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SOLAR ENERGY WATER DESALINATION IN THE UNITED STATES AND SAUDI ARABIA

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ABSTRACT

Five solar energy water desalination systems are described. The systems will each deliver 6000 m^3/day of desalted water from either seawater or brackish water. After the system definition study is completed in August 1981, two systems will be selected for pilot plant construction. The pilot plants will have capacities in the range of 100 to 400 m^3/day.

1.0 BACKGROUND

In October 1977, Saudi Arabia and the United States signed a Project Agreement for Cooperation in the Field of Solar Energy (SOLERAS) under the auspices of the United States-Saudi Arabian Joint Commission on Economic Cooperation. The objectives of the agreement are to:

- cooperate in the field of solar energy technology for the mutual benefit of the two countries, including the development and stimulation of solar industries within the two countries;
- advance the development of solar energy technology in the two countries; and
- facilitate the transfer between the two countries of technology developed under this agreement.

The Solar Energy Research Institute (SERI), as the Operating Agent, is responsible for implementing SOLERAS in accordance with directives of the SOLERAS Executive Board, which has approved a five-year technical program plan.

As part of this technical program plan, an area of Industrial Solar Applications for solar technology has been identified. The objectives of the Industrial Solar Applications program are to introduce solar energy technologies into industrial applications and foster the establishment of domestic industries using renewable energy sources, thereby lessening industrial dependence on fossil fuels and minimizing deleterious effects on the environment. A specific objective is to demonstrate the use of solar energy in desalinating water.

Water desalination is needed in both Saudi Arabia and the United States. In Saudi Arabia, water is needed principally for municipal and agricultural applications. In the United States, desalination is mainly required to control river salinity and provide potable water to selected communities that have critical water quality problems or water shortages.

Conventionally powered desalting plants have been in operation for several years. At the beginning of 1977, about 1500 land-based, fossil-fueled or electric-powered desalting plants with a minimum capacity of 100 m^3/day were in operation or under construction throughout the world. These plants are capable of producing nearly 4 million cubic metres of fresh water daily for municipal or industrial uses. Distillation processes account for 77% of the total plant capacity; the balance is almost entirely membrane processes [1].

In 1977, Saudi Arabia had a conventional desalination plant capacity of 87,000 m^3/day. By 1981 the capacity had increased to 182,000 m^3/day. Projects are underway for plants to be constructed during the next five years with a total capacity of 1.7 million m^3/day. By the year 2000, it is planned that fossil fuel powered plants will provide 8-12 million m^3/day of desalted water. Most of these plants are located along the Arabian Gulf and the Red Sea coast.

In the United States at the beginning of 1977, 510 conventional desalination plants provided about 0.4 million m^3/day of fresh water.

Despite this widespread desalination activity, no significant efforts have been made to replace the conventional power plants associated with desalination of water with solar energy systems. With a few exceptions, most solar desalination work in the world has been restricted to simple solar stills of limited output. To remedy this situation, the SOLERAS Executive Board authorized the initiation of a solar energy water desalination project. The objective is to advance the technical and economic feasibility of large-scale solar-powered desalination of brackish water and seawater.

Because of the differences between desalting seawater and brackish water, two distinct systems will be developed. One system will desalt seawater to provide potable water. The second system will desalt brackish water for either (a) clean-up and reuse or (b) potable applications. The two systems could find applications in both the United States and Saudi Arabia.

Estimates by the Saline Water Conversion Corporation (SWCC) in Saudi Arabia indicate that steam from conventionally powered dual-purpose power-desalting units now being designed, constructed, and operated in the coastal areas of Saudi Arabia for seawater desalination would cost in the range of $0.50 to $1.50 per gigajoule. Solar energy costs presently are considerably higher and are likely to remain higher. Thus, it is unlikely that solar-powered desalination plants could be economically competitive in these locations.

For inland locations the situation is quite different, especially for communities not connected to the national electric power grid. The absence of electric grid power makes the solar-powered alternative much more attractive. Inland solar-powered desalting plants would desalt brackish water rather than seawater as the coastal plants would do.

