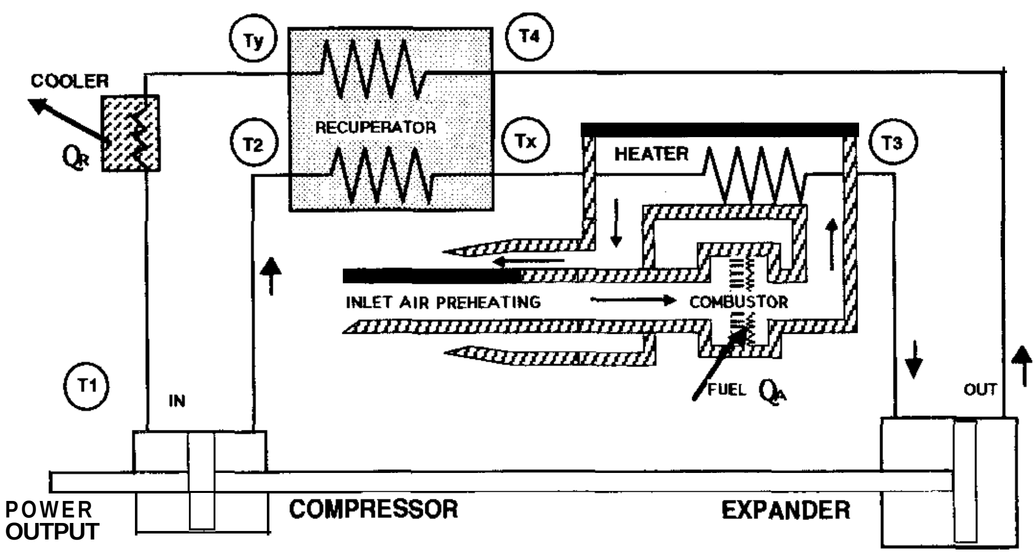

Figure 2 Recuperated Brayton Schematic

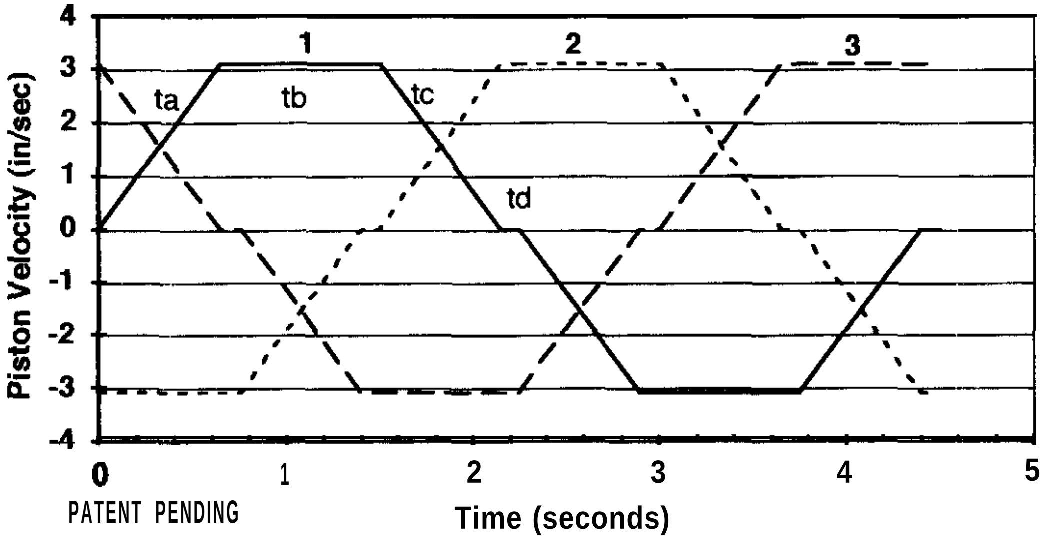

Figure 3 Piston Velocity **Profile**

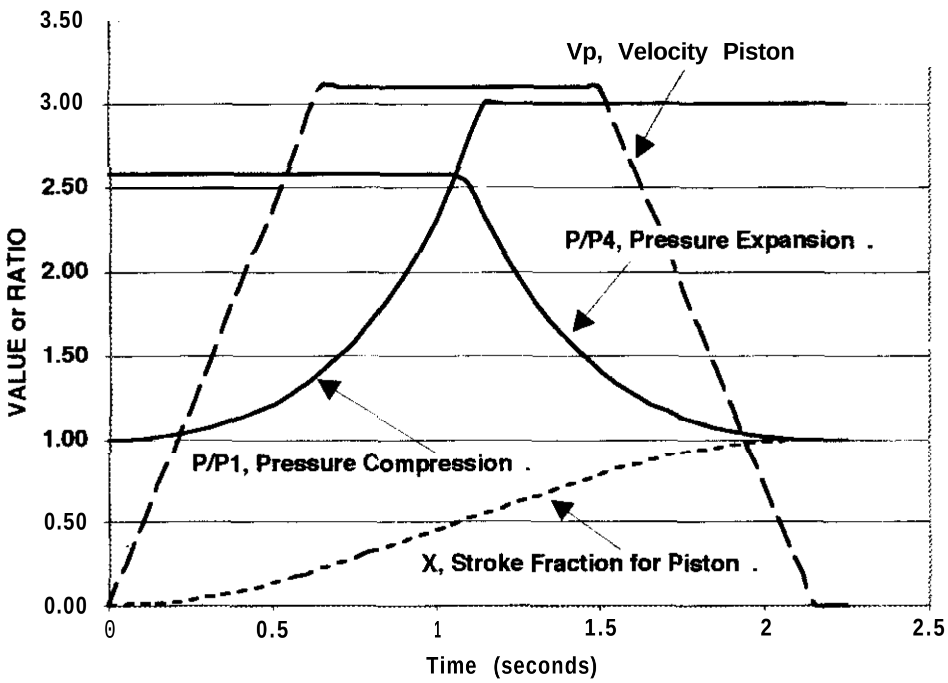

Figure 4 Stroke, Velocity, and Pressures

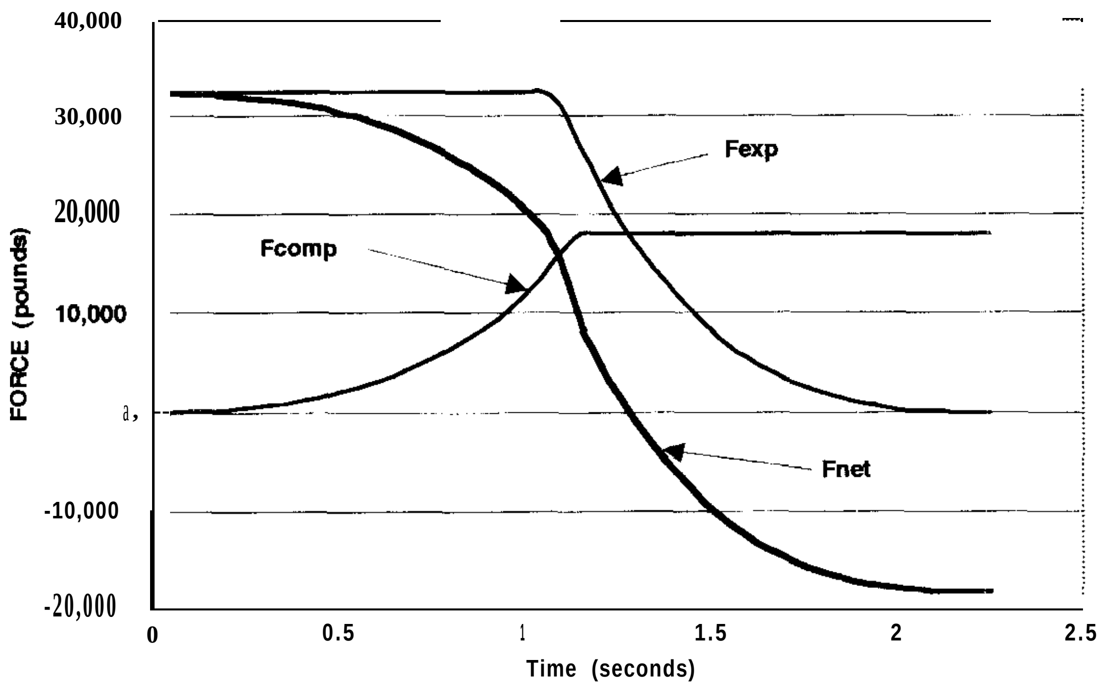

Figure 5 Piston Forces

