

**CLATHRATE DESALINATION PLANT
PRELIMINARY RESEARCH STUDY**

By
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6335 Ferris Square, Suite E
San Diego, California 92121

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Water Treatment Technology Program Report No. 5

June 1995

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Technical Service Center
Water Treatment Engineering and Research Group

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13. ABSTRACT (Maximum 200 words) This report presents preliminary research, design, and cost estimates for a clathrate freeze desalination method and system. A clathrate former is injected through the inner pipe of a submerged pipeline to a predetermined ocean depth at which the ocean temperature is less than the clathrate forming temperature. The agent combines with seawater within the annulus of the outer pipe to form a slurry of clathrate ice crystals and brine that is pumped to the surface. The ice crystals are separated from the brine, washed, and melted; the remaining water is then separated from the clathrate forming agent. The clathrate forming agent may be recovered for reinjection or discarded. The melting of the clathrate ice and the return line of brine water to the ocean provide cold water sources that can be used to cool refrigerant in air conditioning systems in local buildings. The system depicted uses the hydrocarbon HCFC R141B (Dichloromonofluoroethane - CCl ₂ FCH ₃) as the clathrate forming agent with lesser attention on HCFC R22 (Chlorodifluoromethane - CHClF ₂) and carbon dioxide (CO ₂).				
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*Bureau of Reclamation
Mission Statement*

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

*U.S. Department of the Interior
Mission Statement*

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The Naval Auxiliary Landing Field, San **Clemente** Island, California
Scripps Institute of Oceanography, La Jolla, California
ENPEX Corporation, San Diego, California
Jaeger Engineering, Inc., San Diego, California
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Wilfred Hahn, consultant
Fred Jaeger, Consultant
Dr. Robert Hoe, Consultant
Austin F. **McCormack**, Consultant
Dr. John **Ripmeester**, **Physical Chemist**, Canadian National **Research** Council

CONVERSION UNITS

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
LENGTH		
Angstroms	$10^{(-10)}$	Meters
Micron	$10^{(-6)}$	Meters
Inches	2.54	Centimeters
Feet	0.3048	Meters
Miles	1.609344	Kilometers
AREA		
Acre	4,046.9	Square meters
square Miles	2.5899	Square kilometers
VOLUME		
Acre-feet	1233.5	Cubic meters '
Cubic feet	0.0283168	Cubic meters
Gallons (U.S.)	3.78533	Liters
Thousand Gallons	3.78545	Cubic meter
WEIGHT		
Moles	1	Gram molecule
Pounds	0.453592	Kilograms
FORCE/AREA		
Atmospheres	1.033513	Kilograms per square centimeter
Pounds per square inch	0.070307	Kilograms per square centimeter
MASS/VOLUME (DENSITY)		
Pounds per cubic foot	16.0185	Kilograms per cubic meter
MASS/CAPACITY		
Pounds per gallon	119.829	Grams per liter
FLOW		
Acre-feet per year	1233.5	Cubic meters per year
Cubic feet per minute	0.4719	Liters per second
Gallons per minute	0.06309	Liters per second
Gallons per day	3.7854	Liters per day

CONVERSION UNITS - Continued

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
FLOW (Continued)		
Pounds per hour	0.4536	Kilograms per hour
Thousand gallons per year	3.7854	Cubic meters per year
Million gallons per day	3,785.4	Cubic meters per day
WORK AND ENERGY		
British thermal units (BTU)	0.252	Kilogram-calories
British thermal units per pound	2.326	Joules per gram
British thermal units per cubic foot	35.314725	British thermal units per cubic meter
POWER		
Horsepower	745.500	Watts
British thermal units per hour	029307	Watts
Kilowatts	1,000	Watts
Kilowatt-hours per thousand gallons	026417	Kilowatt-hours per cubic meter
TEMPERATURE		
Degrees Fahrenheit	5/9 (after subtracting 32)	Degrees Celsius
REFRIGERATION		
Ton-hours	3.5168	Kilowatts
MONETARY		
Dollars per thousand gallons	0.264178	Dollars per cubic meter
Dollars per acre-foot	810.7 x 10⁽⁻⁶⁾	Dollars per cubic meter
Dollars per pound	2.204	Dollars per kilogram
Dollars per gallon	0.264178	Dollars per liter
Dollars per British thermal unit	3.968	Dollars per kilogram-calorie

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GLOSSARY

Abbreviations:

English Units:

British thermal unit	BTU
Cubic feet per minute	cfm
Fahrenheit	F.
Gallons per day	gpd
Gallons per minute	gpm
Horsepower	hp
Kilowatt-hours	kw-hr
Kilowatts	kw
Parts per million	ppm
Pounds per square inch	psi

Metric Units:

Centigrade	C.
Centimeter	cm
Cubic meter	m ³
Kilogram	kg
Kilometer	km
Meter	m
Square centimeter	cm ²
Square kilometer	km ²
Square meter	m ²

Acronyms:

National Research Council of Canada	NRCC
Natural Energy Laboratory of Hawaii	NELH
Office of Saline Water	osw
Office of Water Research and Technology	OWRT
Reverse osmosis	RO
Secondary refrigerant freeze	SRF
Scripps Institute of Oceanography	Scripps
Thermal Energy Storage, Inc.	TESI
Vacuum freezing vapor compression	VFVC

Clathrate:

A **lattice like** structure in which molecules of one substance are enclosed within the crystal structure of another substance.

Clathrate former:

A hydrocarbon or other non-water molecule that will form a clathrate with water crystals at elevated temperatures above the normal freezing point of water; there are a multitude of clathrate formers that will form clathrate ice at various pressures and temperatures, in both liquid and gaseous form, both as inorganic or organic compounds, with various degrees of toxicity, flammability, and other characteristics.

HCFC R141B:

A specific hydrocarbon (dichloromonofluoroethane - CCl₂FCH₃) clathrate former used as the primary agent in this research report that will form clathrate ice crystals in seawater at 47.5° F. [8.61° C.].

GLOSSARY - Continued

- HCFC R22: A specific hydrocarbon (chlorodifluoromethane • **CHClF₂**) clathrate former **discussed** in Appendix A that will form clathrate ice crystals in seawater at approximately 55° F. [**12.8°** C].
- Latent Heat of Fusion: The heat energy released when a gas is changed into a liquid or a liquid into a solid.

1. SUMMARY

Under a firm-price cost-sharing contract with the Bureau of Reclamation, a feasibility study of a new clathrate desalination process is presented that shows both the technical and economic feasibility of a publicly-financed desalination plant that would produce fresh water at a cost of approximately **\$1.70/1,000 gallons** [**\$0.45/m³**] at a rate of 7.2 million gallons/day [**27300 m³/day**] or 8,000 acre-feet/year [**9.87 million m³/year**]. This plant design represents a major technical **breakthrough** by combining clathrate technology with ocean engineering technology compared to processes developed by the Office of Saline Water (**OSW**) at its Wrightsville Beach Test Facility in **North** Carolina during the 1960 and 1970 decades.

The commercial plant design is expected to reduce the cost of fresh water by a factor of two over that produced by the best desalination technology to date utilizing the reverse osmosis process. For the **first** time, desalination technology can compete with fresh water sources to serve the Southern California area. A metropolitan water authority in Southern California has stated a willingness to sign a contract for the purchase of new water resources at a price of **\$2/1,000 gallons** [**\$0.53/m³**] of fresh water. **The** results of this report show that a desalination plant of this design rated at 7.2 million gallons/day or **8,000 acre-feet/year**, serving a population of 72,000, can achieve this objective. Larger plants could **reduce** the cost of water **further**.

Clathrates have always **attracted** interest for **desalination** purposes since clathrate ice crystals can be formed at elevated temperatures that reduce both the cost of ice **formation from** brine and the cost of melting the ice to form fresh water. **Past** efforts in the 1960 and 1970 decades have failed to achieve low fresh water costs because of two principal difficulties: (1) small ice crystal size; and (2) low yield of **fresh** water per unit of pumped seawater. **The small** ice crystal size developed in OSW **pilot** plants at Wrightsville Beach resulted in a high economic penalty to wash the **crystals** free of **salt**. Thermal Energy Storage, Inc. (**TESI**) has previously solved this problem in a \$4 million research and development program over the period from 1984 to 1993 that increased the crystal size in a batch process by a factor of ten over that developed at the Wrightsville Beach test facilities.

Under this contract, TESI has achieved a theoretical technical breakthrough to solve the second problem by an unique invention of forming the clathrate ice crystals at an ocean depth of 2,000 feet [**610 m**]. This breakthrough combines desalination technology with ocean engineering technology that offers the benefits **of**:

- 0 Developing huger crystals compared to the small crystals of **earlier** designs in a **continuous** process as the crystals continue to grow during the **pumping** of the clathrate ice to the surface.

- o **Eliminating the large** heat exchanger in earlier designs by releasing the latent heat of fusion to the ocean as the clathrate ice is **formed** at depth and pumped to the surface;
- o Reducing the size of the wash columns by a factor of six from earlier designs by increasing the yield of **fresh** water per unit of seawater pumped **from** 4 percent to 25 **percent**;
- o Reducing the need for extensive crystal washing because the ice crystals are scrubbed free of surface salt as the clathrate ice is pumped to the surface;
- o Using air-strippers and liquid-phase carbon **adsorbers** to recover the clathrate former for **reinjection** and to produce fresh water that exceeds potable water standards.

The result is a simple process design, smaller size and less equipment, and a major reduction in power costs. In particular, power costs have been reduced to 3.2 **kilowatt-hours/1,000** gallons [**1.58 kilowatt-hours/m³**] of fresh water compared to more than 120 **kilowatt-hours/1,000** gallons [**31.70 kilowatt-hours/m³**] at Wrightsville Beach,

A second part of the invention is the use of the latent heat of fusion from the melting ice crystals and the cold brine water to provide air conditioning to buildings **and** other **facilities** in the local area Heat exchangers located at these cold water sources would be used to cool the air **conditioning** medium that is pumped to the air conditioning units at each site.

Whether or not this **TESI** invention provides **the** breakthrough expected from combining **desalination** technology with ocean **engineering** technology needs to be proven in a demonstration **facility**. A low-cost demonstration facility can be built at the Natural Energy Laboratory of Hawaii at an estimated cost of \$1.63 million that includes **sufficient** funds to operate the unit for two **years**. It is expected that an existing 40 inch [**102 cm**] pipeline to the 2,000 foot [**610 m**] depth can be modified and **utilized**.

Two other sites have also been investigated, one at the U.S. Navy facility on San Clemente Island off the coast of San Diego and one at Scripps Institute of Oceanography in La Jolla, a seacoast community **in** San Diego. The cost at the latter two **sites** is more expensive since a new pipeline would need to be **installed**. Makai Ocean Engineering, Inc. is an expert in laying many of these large pipes to the 2,000 foot depth off the coast of Hawaii. A **40** inch polyethylene pipeline on the ocean surface ready for submergence **is** shown in Figure 1.1.

The new **pipeline** could be **justified** by the U.S. Navy because of the **high** cost of barging fresh water to San **Clemente** Island. The Scripps **Institute** location has potential as a source of funding **through** a California State grant to the University of California **and** hence to **Scripps** Institute. **The** choice of sites



Figure 1.1
Forty-Inch Pipeline Ready for Submergence to 2,000 Foot Depth

is primarily dictated by the source and adequacy of funds **from** sponsoring organizations since all three sites are technically acceptable.

There are many clathrate forming agents that could be utilized for the desalination process, and nine potential agents are listed:

<u>Agent</u>	<u>Critical Decomposition Temperature</u>	
	<u>Temperature (°F)</u>	<u>Pressure (Psig)</u>
Carbon Dioxide (CO ₂)	50.0	638
HCFC R141B (CH ₂ CCl ₂ F)	52.9	0
HCFC R142B (CH ₂ CClF ₂)	55.6	19
HCFC R152A (CH ₂ CHF ₂)	58.8	49
HCFC R22 (CHClF ₂)	61.3	9
Cyclopropane (C ₃ H ₆)	62.6	72
HCFC R31 (CH ₂ ClF)	64.2	27
Methyl Chloride (CH ₃ Cl)	68.7	56
chlorine (Cl ₂)	82.9	109

The above decomposition temperatures are reduced by approximately **4° to 6° F. [2.2° to 3.3° C.]** when the clathrate is made with seawater.

HCFC **R141B** was selected for use in this research study since **TESI** has the most experience with this **clathrate** former and it produces a lower cost of water than HCFC R22 for applications where ocean or sea temperatures are below **45° F. [7.2° C.]**. HCFC R22 is also a primary candidate agent that has a higher decomposition temperature, but this is offset by the higher pressure required in **certain** parts of the plant process. Even so, HCFC R22 appears attractive for warmer water applications, as discussed in Appendix A, where the ocean or sea temperatures **are** below **55° F. [12.8° C.]**. Carbon dioxide was investigated but the high pressure requirements and compression power to inject the gas into the undersea pipe makes the process uneconomic at this time.

In the proposed design, the clathrate **former** is a halogenated **hydrocarbon** designated HCFC **R141B** (**dichloromonofluoroethane** CCl₂FCH₃). This HCFC **R141B** **clathrate** former produces clathrate ice in seawater at **47.5° F. [8.6° C.]** and is commonly **called** “warm ice”. Jar tests conducted at **TESI** using ocean water recovered from the 2,000 foot [610 m] depth **confirmed** the formation of **clathrate** ice at a temperature of **47.5° F.** using HCFC **R141B** as the clathrate former.

The HCFC **R141B** is recovered in the process and **reinjecte**d to form new ice in pipes at 2,000 foot [610 m] depths where **the** water temperature is approximately **42° F. [5.56° F.]** The clathrate ice is formed directly in **the** lower sections of the pipe. The clathrate ice crystals grow larger as they travel back to the surface facility.

The ice crystals are next separated from the brine and washed in a wash column. The ice crystals are then melted and subsequently separated from the HCFC **R141B** in a decanter. From there, the fresh water is **processed** through an air stripper and a liquid-phase carbon adsorber to **remove** residual amounts of HCFC **R141B** and produce high-quality fresh water. The HCFC **R141B** is **recovered** in the vapor phase by means of a vapor-phase carbon adsorber. It is then condensed for **re injection** to **form** new clathrates at the 2,000 foot ocean depth. A flow diagram is presented, in Drawing PF-1.

The **fresh** water will meet or exceed existing specifications for potable water with total dissolved solids expected to be 100 parts per million or less. If allowable **concentrations** of HCFC **R141B** in **fresh** water need to be less than one part per million, the fresh water can be pumped through a deaerator. **From** the de&nation plant, the fresh water will be pumped to local reservoirs or aqueducts to be mixed with surface water **where** further dilution, evaporation, and decomposition of the HCFC **R141B** (measured in **parts** per billion) **will** occur.

The cost of **the** 7.2 million gallons/day [27300 m³/day] commercial plant is **estimated** at \$18.2 **million**, including **working** capital, **interest during construction**, reserves, and contingency. The annual capital and operating costs are estimated at \$3.8 million if the plant were **publicly-financed**. With six **percent** interest on bonds, the cost of water is calculated to be **\$1.70/1,000** gallons [**\$0.45/m³**].

If the 7.2 million gallons/day commercial plant were privately-financed with 18 percent equity and 82 percent corporate bonds, a 42.5 percent income tax rate, a 15.65 percent return on equity before taxes, and 9 percent **return** on bonds before taxes, the cost of water would be **\$2.02/1,000** gallons [**\$0.53/m³**]. A summary of these estimates and calculations is shown in Tables 1.1 and 1.2 for both the 3.6 **million** gallons/day [13600 **m³/day**] and the 7.2 million gallons/day plants under both public and private **financing**.

The demonstration plant project is **estimated** to cost \$1.63 million including \$1.5 1 million for plant capital costs and two years of operating costs. The small size demonstration plant would produce 36,000 gallons/day [136 **m³/day**] of **fresh** water or 40 acre-feet/year [**49300 m³/year**] if operated continuously.

The technical and economic achievement of low-cost **desalinated** water at approximately **\$2/1,000** gallons [**\$0.53/m³**] would develop major new markets, both nationally and **internationally**, for **fresh** water. Examples include Southern California, Baja California, Israel and other Middle East nations, western Australia, north, eastern, and southwest Africa, and many islands **throughout** the world Further cost

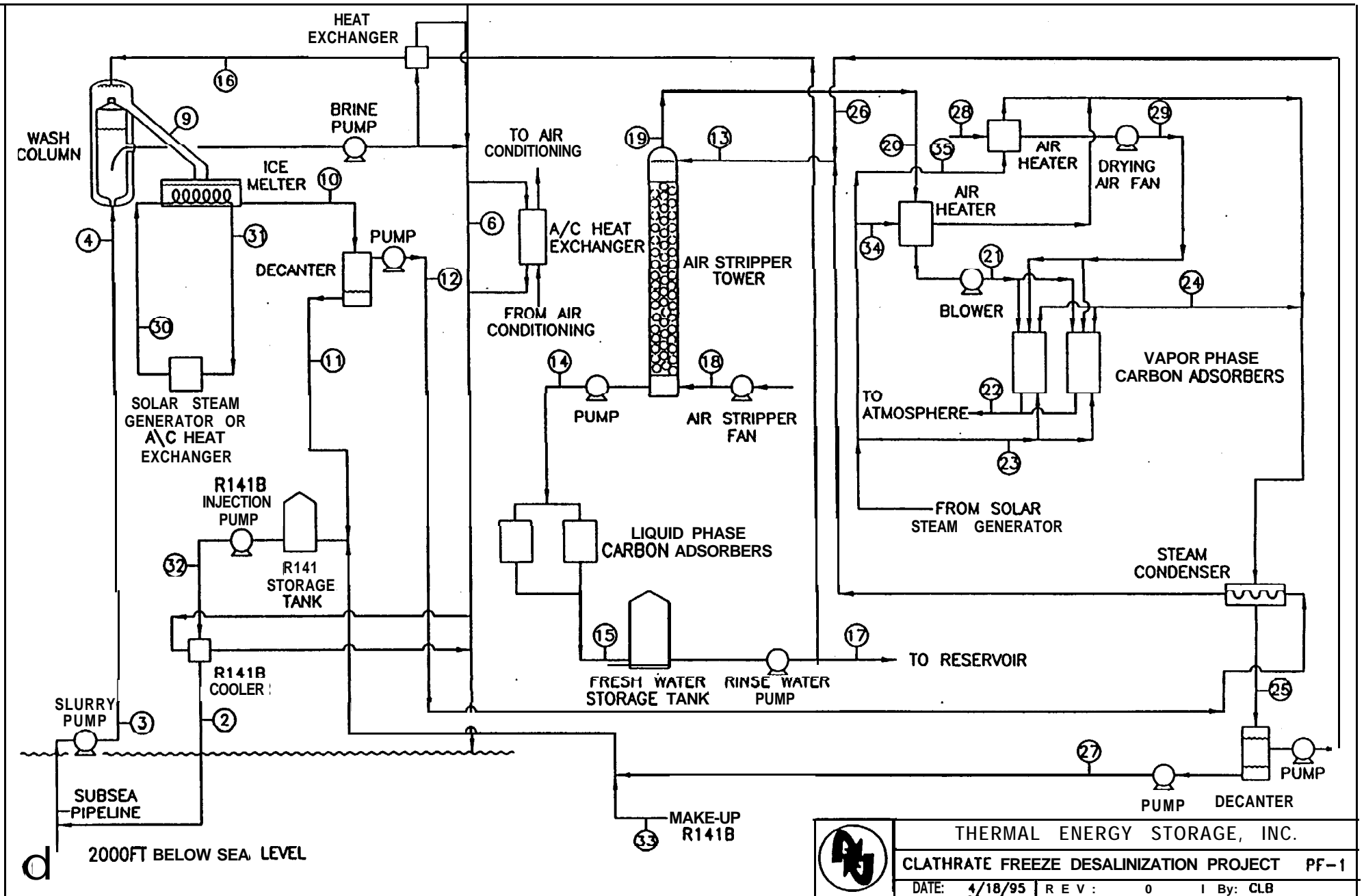


TABLE 1.1
SUMMARY OF FRESH WATER PRODUCTION, PROJECT COSTS, AND FINANCIAL ASSUMPTIONS

	Demonstration Plant	Small Commercial Plant		Large Commercial Plant	
		Privately Financed	Publicly Financed	Privately Financed	Publicly Financed
Fresh water production					
Fresh water output • gallons per minute	25	2,500	2,500	5,000	5,000
Fresh water output • gallons per day	36,000	3,600,000	3,600,000	7,200,000	7,200,000
Fresh water output • 1,000 gallons per year	11,169	1,116,900	1,116,900	2,233,800	2,223,800
Project costs • \$					
Equipment cost installed	280,000	6,479,000	6,479,000	11,986,000	11,986,000
Deep water pipe installed	400,000	1,250,000	1,250,000	2,312,000	2,312,000
Engineering and environmental	250,000	300,000	300,000	450,000	450,000
Site related costs	75,000	100,000	100,000	150,000	150,000
Research and consulting	100,000	-0-	-0-	-0-	-0-
Project development and management	150,000	300,000	300,000	450,000	450,000
Insurance	25,000	50,000	50,000	75,000	75,000
Working capital, interest during construction, reserves, and fees	75,000	897,000	897,000	1,959,000	1,959,000
Contingency	150,000	427,000	427,000	778,000	778,000
Total project cost	1,505,000	9,803,000	9,803,000	18,160,000	18,160,000
Assumptions					
Equity • percent		18.00	-0-	18.00	-0-
Return on equity • percent		9.00	-0-	9.00	-0-
Tax rate • percent		42.50	42.50	42.50	42.50
Interest rate • percent		9.00	6.00	9.00	6.00
Depreciation Term • years		30	30	30	30

TABLE 1.2
SUMMARY OF FUNDING REQUIREMENTS, ANNUAL COSTS, AND COST OF WATER

	Demonstration <u>Plant</u>	Small Commercial <u>Plant</u>		Large Commercial <u>Plant</u>	
		Privately Financed	Publicly Financed	Privately Financed	Publicly Financed
Commercial plant funding requirements • \$					
Equity funding - plant capital		590,300	-0-	1,380,340	-a-
Equity funding - working capital		1,432,000	-0-	2,303,000	-0-
Debt funding - plant capital		9,212,700	9,803,000	16,779,660	18,160,000
Debt funding - working capital		<u>-0-</u>	<u>1,432,000</u>	<u>-0-</u>	<u>2,303,000</u>
Total commercial plant funding required • \$		11,235,000	11,235,000	20,463,000	20,463,000
Annual capital costs • \$					
Return on equity		320,578	-0-	583,889	-0-
Interest on debt		<u>896,731</u>	<u>816,211</u>	<u>1,633,271</u>	<u>1,486,615</u>
Total annual capital costs • \$	1,505,000	1,217,309	816,211	2,217,160	1,486,615
Annual operating costs • \$	60,000	<u>1,432,000</u>	<u>1,432,000</u>	<u>2,303,000</u>	<u>2,303,000</u>
Total Annual Costs • \$		2,649,309	2,248,211	4,520,160	3,789,615
Total demonstration plant funding required • two years of operation • \$	1,625,000				
Unit Cost of Water • \$ per thousand gallons					
Annual capital cost		1.09	0.73	0.99	0.67
Annual operating cost		<u>1.28</u>	<u>1.28</u>	<u>1.03</u>	<u>1.03</u>
Total unit cost of water • \$ per thousand gallons		2.37	2.01	2.02	1.70

reductions likely can be developed through continued research on new clathrate **formers** and this would increase the market size.

2. INTRODUCTION

Human civilization has consistently pursued methods of obtaining fresh water from the oceans **but** the technology to date has been limited to high-cost processes with limited applications to areas willing and able to pay the higher price, principally the Middle East and **the** Pacific islands. Currently desalination processes using reverse osmosis technology are available in large quantity in Southern California at prices ranging from \$4 to **\$6/1,000 gallons** [**\$1.06 to \$1.59/m³**]. This price, between \$1,300 and **\$1,960/acre-foot**, is prohibitively expensive for municipal and county water authorities. To be competitive **with** municipal water systems in Southern **California, desalination** technology must produce fresh water at approximately **\$2/1,000 gallons** [**\$0.53/m³**] or **\$650/acre-foot**.

Historically, the long-term drought in the arid areas of the southwestern United States has generated a **torrent of** words whose message evaporates with the **first rainfall**. Until unit costs of **desalination** can compete with the cost of new surface water sources (reservoirs and aqueducts), there will always be a water crisis in periods of low rainfall.

Water conservation, waste water reclamation, and seawater desalination offer a means to avert crises and foster good government planning. Water **conservation** and waste water reclamation are being promoted and applied, but desalination remains elusive. **The** principal means of reducing the cost of seawater **desalination** is through the reduction in the level of energy used in the process. Clathrate **desalination** now offers the promise of reducing power consumption by a factor of 37, while not **significantly increasing** the cost of the plant, by using technology developed by Thermal Energy Storage, Inc. (**TESI**) over **the** last decade.

A clathrate is an aggregation of water molecules surrounding a central non-water molecule, to **form** an ice crystal. Many of these ice crystals can be formed at elevated temperatures. **TESI** uses this process in **the** field of thermal energy storage to produce clathrate ice during the night for use in air conditioning during the day, thus reducing electrical peak demand **requirements** for electric utilities and reduced electric costs for their customers. **TESI** now markets this product as the **'SNOPEAK "warm ice" thermal energy storage system**.

Clathrate desalination was first investigated by the Department of the Interior in the 1960 and 1970 decades. Current interviews with personnel associated with **the** work at that time speak of the significant

accomplishments and high value of the work performed and the promise of lower energy use offered by the technology. With the demise of the Office of Saline Water and the Office of Water Research and Technology within the Department of the Interior, work ceased on clathrate desalination. Reverse osmosis technology became the acceptable *method* of producing fresh water from seawater. However, the high cost of the energy-intensive reverse osmosis process, especially following the energy crises of 1973 and 1979, has led to renewed interest in other technologies.

TESI is expert in clathrate (or gas hydrate) technology where ice can be formed at elevated temperatures by the use of clathrate formers. The clathrate formation process was developed and refined over a ten year period of research, development, testing, and demonstration work completed in early 1993. **TESI**, through the expenditure of \$4 million of internally-generated funds and with the assistance of the Canadian National Research Council and the Buffalo Research Laboratory of Allied Signal Chemicals, has advanced clathrate technology substantially since the early demonstration facilities at Wrightsville Beach, North Carolina. Prior technical issues in the design and operation of the early test facilities will benefit from the knowledge that now exists on **the formation, transport, and** melting of the clathrate ice crystal.

Now a new invention has been created to produce the clathrate ice at 2,000 foot [**610 m**] ocean depths that result in major improvements to the **desalination** process, including a major reduction in energy costs. This invention can be tested in **existing** pipelines to 2,000 foot depths in Hawaii in a demonstration facility. If the demonstration proves the value of the invention, then desalination can compete with fresh water sources on land.