Huge fossil-fuel-powered plants with individual process trains of up to 200,000 m^3/day and total capacity of 8-12 million m^3/day of desalted water are being planned for the year 1990 for coastal areas in Saudi Arabia. The water needs for small inland communities would be considerably less than those for large coastal communities. Six thousand m^3/day of desalted water could supply the needs for a community of 15,000 to 30,000 people in Saudi Arabia, could irrigate 1.2 km^2 of greenhouse area, or could be used for medium-sized industrial application.

Seventeen states in the United States and the Virgin Islands have critical water quality problems or water shortages. In a study for the Office of Water Research and Technology, U.S. Department of the Interior, 37 communities were identified with problems that can be solved by using desalting technology. The population in these communities ranges from a few hundred to over a million. Twelve of the communities depend considerably on inland brackish groundwater with total dissolved solids ranging from 1,000 to 35,000 mg/litre [2].

In addition, four U.S. islands must desalinate either brackish groundwater or seawater to provide potable water. Also, U.S. river basins such as the Colorado River Basin, the Brazos River Basin of Texas, and the Arkansas and Red River Basins of Oklahoma have salinity problems.

As an example of a possible desalting application, consider the specific problems of the Colorado River Basin. The Colorado River collects water from seven states as it cuts its way some 1,400 miles through the southwest and Mexico, finally emptying into the Gulf of California. The river is a unique water, power, and environmental resource for 14.5 million people. The waters of the Colorado are apportioned among the Upper and Lower Basin States and the Republic of Mexico by compacts, treaty, water delivery contracts, Supreme Court decisions, and congressional legislation. As measured against these existing apportionments, the river basin does not yield a sufficient water supply to develop all its vast land and energy resources.

In 1974, the passage of the Colorado River Basin Salinity Control Act (Public Law 92-320) set in motion a basinwide program to improve the quality of water available to users in the United States and the Republic of Mexico. Under Title II of the Act, $125 million was authorized for constructing four salinity control projects and studying 12 other units under the Colorado River Water Quality Improvement Program to meet national and international obligations and assist the basin states in meeting salinity standards for the Colorado River.

The salinity control units now under study will remove about two million tons of salt per year from the river system by controlling point, diffuse, and irrigation sources in the basin. Structural requirements of source controls mostly involve evaporation ponds and desalting techniques. Because of limited funding for program research, desalting study applications and pilot or field testing of desalting hardware has been minimal.

The following constraints govern the studies of desalting applications for salinity control:

- desalting processes are relatively energy intensive, and the desalted water cost is a strong function of energy costs;
- brine disposal is subject to ever-increasing environmental restrictions resulting in higher costs;
- pretreatment systems are becoming more complex, resulting in higher costs; and
- water recovery using high recovery plants is essential to meet existing water rights in fully appropriated river systems.

In view of these constraints, the demonstration of the technical and economic feasibility of solar energy water desalination may provide new opportunities in salinity control planning. Presently, salinity is reduced by point and diffuse source control. Conventional techniques for such control involve collecting the brackish waters and directing them to evaporation ponds. Such control offers immediate economic advantage over desalting technologies, but it wastes precious water resources. Exercise of control envisioned under the Colorado River Water Quality Improvement Program could result in the removal of over 138 million cubic metres of water per year from the river system out of the 2,800 million cubic metres still unallocated.

Faced with predicted water shortages in the basin by 1995-2000, recovery of brackish water via desalting would not only provide additional fresh water otherwise lost from the river system, but also would reduce the environmental burden created by large brine ponds for evaporation and give greater flexibility in locating water treatment plants.

In general, the desalting applications for salinity control under the Colorado River Water Quality Improvement Program involve relatively remote sites located in the Colorado River Basin. Most sites have brackish groundwater with total dissolved solids ranging from about 2,000 to 19,300 mg/L and planned plant capacities vary considerably from 7,400 to 74,000 m^3/day. Some small-scale (100 to 400 m^3/day capacity) pilot plant testing of candidate pretreatment-desalting systems is already scheduled for on-site evaluation. This range of sizes would be adequate for field evaluation.