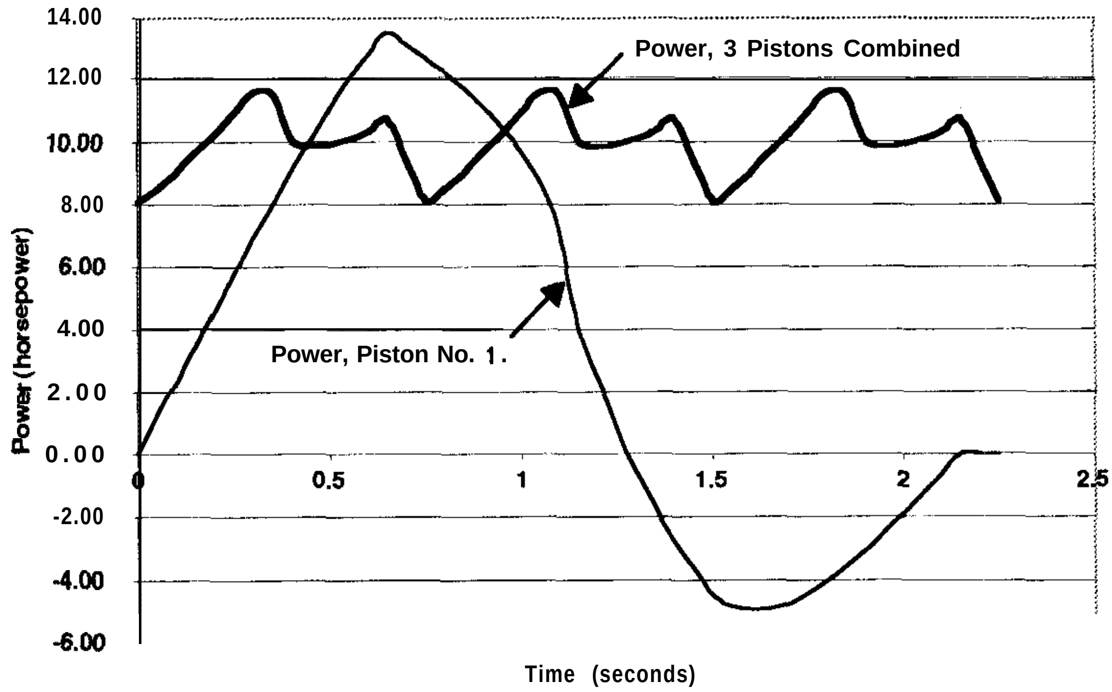

Figure 6 Piston Power

Appendix B

VRO-DDE™ Heat Exchanger Performance Projections

Aerospace Equipment Systems
AlliedSignal Corporation

VRO-DDE™ Heat Exchanger Performance Projections

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This report outlines the thermal design of heat exchangers for use in the VARI-RO™ Direct Drive Engine (VRO-DDE™) system. The engine diagram, shown in Figure 1, includes three heat exchangers: the recuperator, cooler, and heater. The following is a brief description of the design procedure as well as designs for a few different system power and pressure requirements.