3. CONCLUSIONS AND RECOMMENDATIONS

This preliminary research study resulted in the conclusions that:

1. Fresh water can be produced from seawater by **the** freeze desalination process at costs comparable to current surface water collection systems (reservoirs and aqueducts) by means of an invention by Richard A. **McCormack**, President of Thermal Energy Storage, Inc. (**TESI**);
2. The **cost** of producing fresh water by a municipal or district water authority using the **TESI** invention is estimated at less than **\$2/1,000 gallons** [**\$0.53/m³**];
3. The cost of building a 7.2 **million** gallons/day [**27300 m³/day**], equivalent to an 8,000 **acre-foot/year** [**9.87 million m³/year**], commercial facility is estimated at \$18.2 million with annual capital and operating costs of \$3.8 million if publicly **financed**;

4. The clathrate former HCFC **R141B** was selected for use in the process due to (a) TESI experience with this agent in its thermal energy storage business and (b) competitive costs for fresh water achieved by its use;
5. Other clathrate formers are available for testing that might further reduce the cost of producing fresh water, in particular, HCFC R22 is a potential candidate to produce fresh water **from** warmer temperature seas and bays as discussed in Appendix A;
6. The clathrate former HCFC **R141B** will cause low temperature ocean water recovered from a 2,000 foot [610 m] depth to form clathrate ice at **47.5° F. [8.6° C.]** as demonstrated in jar tests;
7. Polyethylene piping up to 48 inches [122 cm] in diameter can be laid to depths of 2,000 feet by **Makai** Ocean Engineering of Hawaii;
8. The **clathrate former** HCFC **R141B** can be pumped through in an inner pipe of a concentric piping system and injected through a diffuser into the outer pipe at an ocean depth of 2,000 feet to produce clathrate ice in **the** outer pipe;
9. The latent heat of fusion of the **clathrate** ice can be released to the ocean through the outer piping prior to the ice crystals reaching the surface;
10. The ice crystals can be grown during the transit to the surface;
11. The ice crystals can be prevented from exceeding a temperature of 2.5° F. [1.4° C.] below their melting point by increasing the **wall** thickness of the polyethylene pipe in the upper length of pipe when ocean waters near the surface exceed **45° F. [7.2° C.]**;
12. Commercial equipment and processes can separate the ice crystals from the brine water, wash and melt the ice crystals, separate **the** HCFC **R141B** from the fresh water, provide potable water for municipal use, and recover the HCFC **R141B** for reuse;
13. Power consumption in the proposed process, the key to economic production of fresh water, is only 3 percent of that required in the earlier demonstration plants at **Wrightsville** Beach, North **Carolina**;
14. Demonstration facilities can be built and operated at either the Natural Energy **Laboratory** of Hawaii, **the Naval** Auxiliary Base on San Clemente Island near San Diego, or at Scripps Institute of Oceanography at La Jolla, a suburb of San Diego;

15. The preferred location, if funding is available, is the Natural Energy **Laboratory** of Hawaii since existing piping and support facilities are readily available to substantially reduce the cost of the demonstration facility;
16. Review of environmental, **regulatory**, and societal effects show no inherent limitations to the construction and operation of a commercial size facility based on the experience of building and operating a commercial size reverse osmosis facility at Santa Barbara, California;

From these conclusions, it is recommended that:

1. The invention of **combining** desalination technology with ocean engineering technology to produce fresh water at economic costs should be patented, and a patent application has been prepared and submitted to the United States Patent Office;
2. A demonstration plant of 36,000 gallons/day [136 **m³/day**] should be built at a site where funding sources are available;
3. Research and development should continue on the investigation of the suitability of other **clathrate** formers to further reduce the cost of producing fresh water **from** seawater at various **temperatures**;
4. In particular, **research** and development should continue on the investigation of **clathrate formers** that form high temperature **clathrates**, such as HCFC R22, since this would expand the technology of freeze desalination to warmer bodies of water as well as shallower ocean water sources.

4. STATUS OF PRIOR TECHNOLOGY OF CLATHRATE FREEZE DESALINATION

4 . 1 **Summary**

A review of the **literature**^(*) on freeze desalination indicates that **there** was a great surge of interest in the process during a 19 year period of support by the Department of Interior, Office of Saline Water (**OSW**), from 1955 through 1974. During this period 11 diverse demonstration plants were **constructed** and operated under the direction of **the** OSW at its **Wrightsville** Beach Test Facility in **North** Carolina.

(*) All further references in this Section 4 refer to references listed in Appendix C.

The demonstration work was supported by research programs sponsored by OSW at several universities. However, due to a number of factors, not the least of which were the problems encountered in the operation of the demonstration plants, interest in freeze desalination was severely curtailed. By 1982 all work on freeze desalination had virtually stopped.

Two publications, one by **Barduhn⁽²⁾** in 1982 and the other by **Wiegandt⁽¹⁰⁾** in 1990, summarize the status of freeze desalination as it existed at each of those dates. A comparison of the two documents shows that there was little, if any, work **performed** or progress made on freeze desalination processes during this eight year span of time. TESI found nothing published since the Wiegandt paper of 1990.

The literature review by Thermal Energy Storage, Inc. (**TESI**) indicates that there were many “**lessons learned**” in the conduct of the OSW program. However, the people who participated in the programs at that time remain positive today about the potential benefits of the freeze desalination process. Nonetheless, a “break&rough” is necessary in order to revive interest in the freeze de&nation process and to generate the support necessary for it to be successful.

TESI believes that the use of clathrate technology together with ocean engineering technology may be the **breakthrough** that is **required** to make the technology of freeze desalination a success. TESI has accumulated those papers that it believes **will** be of benefit to this project and will continue to search for additional information as the work on a demonstration **unit proceeds**.

4.2 Sources of Information

TESI conducted a review of all pertinent **literature** on the subject of freeze desalination and presents a synopsis of **the** current status of **this** technology in this Section 4. This includes a summary of the **results** reported in documents combined with **interviews** of key personnel involved in the technology since 1960.

TESI developed these results from the major sources of the literature on this subject from the following **resources**:

- o Information Services, **Engineering** Societies Library, 345 East 47th Street, New York, New York 10017;
- o National Technical **Information Service**, U.S. Department of Commerce, Springfield, Vira 22161;
- o **U. S.** Department of the Interior, Saline Water Conversion Research and Development Reports.

TESI has also met or directly contacted several individuals who have been prominent in the field of desalinization over the past 40 years and who provided further insight and references to the available literature. These persons include:

- o Dr. Alan Barduhn, Professor, Syracuse **University**;
- o Dr. John Ripmeester, Physical Chemist, National Research Council Canada;
- o Mr. Wilfred Hahn. retired, formerly with the Office of Saline Water, **Wrightsville** Beach Test Facility.

Through these documents and discussions with these persons, an extensive bibliography of reference documents can be identified. For example, Herbert **Wiegandt**, School of Chemical Engineering, **Cornell** University, listed 123 references in a paper entitled “Desalination by Freezing”, March 1990. **TESI** selected and reviewed over 20 of these reports to obtain the background and **understanding** of the history and the **current** status of the technology. A bibliography of the most **significant** documents is presented in **Appendix C**.

4.3 Desalination Processes

There are several processes for desalination by **freezing** seawater that have been proposed and investigated through various stages of development. The two major divisions of these processes are “indirect” and “**direct**” freezing. The indirect process is the simplest where **freezing** is accomplished by circulating a cold refrigerant through a heat exchanger that removes **heat** from the seawater through conduction. The ice is formed on the heat exchanger surface and then must be removed, washed, and melted to produce the fresh water product.

The direct **freezing** process is an **attractive** alternate where heat is removed from the cold sea water by direct contact of the refrigerant with the seawater. The refrigerant may be the seawater itself where heat is removed from the salt water by flashing some of the water into vapor at low **pressure**. The ice that is formed is separated **from** the remaining brine, washed, and then melted by using the recompressed vapor **that has been released in the freezing process**. This process is called the **vacuum freezing vapor compression (VFVC)** process for desalination.

A second alternative in the direct **freezing** classification is called the secondary refrigerant **freeze (SRF)** process. A refrigerant that has a low solubility **in** water and is more volatile is compressed, cooled to a **temperature** close to the freezing temperature of salt water, and mixed with the seawater. As the

refrigerant evaporates, heat is absorbed from the mixture and the water crystallizes into ice. This process takes place at a more convenient pressure than the VFVC process described above. Butane is an example of one of the secondary refrigerants.

The SRF process offers a major advantage over the VFVC process due to the reduced size of equipment needed to provide fresh water. Also, the direct **freezing** feature offers significant advantages over the indirect process due to its higher heat transfer capability.

The third alternative in the direct freezing classification has the lowest energy requirement and is called gas hydrate or clathrate desalination. This process involves **the** use of a class of agents that **form** gas hydrates, or clathrates, with water at temperatures higher than the **normal** freezing temperature of water. "The gas hydrates (clathrates) of the lower **hydrocarbons** and the halogenated methanes and ethanes are colorless crystals that look and behave much like ice. Their heat of formation and the depression of **their** formation temperatures by salts are practically the same as ice. When they melt they form two liquid phases, thus producing fresh water and regenerating the agent **simultaneously**."⁽²⁾

The process for **producing** fresh water using the gas hydrates **is** very similar to the SRF process. **Clathrate** ice is formed by mixing the seawater and the clathrate forming agent at the clathrate forming temperature; **separating** the clathrate ice crystals from the excess brine; washing **the** clathrate ice to remove the brine attached to the **crystals**; melting the crystals; and, finally, **separating** the clathrate agent from the **fresh** water to **reinject** the clathrate former at the beginning of **the** process. The temperature level of the **clathrate** process can be considerably higher than the SRF process. "This is really a high temperature freezing process and thus consumes less energy and requires much less or no heat exchange between feed and **product**."⁽²⁾

In parallel with the OSW interest in freezing **desalination**, work progressed on other processes for water purification and waste water treatment. Among these processes was the development of the reverse osmosis (**RO**) process that uses thin membranes to permit the passage of water molecules through the membrane at a greater rate than the other components of the brine or **impure** water. In 1982 **Barduhn**⁽²⁾ noted: "Reverse osmosis may work on seawater in the future but this is not yet proved economically successful," By 1990 **Wiegandt**⁽¹⁰⁾ **stated**: "Good information on energy and costs for RO are presented by Ericsson, et. **al.**"⁽⁷⁾

At **the** present time, freeze **desalination processes** must compete on an economic **basis** with **the** evaporation/condensation (distillation) process as well as the RO **process**. Although other processes, such as electrodialysis, may be of interest in special applications, they do not appear to **be significant** at the present time for sea water desalination.

4.4 History and Status of Freeze Desalination Programs

Prior to 1950 the only significant method of obtaining **fresh** water from salt water was by evaporation and condensation, i.e., a distillation process where the **salt** water is heated to the boiling point and the water vapor released is condensed as fresh water. The **fresh** water is recovered with essentially no salinity and the concentrated brine is returned to the ocean.

Beginning in 1955 a significant interest was generated in the potential of desalination of seawater by freezing processes. Most of the work conducted on this process was supported by the OSW in partnership with private industry. The OSW was formed in 1955 and disbanded in 1974. This work then continued for a few years under the direction of the Office of Water Research and Technology.

Much of the effort in the period from 1955 to 1974 was expended in the design, development, construction and operation of a number of pilot plants at the OSW test station at Wrightsville Beach, North Carolina. Although early investigators were pessimistic about the **costs** for producing fresh water by freezing, those **that** followed were not dissuaded. These studies "were important, however, since they disposed of the possibility of using indirect heat transfer for freezing . . ." ⁽²⁾ Further, these early investigations discovered the problem areas to be addressed.

Both **Barduhn**⁽²⁾ in 1982 and **Wiegandt**⁽¹⁰⁾ in 1990 provide historical reviews of the experience with freeze desalination. These individuals have been major contributors in this field as witnessed by the large number of papers that they have **published** on the subject. The following information is summarized from these referenced documents.

1. The OSW reports during the period of its existence (1955-1974) cover much of the progress on freeze desalination developments in the United States.
2. The first pilot plant operation was a VFVC facility constructed by **Carrier** Corporation that was transferred to the Wrightsville Beach, North Carolina site for testing. Vapor absorption was accomplished by a lithium bromide (**LiBr**) brine. Although not economically **attractive**, this remarkable effort established a workable new technology.
3. The next unit was a Cornell Process Unit built by Blaw-Knox at a Florida **Power** and Light site **at St. Petersburg, Florida. This was a SRF process using butane as the refrigerant. After some modifications, the facility reached a production rate of 55,000 gallons/day [208 m³/day] of fresh water, 57 percent above the design rate. The Blaw-Knox pilot project was the pioneer for establishing the satisfactory performance of a SRF process for desalting seawater. The OSW contract for this work ended in 1964.**

4. In 1962 OSW started work on a full-scale 200,000 gallons/day [757 m³/day] East Coast Conversion Plant (ECCP). This facility could not begin operation because the secondary compressor had insufficient capacity to allow the primary compressor to start up. There was no surge supply of ice to support condensation until production ice was available. The ECCP was placed on standby and subsequently dismantled when the OSW program ended.
5. A Struthers-Wells subsidiary, Struthers Scientific and International Corporation (SSI), designed and constructed a 15,000 gallons/day [56.8 m³/day] pilot plant at the Wrightsville Beach test station in 1964. After several modifications, sustained runs were accomplished and good results were obtained. Although this pilot plant fell short of providing design data for full-scale plants, it was a sufficient recovery from the earlier failure to serve as a second example of reliable operation of butane freezing in a SRF plant.
6. The performance of two OSW SRF plants (Numbers 7 and 8) that were using gas hydrates to form clathrate ice was unsatisfactory because they were unable to effectively wash the ice crystals. This deficiency was discovered in 1968.
7. In 1968 the OSW suspended further support for new SRF pilot plants. By 1975, seven years after the announced suspension, the final SRF plant (Number 11) experienced failures that further diluted the acceptance of freeze desalination by use of secondary refrigerants.
8. Several other efforts in both the development of SRF and VFVC desalination processes are described in the references. One manufacturer, Colt, developed a successful skid-mounted 100,000 gallons/day [378 m³/day] VFVC unit but subsequently withdrew from the desalination market when the unit did not experience an adequate response. Several gas hydrate projects developed in the 1960 and 1970 decades are also described but the performance of these projects was unfavorable.
9. By 1982 Barduhn had concluded that the gas hydrate process of freeze desalination would not proceed. He stated: "It is probable that this process will not be pursued vigorously until the SRF process becomes commercial since most of the design problems are identical and it (ice) is cheaper and easier to work with than hydrates. The reduced energy and capital costs look attractive, however."
10. Barduhn, in 1982, also stated: "Several companies have done extensive development work on freezing and later ceased; e.g., Carrier, Struthers, Colt, and Blaw-Knox in this country and the British and Israelis abroad. None has said freezing is unworkable or uneconomical. The common feeling seems to be that the development work needed will be extensive and the payout period

will not be short. They need to invest their scarce capital in endeavors which have promise of a quicker return Perhaps as energy costs increase, the economy of freezing will be more compelling and interest will be renewed.” Speaking further on the advantages of freeze **desalination**, he stated: “The energy requirements are low. This was not a sufficient advantage in the 1960s when heat cost about **\$0.50/million BTU** [**\$1.98/million kilogram-calories**] and power cost 0.5 to 0.7 **c/kwhr**, but it becomes an important factor when such costs increase by a factor of 4 or more.”

11. By 1990 Wiegandt had concluded that the SRF process had been successfully demonstrated when butane is used as the secondary refrigerant He cites four successful butane projects **including** the Blaw-Knox project, the SSI modified project and the British and Israeli projects. Wiegandt is critical that insufficient work was performed prior to proceeding to pilot plant and even full-scale design. He states: “The failure of these pilot plants to approach their contract objectives indicated insufficient verification with sound bench-scale work and inadequate previous test data” He also **states**: “Mostly, pilot plants in R&D work are justified for assessment of profitability and for obtaining design **data**; they are not built to find out if some new process scheme is workable.”
12. Wiegandt further states: “In the R&D world ultimately it is only winners that count.” He then expands on this thought: “Needed for a **freeze** desalination winner is sound engineering, a profound respect for thermodynamics, an appreciation for economy of scale, and an application of only those procedures which have been proven to give trouble-free operation.”

Apparently there was little accomplished in the field of freeze desalination between Barduhn’s work in 1982 and Wiegandt’s work in 1990. Of 123 references listed in Wiegandt’s summary of 1990, only nine of the references were between 1982 and 1990 with only one reference **in** the period of **1988-1990**.

Many of the documents on **freeze** desalination reviewed by **TESI** describe the design and operation of several freeze desalination pilot plants that were supported by the OSW. **Most** of these pilot plants were installed at **OSW’s** test site at Wrightsville Beach, North **Carolina**. The information provided in these reports is valuable for further work in the field of freeze **desalination** since the problems encountered in the design and operation of these plants **are** well documented.

There was a general feeling, portrayed **particularly** by **Wiegandt**, that the accelerated effort toward **commercializing** the **freeze-desalination** process had placed too strong an emphasis on the design and fabrication of a number of fairly large pilot plants without sufficient **preliminary laboratory-scale** work to support the designs. As a result, when problems arose, expensive **modifications** were attempted on the pilot plants that caused the overall program to receive a bad name and eventual shut down In many cases laboratory work was initiated only **after** the pilot plants had tried several modifications and failed.

Even so, a considerable amount of work was performed in this field at several universities, notably Syracuse University under the diion of Allen J. Barduhn **and** Cornell University under the direction of Herbert Wiegandt, This research work is reported in papers listed in the references of the documents prepared by **Barduhn**⁽²⁾ and **Wiegandt**⁽¹⁰⁾. The work of Barduhn and Wiegandt also present summaries of the performance of the various pilot plants and particular items of equipment.

In the TESI review there was no record of any **desalination** plant currently operating that uses the SRF process by means of either a direct refrigerant or a gas hydrate (clathrate) agent. TESI believes, however, that the extensive **work** that has been performed and the large number of reports that have been generated will provide invaluable information in the **performance** of its work.

This prior work is particularly valuable in the areas of equipment design and performance where TESI expects to learn considerable from those processes and items of equipment that met performance **requirements** and those that experienced failures including **the** reasons for these failures. It is **TESI's** intent to continue research into the availability of technical information **and** data as the work on the demonstration unit progresses.

4.5 Direct Freeze Desalination Process Design and Equipment

Freeze desalination consists of three basic steps that are common to the several different processes: Partially freeze the seawater, separate the ice **from** the brine; and melt the ice. How these steps are accomplished varies somewhat with the particular process and, in addition, there are various other steps associated with the individual **processes**, such as vapor compression in the VFVC process. In the SRF process, the flow diagrams are basically the same.

Descriptions of the several major process steps and the items of equipment that were designed and developed are presented below:

4.5.1 Freezing Process and Equipment. - "A freezer must perform the functions of (1) preventing excessive nucleation, (2) allowing adequate time for crystal **growth**, (3) providing space or other means for vapor separation without **entrainment**, (4) creating large **interfacial** area and good **turbulence** for refrigerant evaporation, and (5) preventing ice **clusters** from **building** up and causing irregular **slurry flow**."⁽²⁾ The **VFVC** process that depends on low pressure to vaporize water and thus to remove heat and **form** ice **crystals** in the salt water **utilizes** different mechanical equipment in **the freezing** process than does the **SRF** process.

The VFVC process uses large agitated tanks with equipment, such as sprays and fountains, to increase the liquid surface area. The SRF processes use long narrow tanks with the feed supplied at one end and the

slurry leaving the other. **The** SRF process equipment design requirements are more complex because of the presence of several different phases, i.e., liquid and vapor refrigerant, aqueous liquid (brine), and solid ice. Problems associated with the SRF refrigerant, such as butane, include the design of the equipment so that the ice **crystals** would be **sufficiently** large without an excessive carryover of liquid refrigerant **from the freezer. The** ice crystallization process was studied in the laboratory and Wiegandt states: "Today good **freezers** (butane) can be designed, but in 1990 a best choice had not yet been **established.**"⁽¹⁰⁾

4.53 The Wash Process and Equipment. - In the direct freeze-desalination processes, one of the major problems encountered is how to remove contaminants, such as excess brine and **refrigerant**, from the ice crystals after they are **formed**. One of the most common processes used was the vertical hydraulic wash column where the brine-ice mixture is forced upward while a fresh-water wash flows downward over the ice. The brine and wash water are removed near the middle of the column height. As reported in the references, there have been various designs of wash columns that have operated with varying degrees of success. **In** a recent interview, W.J Hahn, (@) who was active in the Wrightsville Beach Test Facility program, expressed confidence that a satisfactory design of the wash column can be accomplished, based upon design methods and a computer program that has been developed.

For a different design of wash process equipment, **Wiegandt**⁽¹⁰⁾ noted that: "Displacement washing of a flooded, screen-supported ice-bed is effective." based on **work** reported by G. Karnofsky and R.F. Steinhoff in OSW Report 40, July 1960. "This suggests that longitudinal diffusion is no complication to wash **column** design; batch washing using 5% net wash gave a product of **<100 ppm salt.**"

4.53 Melting Process and Equipment. - **Several** methods have been used to melt the ice after it is washed free of the brine coating the crystals. **The "dump melter" is used in the VFVC cycle and may be used in** the SRF process. In the dump melter process, the clean ice is dumped into the melter and melted by direct contact with the **compressed** refrigerant, water vapor in the case of the VFVC and compressed butane vapor or other refrigerant in the SRF process. The heat of condensation of the compressed gas melts the ice as it is condensed in **the** porous ice. In **1969** Cornell proposed a dump melter using segmented trays **with the melting ice advanced by rakes carried on a center shaft so that the ice reaching the end of a segment falls onto the tray below.'**

A second method, used for the SRF process, mixes the ice with some of the fresh product water to form a slurry. **The slurry** is pumped into a **baffled** or packed tower where it is contacted with the refrigerant vapor for direct condensation of the refrigerant and melting of the ice. **In** other cases it may be desirable or necessary to melt the **slurry** ice indirectly by passing the slurry **through** tubes and condensing the refrigerant on the outside of the tubes.

Wiegandt⁽¹⁰⁾ noted in 1990: “Although reliable data remain which rest on supportable facts and await development; proposed **are** conceptually sound, inexpensive **melting** with high capacity and low driving forces.”

4.5.4 Pumps and Compressors. - The most unique piece of equipment is the low pressure compressor required for the compression of water vapor in the VFVC process. Special purpose compressors have been designed for this application and have been documented by **Wiegandt**⁽¹⁰⁾. There are no commercial refrigeration compressors for the SRF desalination process since no market exists. In the pilot plant stage, designers will normally look for the best match of their requirements with the compressors that are available. As a market in **freeze** desalination develops, it can be anticipated that compressor designs will be developed to better match the requirements of these processes.

Rumps for the movement of seawater and the fresh water product that meet the designers specifications appear to be commercially available.

4.5.5 Auxiliary Equipment. - Auxiliary equipment is required to resolve some of the problems that are encountered in the design and operation of the freeze **desalination** plants. These include such **requirements** as: removal **of non-condensibles**; recovery of the refrigerants; reduction and removal of foams, haze, and dispersions; reduction of solubles in the fresh water to required levels. For example, the Environmental Protection Administration’s standard for butane dissolved in the fresh water is 0.2 ppm. Experiments show that butane can be readily reduced to this level by “air-stripping”. **In** general, the pilot plant and laboratory work have provided information that supports **the** design of auxiliary equipment for freeze **desalination** projects.

4.6 Economics of Freeze Desalination

Studies made in the 1970 decade indicated that freeze **desalination** would provide a 30 percent cost advantage compared to multistage flash evaporation (**MSF**) or RO **processes**. However, these studies were never fully validated by operating either commercial or pilot plants on a reliable, **economic** basis. Further, studies showed that within the direct **freeze** process, the VFVC process was inherently more expensive by approximately 10 percent than the SRF process.

Because of the overall poor performance of the pilot plants **under the** OSW program, the **freeze desalination** process received a bad name and the successes that were achieved were lost in the close out of the program. Problems associated with process and equipment design led to such a poor **performance** record that to date it has not been demonstrated that the economics favor freeze de&nation

However, there are other processes where the competitive price of fresh water is not the governing economic criteria and in several cases the freezing process has been demonstrated to be useful. The freeze concentration process has been used successfully in the food and pharmaceutical industries and has other potential uses in concentration of industrial waste **streams** from electroplating plants, nuclear power plants, and chemical plants. The continuing work in **these areas** will undoubtedly help the designer of future freeze desalination plants to produce fresh water from the sea.

Both the MSF and RO processes have a considerable lead in the desalination field because of success in the development of reliable equipment and the ability to produce a satisfactory product. For the freeze desalination technology to catch up will undoubtedly require some significant **breakthrough** as well as some **strong**, sound engineering.

4.7 Gas Hydrate (Clathrate) Technology

The gas hydrates were **early** recognized as having good potential in the freeze de&nation processes. **Barduhn**⁽²⁾ writes: "If one chooses **the** direct contact refrigerant in the SRF process to **be...any** one of a number of other agents that form a gas hydrate with **water,...the** temperature level at which the whole process operates may be **increased** by 10 to 50 degrees F. [**5.56** to **27.8°** C.] over those in the SRF process." He then continues: "When they melt they form two liquid phases, thus producing fresh water and regenerating the agent simultaneously." The higher temperature operation of the gas hydrate freezing process results in a reduction in the amount of compressor work that is required relative to the SRF **process**.

Two of the plants that were part of the OSW pilot plant program were gas hydrate plants ('Number 7 and 8). "Koppers built an R-12 (**CCl₂F₂**) hydrate plant and Sweetwater Development built a propane hydrate plant, both at Wrightsville Beach. Both were **unsuccessful** mainly because the hydrate crystals were very small or **dendritic** and were **difficult** to separate from **the brine**."⁽²⁾

As noted above, Barduhn concluded that the hydrate process of **freeze** de&nation would not proceed stating that "It is probable that this **process** will not be pursued vigorously until the SRF process becomes commercial since most of the design problems are identical and it (ice) is cheaper and easier to work with than with hydrates. **The** reduced energy and capital costs look attractive, however." Barduhn himself had participated in **prior** work on gas **hydrates** as evidenced by the paper co-authored by **him**⁽⁹⁾. This paper presents a compilation of the properties of a large number of gas hydrates from which an investigator could select a hydrate for use in the freeze de&nation **process**. Part 1 of this paper "gives a brief review of the status for choosing an hydrating agent for use in the hydrate process for desalting."

4.8 Programs by Thermal Energy Storage, Inc.

For the past several years, **TESI** has investigated, developed, and operated test equipment and demonstration facilities for the development of **clathrates**, or gas hydrates, for storing “cold energy” during off-peak hours for refrigeration and air conditioning use during peak utility operating periods. The use of clathrates as compared to conventional ice storage permits the cold energy storage at higher temperatures that are still compatible with the air conditioning requirements. This permits a significant reduction in the work of compression relative to that required for making conventional ice.

The “ozone depletion” problem associated with the release of certain Freon-type refrigerants has caused **TESI**, as well as all other users of these refrigerants, to look for acceptable **alternatives**. In this research process, **TESI determined** that a refrigerant designated HCFC **R141B** offers considerable promise for use in **TESI's** cold-storage systems. From this work **TESI** has collected all available information on this and many other refrigerants that could be used in its **processes**.

The refrigerant HCFC **R141B** is now included in **TESI's** process design and a significant amount of test **information** has been developed from the **TESI research** and development program under a \$350,000 contract with Consolidated Edison Company of New York and The **Empire State Electric Energy Research Corporation**. This information is privately published but the results are directly available to **TESI** for use **in the current contract**.

TESI has also investigated the information available on the construction of piping systems for **bringing** cold seawater from the ocean depths. Makai Ocean Engineering, Inc., **Kailua**, Hawaii, is an expert in the **design, installation and** operation of deep sea pipe lines. This Company has laid many such large pipelines to depths of 2,000 feet [**610 m**] at the Natural Energy **Laboratory** of Hawaii at **Keahole** Point on the Big Island of Hawaii. Discussions with Joseph Van **Ryzin**, President of Makai Ocean Engineering, provided information and data on the costs for the design and operation of the deep sea pipe lines for bringing cold water to the freeze desalination facility. The deep seawater design, as developed by **TESI** and as discussed throughout this report, eliminates many of the problems and complexities associated with previous **clathrate desalination** systems.