2.0 PROJECT PLANS

To accomplish the objective of the SOLERAS solar energy water desalination project, a 3-phase activity is planned. The phases are as follows:

- Phase 1: Preliminary System Design and Cost Analysis
- Phase 2: Detailed Pilot Plant Design and Construction
- Phase 3: Pilot Plant Operation and Training of Personnel

Phase 1: System analyses and economic analyses will be performed by several companies on a solar energy desalination system of their choice for either seawater or brackish water desalination. The systems will each be for an average daily product water capacity of 6000 m^3. The main criterion for the analysis will be the product water cost. Each system will be designed for a specific site and application. The site, application, and technology will have broad applicability to general water desalination needs in either the United States or Saudi Arabia. It is the intent of this project to encourage innovation without unduly affecting performance and reliability. Subsystems and their interfaces will be defined during Phase 1, and product-water cost projections will be made for commercial plants of a range of capacities.

Finally, a development plan for Phase 2 will be generated including detailed cost estimates for the design and construction of a pilot plant with a capacity of 100 to 400 m^3/day using the technology of the baseline system.

Phase 2: Of the several systems designed in Phase 1, one system in each category [illegible] and seawater desalination) will be chosen for pilot plant construction. The criteria for selection will include levelized cost per unit of product water for the commercial-sized plant, design and construction cost for the pilot plant, consistency in cost between the commercial-sized plant and the pilot plant, maturity of system design, and projected plant reliability. Each pilot plant will have a product-water output capacity of 100 to 400 m^3/day. The pilot plants will be designed in detail and constructed on specific sites.

The size of the pilot plant was selected to be within the budget limitations of the SOLERAS program and is of a capacity that provides useful technical and economic data for the planning, design, and construction of a commercially-sized plant. A pilot plant delivering 400 m^3/day of desalted water would provide water to 2,000 people or could provide irrigation water for about 8,000 m^2 of greenhouse agriculture. If the ratio of the ultimate plant capacity to the pilot plant capacity becomes too great, less useful technical and economic information for application to the full scale plant can be extracted from the pilot plant construction and operation.

Phase 3: The pilot plants will be operated and performance measurements made to provide the information essential for designing commercial-sized desalting plants. Local personnel will be trained in the operation and maintenance of the plant so they can make performance measurements.

The schedule for Phase 1 is from October 1980 to July 1981. Phase 2 is expected to start in October 1981 with the pilot plant construction completed by July 1983. Phase 3 will start at the completion of Phase 2 and will continue until the end of 1983.

3.0 TECHNOLOGY CONSIDERATIONS

Water desalination processes can be divided into four categories, namely: membrane, distillation, crystallization, and chemical processes. Presently, plants using distillation provide most product water. It is projected that in 20 years, the majority of desalination plants will use either membrane or crystalization technology because these processes are more energy efficient [3].

Of the membrane processes, reverse osmosis and electrodialysis represent the technologies most advanced at this time. The crystallization processes currently being developed include: vacuum-freezing vapor-compression, secondary refrigerant freezing, and eutectic freezing.

Some studies regarding the technologies, system designs, and cost for large-scale solar energy water desalination have been ongoing since 1977 [4,5]. One conclusion from these studies was that depending on the escalation rate of fuel costs, solar energy water desalination would become economic somewhere in the time span from 1980 to 1990 assuming solar thermal collector costs of $\$180/m^2$. Another conclusion was that the lowest product water cost would be obtained from plants that depend partially on solar energy and partially on conventional fossil energy.

The selection of an optimum solar energy water desalination system is affected by many factors as illustrated in Figure 1. The feed water characteristics, product water requirements, solar collector type and size, required water recovery ratio, plant utilization factor, site, performance factor, and brine disposal method all affect the selection of the desalination process in a complex manner.

As examples, consider the effect of feed-water salinity upon the product water costs for membrane and distillation processes. Figure 2 shows a hypothetical example. For water recovery ratio A, the membrane process provides less expensive product water than the distillation process below a given feed-water salinity. Increasing the water recovery ratio decreases the feed water salinity for which the cross-over in product water cost occurs.

The second example, shown in Fig. 3, considers the effect of the product-water recovery ratio on the product-water cost. With increasing product-water recovery ratio, the cost for evaporation ponds decreases, but the cost for the desalting process equipment increases, giving a minimum cost at a given water recovery ratio. This minimum is dependent on the evaporation rate; that is, it depends on the particular location of the plant.