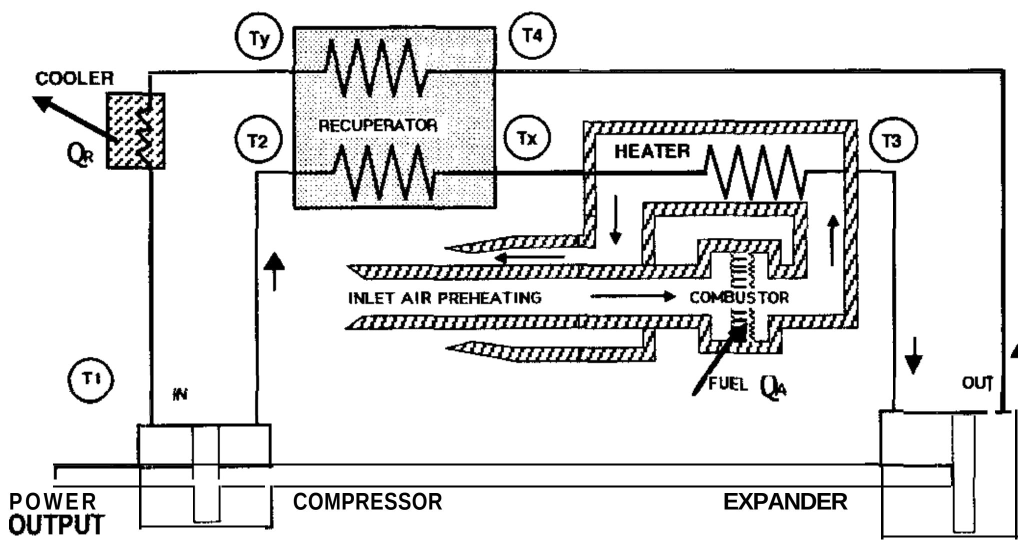

Figure 1: Direct Drive Engine Process Flow Diagram

Design Procedure

In the design of the VARI-RO heat exchangers, the following system requirements were incorporated:

Thermal Performance:
Based on the heat load and required inlet and outlet temperatures, the three heat exchangers require high effectiveness, about 90%. High effectiveness is achievable with counter-flow heat exchangers used in the presented designs.

Weight and Volume:
Using the advanced heat exchange surfaces such as offset plate-tines, the designed heat exchangers are compact with minimum weight and volume.

Pressure Drop:
Minimum pressure drop in a heat exchanger is desired to minimize the power penalty. An optimization technique was employed to select a heat, exchanger design that requires minimum pressure drop and complies with the thermal performance and minimum weight and volume requirements. The pressure drop in a heat exchanger can be reduced by increasing the height (within the manufacturing limits) and the plate fin dimensions.

Material Selection:
The heat exchanger material is selected based on the operating temperature. Stainless steel was used for high temperature conditions of the recuperator and heater, whereas aluminum was used for the cooler, which operates at low temperatures. Also, based on the operating pressure the fin and plate thickness was selected that ensures the unit integrity under design and off-design operating conditions.

Heat Exchanger Designs

The engine heat exchangers, namely, the recuperator, cooler, and heater, were designed for four different system pressure and power requirements. These requirements are:

- 300 psi, 25 hp
- 300 psi, 10 hp
- 150 psi, 10 hp
- 500 psi, 300 hp

The first three designs were considered for a scaled-down pilot plant system whereas, the last design (500 psi and 300 hp) was selected as the full-scale system.

The detail specifications of the VARI-RO heat exchangers for different pressure and power requirements are presented in the following tables.

Table 1: 300 psi, 25 hp

HEX	Recuperator	Cooler	Heater
Fluid 1 (hot)	Air	Air	Air
Fluid 2 (cold)	Air	Water	Air
Flow Rate 1 (lb/min)	39.6	39.6	39.6
Flow Rate 2 (lb/min)	39.6	10.0	39.6
Inlet Temp. 1 (F)	782	351	1250
Exit Temp. 1 (F)	351	90	813
Inlet Temp. 2 (F)	303	60	735
Exit Temp. 2 (F)	735	120	1175
Effectiveness (hot side)	90%	90%	85%
Inlet Press. 1 (psia)	105	105	15.5
Inlet Press. 2 (psia)	315	16	315
Press. Drop 1 (psid)	1.5	1.5	0.6
Press. Drop 2 (psid)	1	0.2	0.4

Length (in)	20.5	13.3	11.3
Width (in)	1.6	4.1	5.9
Height (in)	8.0	[illegible]	20.0
Number of Passages	37	17	94
Volume (in^3)	1246.4	218.1	1333.4
Heat Exch. Mode	Counter Flow	Counter Flow	Counter Flow
Material	Stainless Steel	Aluminum	Stainless Steel
Weight (lb)	165.5	9.2	145.8