The use of existing deep sea pipelines has been **discussed** with Mr. Thomas Daniel, **Scientific/Technical** Director at the Natural Energy Laboratory of Hawaii. This low-temperature seawater can be made available through either one of two existing deep sea pipelines that best meet **TESI's** needs for a demonstration project **The** laboratory also has support personnel and facilities that can be obtained at economical rates.

5. CHOICE OF CLATHRATE FORMER

5.1 The Search for a Clathrate Former

A clathrate is a lattice-like structure in which molecules of one substance are enclosed within the crystal structure of another substance. For example, the clathrate formed by the organic clathrate former HCFC **R141B** has a central organic molecule surrounded by 17 water molecules that **form** a solid crystal lattice **clathrate** at a temperature of **52.9° F. [11.6° C.]** in distilled water, and hence is given the name “warm ice”. The clathrate temperatures **decrease** to **47.5° F. [8.6° C.]** in seawater. Class I **clathrates** have 5 molecules surrounding the **central** organic or gas molecule while Class II clathrates, such as HCFC **R141B**, have 17 molecules **surrounding** the central organic or gas molecule

Many different types of clathrates **form naturally** throughout the world. There **are** a multitude of clathrate **formers** that will form clathrate ice at various pressures and temperatures, in both liquid and gaseous form, both as inorganic and organic compounds, and with various degrees of toxicity, **flammability**, and other **characteristics**. A major effort is required to evaluate this large number of clathrate **formers** for suitability of use.

Criteria were developed to **define** the desirable characteristics of a suitable clathrate former:

Environmentally acceptable

Non-toxic

Non-flammable

Stable

A Class II clathrate former

Low **cost**

Suitable transition temperature (in the range of 42 to **85° F. [5.6° to 29.4° C.]**)

Suitable operating pressure (in the range of atmospheric to seven atmospheres [**1.03 to 7.23 kg/cm²**])

Compatible with **standard** materials

Available in commercial quantities

Remains a liquid over the operating temperature range

5.2 Review of Other Clathrate **Formers** for Desalination

In prior work for **Thermal Energy Storage, Inc. (TESI)**, Dr. John Ripmeester of the National Research Council of Canada (**NRCC**), with the support of Allied Signal's **Buffalo** Research Laboratory, investigated

more than 20 compounds in search for useful clathrate **formers** for thermal energy storage facilities. TESI reviewed this work to determine which of these clathrate formers would be appropriate for **desalination**.

There are many clathrate forming agents that could be utilized for the desalination process, and nine potential agents **are** listed:

<u>Agent</u>	<u>Critical Decomposition Temperature</u>	
	<u>Temperature (°F)</u>	<u>Pressure (Psig)</u>
Carbon Dioxide (CO₂)	50.0	,638
HCFC R141B (CH₃CCl₂F)	52.9	0
HCFC R 142B (CH₃CClF₂)	55.6	19
HCFC R152A (CH₃CHF₂)	58.8	49
HCFC R22 (CHClF₂)	61.3	97
Cyclopropane (C₃H₆)	62.6	72
HCFC R31 (CH₂ClF)	64.2	27
Methyl Chloride (CH₃Cl)	68.7	56
Chlorine (Cl ₂)	82.9	109

The above decomposition temperatures are reduced by approximately 4° to 6° F. [2.2° to 3.3° C.] when the clathrate is made with seawater.

Of these nine agents, three were selected for further investigation:

- o HCFC **R141B** (Dichloromonofluoroethane • **CCl₂FCH₃**)
- o Carbon Dioxide • (**CO₂**)
- o HCFC R22 (Chlorodifluoromethane • **CHClF₂**)

The best candidate for deep ocean desalination and air conditioning applications where water temperatures below 45° F. [7.2° C.] are available was HCFC **R141B**. This clathrate former produced the lowest cost of **fresh** water and is the principal clathrate former discussed in this report.

The carbon dioxide clathrate former was also investigated but the high pressure required for clathrate formation made its use uneconomic at this **time**. This clathrate former is discussed below in this Section 5 and in Section 8.

The **clathrate** former HCFC R22 received less investigation but it appeared suitable for use in warmer waters such as the Mediterranean Sea and Persian Gulf. The cost of fresh water from the HCFC **R22**-based process will be higher due to its higher **formation pressure** but its **warm** water capability might make it attractive in many applications where fresh water is scarce. The use of HCFC R22 is reviewed in Appendix A.

5.3 HCFC **R141B** as a Clathrate Former

HCFC **R141B** is a compound manufactured for the rigid foam insulation industry by two large domestic suppliers as well as several non-domestic suppliers. **NRCC** laboratory tests showed that the HCFC **R141B clathrate** former produced a clathrate with distilled water at approximately **53° F [11.7° C.]**. The freeze temperature reduces to **47.5° F. [8.6° C.]** when mixed with seawater. HCFC **R141B** is a clear, colorless liquid with a faint **ethereal** odor. It is thermally stable at **normal** conditions and is not considered a hazardous waste under the Resource Conservation and Recovery **Act**. It has an intrinsically low toxicity with a permissible exposure limit of 500 parts per million. The compound is considered nonflammable in the liquid state as defined by the Department of Transportation and the National Fire Protection Association. In the vapor state, ignition is **difficult**. Thus, HCFC **R141B** met all of the above criteria with the exception that the material, that has no flash **point**, is slightly flammable.

The domestic suppliers are Allied Signal Chemicals (a subsidiary of Allied **Signal** Inc.) and **Pennwalt** Corporation (a subsidiary of Elf **Atochem** North America). The Environmental Protection Agency has designated the compound **environmentally** acceptable for manufacture through 2005 and material produced can be used and reused indefinitely. **Since** essentially all of the HCFC **R141B** is recovered in the desalination process there is little make-up requirements over the operating life of the plant.

Upon tentative selection of HCFC **R141B** as a clathrate **former**, **TESI** ran a large number of tests in its 15 ton-hour [**53** kilowatts] Clathrate Test Facility to insure rigorous, accurate, and reproducible test results of the operating performance of the clathrate **former** as a suitable working fluid. Although the testing revealed different clathrate **forming characteristics** under different operating conditions, the knowledge gained was utilized to develop a highly suitable clathrate crystal. This work under contract with Consolidated Edison Company of New York and the Empire State Electric Energy Research Corporation was completed in early 1993.

Prior to the current contract with the Bureau of Reclamation, Richard A. **McCormack**, President of **TESI**, recognized the simplicity of injecting HCFC **R141B** into the intake pipes of seawater drawn from the ocean depths. Clathrate ice would be formed in an ocean temperature of approximately **42° F. [5.6° C.]**

at a depth of **2,000** feet [**610** m]. The clathrate ice crystals would be scrubbed of surface salt in the transit to the surface and surface processing of the ice would be minimized. This proved to be an exciting opportunity to blend **clathrate freeze** technology with ocean engineering technology to achieve a significant reduction in **the** cost of the **freeze** desalination process. This led to the proposal to the Bureau of Reclamation and the award of a cost-sharing contract,

5.4 Carbon Dioxide as a Clathrate Former

During the course of this contract with the **Bureau** of Reclamation, Mr. **McCormack** also recognized the simplicity of using carbon dioxide (**CO₂**) as a clathrate **former** to further reduce costs of purifying the fresh water at the surface facility. **Carbon** dioxide met the above criteria of suitability except that it forms a clathrate at approximately **600** pounds/square inch (psi) [**42.2 kg/cm²**]. However, 900 psi [**63.3 kg/cm²**] pressure is realized at the 2,000 foot ocean depth and therefore carbon dioxide is **acceptable** for a **desalination** process. Thus, the carbon dioxide could be obtained from commercial sources, injected at ocean depth, the crystals scrubbed of surface salt during the ascent to surface, the crystals and **brine** separated, and when the crystals were melted the carbon dioxide could be easily recovered or released to the atmosphere leaving essentially pure fresh water.

A large amount of time was spent during the course of the contract on investigating the carbon dioxide process. At the end of the investigation it was determined that **the** cost of compressor power required to compress the gas to high pressure was a disadvantage that was not offset by the **reduced** capital cost and simplicity of the carbon dioxide cycle. Although developing creative ideas about overcoming the disadvantage of this concept is **continuing**, **carbon** dioxide must be termed as not (yet) feasible for consideration in this feasibility study.

5.5 Selection of HCFC **R141B** as the Clathrate Former

With the **current** demise of the carbon dioxide desalination process, attention was **returned** to HCFC **R141B** as the clathrate former of choice. The principal disadvantage of HCFC **R141B** is the additional equipment required to recover the relatively expensive HCFC **R141B** for reuse and **that concurrently** assured the pureness of **the** fresh water. Effort was devoted to the HCFC **R141B** recovery system to simplify and reduce the equipment **requirements**. Investigations were made of vacuum **distillation** towers, steam **strippers**, air strippers, liquid-phase carbon **adsorbers**, and vapor-phase **carbon** adsorbers. As described in Section 9, a low-cost recovery system for the demonstration plant is proposed that is commercially available as a skid-mounted unit **currently** used for waste water **and** ground water cleanup in various applications.

6. CONSIDERATIONS IN SITE SELECTION

6.1 Criteria and Site Choices

Of many sites available for the Clathrate Desalination Demonstration Plant, from Hawaii, the West Coast, the East Coast, or the Caribbean Islands, three sites were selected for detailed evaluation of **suitability**, **ocean** pipeline costs, and potential for funding. Three criteria for selecting sites were paramount in this regard:

- 0 The site must have (1) immediate deep-water ocean access, (2) a space suitable for all equipment, (3) a method of discharging the water, and (4) capability to obtain all permits at low cost; therefore the demonstration plant is best located within a facility that has similar operations and existing permits.
- 0 Pipeline costs play a major role in site selection since the pipe must deliver sea water at **45° F. [7.2° C.]** to the on-shore clathrate desalination demonstration plant; thus, it is necessary to find a location where the ocean depth of about 2,000 feet [**610 m**] is reasonably close to shore.
- 0 The demonstration project will likely require funding in excess of that available from the Bureau of Reclamation, and various governmental groups offer this potential funding if the demonstration plant is located at a site suitable to them.

The three sites selected for evaluation are:

- 0 The Natural Energy Laboratory of Hawaii (NELH) located **at Keahole** Point near **Kailua-Kona** on the Kona Coast of the Big Island of Hawaii;
- 0 The Naval Auxiliary Base on San Clemente Island located approximately 70 miles [113 km] off the coast of San Diego, California;
- 0 Scripps Institute of Oceanography **located** at La Jolla, a suburb of San Diego.

6.2 Site Preference

The order of preference for sites for the Clathrate Desalination Demonstration Plant are as listed above based on all considerations except funding. However, funding is such a major consideration that it will likely dictate the site, and all three sites are technically acceptable.

The reasons for selecting NELH as the preferred site is based on an existing assured source of deep sea water at the Hawaiian location. This avoids the cost of installing a deep sea pipeline **required** at the other two sites. These **three** locations are discussed further below with respect to the site **description**, features, accessibility, advantages, and disadvantages.

63.1 The Natural Energy Laboratory of Hawaii. • The **NELH** is located at Keahole Point adjacent to **the** Kailua-Kona airport on the west coast of the Big Island of Hawaii. NELH manages 870 acres (1.36 square miles) [**3.52 km²**], including the Hawaii Ocean Science and Technology (HOST) **Park**, as shown in Figure 6.1. The NELH provides facilities to support many types of research, demonstration, and commercial projects in ocean and solar technologies. Keahole Point provides access to pristine deep and surface sea water, an abundance of sunshine, and exceptional weather conditions. Private, corporate, governmental and academic sectors use these resources in innovative projects both in research and applied technologies. NELH **maintains** the infrastructure for the demonstration plant, and provides a wide variety of support services that can be rented as required for the project

Some funding for the clathrate freeze desalination demonstration plant may be available from the State of Hawaii and/or other U.S. government agencies. More detailed investigation of the conditions for this funding will be made as part of the continuing efforts to build a demonstration plant,

The ocean floor drops off rapidly at Keahole Point, allowing access to deep sea water relatively close to shore. NELH operates and maintains pipelines and pumping stations that access deep sea water from 2,215 feet [**675 m**] with temperatures at or below **43° F. [6.1° C.]**. There are three deep sea pipelines in operation with a total capacity of 17,100 gallons/minute (**gpm**) [**1080 liters/second**]. The largest pipeline is a 40 inch [**102 cm**] diameter polyethylene line running to a depth of 2,100 feet [**640 m**] that provides 13,400 gpm [**845 liters/second**] of cold sea water. Deployment of the 40 inch pipeline prior to submergence is shown in Figure 6.2. The lower portion of the ocean pipeline is an inverted catenary, 3,337 feet [**1020 m**] long, that floats several hundred feet [**30.5 m**] above the rough bottom, as illustrated in Figure 6.3. This design also **permits** the pipeline to move 500 feet [**152 m**] horizontally and 250 feet [**76.2 m**] vertically to accommodate ocean currents. Seawater **distribution** pipelines on the surface are shown in Figure 6.4 and a solar desalination project is shown in Figure 6.5.

Makai **Ocean** Engineering, Inc. (Makai), headquartered at **Makapuu** Point, **Oahu**, is the Company that laid the cold water pipes at NELH. Makai is highly interested **in** the clathrate technology as a means of providing fresh water and air conditioning on Guam, other **Pacific** islands, and elsewhere in the world. Makai would be available to operate the demonstration plant, **learn** the technology, and provide applications as part of its normal business activities.

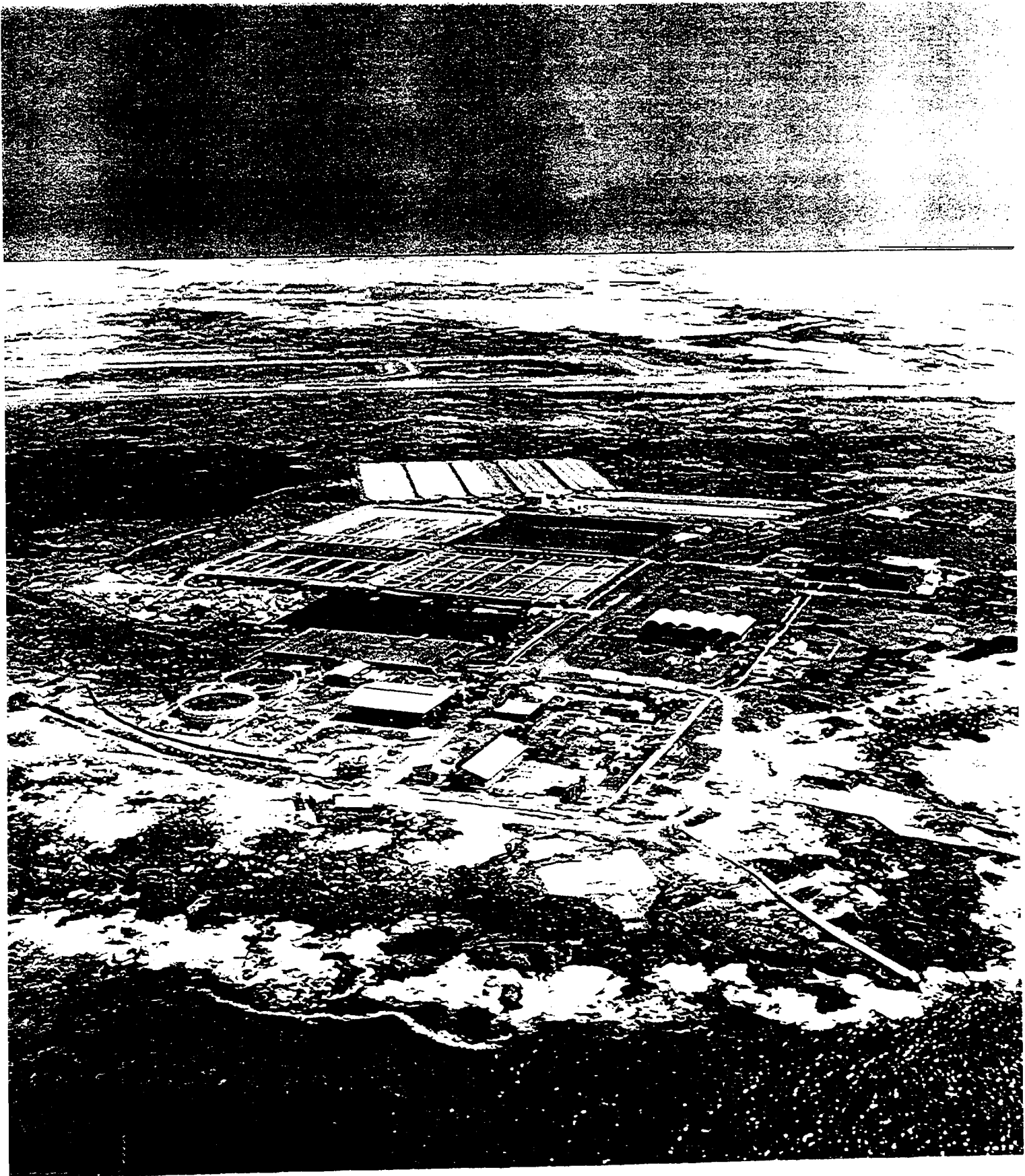


Figure 6.1
Aerial View of the Natural Energy Laboratory of Hawaii

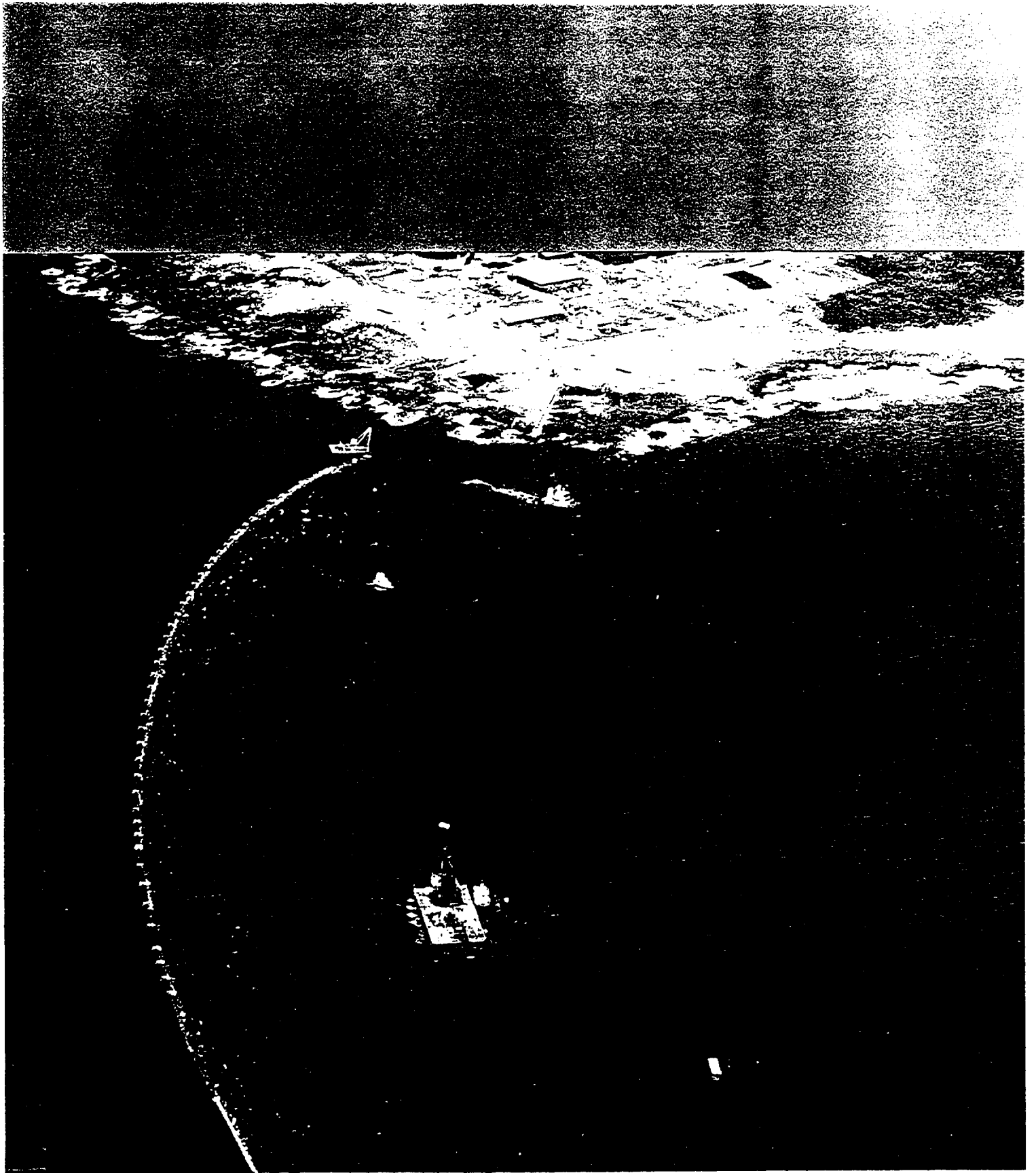


Figure 6.2
Deployment of 40 Inch Pipeline Preparatory to Submergence

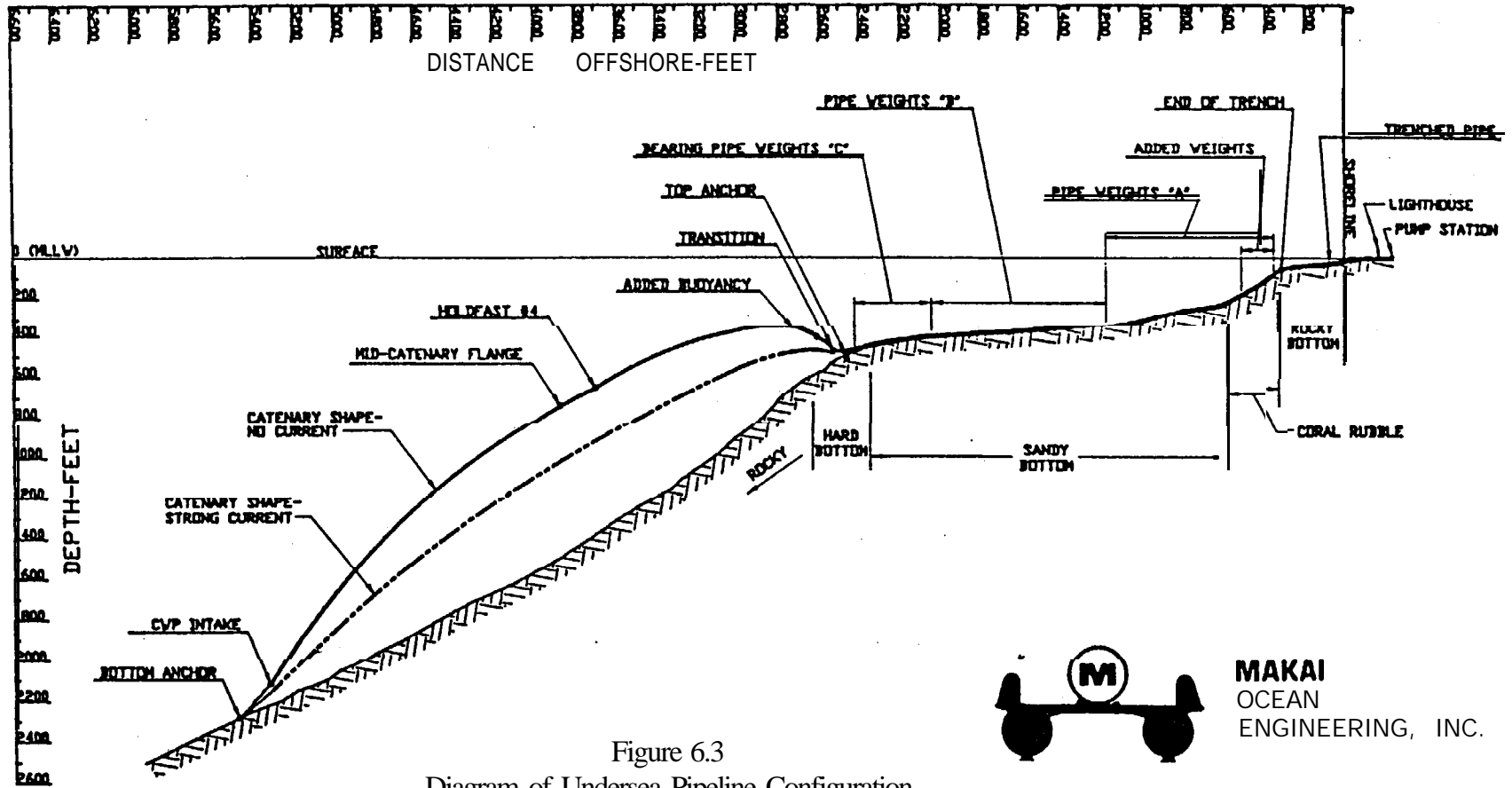
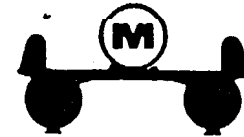


Figure 6.3
Diagram of Undersea Pipeline Configuration



MAKAI
OCEAN
ENGINEERING, INC.