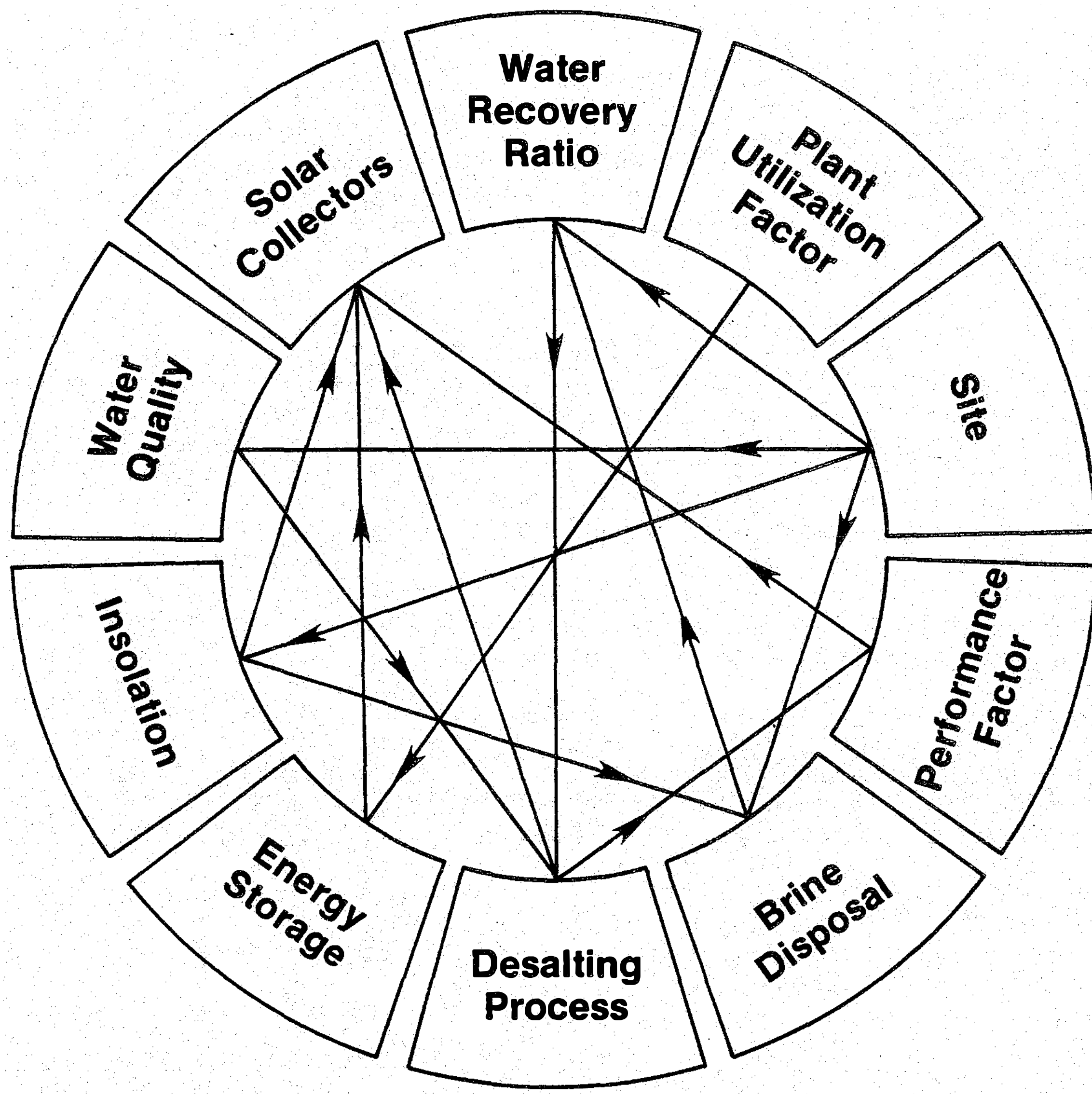

Figure 1. Interaction of Factors in Solar Energy Water Desalination

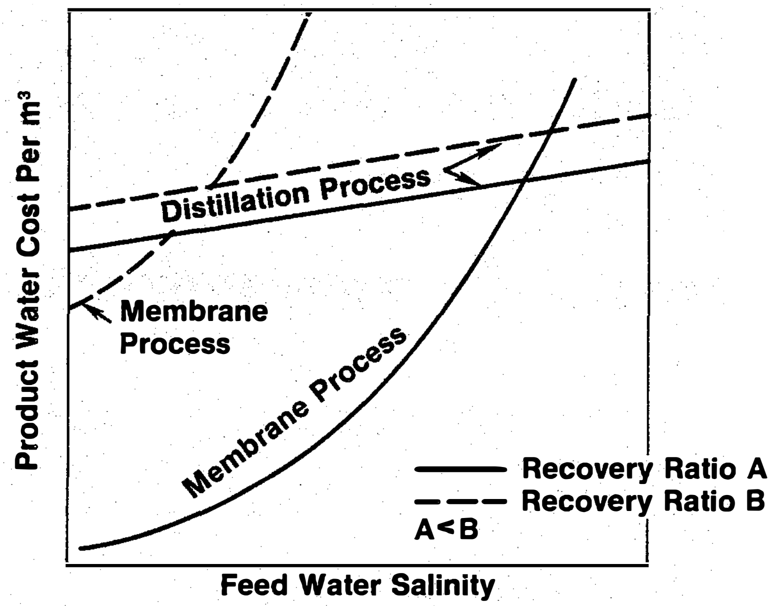

Figure 2. Effect of Feed Water Salinity on Product Water Cost

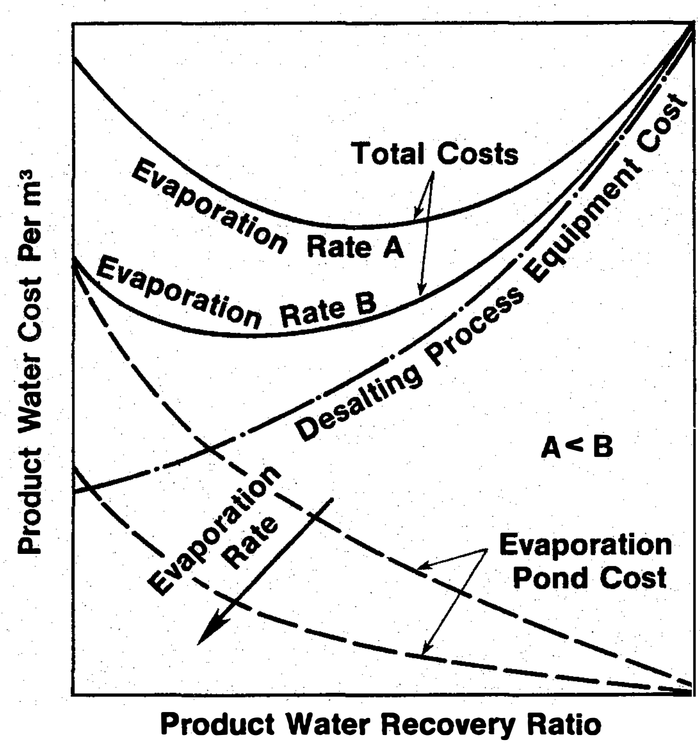

Figure 3. Effect of Product Water Recovery Ratio on Product Water Cost

The product water recovery ratio may be dictated by economic reasons, such as minimum product water cost as shown in Fig. 3, or it may be dictated by the scarcity of the feed water. The product water recovery ratio in its turn is often the determining factor in selecting methods for control of scale formations.

It is because of the complex interaction among many factors that the Phase 1 definition study is being implemented.

4.0 PHASE 1 IMPLEMENTATION

The combinations of desalination and solar technologies that were covered in the 36 proposals received for the Phase 1 definition study are shown in Table 1. This table shows eight solar energy technologies and eight desalination technologies that were represented by the proposals. The numbers in Table 1 indicate the number of proposals incorporating each of the solar energy/desalination technology combinations. Since some proposals offered a coupling of several solar technologies or of several desalination technologies, the total number (55) shown in this table is higher than the number of proposals received.

The most frequent solar energy technology was line-focus collectors, particularly in combination with reverse osmosis. Photovoltaic solar energy conversion, particularly in combination with other solar energy technologies, was the second most frequent option.