Table 2: 300 psi, 10 hp

HEX	**Recuperator**	**Cooler**	**Heater**
Fluid 1 (hot)	Air	Air	Air
Fluid 2 (cold)	Air	Water	Air
Flow Rate 1 (lb/min)	9.6	9.6	9.6
Flow Rate 2 (lb/min)	9.6	4.0	9.6
Inlet Temp. 1 (F)	782	339	1250
Exit Temp. 1 (F)	339	90	813
Inlet Temp. 2 (F)	290	70	733
Exit Temp. 2 (F)	733	215	1175
Effectiveness (hot side)	90%	93%	85%
Inlet Press. 1 (psia)	105	105	15.5
Inlet Press. 2 (psia)	315	15	315
Press. Drop 1 (psid)	0.5	0.5	0.3
Press. Drop 2 (psid)	0.7	0.2	0.6
Length (in)	18.5	7.0	7.6
Width (in)	4.0	2.2	6.2
Height (in)	4.0	2.2	6.2
Number of Passages	18	10	29
Volume (in^3)	296.0	33.9	292.1
Heat Exch. Mode	Counter Flow	Counter Flow	Counter Flow
Material	Stainless Steel	Aluminum	Stainless Steel
Weight (lb)	35.5	1.3	33.8

Table 3: 150 psi, 10 hp

HEX	**Recuperator**	**Cooler**	**Heater**
Fluid 1 (hot)	Air	Air	Air
Fluid 2 (cold)	Air	Water	Air
Flow **Rate 1 (lb/min)**	9.6	9.6	9.6
Flow Rate 2 **(lb/min)**	9.6	4.0	9.6
Inlet **Temp. 1 (F)**	782	339	1250
Exit **Temp 1 (F)**	339	90	813
Inlet Temp. 2 (F)	290	70	733
Exit **Temp. 2 (F)**	735	215	1175
Effectiveness (hot side)	90%	93%	85%
Inlet Press. 1 (psig)	**50**	(105	**0.3**
Inlet **Press. 2 (psig)**	**150**	15	**150**

Press. Drop 1 (psid)	0.2	0.5	0.3
Press. Drop 2 (psid)	0.7	0.2	0.6
Length (in)	23.5	7.0	7.8
Width (in)	4.3	2.2	5.2
Height (in)	4.3	2.2	7.7
Number of Passages	15	10	36
Volume (in^3)	434.5	33.9	312.3
Heat Exch. Mode	Counter Flow	Counter Flow	Counter Flow
Material	Stainless Steel	Aluminum	Stainless Steel
Weight (lb)	44.0	1.3	35.9

Table 4: 500 psi, 300 hp

HEX	**Recuperator**	**Cooler**	**Heater**
Fluid 1 (hot)	Air	Air	Air
Fluid 2 (cold)	Air	Water	Air
Flow Rate 1 (lb/min)	238.8	9.6	238.8
Flow Rate 2 (lb/min)	238.8	4.0	238.8
Inlet Temp. 1 (F)	1026	339	1600
Exit Temp. 1 (F)	388	90	1049
Inlet Temp. 2 (F)	317	70	955
Exit Temp. 2 (F)	958	215	1512
Effectiveness (hot side)	90%	93%	85%
Inlet Press. 1 (psig)	**157**	105	**0.8**
Inlet Press. 2 (psig)	**500**	15	**500**
Press. Drop 1 (psid)	0.95	0.5	0.8
Press. Drop 2 (psid)	1.0	0.2	1.7
Length (in)	30.2	7.0	11.5
Width (in)	12.5	2.2	24.3
Height (in)	15.7	2.2	30.4
Number of Passages	67	10	146
Volume (in^3)	5926	33.9	8495
Heat Exch. Mode	Counter Flow	Counter Flow	Counter Flow
Material	Stainless Steel	Aluminum	Stainless Steel
Weight (lb)	582.6	1.3	887.1

Appendix C

VRO-DDE™ Mechanical and System Design

Vari-Power Company
and
Cal-West Machining

Confidential and Proprietary

NOTE: The "VRO-DDE™ Mechanical and System Design" report contains confidential and proprietary information of the Vari-Power Company, and cannot be released to the general public.