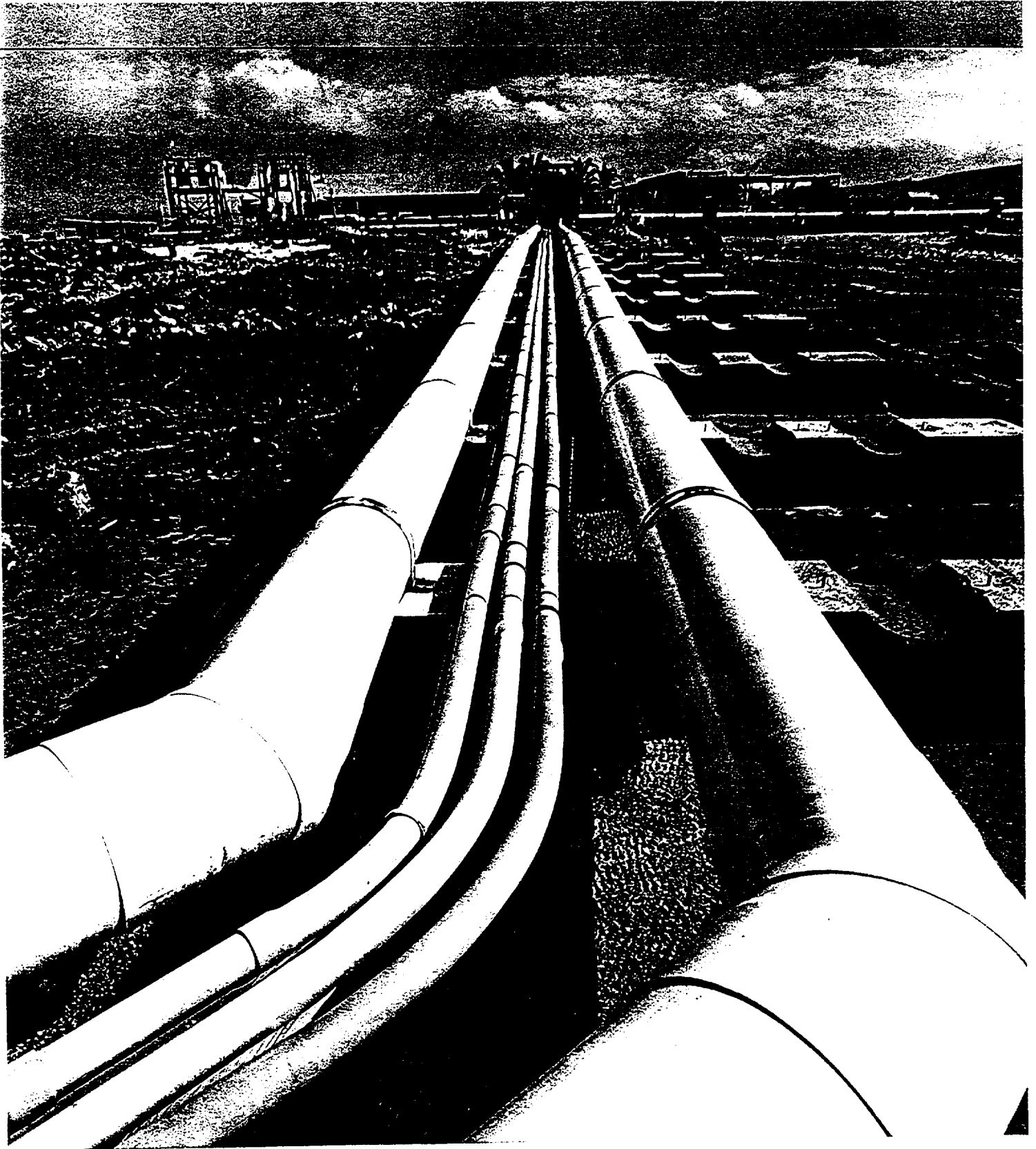


Figure 6.4
Seawater Distribution Pipes

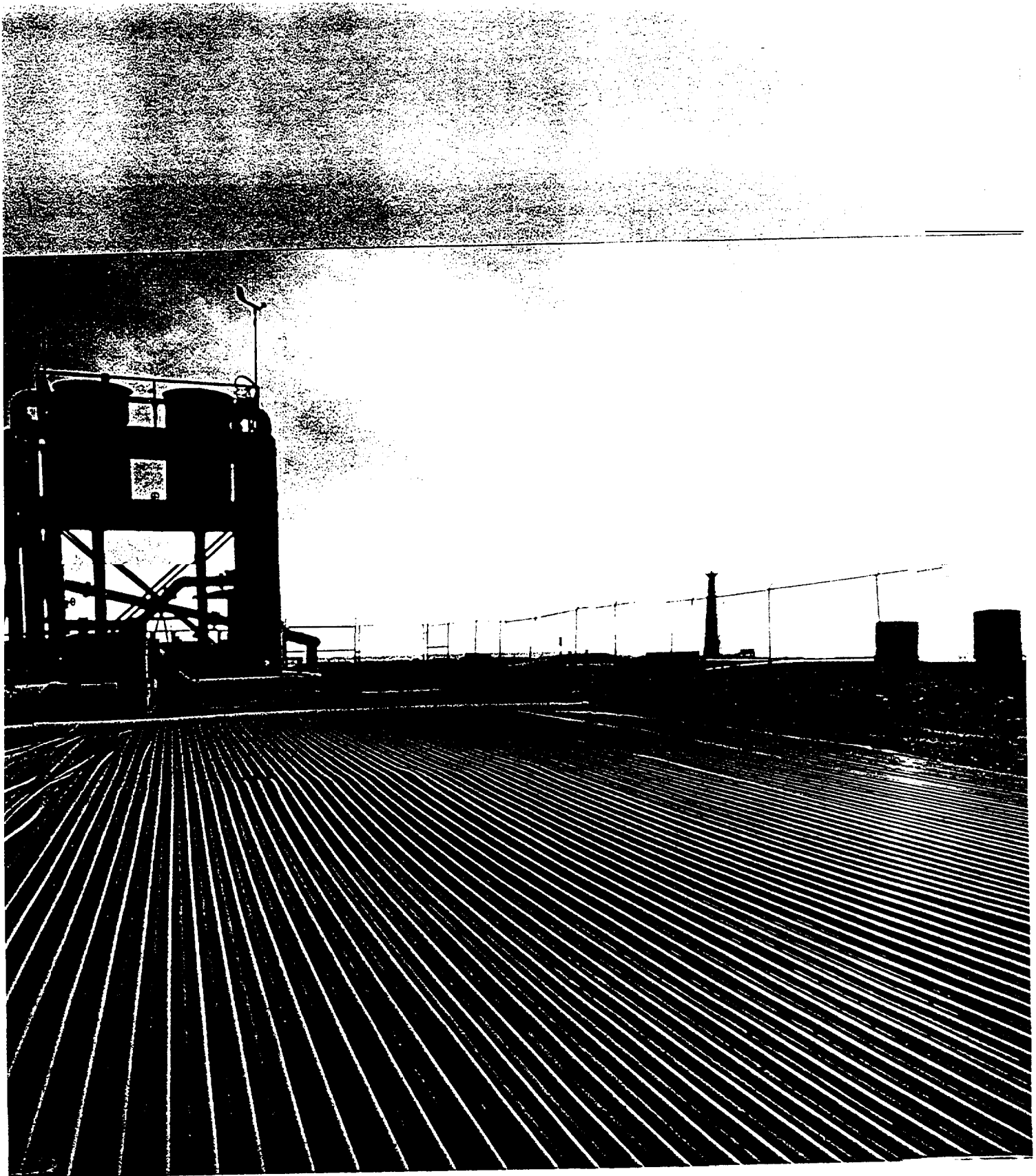


Figure 6.5
Solar Desalination Experiment

The **principal** advantages of the Hawaii location are these:

1. **There** is certainty that delivered sea water will be at a temperature **sufficiently** low to form a clathrate at **47.5° F. [8.6° C.]**.
2. The high cost of laying a new deep sea pipeline is avoided; the 132 gpm [**8.33** liters/second] supply to the demonstration plant to provide 25 gpm [1.58 liters/second] of **fresh** water product is available by inserting new smaller coaxial pipes into an existing pipeline thereby providing the seawater flow directly to the demonstration plant
3. The monthly cost of the water from the pipeline is low at **\$3.25/gpm/month [\$0.86/liter/minute/month]**; for a 132 gpm supply, the cost would be **\$429/month**.
4. **NELH** is enthusiastic about using its facility for the demonstration plant and may be able to assist in obtaining additional funding from the State of Hawaii and other U.S. government agencies.
5. The site has all the necessary environmental permits for operation of the plant
6. The site and all the necessary support **services** are available at economical **pre-set rental** fees from the NELH at the HOST site.
7. Makai is available to operate the demonstration plant and extend the **application** of the **clathrate** process to commercial fresh water and air conditioning opportunities on Guam, **other Pacific** islands, and elsewhere in the world.
8. The **airport at Kailua-Kona** provides direct service to the U.S. mainland with connecting **flights** to all countries of the world.

The **principal** disadvantages of **the** Hawaii location are these:

1. The location is the most expensive to reach from San Diego and Denver.
2. Day-today reliance on NELH or Makai would be necessary to collect test data and operate and maintain the demonstration plant.
3. There is no cost/benefit justification for the water produced by the project in Hawaii compared to the **demonstration** plant at San **Clemente** Island where **the** water cost to users is **\$35/1,000** gallons [**\$9.25/m³**].

On balance, saving funds by not installing a deep sea water pipeline for the demonstration plant overcomes the cost of travel and other expenses by many factors. The low cost of the demonstration plant in Hawaii means that sources of funds will be easier to find. However, the unavailability of adequate funding from the State of Hawaii and other sources may preclude the selection of this site.

633 The Naval Auxiliary Base on San Clemente Island. - The U.S. Government owns San Clemente Island and the U.S. Navy maintains a **training** facility, including a landing field, on the Island, about 70 miles [113 km] off the coast of San Diego. The **Island** is about 21 miles [**33.8 km**] long with a land area of 57 square miles [148 **km²**]. Navy activities are conducted **at** the northern end of the Island, principally at Wilson Cove, as shown in Figures 6.6 and 6.7.

The Island serves a variety of weapons research, development, testing, and evaluation activities, and a number of military **training** functions. The Island is used primarily by several major Naval tenants but also by **research divisions** of government agencies and private companies working on government contracts.

The Navy imports 300,000 **gallons [1140 m³]** of potable **water** weekly to the Island by barge at a cost of **\$10,000/week** or approximately **\$500,000/year**. Figure 6.8 shows the barge, tug, and pier at Wilson Cove. **The** Navy is encouraging the use of the site for the **clathrate desalination** demonstration plant and might be able to provide some funding for **the** project. A letter from the Department of the Navy is reproduced in **Appendix B**.

A **clathrate** desalination demonstration plant operating at 25 gpm [1.58 liters/second] of **fresh** water output at 80 percent **availability** would provide over one-half the potable water supply and could save the Navy over **\$250,000/year**. If the demonstration plant was successful, a second 25 gpm duplicate plant could be added to provide the total potable water supply **required** for the Island. The second unit would be quite inexpensive since the pipeline would have adequate capacity for the two units. This two-unit system would pay for the facility, including the deep sea pipeline, in approximately three years.

The Island's water storage facilities are located at Wilson Cove and the demonstration **plant** would be located near the water storage **area**. The sea water pipeline would extend across a short underwater coastal **shelf** and then descend into deep water. Although a depth of **2,000 feet [610 m]** is expected to provide sufficiently cold water, **at-depth** tests would be **required** to ensure it. A pipeline of about 7,500 feet [**2290 m**] in length producing a 1,000 gpm [**63.1 liters/second**] flow rate would be **required**. **The** higher flow rate is **required** to **achieve the** desired **temperature water** at the demonstration **plant**; lower flow rates require more pipe insulation that rapidly **increase costs**. **Thus, there is a minimum pipeline cost that** occurs at about 1,000 gpm flow. Without knowing the **condition of the** ocean bottom, **currents, and other** ocean factors the cost of the pipeline has been estimated at \$2 million.

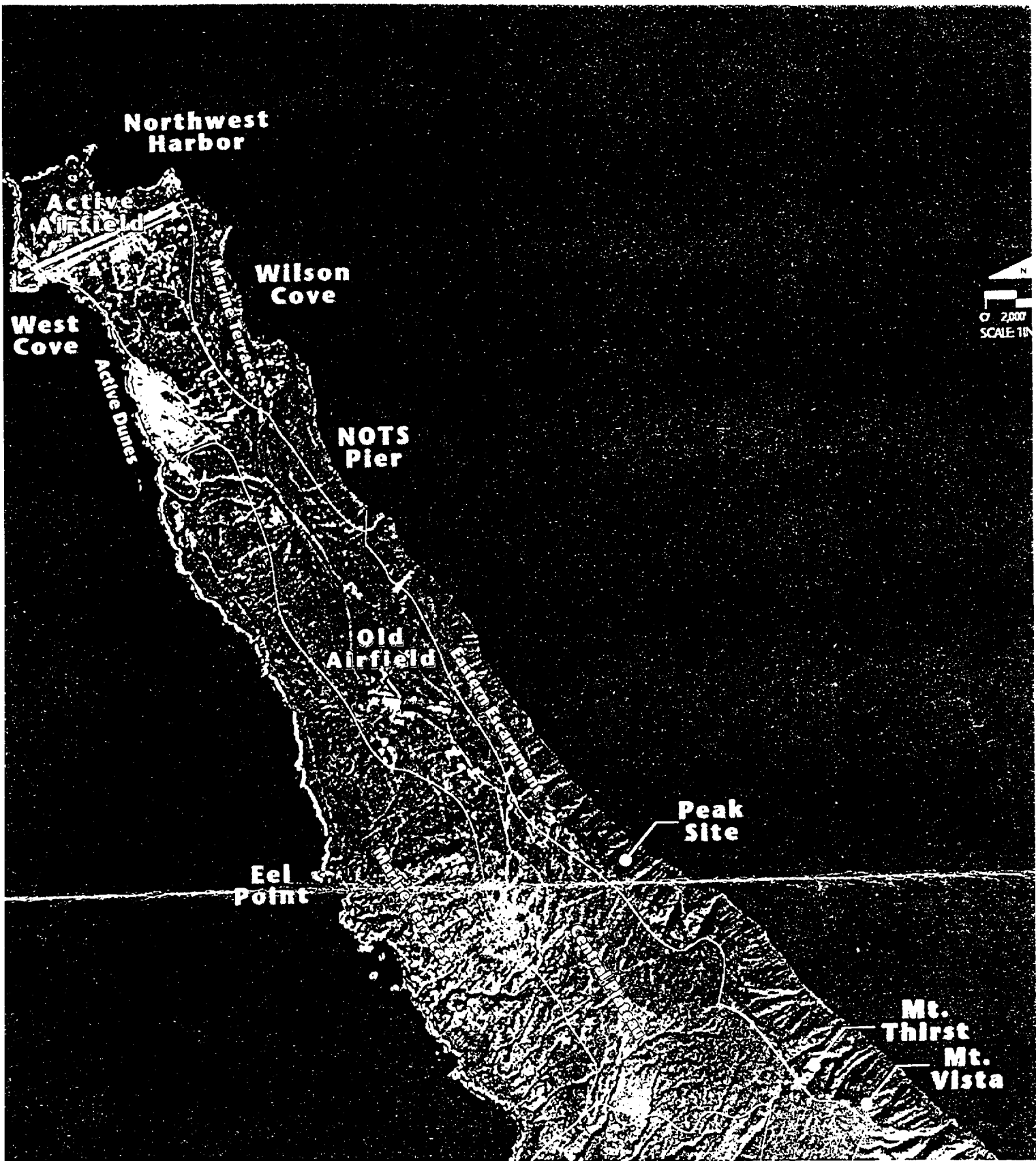


Figure 6.6
Aerial View of Northern Portion of San Clemente Island



Figure 6.7
Aerial View of Navy Facilities at Wilson Cove

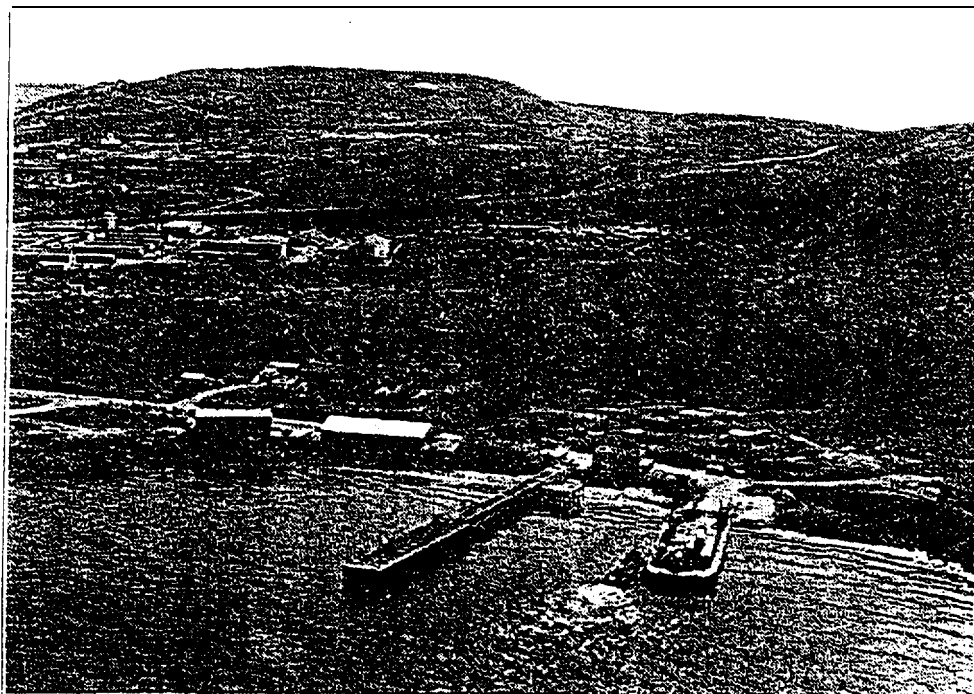


Figure 6.8
Aerial View of Barge, Tugboat, and Pier at Wilson Cove

The 1,000 gpm [**63.1 liters/second**] seawater flow rate could produce 189 gpm [11.9 liters/second] of fresh water, but the Navy only needs 30 gpm [**1.89 liters/second**] of fresh water to meet its 300,000 gallons [1140 **m³**] of weekly supply. If two 25 gpm [158 **liters/second**] units were built, the Navy could produce the 30 gpm of fresh water needed by operating the plant at 60 percent capacity factor. The 50 gpm [**3.15 liters/second**] of fresh water would normally require 264 **gpm [16.7 liters/second]** of seawater flow. Of the 1,000 gpm pumped from the sea, only **sufficient HCFC R141B** would be injected to produce the desired **50 gpm** of fresh water. The brine **would** have a lower increase in salinity than the Hawaiian location and could be returned to the sea with minimal environmental concern

A second small pipeline could be used to collect higher temperature surface water so that melting of the clathrate crystal can be achieved. Alternatively a solar heating system or the return line of refrigerant from an air conditioning system could supply the low grade heat **required** for melting.

The principal advantages of the San Clemente Island location are these:

1. There is an economic benefit to the U.S. Navy in the supply of potable water to the Island, although the demonstration plant would need to be expanded to a 50 gpm [**3.15 liters/second**] plant meet the Island's needs and to achieve a three year payback period.
2. The U.S. Navy is encouraging the project at **the** Island, and in addition to providing the site, may be able to provide some supplementary funding.
3. Laying a new pipeline would facilitate the use of a concentric piping system whereby the HCFC **R141B** clathrate former is directly injected into the cold sea water at depth and the latent heat of formation is released to the surrounding ocean
4. The site is more readily available from San Diego and somewhat more convenient from Denver.

The principal disadvantages to the San Clemente Island location are **these**:

1. Building a high-cost pipeline for a demonstration plant is difficult to justify when adequate cold water is available at minimum **cost** at another **location**.
2. Access to the Island is principally by air, and **government contractors** have the lowest priority for available seating in helicopters or other **aircraft**.
3. Information on the need for environmental and coastal water permits is not immediately available.

On **balance**, the economic contribution of the demonstration plant may justify partial funding by the U.S. Navy. Even **though** larger **funding** is required to lay the ocean pipeline, if this funding is available then San Clemente Island would be the chosen site.

6.2.3 Scripps Institute of Oceanography at La Jolla. - The Scripps Institute of Oceanography (Scripps) is located on the California shoreline at La Jolla a residential area in San Diego. Scripps Institute has a 1,000 foot [**305** m] pier extending into La Jolla Cove as pictured with research vessels in **Figure 6.9**. Scripps is amenable to locate the demonstration plant at the land side of the pier. Although there is no apparent economic benefit for the potable water, there is the possibility that it could be pumped to the top of the mesa to reduce water **purchases** by **the** University of California at San Diego. Sale of the water at a price of **\$2/1,000** gallons [**\$0.53/cm³**] would defray operating costs and permit a return on the **investment**.

The sea water pipeline would extend along the pier and across a short underwater coastal shelf before descending into deep water in the **La Jolla** canyon. Extrapolating data from oceanographic charts, it appears that a depth of 2,000 feet [**610** m] would provide **sufficiently** cold water, but **at-depth** tests would be **required** to ensure it. The Scripps location would require a pipeline of about **6,300** feet [**1920** m] in length producing a 1,000 gpm [**63.1** liters/second] flow rate to achieve minimum cost Without **knowing** the condition of the ocean bottom, currents, and other ocean factors the cost of the pipeline has been estimated at \$1.2 million.

Only sufficient HCFC **R141B** would be injected into the seawater to demonstrate the process at 25 gpm [1.58 liters/second] of fresh water, and unless a use was found for the potable water, all water would be returned to the ocean with minimal environmental concern

The principal advantages of the Scripps location **are** these:

1. While Scripps personnel have **no** incentive for locating the demonstration plant at the pier, they **are interested in the chemical and ocean engineering aspects of the project and have readily agreed** to provide the site because of this interest.
2. Laying a new pipelii would facilitate the use of a concentric piping system whereby the HCFC **R141B** clathrate former is directly injected into the cold sea water at depth and the latent heat of fusion is released to the **surrounding** ocean
3. The site is readily available **from** San Diego and convenient from Denver.

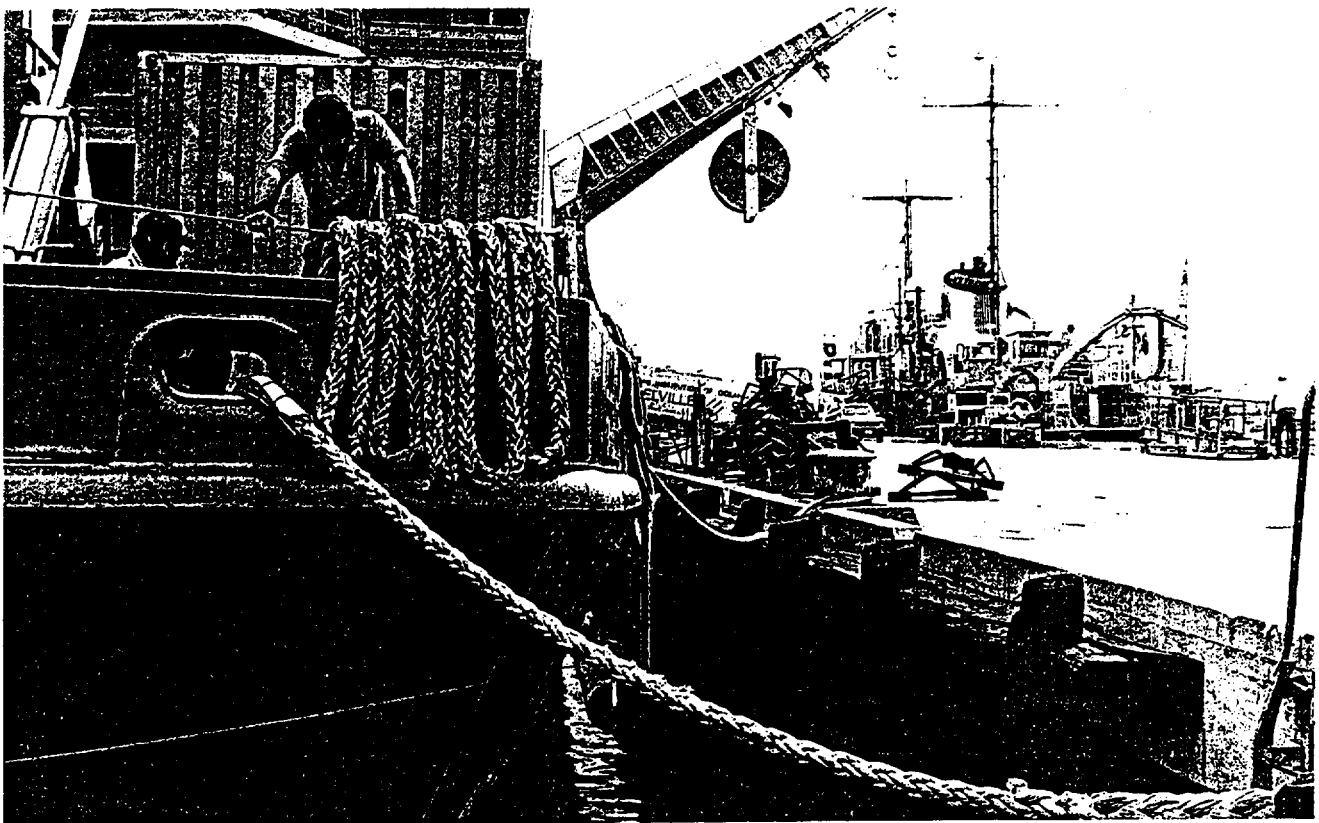
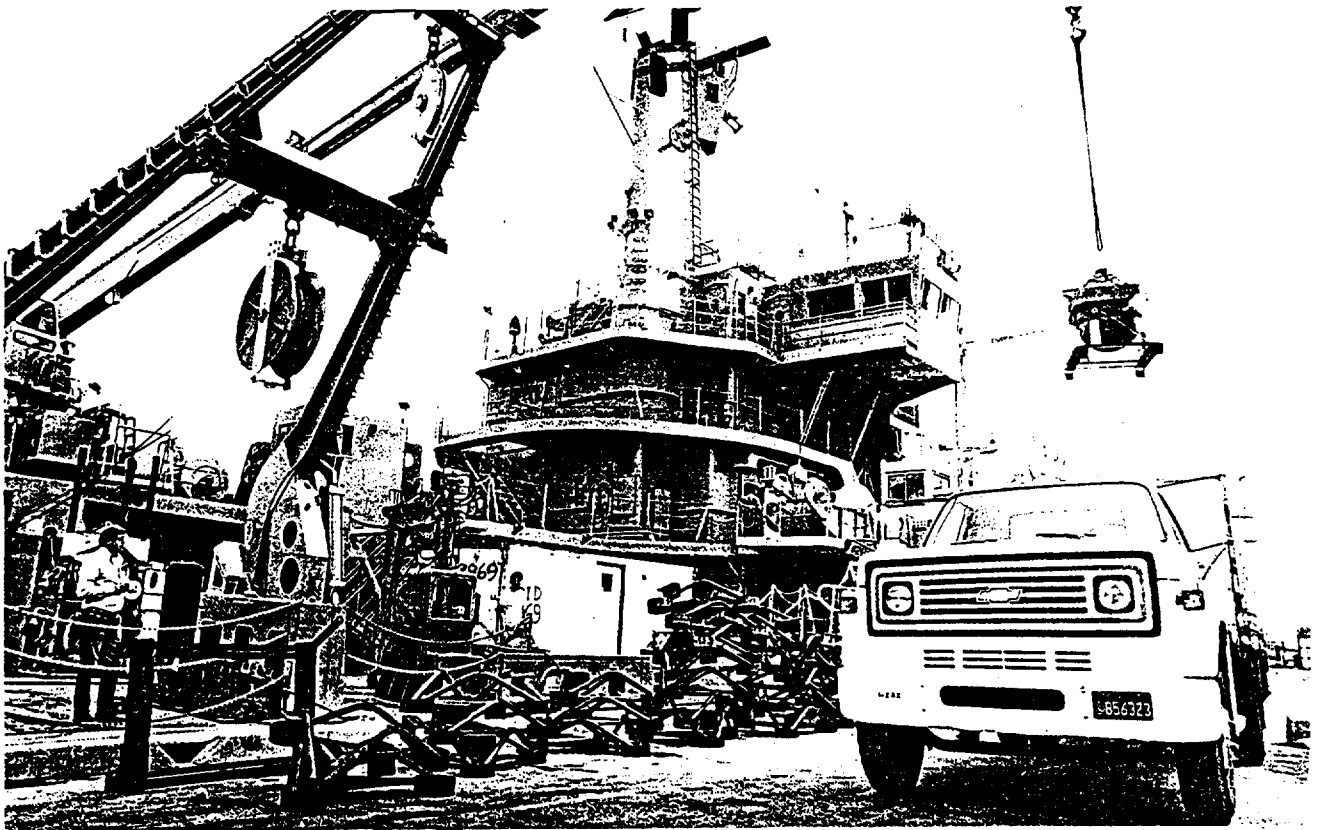


Figure 6.9
Research Vessels at Pier at Scripps Institute of Technology

The principal disadvantages of the Scripps location are these:

1. Building a high-cost pipeline for a demonstration plant may not be justified when adequate cold water is available at minimum cost at another location.
2. The site has **no** economical use for **the** potable water produced unless new pipelines **are** extended up the mesa to connect with the water system at the University of California at San Diego.
3. Information on the need for environmental and coastal water permits is not immediately available.

Despite the extra **cost**, the State of California may partially fund the project **through** a grant to the University of California at San Diego. Scripps Institute of Oceanography is part of **the** University of California system and these funds would be transferred to them for **financing** the demonstration project.

Justification for the demonstration plant would be based on the need for a commercial **desalination** facility to permit the **manufacturing**, commercial, and residential development of the Otay Mesa area of San Diego County along the border with Mexico. As one possible example, the commercial **desalination** facility could be built in conjunction with new **electric** power plants planned to serve that area. **The desalination plant might be located near the Scripps site with fresh water pumped into the fresh water outlet lines of** the large waste water reclamation facility now under construction in the **nearby Sorrento** Valley area of San Diego. **The** waste water reclamation facility is designed to produce potable water to be pumped to fresh water reservoirs. Studies would be necessary to determine the feasibility of this location. Other locations are also available for **consideration**.

7. ENVIRONMENTAL, REGULATORY, AND SOCIETAL EFFECTS

7.1 The **Environmental** Impact Report

The environmental, regulatory, and societal effects of the location and operation of a desalination plant **are** reviewed in an environmental **impact report**. These reports are **prepared** by the lead agency supporting the **project who** contacts all applicable regulatory bodies for laws, regulations, and reviews **required** to meet initial compliance **standards** and who then monitors operations to insure these **standards** are met. After a draft environmental impact **report** is **prepared**, these agencies and the public review the results and forward comments. A final **report** is then issued that complies with all **requirements**. The principal eleven topics that would be reviewed in an environmental impact report for a desalination plant are:

1. **Land Use**
2. Geology, Soils, and Seismic **Hazards**
3. Groundwater Resources
4. Marine Water Quality
5. Marine Biological Resources
6. Water Quality
7. Noise
8. Liquid and Solid Waste
9. **Energy**
10. Electromagnetic Fields
11. Visuals and Aesthetics

A brief review of each of these topics for each of the **three** sites is presented below.

7.2 The Demonstration Desalination Plant

The clathrate desalination demonstration facility is not expected to **require** an environmental impact **report** at any of the **three** sites evaluated since the plant will be located within facilities that have previously **prepared these reports or are not required to do so**. It may be necessary to prepare a supplementary descriptive or qualification report if the plant is located at the U.S. Navy **facility** on San Clemente Island or at Scripps Institute of Oceanography at La Jolla, **California**. The Natural Energy Laboratory of Hawaii already withdraws and discharges seawater for use in various types of projects. The situation at each of the three sites is somewhat different and is reviewed individually below.

No detailed analysis of the environmental impact for the demonstration plant has been made. The discussion in this Section 7 is based on the Draft **Environmental** Impact Report for the **desalination** plant built by the City of Santa Barbara, California⁽¹⁾ supplemented by individual **reports** on the three sites evaluated for the clathrate demonstration plant, as referenced in the discussion of each site.

The City of Santa Barbara has **constructed** a 9 million gallons/day [**34100 m³/day**] or 10,000 acre-feet/year [**12.3 million m³/year**] desalination plant that went into operation on March 4, 1992. The Draft Environmental Impact Report showed no deleterious effects or impediments to the operation of the **desalination** plant in any of the above eleven categories.

(1) Draft Environmental Impact Report for the City of Santa Barbara Long Term Water Supply Program, **EIP** Associates, Pasadena, California, November 1993.

Since the demonstration facility is 250 times smaller than the Santa Barbara facility and will utilize seawater with little marine life at 2,000 foot [610 m] depths rather than surface water with high **concentrations** of **marine** life, it was judged that no major environmental obstacles existed for the demonstration facility. At the Santa **Barbara** site, the brine was mixed with waste water before returning to the sea and encountered no problems. The small flow of brine from the demonstration plant should also pose no problems. The discussion below is based on what appears to be reasonable as judged **from** the Santa Barbara analysis, but is not **the** result of any significant investigation.

7.2.1 The Natural Energy Laboratory of Hawaii. - The Natural Energy Laboratory of Hawaii (NELH) now operates several pipelines going into the ocean and distributes this water to various **customers** in the Hawaii Ocean Science **and** Technology (**HOST**) **Park**.⁽²⁾ This water is not **permitted** to be **returned** directly to the ocean but must be discharged over lava rock beds to evaporate or percolate back **to** the ocean. This appeared to be the only significant requirement in the use of the ocean water.

The clathrate demonstration facility will use only a small amount of water compared to the total quantity of water pumped to the surface for all programs **underway** at **NELH**. In this **respect**, the demonstration plant project is just another customer at **the** **HOST** **Park** that will operate under rules and **regulations** previously imposed by regulatory agencies. **Further**, the demonstration plant is not likely to be a **permanent** facility since there is no need for the potable water produced.

Thus, permits for the demonstration plant at the NELH is expected to be at no cost or, at worst, the least costly and restrictive of the **three** sites. If **the** demonstration plant is not placed at **NELH**, the prior experience of NELH will be helpful in locating the plant at other sites.

The environmental impact with respect to the eleven topics listed above is briefly reviewed with **respect** to the **NELH** site.

1. Land Use: **NELH** is an **approved research** and development facility that has responsibility for control of land use. The Laboratory is located in a remote **area** on dedicated land. Space for the demonstration plant would be **rented**.
2. Geology, Soils, and Seismic **Hazards**: **The** demonstration plant will be located at existing facilities so that no additional development of land will be **required**. **Much** of the equipment will be skid-mounted to permit easy dismantling of the facility with no significant **cleanup** and restoration **required**. Seismic hazards are not a serious problem since rupture of the equipment piping would

(2) **Annual Report**, Natural Energy Laboratory of Hawaii Authority, 1992.

- not release any significant amount of HCFC **R141B** and any material released can be easily recovered and any residual material will quickly evaporate.
3. Groundwater Resources: No groundwater resources are involved in the operation of the demonstration plant. No wastes will be discharged to the soil except for minute amounts of HCFC **R141B** that will be mixed with huge volumes of seawater from all **NELH** operations that are discharged onto lava rock beds to evaporate and percolate back to the sea in an approved manner. **The HCFC R141B** is non-toxic and will quickly evaporate on the lava rock.
 4. Marine Water Quality: The demonstration plant will utilize 132 gallons/minute (**gpm**) [**8.33 liters/second**] from a **NELH** deep-sea system pumping 17,100 gpm [**1080 liters/second**]; this is less than one percent of the total. All water pumped is **pristine** seawater. No concentrated brine is produced by the demonstration plant since the fresh water is not retained and **all** water employed is **returned indirectly to the sea**.
 5. Marine Biological Resources: The deep sea pipes used by **NELH** draws water from the **photic zone** where the water has been out of contact -with the surface for centuries. Therefore it contains few living plants **and** animals. Thus, the pumping of deep sea water has essentially no effect on marine biological resources.
 6. Water Quality: Water quality is not a problem since the **fresh** water product from the demonstration plant is not used and is discharged with the seawater on the lava rock beds.
 7. Noise: The plant is small and generates little noise and the site is remote.
 8. Liquid and Solid waste: The cost of the clathrate former makes it economical to recover **99.99** percent of the HCFC **R141B**. Approximately 0.032 gallons/day [**0.12** liters/day] of HCFC **R141B** is lost to the seawater or the atmosphere while the demonstration plant is operating. The HCFC **R141B** quickly evaporates, is non-toxic and is not a hazardous waste. Thus there are **essentially** no liquid or solid wastes generated by the plant other than a minimum amount of office paper products.
 9. Energy: Energy **requirements** for the demonstration plant are insignificant compared to the pumping power already employed at the Laboratory.
 10. Electromagnetic Fields: A minor **increase** in electromagnetic fields will arise **from** the pumps in the demonstration facility but this is insignificant compared to Other Laboratory sources.

11. Visuals and Aesthetics: The **HOST** facility is designed for use as a research **and** demonstration facility and its remote location does not require special treatment

7.23 Sun **Clemente Island**. - It is not believed that **the** U.S. Navy is required to prepare environmental impact reports for its operations at the Naval Auxiliary Landing Field on San Clemente Island. However, the U.S. Navy has published an Operational and Land Use Compatibility **Study**⁽³⁾ that serves as a basis for reviewing the environmental impact of the demonstration plant on the island.

1. Land Use: San Clemente Island is owned by the U.S. Government and used by the U.S. Navy as a Naval Auxiliary Landing Field and training facility. The U.S. Navy has responsibility for control of land use. It approves the use of all activities conducted on the Island including other government agencies and **contractors**.
2. Geology, Soils, and Seismic Hazards: The demonstration plant will be located in **presently** occupied areas of Wilson Cove so that no new land need be developed for the site. The facility **is small and the fresh water produced will be pumped into existing fresh water storage tanks**. Much of the equipment will be skid-mounted to permit easy dismantling of the facility with no significant cleanup and restoration required. Seismic hazards are not a serious problem since rupture of the equipment piping would not release any significant amount of HCFC **R141B** and any material released can **be** easily recovered and any residual material will evaporate.
3. **Groundwater** Resources: No groundwater resources are involved in the operation of the demonstration plant **Fresh** water produced from seawater at the plant will meet potable **drinking water standards or will be returned to the sea**. **No wastes will be discharged to the soil unless a** drum of HCFC **R141B** were to be accidentally ruptured in transit. In this event, cleanup is easy due to the small amount of material released and the quick evaporation of any residual material after cleanup. The HCFC **R141B** is non-toxic and nonhazardous.
4. Marine Water Quality: The demonstration plant will receive 1,000 gpm [**63.1** liters/second] from a deep sea pipeline drawing pristine water to the surface. The 25 gpm [1.58 liters/second] of fresh water produced at the demonstration plant will be utilized for **drinking** water or **returned** to the sea. **The fresh water extracted is only about 2.5 percent of the total flow so that the brine returned**

(3) San **Clemente** Island Compatibility Study: Land Use, Operations and Natural Resource **Compatibility** Report, Southwest Division, Naval Facilities Engineering Command, 1993.

to the sea **is** about the same concentration as that withdrawn. Any minute quantities of **HCFC R141B** in the discharged water will quickly evaporate.

5. Marine Biological Resources: Although **currents** in the vicinity of Wilson Cove have not been investigated, the deep sea pipes draw water from a zone of the ocean that likely has been out of contact with the surface for centuries. Therefore it contains few living plants and animals. Thus, the **pumping** of deep sea water has essentially no effect on marine biological resources.
6. Water Quality: Water quality must meet potable water **standards** or it cannot be pumped to the fresh water storage tanks. Water not meeting these **standards is returned to the sea with the brine** water.
7. Noise: The plant is small and generates little noise. It can be located away **from** occupied buildings so that noise is not a problem.
8. Liquid and Solid waste: The cost of the **clathrate** former makes it economical to recover 99.99 percent of the HCFC **R141B**. Approximately 0.032 gallons/day [**0.12** liters/day] of HCFC **R141B** is lost to the seawater or the atmosphere while the demonstration plant is operating. **The** HCFC **R141B** quickly evaporates, is non-toxic and is not a hazardous waste. Thus there are **essentially** no liquid or solid wastes generated by the plant other than a minimum amount of office paper **products**.
9. Energy: Energy requirements for the demonstration plant are small compared to the **current** power usage at the Naval **Auxiliary** Landing Field.
10. Electromagnetic Fields: A minor increase in electromagnetic fields will arise from the pumps in the demonstration facility but this is insignificant compared to other sources on **the** Island.
11. Visuals and Aesthetics: The Naval Auxiliary Landing Field is used for **training** of navy, marine, and air force personnel and does not require an **aesthetic** appearance. The small demonstration plant will not detract from the general appearance of the facility.

7.23 Scripps **Institute** of Oceanography. • The site at Scripps Institute of Oceanography (Scripps) is likely the most environmentally sensitive of the three sites. Although Scripps is isolated **from** urban areas it is located not **far** from the **suburbs** of La Jolla, a commercial, residential, and scenic area of San Diego. Even so, Scripps **maintains** a large global oceanographic research operation including several **research** and

support vessels. These ships are sometimes docked along a 1,000 foot [305 m] pier extending into the ocean.⁽⁴⁾

1. Land Use: Scripps is an approved research and development facility and the Institute has responsibility for **control** of land use.
2. Geology, Soils, and Seismic Hazards: The demonstration plant will be located on land near the pier so that no new land need be developed for the site. The facility is small and the fresh water produced will be returned to the sea. Much of the equipment will be skid-mounted to permit easy dismantling of the facility with no **significant** cleanup and restoration **required**. Seismic hazards are not a serious problem since rupture of the equipment piping would not release any significant amount of HCFC **R141B** and any material released can be easily recovered or will evaporate.
3. Groundwater Resources: No groundwater resources **are** involved in the operation of the demonstration plant Fresh water produced at the plant **will** be returned to **the** sea No wastes will be discharged to **the** soil unless a drum of HCFC **R141B** were to be accidently ruptured in transit. In this event, cleanup is easy due to the small amount of material released and the quick evaporation of any residual material after cleanup. The HCFC **R141B** is non-toxic.
4. Marine Water Quality: The demonstration plant will receive 1,000 gpm [**63.1** liters/second] from a deep sea pipeline drawing pristine water to the surface. The 25 **gpm** [1.58 liters/second] of fresh water produced at the demonstration plant will be **returned** to the sea so that the brine concentration **will** not be changed. Any minute quantities of HCFC **R141B** in the discharged water will quickly evaporate
5. Marine Biological Resources: Although currents in the **La** Jolla Canyon have not been investigated, the deep sea pipes draw water from a zone of the ocean that likely has been out of contact with the surface for centuries. Therefore it contains few living plants and animals. Thus, the pumping of deep sea water has **essentially** no effect on marine biological resources.
6. Water Quality: Water quality is not a problem since the **fresh** water product from the demonstration plant is not used and is discharged with the seawater.
7. Noise: The plant is **small** and **generates** little **noise**. It can be located away from occupied buildings so that noise is not a problem.

(4) Annual Report, Scripps Institute of **Oceanography**, University of California, 1989.

8. Liquid and Solid waste: The cost of the clathrate **former** makes it economical to recover 99.99 percent of the HCFC **R141B**. Approximately 0.032 gallons/day [0.12 liters/day] of HCFC **R141B** is lost to the seawater or the atmosphere while the demonstration plant is **operating**. The HCFC **R141B** quickly evaporates, is non-toxic and is not a hazardous waste. Thus there are essentially no liquid or solid wastes generated by the plant other than a minimum amount of office paper **products**.
9. Energy: Energy requirements for the demonstration plant are small compared to the current power usage at **Scripps**.
10. Electromagnetic Fields: A minor increase in electromagnetic fields will arise **from** the pumps in the demonstration facility; this is insignificant compared to other sources at the Institute.
11. Visuals and Aesthetics: The Scripps facility is designed for use as a research and demonstration facility and its isolated location does not require special treatment. The perimeter of the facility is screened by trees.

73 Commercial Clathrate **Desalination** Plant

If the demonstration plant is successful and a **commercial desalination** plant is to be built, **it will require** an **environmental impact report** to be **prepared**. When **alternates** of building new dams or aqueducts are considered, the **clathrate** desalination plant will likely be shown to have the least environmental impact. No evaluations can be made until alternate locations for the plant are **determined**.

Locating a plant within or near the Scripps Institute of Oceanography to draw seawater **from** the La Jolla Canyon appears to be one site for consideration. **The** fresh water could be pumped to the fresh **water** discharge at the nearby waste water treatment plant in Sorrento Valley. The waste water reclamation facility is designed to produce potable water to be pumped to fresh water reservoirs.

8. THERMODYNAMICS AND SYSTEM ANALYSIS

8.1 **Thermodynamics** of **Clathrate** Formation

The formation of a clathrate essentially elevates the **freezing temperature** of water. **Clathrate formation temperatures** of 40 F. [4.4° C.] **or** higher are desirable for desalination processes to allow for both (1)

higher temperature seawater to form the clathrate crystals and (2) the relative ease of melting the clathrate to form **fresh** water. However, freezing **and** melting temperatures are not the only consideration. Not all clathrate **formers** that provide useful **clathrates** in the above temperature range meet other requirements for designing an economic desalination process.

The two clathrate **formers** evaluated in the main body of this report¹, HCFC **R141B** and carbon dioxide, have acceptable temperatures of clathrate formation and latent heat of **fusion**. The clathrate former HCFC **R141B** in seawater **forms** a clathrate ice at **47.5° F. [8.6° C.]** at or above atmospheric pressure with a latent heat of fusion of 137 BTU/pound [**319 joules/gram**]. Carbon dioxide forms a clathrate at **46.8° F. [8.2° C.]** at 595 pounds/square inch gage (**psig**) [**41.8 kg/cm²**] with a latent heat of fusion of 152 BTU/pound [**354 joules/gram**]. This compares with water-formed ice that freezes at **32° F. [0° C.]** with a latent heat of fusion of 144 BTU/pound [**335 joules/gram**].

To build a **desalination unit** where surface ocean water would be used to remove **the** latent heat of fusion of this clathrate ice would increase the cost significantly. In thinking about this problem, Richard A. **McCormack**, President of Thermal Energy Storage, **Inc. (TESI)** conceived **the** idea of **producing** the **clathrate** ice at depth in **the** ocean. He developed the concept of injecting the clathrate former at ocean **depth through use** of a concentric pipe **arrangement**. The clathrate former in the **inner** pipe would be **diffused** into the seawater flowing upward in the outer pipe at the **2,000 foot [610 m]** depth and form clathrate ice as it is pumped to the surface. Thus, both the HCFC **R141B** and the carbon dioxide would **form** clathrate ice at a 2,000 foot ocean depth where the temperature of the water is approximately 42° F. [**5.6° C.**] and the pressure is approximately 900 **psig [63.3 kg/cm²]**.

One major advantage of the injection of the clathrate former at the 2,000 foot depth is that the latent heat of fusion to form the clathrate can be rejected during the upward flow of the seawater **slurry** to the surface. The second major advantage is that larger crystals can be formed due to (1) **the** increased retention time by virtue of the length of the pipe and (2) heat removal over the **length** of pipe in which **clathrate** formation occurs. The amount of seawater required and the pumping power consumed to produce a **unit** of fresh water is thus greatly reduced.

For example, if the HCFC **R141B** clathrate is formed at the surface by pumping **42° F.** seawater through heat exchangers, the yield is one gallon/minute (**gpm**) [**0.063 liters/second**] of fresh water for 26 gpm [1.64

(1) The clathrate former HCFC R22 is **discussed** in Appendix A for potential use in higher temperature seawater.

liters/second] of seawater **coolant.**⁽²⁾ This provides a 3.8 percent yield for the clathrate desalination process by removing the latent heat of crystal formation by means of a conventional heat exchanger arrangement.

If the **clathrate** is formed as the clathrate **former** travels up the seawater pipeline it loses heat to **the** ocean. This **permits the** seawater flow to be regulated to a level consistent with requirements of the wash column, or approximately 25 percent solids concentration. This design requires 4 gpm [**0.252** liters/second] of seawater flow per one gpm [**0.063** liters/second] of **fresh** water product, thereby **increasing** the yield to 25 percent. **The required** seawater flow and pumping power have been reduced by a factor of six. This is a significant improvement over prior clathrate pilot plants built at Wrightsville Beach, North Carolina in **the** 1960 and 1970 decades. It comes from matching **desalination** technology with ocean engineering to produce a unique solution.

8.2 The Carbon Dioxide Clathrate

The design concept of injecting the clathrate former at **ocean** depth enables the designer to utilize **carbon** dioxide as the clathrate former if a means can be developed to inject the carbon dioxide at some point in

(2) **The** seawater cooling water flow, as a function of **fresh** water output is expressed in the following expression:

$$CW = LH * DC * FWTP / [(T1 - T2) * DCW]$$

where:

CW	=	Seawater Cooling Water Flow, gpm
LH	=	Latent Heat of Clathrate, BTU/pound
DC	=	Density of Clathrate, pounds/gallon
FWTP	=	Fresh Water Output, gpm
T1	=	Freeze Temperature of the Clathrate, °F
T2	=	Cooling Water Temperature, °F
DCW	=	Density of Cooling Water, pounds/gallon,

therefore, the seawater cooling flow for one gpm of product water is:

$$CW = 137 * 8.7 * 1 / (47.5 - 42) * 8.33 = 26 \text{ gpm}$$

the seawater pipeline at **normal** commercial pressures. The means of injection has not been developed as yet and currently prevents the continued promotion of **carbon** dioxide as a clathrate former. Even so, it is interesting to look at the **characteristics** of a carbon dioxide process to determine the advantages in seawater **desalination** it may hold.

The composition of the carbon dioxide clathrate former, with a Type I clathrate **structure**, is 7.3 moles of water per mole of clathrate former. Carbon dioxide forms a fresh water clathrate at **50° F. [10.0° C.]** at a **pressure** of 44.4 atmospheres equivalent to 653 psig [**45.9 kg/cm²**]. Salt water affects the carbon dioxide clathrate formation temperature as follows:

<u>Salinity NaCl)</u>	<u>Temperature Depression (°C)</u>	<u>Temperahue Depression (°F)</u>
2	0.99	1.78
4	2.03	3.65
6	3.13	5.63
8	4.32	7.78
10	5.60	10.08

The salinity of seawater at a 2,000 foot [**610 m**] depth off the coast of the **Island** of Hawaii is 3.4 percent and the water temperature is **42° F. [5.6° C.]**. **The** clathrate formation **temperature** at this salinity is 46.8° F. (8.2° C.). At this salinity and temperature, the carbon dioxide clathrate forms at a **pressure** of 40.3 atmospheres, or 592 psig [**41.6 kg/cm²**]. Thus the design operating conditions, allowing for a **4° F. [2.2° C.]** temperature differential in forming the clathrate, **will** be 42.8° F. [**6.0° C.**] **and** 610 psig [**42.9 kg/cm²**].

The molecular weight of the carbon dioxide **clathrate** is 175.4 and of carbon dioxide is 44. **This requires 2,200 pounds of carbon dioxide/1,000 gallons [264 kg/liter]** of fresh water produced. **This** is only about 57 percent of the amount required for HCFC **R141B**. The latent heat of the carbon dioxide clathrate is 152 BTU/pound [**354 joules/gram**] at **50° F. [10.0° C.]** which is also higher than HCFC **R141B**.

8.3 The HCFC **R141B** Clathrate

The composition of the HCFC **R141B clathrate** former, with a Type II clathrate **structure**, is 172 moles of water per mole of **clathrate** former. HCFC **R141B forms** a fresh water **clathrate** at **52.9° F. [11.6° C.]** at or above atmospheric **pressure**. In ocean water recovered **from** the 2000 foot level, this forming agent produces clathrate at **47.5° [8.6° C.]**. **Thus**, the **42° F.** seawater temperature at a 2,000 foot depth provides a **5.5° F. [3.1° C.] temperature** differential.

The molecular weight of the **clathrate** is 426.5 and of HCFC **R141B** is 116.9. This requires 3,043 pounds of HCFC **R141B** per 1,000 gallons [365 grams/liter] of fresh water produced. The latent heat of fusion of the HCFC **R141B** is 137 BTU/pound [319 joules/gram] slightly below that of water.

The HCFC **R141B** has an ozone depletion potential of 0.1 **1**, that means it is nine times less effective in depleting the ozone layer as CFC **R11** (dichlorodifluoromethane, **CCl₂F₂**), the common Freon refrigerant. With the discontinuance of production of CFC **R11** due to potential ozone depletion, HCFC **R141B** was approved for production as a replacement to CFC **R11** for use in the rigid foam insulation industry. HCFC **R141B** is now widely manufactured in various countries. Depending on results from continuing studies of the atmosphere and the need for a less-damaging replacement, the U.S. Environmental Protection Agency has approved the use of HCFC **R141B** through 2005. Whether **the** manufacture of HCFC **R141B** will be continued after 2005 is not known. All material manufactured by that date can continue to be used in existing facilities and systems. Other characteristics of HCFC **R141B** are shown in Table 8.1.

8.4 Crystal Formation and Growth

Tests performed by **TESI** have shown that **there** is virtual 100 percent clathrate formation when the clathrate former is mixed with an excess of water equal to **300** percent over stoichiometric **requirements**. **In a batch process, such as a thermal energy storage process, this factor increases the size of the storage vessels substantially.** In a **continuous** process, such as the proposed desalination process **utilizing** HCFC **R141B** as the clathrate former, its effect is to add to the pumping power and reduce the power required for recovery of the clathrate **former**. **This** is a desirable trade-off.

Increasing the size, or ‘growing’ the crystal, is desirable since the size of the wash column is determined by crystal size. This relationship was determined from tests conducted at the Wrightsville Beach Test Facility. **TESI** has learned to grow **clathrate** crystals during their formation stage to much larger sizes than those developed at Wrightsville Beach. Several factors **are** involved **in** this process, **including** increased retention **time** at **formation** temperature, **minimized** supercooling, adequate rate of heat removal, and **appropriate** nucleation.

8.5 Crystal Washing

Work by the Office of Saline Water (**OSW**) and the Office of Water Research and Technology (**OWRT**) **has demonstrated that a key element in washing a clathrate crystal was crystal size itself.** The size of the clathrate former molecule is 5 angstroms. Ideal crystal size is in excess of **400,000** angstroms or, since there are 1000 angstroms in a micron **400** microns. Work performed at Wrightsville Beach suffered from small crystal size on the order of 40 microns, or one-tenth the desired **size**. Small crystal **size fosters high**

TABLE 8.1
COMPARISON OF IMPORTANT PROPERTIES OF HCFC **R141B** AND WATER

		<u>HCFC R141B</u>	<u>Water</u>
Molecular Formula		CCl₂FCH₃	H₂O
Molecular Weight		116.9	18
Ozone Depletion Potential		0.11	0
Freezing Point of ice	°F.	52.9	32.0
Adjusted Freezing Point of ice	°F.	47.5	32.0
Boiling Point	°F.	89.6	212.0
Density	Pounds/foot³	76.9	62.4
Density	Pounds/gallon	10.3	8.3
Energy Density of Ice	BTU/pound	137.0	144.0
Energy Density of Ice	BTU/foot³	9,305	8216

interstitial water quantities and low yields while large crystals foster high yields approaching 100 percent for the desalination process. Larger crystal size is **important** in the **thermal** energy storage process as well, TESI has successfully grown crystals in its **Clathrate** Test Facility well in excess of 400 microns.

When the **clathrate** is **formed** at 2,000 foot [610 m] ocean depth, the upward flow of the clathrate crystal in the seawater slurry **will** provide a high degree of washing of the salt from the crystal from the fluid effects of the brine and from the tumbling of the crystals against each other. Thus, the crystals should not be difficult to wash in the wash column with the benefit of pre-washing in the pipeline and large **crystal** size.

8.6 Crystal Melting

The clathrate ice is **first** separated **from** the brine and then melted. The same **amount** of heat is involved in melting the crystal in the crystal melter as in the formation of the crystal at ocean depth. This **low**-grade heat, at a temperature at approximately **55° F. [12.8° C.]**, can be supplied by surface ocean water, by solar heat, or by removing heat from refrigerant lines **from** air conditioning systems. A solar heat generator **proved** to be lower in cost compared to **the** large amount of seawater that would have to be used. **The** cost of using the latent heat of fusion for providing air conditioning to local buildings **and** facilities would depend on the need and layout of these facilities at the **desalination plant** location.

87 Fresh Water Separation

After the crystal is melted, it is necessary to remove the **clathrate former** for recycle and to meet potable water **standards** for the fresh **water**. **Separating the** fresh water from the HCFC **R141B** will be accomplished in a decanter. The density of HCFC **R141B** is greater than **that** of water, 10.3 pounds/gallon [1.23 kg/liter] and 8.33 pounds/gallon [1.00 kg/liter] respectively. If desired to speed the process and/or to reduce the size of the **decanter**, a **centrifuge** can be **added**.

8.8 Fresh Water Recovery

The **fresh** water leaving the decanter is expected to have a small residual **concentration** of 350 parts per million (**ppm**) of HCFC **R141B**. The air **strippers** are designed to remove 99.7 percent of the HCFC **R141B** thus leaving the **fresh** water with a **concentration** level of 1 ppm of HCFC **R141B**. The water is then **routed** to liquid-phase carbon **adsorbers** where the HCFC **R141B** will **be** adsorbed onto the carbon particles. The result is essentially zero **concentration** of HCFC **R141B** in the fresh water. A HCFC **R141B** concentration of less **than** one ppm is thought to meet potable water **standards**, but this was not as yet **confirmed** with the U.S. Environmental **Protection** Agency at the time of report publication. If the potable water requires that HCFC **R141B** requires **concentrations** of just a few parts per **billion**, the **fresh**

water can be pumped through a deaerator. As the water is pumped to reservoirs for storage, **further** dilution, evaporation, and decomposition will occur.

8.9 HCFC **R141B** Recovery

Recovery of the HCFC **R141B** is important to the economics of the de&nation system. **The** air strippers and vapor-phase carbon **adsorbers** are designed to recover 99.9997 weight percent of the HCFC **R141B**, resulting in a loss of approximately 3.6 gallons/day [13.6 liters/day] for the 3.6 million gallons/day [13600 **m³/day**] facility. This is equivalent to 0.001 **gallons/1,000 gallons [0.001 liter/m³]**. Sii HCFC **R141B** costs approximately \$10.50 per gallon [\$2.77 per liter], the cost of makeup requirements are **approximately \$0.01/1,000 gallons [\$0.003/m³]** of fresh water. Even if the cost of HCFC **R141B** makeup were ten times that amount, the cost of water would remain economic.

The recovered HCFC **R141B** is recycled and **reinjecte**d into the ocean pipeline to form new clathrate ice.

9. PROCESS DESIGN AND EQUIPMENT

9.1 Process Design and Description

The process design is identical for both the demonstration plant and the commercial size plant except for **the** size or capacity of equipment to be used. **The** process design is described for the 3.6 million gallons/day **commercial** size plant with comments on equipment differences for the demonstration plant. The 7.2 million gallons/day [**27300 m³/day**] plant would have a second deep sea **pipeline** and a duplicate process line. The process consists of the following functions:

- o Formation of the clathrate ice at an ocean depth of 2,000 feet [**610 m**];
- o Separation of ice **crystals** and brine **water**;
- o Melting of the ice crystals and **separation** of **fresh** water **from** the clathrate **former**;
- o Removal and recovery of clathrate former from the **fresh water**;
- o **Polishing of the fresh** water and storage;
- o **Discharge** of **the** brine.

Each of these process functions are described in the following sections with a process flow diagram shown in Drawing PF-1 and a performance summary in Table 9.1. Heat and mass balance diagrams for both the 3.6 million gallons/day [13600 **m³/day**] commercial plant and the demonstration plant are presented in Table 9.2 and Table 9.3, respectively. Also, included in this Section 9 is a discussion of fresh water quality, technological risks in the process, and alternate process **designs** that could be substituted if the demonstration plant shows a need.

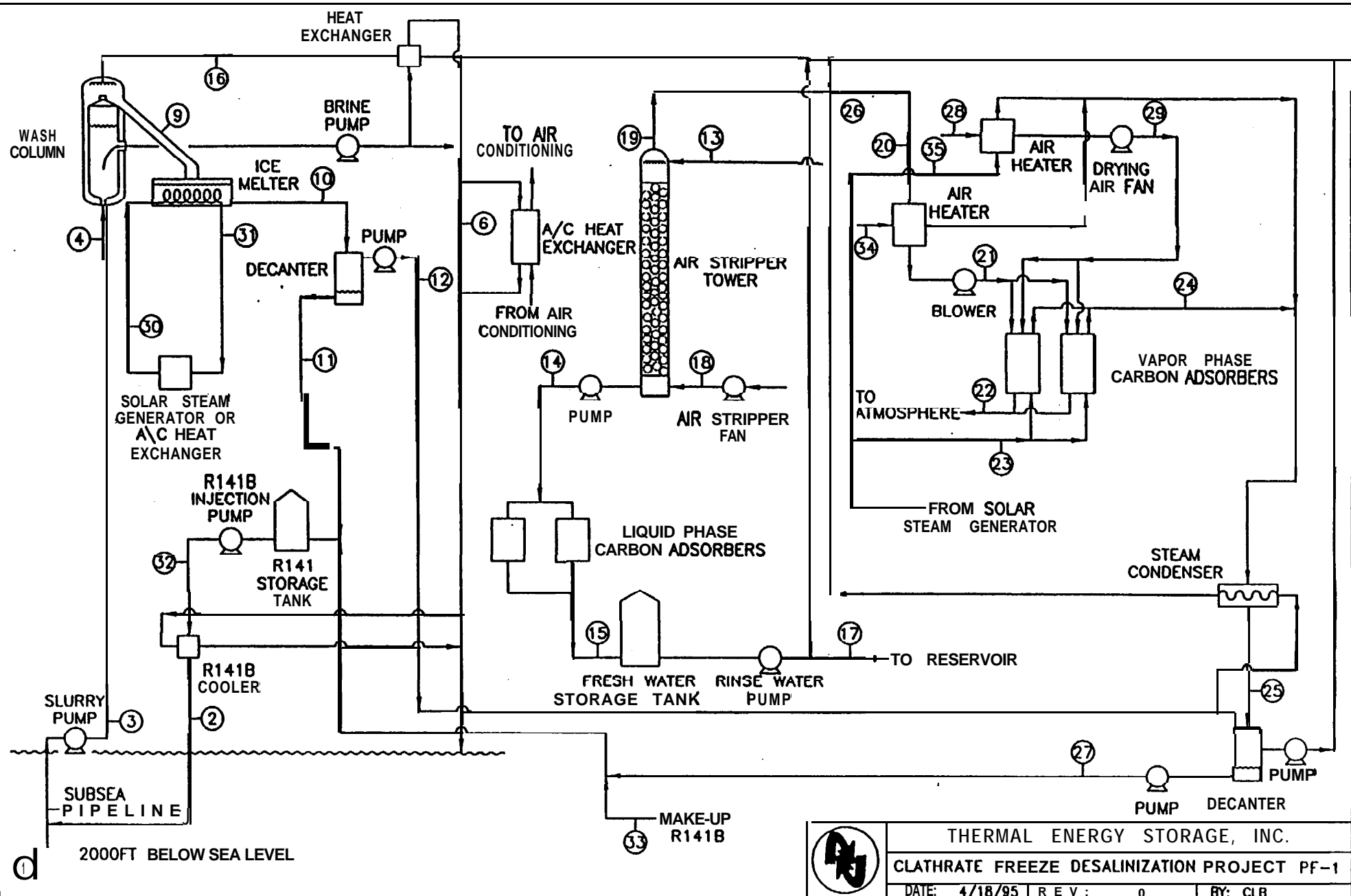
9.2 Formation of the Clathrate Ice

For a commercial plant, a **48-inch** [122 cm] diameter polyethylene pipeline would extend into the sea and down to a depth of approximately 2,000 feet [**610 m**] to withdraw pristine water at a temperature of approximately **42° F. [5.6° C.]**. Malcai Ocean Engineering, Inc. (Makai) has installed similar pipelines with high success at the Natural Energy Laboratory of Hawaii (**NELH**) on the Big Island of Hawaii, the largest being a **40-inch** [102 cm] pipeline now in use for a variety of research projects. Plans are *currently* underway to install a 55 inch [**140 cm**] pipeline for an Ocean Thermal Energy Conversion project As shown in Figures 6.2 and 6.3 in Section 6, Malcai floats these pipelines off shore and then submerges and anchors them at depth. Makai is confident that it could install a **48-inch** pipeline off the coast of California or other locations without difficulty.

The pipeline has a large diameter to **minimize** the flow pressure drop to approximately 15 feet [**4.57 m**] of hydraulic head. The cold water at 2,000 feet is heavier than surface water and that adds another 2 or 3 feet [**0.61 to 0.91 m**] of hydraulic head. Since a pump can only lift an equivalent of 34 feet [**10.4 m**] of water, this provides a factor of hvo margin.

The **48-inch** pipeline would contain a smaller (up to **6-inch [15.3 cm]**) diameter concentric pipe to inject the **clathrate** former HCFC **R141B** into the cold seawater in the larger pipe at a depth of **2,000** feet. The HCFC **R141B forms** clathrate ice at **47.5° F. [8.6° C.]**. The ice **crystals** that form consist of 17 parts of pure water to one part of HCFC **R141B**. The dissolved solids precipitate from the water as the ice crystals form. The salinity of the surrounding water increases as a result of the increased solids available. Since the seawater is **5.5° F. [3.1° C.]** colder than that required for ice to **form**, some heating of the water and clathrate ice is permissible during travel to the surface and to the ice-brine separation facilities.

The lower sections of the pipeline has a thinner wall section to dissipate the heat of fusion as the ice forms. The water surrounding the ice crystals first absorbs the heat of fusion and begins to increase in temperature. Even though polyethylene provides some insulation, the colder water on the outside of the thinner wall absorbs this heat from the ice **slurry** to achieve temperature equilibrium. The ice **slurry** consists of 25 percent by weight ice crystals that grow to approximately 400 microns in diameter as the flow moves upward in the pipe. The other 75 percent is brine water of increased **salinity**.



THERMAL ENERGY STORAGE, INC.
 CLATHRATE FREEZE DESALINIZATION PROJECT PF-1
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TABLE 9.1
PERFORMANCE **SUMMARY**

	<u>Demonstration Plant</u>	<u>Commercial Plant</u>
Brine water-ice slurry flow - gpm	139.6	13960
Brine water flow - gpm	104.7	10,470
Ice flow (fresh water & chthrate) - gpm	34.9	3,490
Fresh water flow - gpm	27.5	2,750
HCFC R141B flow - gpm	7.4	740
Ice crystals - percent	25	25
Density of ice crystals - pounds per gallon	8.76	8.76
Heat of fusion - million BTU per hour	2.5	251
Waste brine flow from wash column - gpm	107.2	10,720
Fresh water produced - gpm	25.0	2,500
Recovered HCFC R141B - gpm	7.4	740
Initial concentration of HCFC R141B in brine water - ppm	0	0
Final concentration of HCFC R141B in brine water - gpm	0	0
HCFC R141B lost in brine water	0	0
HCFC R141B recovery from brine water - percent	100.0	100.0
Initial concentration of HCFC R141B in fresh water - ppm	350.0	350.0
HCFC R141B in fresh water to carbon filter - ppm	1.0	1.0
HCFC R141B lost in fresh water - gallons per day	0.032	3.21
HCFC R141B recovery from fresh water - percent	99.7	99.7
Total HCFC R141B lost - gallons per day	0.032	3.21
Total HCFC R141B recovery - percent	99.9997	99.9997
Physical properties of HCFC R141B		
Molecular weight	116.95	
Specific gravity at 70° F.	1.24	
Liquid density at 77° F. - pounds per gallon	10.28	
Nonnal boiling point - degrees F.	89.7	
Vapor pressure at 77° F. - psia	11.46	
Vapor pressure at 50° F. - psia	6.51	

TABLE 9.2 HEAT AND MASS BALANCE - Commercial Plant

Stream no. Fluid		1 Sea water supply	2 R141B injection	3 Brine/ice slurry at surface	4 Brine/ice slurry to wash col	5	6 Waste brine water to ocean	7	8
Flow rate	gpm	13,220	740	13,960	13,960		10,720		
Temperature	F	42	45	43	44		45		
Pressure	psia	860	100	40	20		20		
Enthalpy	btu/lb								
Conc R141B	ppm	0		64,543	64,543		0		
Conc R141B	lb/hr	0	456,432	456,432	456,432		0		
Line size	inch dia		6"	24" x .738"	24" x .738"		24-x.736"		
Line material		Poly	poly	Poly	Poly		Pol y		
Stream no. Fluid		9 Ice to ice melter	10 Freshwater & R141B to decanter	11 R141B to storage tank	12 Freshwater to steam condenser	13 Fresh water 8 cond to air stripper	14 Water to carbon adsorber	15 Fresh water to storage tank	16 Rinse water to wash col
Flow rate	gpm	3,490	3,490	739.22	2,750	2,756	2,756	2,756	250
Temperature	F	45	50	50	50	60	60	60	45
Pressure	psia	15	20		50	40	30		25
Enthalpy	btu/lb								
Conc R141B	ppm	249,072	249,072		350	353	1	0	0
Conc R141b	lb/hr	456,432	456,432	455,950	482	487.0	1.38	0	0
Line size	inch dia			6"	14"	14"	14"	14"	4"
Line material		Poty	Poly	Poly	Poly	Poly	Poly	Poly	Poly
Stream no. Fluid		17 Fresh water to water sales	18 Amb air to air stripper	19 Air/R141B from air stripper	20 Air/R141B to heater	21 Air/R141B to carbon adsorber	22 Air from carbon adsorber	23 LP steam to carbon adsorber	24 Steam/R141B cond to condenser
Flow rate	gpm	2,506	24,000 cfm	24,000 cfm	24,000 cfm	24,000 cfm	24,000 cfm	3000 pph	6.97
Temperature	F		60	50	60	80	80	250	220
Pressure	psia							30	20
Enthalpy	btu/lb							1164	1131
Conc R141B	ppm	0		4477	4,477	4477	0		139,330.
Conc R141b	lb/hr	0		485.7	485.7	485.7	0		485.7
Line size	Inch dia	14"							
Line material								C. stl	

TABLE 9.2 HEAT AND MASS BALANCE - Commercial Plant Continued

Stream no.		25	26	27	28	29	30	31	32
Fluid		Steam cond/ R141B to decanter	Steam cond to air stripper	R141B from decanter	Drying air intake	Drying air to carbon adsorber 24,000 cfm	Steam to ice melter 450	Condensate return to Solar heater 450	R141B to cooler 740
Flow rate	gpm	6.97	6.0	0.78	24.000 cfm	140	250	38	70
Temperature	F	70	70	70	60	14.7	30	38	1000
Pressure	psia						1164		
Enthalpy	btu/lb	38							
Conc R141B	ppm	139,330	1800						
Conc R141B	lb/hr	485.7	5.40	480.3					
Line size	inches dia								6" sch 40
Line material			Poly	Poly					C.stl
Stream no.		33	34	35					
Fluid		R141B Makeup	Steam to process air heater 500 pph	Steam to carbon air dryer 1000 pph					
Flow rate	gpm	0.002	250	250					
Temperature	F	60	30	30					
Pressure	psia		1164	1164					
Enthalpy	btu/lb								
Conc R141B	ppm								
Conc R141B	lb/hr	1.36							
Line s&e	inches dia								
Line material		Poly	c. stl	C.stl					

TABLE 9.3 HEAT AND MASS BALANCE • Demonstration Plant

Stream no.		1	2	3	4	5	8	7	8
Fluid		Sea water supply	R141B injection	Brine/ice slurry at surface	Brine/ice slurry to wash col		Waste brine water lo ocean		
Flow rate	gpm	132.2	7.4	139.6	139.6		107.2		
Temperature	F	42	45	43	44		45		
Pressure	psia	880	100	30	20		20		
Enthalpy	btu/lb								
Conc R141B	ppm wt	0		64,543	64,543		0		
Conc R141B	lb/hr	0	4564.32	4564.32	4564.32		0		
Line size	inch dia		3/4"	3" x 0.318"	3"		3"		
Line material		Poly	poly	Poly	Poly		Poly		
Stream no.		9	10	11	12	13	14	15	16
Fluid		Ice lo Ice melter	Fresh water & R141B to decanter	R141B to storage tank	Fresh water to steam condenser	Fresh water & cond to air stripper	Fresh water to carbon adsorber	Fresh water to storage tank	Rinse water to wash cot
Flow rate	gpm	34.9	34.9	7.39	27.5	27.6	27.6	27.8	2.5
Temperature	F	45	50	50	50	60	60	60	45
Pressure	psia	14.7	20		50	40	35		25
Enthalpy	btu/lb								
Conc R141B	ppm wt	249,072	249,072		350	353	1	0'	0
Conc R141B	lb/hr	4,564.32	4564.32	4,559.50	4.82	4.87	0.01	0	0
Line size	inch dia		1.5"	1'	1.5"	1.5"	1.5"	1.5"	0.5"
Line material		Poly	Poly	Poly	Poly	Poly	Poly	Poly	Poly
Stream no.		17	18	19	20	21	22	23	24
Fluid		Fresh water to water sales	Amb air to air stripper	Air/R141B from air stripper	Air/R141B to heater	Air/R141B to carbon adsorber	Air from carbon adsorber	LP steam to carbon adsorber	Steam/R141B cond to condenser
Flow rate	gpm	25.1	250 cfm	250 cfm	259 cfm	250 cfm	250 cfm	30 pph	0.07
Temperature	F		60	50	60	80	80	250	220
Pressure	psia								20
Enthalpy	btu/lb							1 %	1131
Conc R141B	ppm wt	0		4298	4,298	4298	0		139,330
Conc R141B	lb/hr	0		4.88	4.86	4.86	0		4.86
Line size	Inch dia								0.25'
Line material								C. stl	Poly

TABLE 9.3 HEAT AND MASS BALANCE • Demonstration Plant Cont

Stream no. Fluid		25 Steam cond/ R141B to decanter	26 Steam cond to air stripper	27 R141B from decanter	28 Drying air intake	29 Drying air to carbon adsorber	30 Hot water to ice melter	31 Cold water return to Solar heater	32 R141B to cooler
Flow rate	gpm	0.07	0.06	0.01			35	35	7.4
Temperature	F	70	70	70	250 cfm	250.4 cfm	210	70	70
Pressure	psia				14.7		30	20	1000
Enthalpy	btu/lb	38							
Conc R141B	ppm wt	139,330	1000						
Conc R141B	lb/hr	4.06	0.05	4.80					
Line size	Inches dia		0.25"	0.25"			2"	2"	
Line material			Poly	Poly			c. stl	c. su	
Stream no. Fluid		33 R141B Makeup	34 Steam to process air heater	35 Steam to carbon air dryer					
Flow rate	gpm	0.0000	20 pph	20 pph					
Temperature	F	60	250	250					
Pressure	psia		30	30					
Enthalpy	btu/lb		1164	1164					
Conc R141B	ppm wt								
Conc R141B	lb/hr	0.014							
Line size	Inches dia								
Line material									

At a proper depth, the thickness of the polyethylene pipe is increased significantly to provide thermal insulation to prevent the warmer seawater near the surface from melting the ice. The temperature gain **as the slurry flows to the surface is expected to be less than 3° F. [1.7° C.]**. The temperature of the ice **slurry** is expected to be no **more** than **45° F. [7.2° C.]** when it reaches the surface and, thus, **2.5° F. [1.4° C.]** below the melting point of the ice crystals. This provides an adequate margin to insure the ice crystals do not begin to melt before they are separated from the brine in the wash column

At the surface, the **48-inch pipeline⁽¹⁾** (1) discharges into an intake structure at the shore. A slurry pump transports the **slurry** through a 24 inch **[61.0 cm]** polyethylene pipeline (3 and 4) to a wash column, as pictured in Figure 6.4 of Section 6.

In the demonstration plant, it is planned to avoid the cost of laying a pipeline by using an existing pipeline at the **NELH** facility. The lowest cost alternate, on which the cost estimate is based, is to insert 3 inch **[7.6 cm]** diameter and 0.75 inch **[1.90 cm]** diameter concentric pipes into an existing **40-inch [102 cm]** pipeline currently in use to permit the injection of HCFC **R141B** at **the** 2,000 foot **[610 m]** depth.

In discussions with Mr. Thomas Daniel, **Scientific/Technical** Director of NELH, he suggested this approach **since** the **concentric** pipe could be inserted with no **obstructions** from a sump tank at the surface. The concentric pipe would extend beyond the end of the **40-inch** pipe to ensure no **possibility** of **contamination** of the pristine water being withdrawn by the larger pipe for other uses. Other possibilities are to use other pipelines not in use but additional pump installation costs would be involved.

93 Separation of Ice **Crystals from** Brine

The ice **slurry** discharges **from** the transport pipeline (3 and 4) and enters the bottom of a wash column. The wash column is a vertical cylindrical tank with screened openings around its circumference approximately at mid-height. An ice scraper and ice paddle are located at the top. The tank is internally lined with polyethylene to minimize ice adhering to the walls.

As the ice **slurry** rises in the wash column the ice crystals consolidate into a bed. This bed continuously moves upward to the top of the wash column as a porous mass. The brine water moving up **from** below the ice bed continuously deposits ice crystals to the bottom of the bed and the hydraulic **pressure** causes

(1) **Pipelines are numbered on the process flow drawing PF-1 and referenced in the text to aid in** following the process description. These pipe numbers also refer to **the** heat and mass balances tabulated in Table 9.2 and Table 9.3.

the ice bed to float upward. At mid-point in the column, the brine water flows out of the wash column through the screened openings along **the** circumference of the column

In the upper half of the wash column, the ice bed is sprayed (16) with a portion of the fresh water product to rinse any remaining film of brine water from the ice. This fresh rinse water trickles down through the ice mass and exits with the brine water at mid-height of **the** wash column. Most of the **rinse** water is lost with the brine water, but some flows out with the ice.

At the top of the wash column a rotary ice scraper shaves 0.125 to 0.25 inch [**0.318** to 0.635 cm] thick slices of the clean ice from the ice mass. A paddle pushes the shaved ice to a chute (9) where the ice drops into an ice melter.

9.4 Ice Melting and Separation of Fresh Water and HCFC R141B

The ice crystals fall by gravity into the ice melter for conversion to a liquid. The ice melter is a water bath with an array of heating coils. A solar steam generator provides hot water and steam for circulation (30 and 31) through the heating coils to melt the ice. **Some** heat may also be removed from the refrigerant in **the** return lines from air conditioning systems in local buildings and facilities.

The melted ice water and liquid HCFC **R141B** flow (10) to a decanter for gravity **separation**. **The** HCFC **R141B** is heavier than water and thus sinks to **the** bottom of the decanter. The decanter is designed to provide a residence time of **three** hours. The fresh water at the top of **the decanter** is then pumped (12 and 13) to an air stripper for recovery of any dissolved HCFC **R141B**. The HCFC **R141B** from the bottom of the decanter is pumped (11) to a storage tank **prior** to pumping (32 and 2) down to **the** 2,000 foot [**610** m] depth for reuse in new clathrate ice formation.

9.5 Removal and Recovery of HCFC R141B from the Fresh Water

The cold fresh water from the decanter is pumped (12) to a steam condenser (described in Section 9.8) where it is preheated prior to entering (13) the fresh water air stripper to remove the **remaining** dissolved HCFC **R141B**. **Preheating** the water **enhances** the removal of **the** HCFC **R141B**. The **concentration** of the dissolved HCFC **R141B** is expected to be approximately 350 parts per million (**ppm**) as it enters the airstripper. **The air stripper is a tall cylindrical fiberglass tower that contains a deep bed of packing**. The fresh water flows down through the **packing** while air flows up through **the** packing, carrying with it vapors that evaporate from the fresh water.

At the top of the tower are a number of spray nozzles that evenly distribute the fresh water over the cross section of the tower. **The** fresh water trickles down through the packing that consist of 1.5 inch [**3.81** cm]

diameter **polypropylene** balls. The fresh water flows around these balls forming a thin water film that greatly increases the water surface area exposed to **the** air. Ambient air is delivered (18) to **the** bottom of the tower by an air stripper fan and flows up through the packing. The air becomes more and more **saturated** with volatile vapors as it rises through the column packing. Vaporization of the HCFC **R141B** is assisted by the increased water surface **area** of the packing and warmth of the air.

HCFC **R141B** has a low boiling point of **90° F. [32.2° C.]** and a low solubility in water and hence is easy to **remove** from the water. **The** air stripper is designed to remove 99.7 percent of **the** HCFC **R141B**. Based on an inlet concentration of 350 ppm HCFC **R141B**, the outlet concentration is only one **ppm**.

9.6 Polishing of the Fresh Water and Storage

The fresh water draining from the bottom of the fresh water air stripper with a residual one ppm concentration of HCFC **R141B** may **require** further processing to meet state and federal potable water **standards**. If so, **the** water will be pumped (14) to a set of liquid-phase carbon adsorbers for removal of the remaining HCFC **R141B**. As the water entering the **liquid-phase** carbon **adsorbers** passes through a bed of carbon particles, the HCFC **R141B** is **adsorbed onto** the carbon particles. The fresh water that **exhausts through the** bottom of the carbon bed will have essentially a zero **concentration** of any **residual** HCFC **R141B** and will thus meet potable water **standards**.

The minute amounts of HCFC **R141B** collected in the carbon adsorbers is not **recovered** since the regeneration of liquid-phase **carbon adsorbers** is not efficient. There are two **carbon** adsorbers in parallel, **with one unit in service at all times and the other unit maintained in a standby mode**. **When a carbon unit in service** becomes saturated with HCFC **R141B**, that carbon is replaced **with fresh carbon** and **the** saturated carbon it is sent off-site for reactivation. During reactivation the **carbon** is heated to a **high** temperature in a kiln. The HCFC **R141B** is driven off as a vapor and not recovered.

The time duration between replacement of the carbon adsorbers is **approximately** two to four weeks for a commercial size **plant**. **The time duration between** carbon replacements is **dependent** upon the water **throughput**, the inlet **concentration** of HCFC **R141B**, and the amount of **carbon** in the adsorber unit. **The size and cost of the carbon adsorbers is optimized against the frequency of carbon replacement**.

The fresh water then flows (15) to a tank for **temporary** storage. Approximately 10 percent of **the fresh water is pumped (16) to the wash column for rinsing the brine water from the ice, as described in Section 9.3**. **The** remaining net output of fresh water is then pumped (17) to a local **reservoir** or aqueduct for use in municipal water systems..

9.7 Desalinated Water Quality

The fresh water produced will be of exceptionally high quality. The total dissolved solids in **the water** is expected to be less than 100 ppm, which is low for typical potable water. The total dissolved solids in the water will depend on the effectiveness of the rinse water in washing the ice crystals in the wash column. The size, shape, **and** strum of the ice **crystals** will have a strong influence on the effectiveness of the ice wash process in the wash column. If the total dissolved solids are exceptionally low, the quantity of rinse water used in the wash column can be reduced to increase the output of fresh water from the plant.

9.8 Recovery of the Residual HCFC **R141B** from the Fresh Water

Due to the cost of the HCFC **R141B**, it is economical to recover this material for reuse. The recovered HCFC **R141B** is **reinjecte**d (2) in combination with a small quantity of makeup HCFC **R141B** (33) into the seawater at the 2,000 foot [610 m] depth to form new clathrate ice.

Continuing **from** Section 9.5, the air exiting (19) the top of the air stripper **containing** the HCFC **R141B** vapors is at 100 percent relative humidity since some water evaporates along with the HCFC **R141B**. The air must be reduced to approximately 50 percent relative humidity before entering a vapor-phase carbon adsorber. The carbon in the **adsorbers** acts as a desiccant and has difficulty adsorbing the volatile **organics** at high humidities.

The air from the air stripper is first passed (19) through an air heater to heat the air to approximately 80° F. [26.7° C.] and to decrease the humidity to approximately 50 percent. Low pressure steam from the solar generator (used to melt the clathrate ice in the ice melter) is also routed (34) to the air heater. As the warm air passes through the vapor-phase carbon adsorbers, the HCFC **R141B** vapors adsorb onto the carbon particles. The carbon adsorbers have an HCFC **R141B** removal efficiency of 99 percent. The air exhausts (22) through **the** bottom of the carbon bed essentially void of any residual HCFC **R141B**.

The carbon adsorbers come in parallel sets of two, with one unit in service at all times and the other unit maintained in a fully regenerated standby mode. When the unit in service becomes **saturated** with HCFC **R141B**, it is replaced with the fresh unit. Vapor-phase carbon adsorbers, unlike liquid-phase carbon adsorbers, can be regenerated with steam. The **saturated** unit is **regenerat**ed by passing (23) low pressure steam, 15 pounds/square **inch gage [1.1 kg/cm²], saturated**, through the carbon bed in reverse flow. As the **hot** steam flows through the carbon bed, the HCFC **R141B** vaporizes and is carried (24) with the steam to a condenser. Subsequently, ambient air is drawn (28) through an air heater by a drying air fan to dry the regenerated carbon unit.

The steam flowing (34 and 35) to the two air heaters is also recovered and sent to the condenser. In the condenser the steam and HCFC **R141B** are condensed and cooled to approximately **70° F. [21.1° C.]** by the cold water circulating (12 and 13) in the tubes. The cold water is the **fresh** water recovered **from** the decanter described in Section 9.5.

The steam condensate and the liquid HCFC **R141B** flow (25) to a decanter for gravity **separation**. The recovered HCFC **R141B** is pumped (27) to the HCFC **R141B** storage **tank**. The steam condensate **that** contains dissolved HCFC **R141B** is pumped (26) to the air stripper for further processing.

93 Disposal of the Brine Water

- . It is not considered necessary to remove the HCFC **R141B** from the brine water due to insignificant **amount of HCFC R141B remaining in the brine at the time it is discharged (6) to the sea**. Tests at the **Clathrate** Test Facility at Thermal Energy Storage, Inc. (**TESI**) have shown that 300 percent excess water over stoichiometric requirements results in 100 percent clathrate formation. The process is designed so that all HCFC **R141B** injected will form clathrate ice. Also the process is designed to bring the clathrate ice to the wash column at a temperature of **45° F. [7.2° C.]** which is **2.5° F. [1.4° C.]** below its melting **temperature so that the ice will not melt until after the brine water is separated in the wash column**.

If the demonstration plant proves that more than minute quantities of HCFC **R141B** remain dissolved in the brine water, this water can be routed to an air stripper (not shown on Drawing PF-1). The brine water air stripper performs like **the** fresh water air stripper except that it is physically larger to accommodate the larger water throughput. The air stripper is designed to remove 98 percent of the HCFC **R141B**. This air would be combined with the air from the fresh water air stripper and routed (19 and 21) to **the** air heater and vapor-phase carbon **adsorbers** for recovery.

-Based on an inlet concentration of 350 ppm of HCFC **R141B**, the outlet concentration from the brine water air stripper would be 7 ppm. The brine water air stripper could be designed to remove 99.9 percent of the HCFC **R141B**, but this would require a larger tower and may not be economical. The brine water **would flow through the drain at the bottom of the tower and by gravity back to the ocean**. This minute amount of HCFC **R141B** in the brine water does not impose an environmental problem since HCFC **R141B** is not a hazardous material. Any minute amounts of HCFC **R141B** will continue to evaporate in the ocean.

9.10 Technological Risks

Makai and the NELH have extensive experience pumping cold seawater to the surface **from** depths over 2,100 feet [**640 m**] through pipelines from 12 to **40 inches [30.5 to 102 cm]** in diameter. A new 55 inch

[140 cm] diameter, 10,000 foot [3050 m] long, pipeline is being planned to deliver 27,000 gallons/minute [1700 liters/second] of cold water from a depth of 3,000 feet [914 m] to the surface at a temperature of 40.5° F. [4.7° C.]. The pipeline is **constructed** of thick wall polyethylene with no additional thermal insulation. The temperature gain of the water on its rise to the surface is expected to be a fraction of 1° F. [0.6° C.]. Advancements in pipeline design and polyethylene materials **are** permitting consideration of pipeline diameters of 63 inches [160 cm]. From this successful effort since 1979, Makai is confident that it can lay the 48 inch [122 cm] pipelines proposed in this feasibility study.

Previous experimental research indicates that **clathrate** ice crystals larger than 200 microns **are** difficult to attain. Larger crystals up to 400 microns have been grown in the **Clathrate** Test Facility of **TESI** and this size crystal is proposed in the design of **the** commercial **desalination** plant. The principal conditions **required** to **grow** 400 micron crystals are an increased retention time at formation temperature, adequate rate of heat removal, minimized supercooling, and appropriate nucleation.

The undersea pipeline will be designed to provide for adequate retention time and heat removal. Growing crystals of this size is expected to be achieved through the long residence time as the ice crystals flow to the surface through the deep sea pipe. The salt water will also cause immediate nucleation and minimum supercooling, thereby avoiding the use of other nucleating agents. The demonstration plant will prove the feasibility of growing 400 **micron** crystals in the pipeline. Somewhat smaller crystals are acceptable since the crystals **will** be scrubbed as they rise to the surface. At worst, somewhat smaller crystals may require more fresh water in the wash column and thus reduce the net production of fresh water.

One major problem that arose at the **Wrightsville** Beach Test Facility was the large quantities of **fresh** water **required** to wash the clathrate ice **free** of **salt**. The fact that the ice crystals will be approximately 10 times larger than those at Wrightsville Beach and will be scrubbed **free** of salt as they tumble through the seawater line gives **TESI confidence** that the amount of fresh water **required** to wash the crystals will not exceed 10 percent of the **fresh** water produced. One of the important results expected in the demonstration tests is to show that approximately 10 percent of the **fresh** water is adequate to wash the **crystals**.

The technology for recovering compounds such as HCFC **R141B** from water has been well **demonstrated** by the environmental industry. Air strippers with vapor-phase carbon **adsorbers** are used extensively for wastewater and groundwater cleanup. **There are a number of these systems being used by the Environmental Protection Agency** at Super Fund sites with sizes comparable to that **required** for a commercial size **desalination** plant. Liquid-phase carbon **adsorbers** for removal of trace quantities of HCFC **R141B** are not as well developed and may require further **testing**.

9.11 Other HCFC R141B Recovery Technology

Steam strippers were evaluated as an alternative technique for recovering the HCFC R141B from the fresh water and the brine. Steam strippers are used primarily in the petrochemical industry for distillation and removing compounds with high boiling points and high solubilities since they provide a high recovery efficiency. In a steam stripper, water flows down through a deep bed of packing installed in a tall column with steam flowing upward from the bottom. The water is heated to near its boiling point in the process. The steam and stripped volatiles exit at the top and flow to a condenser.

The water in a steam stripper would not be required to reach as high a temperature in the desalination plant since the HCFC R141B has a 90° F. [32.2° C.] boiling point and a low solubility in water. Even so, the process is energy intensive. A steam generator would be required for operation on a continuous basis. In addition scaling, fouling, and corrosion would present a problem with steam strippers.

Vacuum distillation towers were also evaluated on their capability to remove HCFC R141B from the fresh water and the brine, but vacuum distillation should prove unnecessary. A vacuum distillation system consists of a tall tower with a deep bed of packing. A vacuum pump or steam jet air ejector is used to develop a vacuum at the top of the tower to lower the vapor pressure and thus lower the boiling temperature of the liquids flowing down the column.

The vapor pressure of the HCFC R141B at the temperature of the water entering the tower, between 40 and 50° F. [4.4 and 10.0° C.], is quite low. Thus a high vacuum would be required combined with heating of the water to achieve significant improvement in recovery efficiency. Due to the low boiling temperature and low solubility of HCFC R141B, it is believed that vacuum distillation would not be beneficial.

Both of these alternate technologies are available, but both involve more expensive equipment and higher operating costs compared to air strippers. The air strippers and carbon adsorbers reduce the HCFC R141B concentration to essentially zero ppm and that is considered adequate.

10. CAPITAL COST ESTIMATES

10.1 Summary of Capital Costs for Demonstration and Commercial Plants

The total project costs for the demonstration plant and the two commercial plants are summarized below and described by cost items in the discussion below:

- o **Demonstration** plant at Natural Energy Laboratory of Hawaii (**NELH**) to produce 36,000 **gallons/day** [**136 m³/day**] or 40 **acre-feet/year** [**49300 m³/year**] if operated continuously: \$ 1.505 million
- o Demonstration plant at San Clemente Island or Scripps **Institute** of Oceanography of same size, dependent on cost of laying deep sea pipeline: \$2.7 to 3.5 million
- o Commercial plant at unspecified location to produce 3.6 million gallons/day [**13600 m³/day**] or 4,000 **acre-feet/year** [**4.93** million **m³/year**] \$ 9,803,000
- o Commercial plant at unspecified location to produce 7.2 million gallons/day [**27300 m³/day**] or 8,000 **acre-feet/year** [**9.87** million **m³/year**] \$18,160,000

10.2 Estimated Capital Cost for the **Demonstration Plant**

The demonstration plant is designed to **produce** 36,000 gallons/day of fresh water or 40 acre-feet/year if operated continuously. The total project costs for an operational plant at **NELH** based on the process flow diagram in Drawing PF-1 of Section 9 are estimated as follows:

Equipment cost installed	\$ 280,000
Deep water pipe installation	400,000
Engineering and environmental costs	250,000
Site related costs	75,000
Research and consulting	100,000
Project Development and Management	150,000
Insurance	25,000
Working capital, reserves , and fees	<u>75,000</u>
Project cost before contingency	\$1,355,000
Contingency	<u>150,000</u>
Total Estimated Cost	\$1505,000

In preparing this estimate, it is important that the costs not be under estimated since these costs will form a basis for soliciting external funding. In development programs, projects are often doomed by depleting funds before the project is operational. The factor of 2.2 between total project cost and installed equipment and pipeline cost is designed to provide conservatism for unexpected costs. Even so, it is likely prudent to obtain funding for approximately \$2 million for the Hawaiian demonstration plant to cover two years of operating costs and unexpected problems. The cost of the demonstration plant can be reduced by renting the more costly components. The air strippers and both the vapor-phase and liquid-phase carbon adsorbers can be rented.

In Table 10.1 each of the equipment items **are** identified with cost of equipment, freight, and installation shown separately. The source of **the** cost is shown with respect to vendor quotes or engineering estimates. These estimates are supported by the equipment descriptions in the mechanical equipment list in Table 10.2. The HCFC **R141B** recovery system is a complete skid-mounted assembly with a vendor quotation of \$195,000, or approximately 69 percent of the cost of the demonstration plant equipment. This **skid-mounted** assembly will significantly reduce the installation cost of the demonstration plant equipment.

The deep water pipe installation is based on inserting a concentric pipe (3 inch and **0.75-inch**) [**7.6** cm and 1.90 cm] into an existing **40-inch** [**102** cm] pipeline as described **in** Section 9.2. The cost of the pipe is small at approximately **\$4/foot** [**\$1.22/m**] and most of the deep sea pipe cost is labor to insert the pipe from a surface sump to a 2,100 foot [**640 m**] depth.

The engineering process design and equipment selection has been partially developed in this study and that will reduce engineering costs. The skid-mounted HCFC **R141B** recovery system is delivered as a complete unit and **this** reduces engineering costs further. Environmental costs are expected to be minimal since the demonstration plant will be installed at a licensed facility with existing regulations. The **small size of the demonstration plant and the remixing of the fresh water with the brine to return to the sea** minimizes the environmental concerns. Even so, engineering and environmental costs are estimated at 17 percent of total project cost.

The site related costs are also expected to be small since the demonstration plant will be located at an existing facility where space is available for rent and support services are provided at hourly rates. Site related costs are estimated at 5 percent of total project cost.

It is seldom that a demonstration plant can be built and operated without some problems **arising**. An allowance for **research** and consulting is **included** at **approximately 7 percent** of project costs. **TESI** has utilized various types of experts over the years to assist **in** technical work **from** fundamental research to

TABLE 10.1 CAPITAL EQUIPMENT COST ESTIMATE - Demonstration Plant

EQUIPMENT ITEM	Equipment Description	Equipment cost	Freight Cost	Installation Cost	Total cost	Cost Source
Salt Water Slurry Pump	140 gpm @ 30psig. 4 hp	\$3,230	\$100	\$1,000	54,330	Vendor quote
R141B Injeclon Pump	7.5 gpm @ 100 psig. 1 hp	\$1,000	\$50	\$200	\$1,250	Estimate
Wash Column	3 ft dia x 6 ft high, c.stl w/ poly liner	\$25,000	\$1,000	\$3,000	\$29,000	Estimate
Wash Col Rinse Pump	2.5 gpm @ 20 psig, 1/4 hp	\$500	\$100	\$100	\$700	Estimate
Wash Col Rinse water Cooler	25,000 btu/hr	\$1,000	\$100	\$100	\$1,200	Estimate
Ice Melter	1000 gal tank w/ heat coil, 2.5 mm btu/hr	\$5,000	\$300	\$600	\$5,900	Estimate
Fresh Water Decanter	6000 gal poly, 3 hr residence	\$7,000	incl	\$1,000	\$8,000	Estimate
Fresh Water Tank	One 12,000 gal poly, 12 ft dia x 16 ft high	\$6,550	incl	\$1,000	\$9,550	Vendor Quote
R141B Storage Tank	One 12,009 gal poly, 12 ft dia x 16 ft high	\$8,550	incl	\$1,000	\$9,550	Vendor Quote
Solar Steam Generator	2.5 mmbtu/hr hot water.	\$10,000	\$500	\$1,000	\$11,500	Estimate
Solar Steam Generator Pump	35 gpm @ 15 psig, 1/2 hp	\$1,000	\$150	\$300	\$1,450	Estimate
TOTAL ABOVE COSTS		\$70,830	\$2,300	\$9,300	\$82,430	
Refrigerant recovery system, Including		\$150,900	\$10,000	\$35,090	\$195,000	Vendor Quote
Air Stripper • fresh water						
Ambient air blower						
Fresh Water Feed Pump-air stripper						
Process Air Heater						
Process Air Blower						
Vapor Phase Carbon Adsorber						
Steam/R141B Condenser						
Waste Water Decanter						
Waste Water Transfer Pump						
Air Heater • drying blower						
Drying Air Blower						
Drying Air Filter						
Liquid Phase Carbon Adsorber						
Liquid Phase Adsorber Feed pump						
Salt Water Slurry Pipeline	500 ft x 3" poly	\$545	\$100	\$300	\$945	Vendor Quote
Waste Water Pipeline	500 ft x 3" poly	\$545	\$100	\$300	\$945	Vendor Quote
R141B Pipeline	500 ft x 3/4" poly	\$375	\$50	\$200	\$625	Vendor Quote
TOTAL COSTS		\$222,295	\$12,550	\$45,100	\$279,945	

TABLE 70.2 EQUIPMENT LIST- Demonstration Plant

Salt Water Slurry Pump	140 gpm @ 30 psig, 4 hp horizontal centrifugal pump, cast iron const
R141B Injection Pump	7.5 gpm @ 100 psig, 1 hp
Wash Column	3 ft dia x 6 ft high carbon stl tank w/ polyethylene liner 1 hp Ice scraper. 1/4 hp Ice paddle
Wash Cot Rinse Pump	2.5 gpm @ 15 psig, 1/4 hp electric motor, polyethylene
Wash Col Rinse water Cooler	25,000 btu/hr
Ice Melter	Tank w/ heating coil, 2.5 mmbtu/hr
Solar Steam Generator	2.5 mmbtu/hr
Circulating Hot Water Pump	35 gpm @ 15 psi, 1 hp
Fresh Water Decanter	6000 gal, 3 hr residence time, interface at 20% level
Fresh Water Tank	One 12,000 gal polyethylene tanks, 12 ft dia x 16 ft high 3" suction, 16" top access hatch, 6 hour storage
R141 B Storage Tank	One 12,000 gal polyethylene tanks, 12 ft dia x 16 ft high 3" suction, 16" top access hatch, 24 hour Storage
Alr Stripper • fresh water Ambient air blower	16' dia x 27 ft high, FRP fiberlass shell, poly mist eliminator packing • 20 ft bed of 1-1/2" dia polypropylene balls Centrifugal blower, 250cfm, 1 hp
Fresh Water Feed Pump-air stripper	Centrifugal pump, 25 gpm @ 40 psig, 1 hp, polypropylene
Process Air Heater	5600 btu/hr
Process Air Blower	centrifugal blower, 250 cfm, 3/4 hp, carbon stl construction
Vapor Phase Carbon Adsorber	Dual 4 ft dia x 4 ft high stainless steel vessels 450 lb activated carbon per vessel, 98% removal eff.
Steam/R141B Condenser	50,000 btu/hr coil heat exchanger
Waste Water Decanter	50 gal poly, 3 hour residence time, interface at 20% level
Waste Water Transfer Pump	0.15 gpm at 25 psig, polyethylene construction
Air Heater • drying air blower	25,000 btu/hr
Drying Air Blower	250 cfm, 3/4 hp centrifugal blower w/ variable inlet damper
Drying Air Blower inlet Air Filter	250 cfm, 5 micron
Liquid Phase Carbon Adsorber	Dual 3 ft dia x 6 ft high vessels, c. steel shell w/ poly liner 660 lb activated carbon per vessel
Liquid Phase Adsorber Feed pump	Centrifugal pump, 25 gpm @ 20 psig, 1/2 hp, poly const
Salt Water Slurry Pipeline	500 ft of 3' dia x 0.318" wall SDR 11 HDPE poly pipe 50 ft lengths, butt fusion ends, 160 psig internal design pres
Waste Brine Water Pipeline	500 ft of 3" dia x 0.318" wall SDR 11 HDPE polyethylene pipe 50 ft lengths, butt fusion ends. 160 psig internal design pres
R141 B Injection Pipeline	500 ft of 3/4" dia polyethelyne pipe

trouble-shooting, including the Canadian National Research Laboratory, Allied Signal Chemicals, Jaeger Engineering, and **ENPEX Corporation**.

Project development and management is based on a project manager from **Thermal** Energy Storage, Inc. (**TESI**) being on site to manage the equipment installation and testing. Work **would** be performed under subcontracts with **Makai Ocean Engineering**, Inc. (Makai) and the **Natural** Energy Laboratory of Hawaii (**NELH**). These two **organizations** have worked together for many **years** and would form a good team. **Project** development and management is estimated at 10 percent of total project cost.

Insurance was estimated at less than 2 percent of total project cost since no high pressure equipment is involved in the process and the **working** fluid is not toxic or hazardous. The working capital, reserve, and fees may not apply, but since the source of the funding is not known, they are included as if the demonstration plant **were** to be a small private facility furnishing fresh water to a community of 360 people. These costs are estimated at 5 percent of the total project cost. The contingency funds were set at 11 percent of the total project cost before contingency.

103 Estimated Capital Cost of the 3.6 Million Gallons/Day [13600 M³/Day] Commercial Plant

One of two commercial plants is designed to produce 3.6 million gallons/day of fresh water or 4,000 acre-feet/year [14.93 million m³/year]. The total project cost based on the process flow diagram in Drawing **PF-1** of Section 9 is estimated as follows:

Equipment cost	\$6,479,000
Deep water pipe installation	1,250,000
Engineering and environmental costs	300,000
Site related costs	100,000
Project Development and Management	300,000
Insurance	50,000
Working capital, interest during construction, reserves, and fees	<u>897,000</u>
Project cost before contingency	\$9,376,000
Contingency	<u>427,000</u>
Total Estimated Cost	\$9,803,000

In Table 10.3 each of the equipment items are identified with **cost** of equipment, freight, and **installation** cost shown separately. The source of the **cost** is shown with respect to vendor quotations or engineering

TABLE 10.3 CAPITAL EQUIPMENT COST ESTIMATE - Commercial Plant

EQUIPMENT ITEM	Equipment Description	Equipment cost	Freight cost	Installation cost	Total cost	Cost Source
Salt Water Slurry Pump	14,000 gpm @ 30psig, 350 hp	\$125,900	\$5,000	\$10,006	\$140,906	Vendor quote
R141B Injection Pump	740 gpm @ 100 psig, 60 hp	\$8,000	\$750	\$2,000	\$10,750	Estimate
Wash Column	Four units • 15 ft dia x 54 ft, c.stl w/ poly lin	\$809,000	\$40,000	\$240,000	\$1,089,000	Estimate
Wash Col Rinse Pump	250 gpm @ 20 psig, 4 hp	\$8,000	\$1,000	\$2,000	\$11,000	Estimate
Wash Col Rinse water Cooler	3.1 mm btu/hr	\$15,000	\$1,000	\$3,000	\$19,000	Estimate
Ice Melter	50,000 gal tank w/ heat coil, 250 mm btu/hr	\$100,000	\$10,000	\$35,000	\$145,000	Estimate
Fresh Water Decanter	500,000 gal , 3 hr residence	\$265,000	incl	\$25,000	\$290,000	Estimate
Fresh Water Tank	Two 500,000 gal. tanks, 50 ft dia x 32 ft high	\$530,000	ind	\$50,000	\$580,000	Vendor Quote
RI41 B Storage Tank	500,000 gal, c.stl	\$280,000	incl	\$25,000	\$305,000	Vendor Quote
Solar Steam Generator Pump	500 gpm @ 30 psig, 15 hp	\$12,000	\$1,500	\$2,500	\$16,000	Estimate
Solar Steam Generator	250 mm btu/hr, 15 psig sat. steam	\$500,000	\$50,000	\$250,000	\$800,000	Estimate
TOTAL ABOVE COSTS		\$2,131,000	\$57,750	\$392,000	\$2,580,750	
Refrigerant recovery system, Including		\$2,500,000	\$100,000	\$1,000,000	\$3,600,000	Estimate
Air Stripper • fresh water						
Ambient air blower						
Fresh Water Feed Pump-air stripper						
Process Air Heater						
Process Air Blower						
Vapor Phase Carbon Adsorber						
Steam/R141 B Condenser						
Waste Water Decanter						
Waste Water Transfer Pump						
Air Heater • drying blower						
Drying Air Mower						
Drying Air Filter						
Liquid Phase Carbon Adsorber		\$150,000	\$15,000	\$50,000	\$215,000	
Liquid Phase Adsorber Pump	2500 gpm @ 20 psig, 40 hp	\$15,000	\$2,000	\$4,000	\$21,000	
Pipelines						
Salt Water Slurry	1000 ft x 24" poly	\$17,190	\$700	\$10,000	\$27,890	Vendor Quote
Waste Water	1000 ft x 24" poly	\$17,190	\$700	\$10,000	\$27,890	Vendor Quote
R141B	1000 ft x 6" poly	\$3,000	\$400	\$3,000	\$6,400	Vendor Quote
TOTAL COSTS		\$4,833,380	\$176,550	\$1,469,000	\$6,478,930	

estimates. These estimates are supported by the equipment descriptions in the mechanical equipment list in Table 10.4.

The cost of the **48-inch** [122 cm] deep sea pipeline is based on locating the commercial plant where the ocean bottom of 2,000 feet [**610** m] is reasonably close to shore without a difficult terrain for the pipeline. **When** a specific location for the commercial plant is **selected**, costs can be adjusted to reflect the specific site since undersea conditions have a significant effect on the **cost**.

Based on the successful operation of **the** demonstration plant, the **engineering** design of the commercial plant is not complicated, based **mostly** on sizing and layout of commercially-available equipment. The environmental costs are based on the preparation of an environmental impact report without strenuous objections and extra costs associated **with** meeting environmental requirements. The 9 million gallons/day [34100 **m³/day**] desalination plant at Santa Barbara, California was built without delay **from** environmental concerns, and this plant is only 40 percent as large. Engineering and environmental costs **are** estimated at 3 percent of the total project cost,

The site related costs are based on a seacoast location that **does not require extensive development or** costly buildings. Aesthetics are not of high importance with trees used to screen the site. These costs are estimated at 1 percent of the total project cost.

Project development and management is based on an **architect-engineer-constructor** managing the project **with** technical support from TESI. The project management would be conducted by the same **firm** that designed the plant to minimize costs. **Project** development **and** management is estimated at 3 percent of total project cost

Insurance was estimated at approximately 0.5 percent of total project costs since no high **pressure** equipment is involved in the **process** and the working fluid is not toxic or **hazardous**. The working capital, interest **during** construction, reserves, and fees are based on commercial' considerations estimated at 9 **percent** of the total **project** cost. The contingency funds were set at 4.5 percent of the total project cost before **contingency**.

10.4 Estimated Capital Cost of the 7.2 Million Gallons/Day [27300 M³/Day] Commercial Plant

The second commercial plant is designed to produce 7.2 million gallons/day or 8,000 **acre-feet/year** [**9.87** million **m³/year**]. **The** total project cost based **on** the process flow diagram in Drawing PF-1 of Section 9 **are** estimated as follows:

TABLE 10.4 EQUIPMENT LIST - Commercial Plant

Salt Water Slurry Pump	14,000 gpm @ 30 psig, 350 hp horizontal centrifugal pump, cast iron const
R141 B Injection Pump	740 gpm @ 100 psig, 60 hp
Wash Column	Four units - 15 ft dia x 54 A high carbon stl tank w/ poly liner 75 hp Ice scraper, 15 hp ice paddle
Wash Col Rinse Pump	250 gpm @ 15 psig, 4 hp electric motor, polyethylene
Wash Col Rinse water Cooler	3.1 mm btu/hr
Ice Melter	50,000 gal tank w/ heating coil - 250 mmbtu/hr, 15 minute residence time for ice to melt.
Solar Steam Generator	250 mmbtu/hr 15 psig sat steam,
Solar Stream Generator Pump	500 gpm @ 30 psig, 15 hp
Fresh Water Decanter	500,000 gal, 3 hr residence time, interface at 20% level
Steam generator	500 pph @ 15 psig saturated, 600,000 btu/hr
Fresh Water Tank	One million gal, c. stl with epoxy lining, 37 ft dia x 32 ft high, 10 hour storage
R141 B Storage Tank	500,000 gal, c. stl with epoxy lining, 26 ft dia x 32 A high, 12 hour storage
Air Stripper- fresh water	dia x 27 ft high, FRP fiberlass shell, poly mist eliminator packing - 20 ft bed of 1-1/2" dia polypropylene balls
Ambient air blower	Centrifugal blower, 24,000 cfm, 75 hp
Fresh Water Feed Pump-air stripper	Centrifugal pump, 2750 gpm @ 25 psig, 60 hp
Process Air Heater	0.54 mm btu/hr
Process Air Blower	centrifugal blower, 24,000 cfm, 50 hp, carbon stl const
Vapor Phase Carbon Adsorber	Dual stainless steel vessels 10,000 lb activated carbon per vessel, 99% removal eff.
Steam/R141B Condenser	3.6 mm btu/hr coil heat exchanger
Steam Condensate/R141 B Decanter	1250 gal poly , 3 hour residence time, interface at 20% level
Steam Condensate Transfer Pump	6 gpm at 20 psig, polyethylene construction, 1/4 hp
Air Heater - drying air blower	2.0 mm btu/hr
Drying Air Blower	24,000 cfm, 50 hp centrifugal blower w/ variable inlet damper, c stl const
Drying Air Blower Inlet Air Filter	24,000 cfm, 5 micron
Liquid Phase Carbon Adsorber	Dual vessels, c stl shell w/ polyethylene liner 10,000 lb activated carbon per vessel, 2 week run
Liquid Phase Adsorber Feed pump	Centrifugal pump, 2750 gpm @ 20 psig, 40 hp,
Salt Water Slurry Pipeline	1000 ft of 24" dia x 0.736" wall SDR 32.5 HDPE poly pipe 50 ft lengths, butt fusion ends, 160 psig internal design pres
Waste Brine Water Pipeline	1000 A of 24" dia x 0.738" wall SDR 32.5 HDPE poly pipe 50 ft lengths, butt fusion ends, 160 psig internal design pres
R141 B Injecti on Pipeline	1000 ft of 6" dia poly

Equipment cost	\$11,986,000
Deep water pipe installation	2,312,000
Engineering and environmental costs	450,000
site related costs	150,000
Project Development and Management	450,000
Insurance	75,000
Working capital, interest during construction , reserves, and fees	<u>1,959,000</u>
Project cost before contingency	\$17,382,000
Contingency	<u>778,000</u>
Total Estimated Cost	\$18,160,000

This cost estimate was not developed **from** equipment quotations and engineering estimates. Instead the deep sea pipeline and process equipment costs were scaled from the cost of the smaller commercial plant using a scaling factor of 1.85. It is expected that two **48-inch [122 cm]** pipes would support the flow requirements for the larger **commercial plant**. The **cost** of the pipeline material is small **compared** to the cost of laying the pipes. Laying two pipes in the same vicinity with the same equipment would **reduce** the unit costs. Similarly, dual **process** equipment lines would be **necessary** to handle flow **requirements** and the cost of installation of two identical process lines would reduce costs. In some cases larger size equipment could serve both process lines to further reduce costs.

Engineering and environmental costs were estimated at 50 percent higher **for** the larger **plant** compared to **the** smaller **plant**. This is also true for the site related costs, project development and management costs, and **insurance** costs. Working capital, interest during construction, **reserves**, and fees were **more** than doubled for the larger plant while the contingency was increased by a factor of 1.8. The total project **costs** for the larger plant was a factor of 1.85 higher than **the** smaller **plant**.

10.5 Alternate Cost Estimates for **the** Demonstration Plant

The capital cost of the project on San Clemente Island or at Scripps Institute of Oceanography would be in **the** range of \$2.7 to \$3.5 million due to the added cost of laying a deep sea pipeline. **No** reliable estimates of the deep sea pipeline **are** possible until **underwater temperatures and** the routing and length of the pipeline can be **established**.

An alternate **estimate** was made of the equipment costs of the demonstration plant if the vapor-phase **carbon adsorbents are eliminated and the air from the air stripper is discharged to the atmosphere**. Since

the HCFC **R141B** is not a hazardous compound this is feasible. The equipment cost estimate would decrease to \$123,000 from the \$280,000 cost shown in Table 10.1, or more than 50 percent. However, the cost of lost HCFC **R141B** showed this was not attractive dependent upon the expected operating time of the demonstration plant. Since it is not desirable to limit the operating hours of the demonstration **plant**, this option was not selected.

Another alternate was investigated by using the warm surface sea water as a source to melt the ice in the ice melter. This was not economic due to the higher equipment cost of the demonstration plant of \$391,000 as well as the increased cost of pumping the sea water.

The liquid-phase carbon adsorbers might also be deleted if the HCFC **R141B** concentration of one ppm were acceptable in the potable water. Not currently knowing these limits, this option was also not selected and no **cost** estimate was prepared.

10.6 Alternate Cost Estimate for the Commercial Plant

An alternate estimate was made for deleting the vapor-phase **carbon** adsorbers with the air from the air stripper discharged to atmosphere. Since the HCFC **R141B** is not a hazardous material this is feasible. **The equipment cost estimate decreases to \$3,676,000.** However, as with the demonstration plant, the cost of lost HCFC **R141B** showed this was not an **attractive** alternate for continuous operation of the plant.

11. OPERATING COST ESTIMATES

11.1 Summary of Operating Costs for Demonstration and Commercial Plants

The estimated annual operating costs for the **demonstration** plant and the two commercial plants **are summarized** below and described by cost items in **the** discussion below:

- o Demonstration plant at any location to produce
36,000 gallons/day [**136 m³/day**] or **40** acre-feet/year
[**49300 m³/year**] if operated continuously **\$ 60,000**

- o Commercial plant at **unspecified** location to produce
3.6 million gallons/day [**13600 m³/day**] or **4,000**
acre-feet/year [**4.93** million **m³/year**] **\$1,432,000**

- o Commercial **plant** at unspecified location to produce 7.2 million gallons/day [**27300 m³/day**] or 8,000 acre-feet/year [**9.87 million m³/year**] **\$2,303,000**

113 Estimated Operating Costs for Demonstration Plant

The demonstration plant is designed to produce 36,000 gallons/day of fresh water or 40 acre-feet/year if operated continuously. **The** annual operating costs are estimated as follows:

Electric power, at \$0.10/kilowatt-hour	\$ 3,895
Make-up HCFC R141B , at \$10.50/gallon	105
Carbon for liquid-phase carbon adsorbers, at \$1.00/pound	2,054
Management and labor, including part-time technician	<u>54,000</u>
Total Operating Cost	\$60,054

Electric power consumption is derived **from the** electric motor list as shown in the top portion of Table 11.1. **Assuming** the demonstration plant is operated continuously, injecting the HCFC **R141B clathrate** former at the 2,000 foot [**610 m**] depth consumes 2,997 kilowatt-hours/year and pumping the ice slurry from the **2,000-foot** depth consumes 17,012 **kilowatt-hours/year**. This accounts for over 50 percent of the **annual** power requirements of 38,954 **kilowatt-hours**.

The **desalination** process recovers 99.99 percent of the HCFC **R141B** used in the plant. This reduces make-up requirements to an **annual** consumption of 10 gallons [37.9 liters]. If the carbon **adsorbers** were deleted **from** the process, the desalination process recovers only 99.87 percent of the HCFC **R141B** and that **increases** the annual cost of HCFC **R141B** to \$36,630 and increases the annual operating costs to \$96,579. This trade-off is not economic based on plans to operate the demonstration plant over a two-year period.

The carbon **for** the liquid-phase carbon **adsorbers** is replaced at the rate of 20 pounds [**9.07 kg**] of **carbon** per pound [**0.454 kg**] of HCFC **R141B** recovered. This results in the consumption of 2,054 pounds [**932 kg**] of carbon per year.

Management and labor are both **considered** part-time activities over the planned **two year operating** period. The demonstration plant will be operated continuously for many months to insure stable reproducible **operating** characteristics and proof of yields of both **fresh** water and recovered HCFC **R141B**. Depending

TABLE 11.1
ELECTRIC MOTOR LIST FOR DEMONSTRATION AND COMMERCIAL PLANT

	<u>Flow (gpm or cfm)</u>	<u>Delta Pressure (psi)</u>	<u>Power Required (HP)</u>	<u>Power Required (KW)</u>	<u>Annual Consumption (KW-HR)</u>	<u>Connected Power (HP)</u>
Demonstration Plant						
HCFC R141B injection pump	7.4 gpm	100	0.54	0.4	2,997	1
Ice slurry pump	140 gpm	30	3.06	2.3	17,012	4
Wash column rinse pump	2.5 gpm	15	0.03	0.2	152	0.25
Wash column ice scraper				0.6	4,166	1
Wash column paddle				0.1	1,042	0.25
Solar steam generator pump	35 gpm	15	0.38	0.3	2,127	0.5
Feed pump • fresh water air stripper	25 gpm	25	0.46	0.3	2,532	1
Air blower • fresh water air stripper	250 cfm	0.16		0.4	3,125	0.75
Process air blower	250 cfm			0.4	3,125	0.75
Drying air blower	250 cfm			0.1	651	0.75
Liquid-phase adsorber feed pump	25 gpm	20	0.36	<u>0.3</u>	<u>2,025</u>	<u>0.5</u>
Totals				5.4	38,954	10.75
Commercial Plant						
HCFC R141B injection pump	740 gpm	100	54	40.3	299,738	60
Ice slurry pump	14,000 gpm	30	306	228	1,701,217	350
Wash column rinse pump	250 gpm	15	3	2	15,189	4
Wash column ice scraper				42	312,453	7s
Wash column paddle				8	62,491	1s
Solar steam generator pump	600 gpm	30	11	8	62,491	1s
Feed pump • fresh water air stripper	2,750 gpm	25	50	37	278,473	60
Air blower • fresh water air stripper	24,000 cfm	0.18		42	312,453	75
Process air blower	24,000 cfm			28	208,302	so
Drying air blower	24,000 cfm			28	43,396	50
Liquid-phase adsorber feed pump	2,750 gpm	20	40	30	222,778	40
Steam condensate transfer pump	6 gpm	20	0.1	<u>0.1</u>	<u>304</u>	<u>0.25</u>
Totals				493	3,519,285	794

on initial results, other clathrate **formers** may be **demonstrated** in the plant. Thereafter, the plant will be used only for demonstrations to visitors. It is planned that a technician from the Natural Energy Laboratory of Hawaii (**NELH**) or Makai Ocean Engineering, Inc. (Makai) will operate the plant with technical support from Thermal Energy Storage, Inc. (**TESI**) as required. If the demonstration **plant** is located at San Clemente Island or **Scripps Institute** of Oceanography, **TESI** will supply the technician and technical **support**.

To insure adequate funding, the operating costs for two years are combined with the capital costs of the demonstration plant to determine that the amount of funding required is \$1.63 million. It is deemed prudent to seek **funding** for \$2 million.

11.3 Estimated Operating Costs for 3.6 Million Gallons/Day [13600 M³/Day] Commercial Plant

One of two commercial plants is designed to produce 3.6 million gallons/day of **fresh** water or **4,000 acre-feet/year** [**4.93 million m³/year**]. The annual operating costs are estimated as follows:

Electric power, at \$0.10/kilowatt-hour	\$ 351,928
Make-up HCFC R141B , at \$10.50/gallon	10,489
Carbon for liquid-phase carbon adsorbers , at \$1.00/pound	205,376
Management and labor	
One plant manager	97,500
One operations supervisor	91,000
One maintenance supervisor	78,000
Eight plant operators	457,600
Three maintenance technicians	<u>140,400</u>
 Total Operating Cost	 \$1,432,293

Electric power consumption is derived from the **electric** motor list as shown in the **bottom** portion of Table 11.1. Injecting the HCFC **R141B clathrate** former at **the** 2,000 foot (610 m) depth consumes 299,738 kilowatt-hours/year and pumping the ice **slurry** from the **2,000** foot depth consumes **1,701,217** kilowatt-hours/year. This **accounts** for 57 percent of the annual power **requirements** of **3,519,285** kilowatt-hours.

The **desalination** process recovers 99.99 percent of the HCFC **R141B** used in the plant. This reduces make-up **requirements** to an annual consumption of 999 gallons [**3780** liters]. If the carbon adsorbers were

deleted from the process, the **desalination** process recovers only 99.87 percent of the HCFC **R141B** and that increases the annual cost of HCFC **R141B** to **\$3,663,000** and increases the **annual** operating costs to **\$5,084,770**. **This** trade-off is not economic.

The carbon for the liquid-phase carbon adsorbers is replaced at **the** rate of 20 pounds [**9.07** kg] of carbon per pound [**0.454** kg] of HCFC **R141B** collected. **This** results in the consumption of 205,376 pounds [**93100** kg] of carbon per year.

The management and labor costs represent slightly more than 60 **percent** of **the** annual operating costs. **The 14-person** management and labor staff consists of one plant manager, two supervisors, eight operators, and **three** maintenance technicians.

11.4 Estimated Operating Costs for 7.2 Million Gallons/Day [**27300 M³/Day**] Commercial Plant

The second commercial plant is designed to **produce** 7.2 million gallons/day of fresh water or 8,000 **acre-foot/year** [**9.87** million **m³/year**]. The annual operating costs **are** estimated as -follows:

Electric power, at \$0.10/kilowatt-hour	\$ 703,857
Make-up HCFC R141B , at \$10.50/gallon	20,978
Carbon for liquid-phase carbon adsorbers, at \$1.00/pound	410,752
Management and labor	
One plant manager	112,500
One operations supervisor	101,000
One maintenance supervisor	90,000
Eight plant operators	528,000
Six maintenance technicians	<u>336,000</u>
 Total Operating Cost	 \$2,303,087

Electric power **consumption**, make-up HCFC **R141B** **consumption**, and carbon consumption **are twice** the costs for the smaller commercial plants.

The management and labor costs at **\$1,167,500** now represent slightly more **than 50 percent** of **the annual** operating **costs**. It is expected that the same number of management **and** operations **personnel** can operate **the** plant and only the **maintenance personnel are** increased to six technicians. However, due to the **increased** responsibilities, annual wmpensation is increased for all personnel. The **17-person** management and labor staff **consists** of one **plant** manager, two **supervisors**, eight **operators**, and three **maintenance technicians**.

12. COST OF FRESH WATER

12.1 Summary of Costs of Fresh Water

The estimated costs of producing **fresh** water from the commercial **clathrate** desalination plants **are** summarized below with the assumptions discussed in the subsequent sections:

- o Commercial plant at unspecified location to produce 3.6 million gallons/day [13600 **m³/day**] or 4,000 m-feet/year [**4.93** million **m³/year**] under public **financing** \$2.0 /1 ,000 gallons
[**\$0.53/m³**]
- o Commercial plant at unspecified location to produce 3.6 million gallons/day or 4,000 acre-feet per/year under private **financing** **\$2.37/1 ,000** gallons
[**\$0.63/m³**]
- o Commercial plant at unspecified location to produce 7.2 **million** gallons/day [**27300 m³/day**] or 8,000 acre-feet/year [**9.87** million **m³/year**] under public **financing** **\$1.70/1,000** gallons
[**\$0.45/m³**]
- o Commercial plant at unspecified location to produce 7.2 million gallons/day or **8,000** acre-feet per/year under private financing **\$ 2.02/1,000** gallons
[**\$0.53/m³**]

The 7.2 million gallons/day commercial plant under municipal financing produces fresh water at the lowest **unit** cost **This** cost of **\$1.70/1,000** gallons is below the target price of **\$2/1,000 gallons [\$0.53/m³]** set by a public water authority in **Southern** California to compete with surface water. **The** 7.2 **million** gallons/day commercial plant under private **financing** is also essentially competitive in this same market at **\$2.02/1,000** gallons. If the plant size were **increased** to 9 million gallons/day [**34100 m³/day**], or 10,000 acre-feet/year [12.3 million **m³**], this **desalination** plant would be **even** more competitive.

12.2 Assumptions for Publicly-Financed Plants

The two **publicly-financed** desalination **plants** producing 3.6 **and** 7.2 million gallons/day of fresh water would be **financed** by bonds issued by a municipal or district water authority. **The** smaller plant could

be financed by an \$1.1.2 million bond issue and **the** larger plant by a \$20.5 million bond issue. Both bond issues include one year of operating expenses to provide working capital. The interest on the bonds is set at 6 percent with payback over the **30-year** life of the plant. The annual capital and operating cost for the smaller plant is \$2.3 million, and for the larger plant is \$3.8 million.

The annual costs, the **fresh** water produced, and the unit cost of **fresh** water **are** as follows:

	3.6 Million <u>Gallons/Day</u>	72 Million <u>Gallons/day</u>
Annual cost of debt	\$ 816,211	\$1,486,615
Annual operating costs	<u>1,432,000</u>	<u>2,303,000</u>
Total annual costs	\$2,248,211	\$3,789,615
 Annual freshwater in thousands of gallons	 1,116,900	 2,233,800
 Unit cost of freshwater in dollars/gallon	 \$2.01	 \$1.70

123 Assumptions for Privately-Financed Plants

The two **privately-financed desalination plants** producing 3.6 and 7.2 million gallons/day of **fresh** water **would be financed by 18 percent equity and 82 percent debt raised in common stocks and bonds in the** capital markets. The smaller plant would be **financed** by \$2.0 million in common stocks and \$9.2 million in corporate bonds for a total investment of \$11.2 **million**, including one year of operating costs to provide working capital. The larger plant would be financed by \$3.7 million in common stocks and \$16.8 million in corporate bonds for a total investment of \$20.5 **million**, including one year of operating costs to provide working capital.

The total equity **return** before income taxes is set at 15.65 percent with a 42.5 percent federal and state **income tax rate. This provides a 9 percent return after taxes. The interest on the bonds is set at 9 percent** before taxes with payback over the **30-year** life of the plant. **The** annual capital and operating cost for **the** smaller plant is \$2.7 million, **and** for **the** larger plant is \$4.5 million.

The annual **cost**, the **fresh** water **produced**, and the unit cost of fresh water **are** as follows:

	3.6 Million <u>Gallons/Day</u>	7.2 Million <u>Gallons/Day</u>
Annual cost of equity	\$ 320,578	\$ 583,889
Annual cost of debt	896,731	1,633,271
Annual operating costs	<u>1,432,000</u>	<u>2,303,000</u>
Total annual costs	\$2,649,309	\$4520,160
Annual fresh water in thousands of gallons	1,116,900	2,233,800
Unit cost of fresh water in dollars/gallon	\$2.37	\$2.02

APPENDIX A: WARM WATER DESALINATION

A.1 The Need for a **Clathrate** Former for Warm Water Applications

In the course of investigating clathrate **formers** for suitability, attention focused on **finding** a clathrate former with the ideal conditions of high temperature clathrate formation at low **pressure** by a non-toxic clathrate **former**. Usually two of the three combinations could be found in one **agent**. The best solution was a compromise wherein HCFC **R141B** **produced** the lowest cost water, but the clathrate formation temperature was low. The principal disadvantage of HCFC **R141B** is that is not suitable for use in ocean or seawater with temperatures above approximately **45° F. [7.2° C.]**. **Thus**, the need for a clathrate former for warm water desalination applications was **apparent**.

A.2 Use of HCFC R22 as a Clathrate Former for Warm Water Applications

Further investigation indicated that the hydrocarbon HCFC R22 might be the most suitable for **desalination** of warmer water although recognizing that the cost of fresh water would be somewhat higher than that using the HCFC **R141B** **process**. HCFC R22 forms a **clathrate** at approximately **55° F. [12.8° C.]** in seawater, considerably higher than the **47.5° F. [8.6° C.]** formation temperature of HCFC **R141B**. **This means** a warmer ocean or sea temperature, possibly as high as **50° F [10.0° C.]** can be used to **form** the clathrate ice.

This high **clathrate** formation temperature is a major advantage for **desalination** of seawater in wanner bodies of water where the water is shallow or is farther from shore. For example, this application would be useful for the more-arid **countries** on the Mediterranean Sea and the Persian Gulf.

The principal disadvantages of HCFC **R22** as a **clathrate** former is that (a) the clathrate ice forms at a pressure of 97 pounds per **square** inch gage (**psig**) [**6.82** kg/cm*] and (b) HCFC R22 has a relatively high solubility of 3,000 parts per million at **60°** F. [**15.6°** C.] of the agent in water.

The **first** disadvantage means that the clathrate ice must be maintained at a pressure of approximately 120 psig [**8.44** kg/cm*] to prevent the clathrate ice from decomposing as the ice slurry rises to the surface. **One** solution is to use a submersible pump installed near shore at a depth of approximately 300 feet. For the demonstration **plant**, this pump will require approximately 15 horsepower [**11.2** kilowatts] to lift and pressurize the ice slurry to 120 psig.

The wash column will also have to be **maintained** at 120 psig to prevent decomposition of the ice crystals. **After the ice crystals and brine water are separated in the wash column the pressure can be reduced** to atmospheric. This reduction in pressure will cause the HCFC R22 to vaporize to **separate** the HCFC R22 from the fresh melt water. A performance summary for the HCFC R22 process is shown in Table A1.

With the HCFC R22 removal and recovery process equipment operating at atmospheric **pressure**, the complexity, capital costs, and operating costs will be less than a **pressurized** system. However, in the demonstration plant, approximately 6 horsepower [**4.47** kilowatts] **will** be required to recompress the HCFC R22 vapor to a liquid at 120 psig. The consumption of electric power **increases** by a factor of 4.4 over that of a comparable process based on HCFC **R141B** (refer to the electric motor list in Table A.2 compared to the electric motor list shown in Table 11.1 for the HCFC **R141B** demonstration plant).

Also, approximately **140** gallons per **minute** of cold water at **60°** F. [**15.6°** C.] will be **required** to remove the latent heat of condensation and the heat of compression for converting the HCFC R22 vapor to a liquid. This heat would be removed by the cold brine water. Some of this heat can be rejected to the ice melter for melting the ice crystals.

The second disadvantage of HCFC **R22** is its solubility in water of 3,000 parts per million at **60°** F. [**15.6°** C.] and atmospheric **pressure**. This compares with **the** solubility of HCFC **R141B** of 350 parts per million at **these** same conditions. **This** high **solubility increases** the complexity and cost of the **HCFC** R22 recovery system. Also recovery of HCFC **R22** might be **required from** the brine water to **improve** economic production of fresh water by recycling this recovered material.

TABLE A.1
PERFORMANCE SUMMARY - HCFC R22-BASED DEMONSTRATION PLANT

Brine water-ice slurry flow	gpm	139.6	
Brine water flow	gpm	104.7	
Ice flow (fresh water & clathrate)	gpm	34.9	
Fresh water flow	gpm	27.5	
HCFC R22 refrigerant flow	gpm	7.4	
Ice crystals	percent	25	
Density of ice crystals	pounds per gallon	8.76	
Heat of fusion	BTU per pound	137	
Heat of fusion to dissipate	Million BTU per hour	2.5	
Temperature of ice slurry at surface	° F.	60	
Waste brine flow from wash column .	gpm	107.2	
Fresh water produced	gpm	25.0	
Recovered HCFC R22	gpm	7.4	
Initial concentration of HCFC R22 in brine water	ppm	0	
Final concentration of HCFC R22 in brine water	gpm	0	
HCFC R22 lost in brine water	gallons per day	0	
HCFC R22 recovery from brine water	percent	100.0	
Initial concentration of HCFC R22 in fresh water	ppm	3,000	
HCFC R22 in fresh water to carbon filter	ppm	1	
HCFC R22 lost in fresh water	gallons per day	0.04	
HCFC R22 recovery from fresh water	percent	99.9997	
Total HCFC R22 lost	gallons per day	0.04	
Total HCFC R22 recovery	percent	99.9997	
Physical properties of HCFC R22	Chlorodifluoromethane		
Molecular formula	CHClF₂		
Molecular weight		86.5	
Liquid density at 65° F.	pounds per cubic foot	75.93	
Specific heat - liquid at 65° F.	BTU per pound per °F	0.29	
Saturated vapor pressure at 65° F.	psia	126.0	
Specific volume of saturated vapor at 65° F.	cubic feet per pound	0.4355	
Specific heat of vapor at 65° F.	BTU per pound per ° F.	0.20	
Energy to compress HCFC R22 vapor	horsepower	6	0
Inlet pressure	psia	14.7	
Discharge pressure	psia	126	
Inlet volume of gas	scfm	32.7	
Ratio of specific heats, n		1.35	
n/(n-1)		3.86	
(n-1)/n		0.26	
Heat of condensing HCFC R22 vapor	BTU per hour	365,974	
Enthalpy of saturated vapor at 65° F.	BTU per pound	110.1	
Enthalpy of saturated liquid at 65° F.	BTU per pound	28.9	
Cooling water required	gpm	146	
Cooling water inlet temperature	° F.	60	
Cooling water outlet temperature	° F.	65	
Energy to pump ice slurry to wash column	horsepower	15.4	

TABLE A.2
ELECTRIC MOTOR LIST FOR HCFC **R22-BASED** DEMONSTRATION PLANT

	<u>Flow (gpm or cfm)</u>	<u>Delta Pressure (psi)</u>	<u>Power Required (HP)</u>	<u>Power Required (KW)</u>	<u>Annual Consumption (KW-HR)</u>	<u>Connected Power (HP)</u>
HCFC R22 injection pump	7.4 gpm	1000	5.40	4.03	29,974	6
Ice slurry lift pump	140 gpm	130	13.27	9.90	73,719	15
Ice slurry transfer pump	140 gpm	30	3.06	2.28	17,012	4
Wash column rinse pump	2.5 gpm	-15	0.03	0.02	152	0.25
Wash column ice scraper			0.56	0.56	4,166	1
Wash column paddle			0.14	0.14	1,042	0.25
Solar steam generator pump	35 gpm	15	0.38	0.29	2,127	0.5
Feed pump - fresh water air stripper	25 gpm	25	0.46	0.34	2,532	1
Air blower - fresh water air stripper	250 cfm	0.18		0.42	3,125	0.75
Process air blower	250 cfm			0.42	3,125	0.75
Drying air blower	250 cfm			0.42	651	0.75
Liquid-phase adsorber feed pump	25 gpm	20		0.28	2,083	0.5
HCFC R22 vapor compressor			6.00	4.50	33,328	8
Totals				23.60	173,036	38.75

From the above description of the HCFC R22 process, it is clear that the cost of fresh water produced by this process would be higher than that produced by the HCFC **R141B** process. The capital and operating costs for a large HCFC **R22-based desalination** plant were not developed since the **warm** water desalination application is not a primary need in the United States where cold ocean water is available in Southern California and other coastal areas to meet the need for additional fresh water.

A.3 Use of HCFC R22 as a **Clathrate Former** for Cold Water Applications

If HCFC R22 has application for desalination in **warm** waters, the question arises on how it would perform in cold water. A brief review indicates that it would produce fresh water for a lower cost than fresh water produced by warmer ocean or sea temperatures but at a higher cost than fresh water produced by the HCFC **R141B** process.

If HCFC R22 is used as the **clathrate former** in an ocean or sea pipeline **where 40° F. [4.44° C.]** is available, the amount of heat **transfer** surface area for the liberation of the heat of fusion during clathrate formation will be approximately five times less than **if HCFC R141B** is used. Some of the heat of fusion liberated can be absorbed by the ice **slurry** mass provided the **temperature** of the ice **slurry** is **maintained** below the melting point of the clathrate. Also, **the** temperature **differential** for heat transfer **from** the ice **slurry** to the surrounding water on the outside of the pipe will be greater. Thus the amount of heat **transfer surface area and the length of the pipe will be less.**

The trade-off of less undersea pipeline surface **area** with the higher capital costs and operating costs associated with the HCFC R22 clathrate **former** will likely result in a higher cost of fresh water for the **system** using HCFC R22. Further investigation **is** necessary to determine how much **difference** would exist between the two systems. However, the two systems are best employed under different ocean or sea conditions. Cold ocean water close to shore will likely favor the HCFC **R141B** clathrate former while warmer sea or bay water will require the use of HCFC R22.

APPENDIX B. LETTER FROM U.S. NAVY

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DEPARTMENT OF THE NAVY
NAVAL AIR STATION
NORTH ISLAND
SAN DIEGO, CALIFORNIA 92135-5000

IN REPLY REFER TO:
11000
Ser 183/667
25 SEP 1992

Mr. Richard A. **McCormack**, President
Thermal Energy Storage, Inc.
6335 Ferris Square, Suite E
San Diego, CA 92121

Dear Mr. **McCormack**:

In response to your letter of August 27, 1992, Naval Air Station, North Island would be willing to coordinate the use of a limited area of land at Naval Auxiliary Landing Field, San Clemente Island for the purpose of supporting a Federally sponsored demonstration project utilizing the clathrate desalination technology described in your letter.

The determination **of** actual support requirements for such a project is, of course, essential prior to any specific commitment of Navy property to support this effort.

For additional information and coordination **of** requirements regarding this project, the Naval Air Station, North Island point of contact is Mr. A. Langevin (Code **183**), Facility Planning Director, Staff Civil Engineer, telephone **545-1126**.

N. W. CLEMENTS
By direction

APPENDIX C. REFERENCES

1. Avco **Systems** Division, **Secondary Refrigerant Freezing Pilot Plant, Crystalex** Pilot Plant - Single Stage • 75,000 **gpd**, Office of Water Research and Technology Test Facility at Wrightsville Beach, North Carolina, Wilmington, Massachusetts, 1979.
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3. **Burns and Roe Industrial Services Corporation, Absorption Freezing Vapor Compression (AFVC) 25,000 gpd, Office** of Water Research and Technology Freezing Power Plant at Wrightsville Beach, **North** Carolina, Paramus, New Jersey, **January** 1982.
4. Burns **and** Roe **Industrial** Services **Corporation, Falling Film indirect Freezing • 6,000 gpd, Office** of Water Research and Technology Freezing Power Plant at **Wrightsville** Beach, North Carolina, Paramus, New Jersey, January 1982; test facility located at Chicago Bridge **and Iron** Company, **Oakbrook, Illinois**.
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