Table 1. MATRIX SHOWING COMBINATION OF DESALINATION AND SOLAR ENERGY TECHNOLOGIES

	Solar Energy Technology								
Desalination Technology	Central Receiver	Point Focus	Line Focus	Evacuated Tube	Photo-voltaic	Wind	Solar Pond	OTEC	Total
Electro-dialysis					4	1			5
Reverse osmosis-seawater	3	4	6		1	2	1		17
Reverse osmosis-brackish	1	2	5		2	1			11
Multieffect distillation	1		2						3
Multistage flash distillation	1		2		2	2	1	2	10
Vapor compression		1	2	2					5
Freezing		1			1		1		3
Solar still					1				1
Total	6	8	17	2	11	6	3	2	55

Note: Numbers in chart are the number of proposals in each category. Several proposals offered a combination of technologies; therefore, a higher number than the number of proposals is shown.

The five companies that have been awarded contracts for Phase 1 and their team members are shown in Table 2. The technologies involved in the five systems, the water type, and projected plant locations are given in Table 3. Table 3 shows that these five contracts represent six different desalination technologies (seawater and brackish water reverse osmosis are regarded as two different processes) and five different solar energy technologies.

Table 2. CONTRACTORS FOR PHASE 1

Prime Contractor	Team Members
Boeing Engineering & Construction Co.	Resources Conservation Co. International
Catalytic, Inc.	Science Applications, Inc.
Chicago Bridge & Iron Co.	Foster-Miller Associates Inc. Arabian Chicago Bridge & Iron Co.
DHR, Inc.	Science Applications, Inc. Ionics, Inc. Al-Radwan
Exxon Research & Engineering Co.	Permutit Co., Inc. Ecodyne-Unitec Div. Martin-Marietta Badger Energy, Inc. Saudi Investment Development Center

Table 3. WATER TYPES, PLANT LOCATIONS, AND TECHNOLOGIES FOR FIVE SYSTEMS

Prime Contractor	Water Type	Plant Location	Desalination Technology	Solar Energy Technology
Boeing	Brackish water	Upton County, Texas, United States	One stage reverse osmosis, 2.9 MPa.	Heliostats and central receiver
Catalytic, Inc.	Brackish water	Brownsville, Texas, United States	Reverse osmosis, 2 stages in series, 2.1 and 4.5 MPa.	Wind generators and line-focus thermal collectors
Chicago Bridge & Iron Co.	Seawater	Yanbu, Red Sea, Saudi Arabia	Indirect freezing	Point-focus thermal collectors
DHR, Inc.	Seawater	Yanbu, Red Sea, Saudi Arabia	One stage reverse osmosis in series with electrodialysis	Line-focus thermal collector and photovoltaics
Exxon	Seawater	Yanbu, Red Sea, Saudi Arabia	Two stages of reverse osmosis in parallel with 24-effect distillation	Heliostats and central receiver

The feed-water characteristics for the seawater and the brackish water that the plants must handle are shown in Table 4. The product water provided by the systems must not exceed 500 mg/L of total dissolved solids.

Table 4. FEED WATER ION CONCENTRATION

(in mg/L unless other units are specified)

	Conditions for Seawater	Conditions for Brackish Water
Total Dissolved Solids	44,000	6000
Calcium	510	500
Magnesium	1,600	75
Sodium	14,000	1500
Potassium	500	120
Iron	0.002 - 0.05	0.1
Manganese	—	0.1
Bicarbonate	200	690
Carbonate	—	0
Chloride	24,000	2000
Sulfate	3,400	1100
Nitrate	—	1
Phosphate	0.01	0
Silica	0.01 - 4.00	35
Fluoride	—	4
Total organic carbon	2	—
Turbidity	0.5	—
Plugging Index (%)	95	—
Suspended solids	2	0.5
Temperature (°C)	35	38
Specific gravity	—	1.010
pH (units)	7.3 - 8.1	7 - 7.5

Block diagrams of the five systems are given in Figures 4 through 8. Further details on the subsystems are given in Table 5. Table 5 and the block diagrams should give a good understanding of all systems. All systems have a product water storage capacity of 60,000 m^3.

The Boeing system uses a 20,448 m^2 heliostat field with a central receiver operating at a heat transfer medium (air) temperature of 788° C. The energy storage capacity of 130 MWh is obtained using 1.68 million kg magnesia bricks operating over a temperature range of 227°-788° C. Energy conversion is achieved using a Brayton gas turbine connected to a 0.8 MW electric generator. Backup power is provided by a combustor attached to the turbine and a separate diesel-generator set.

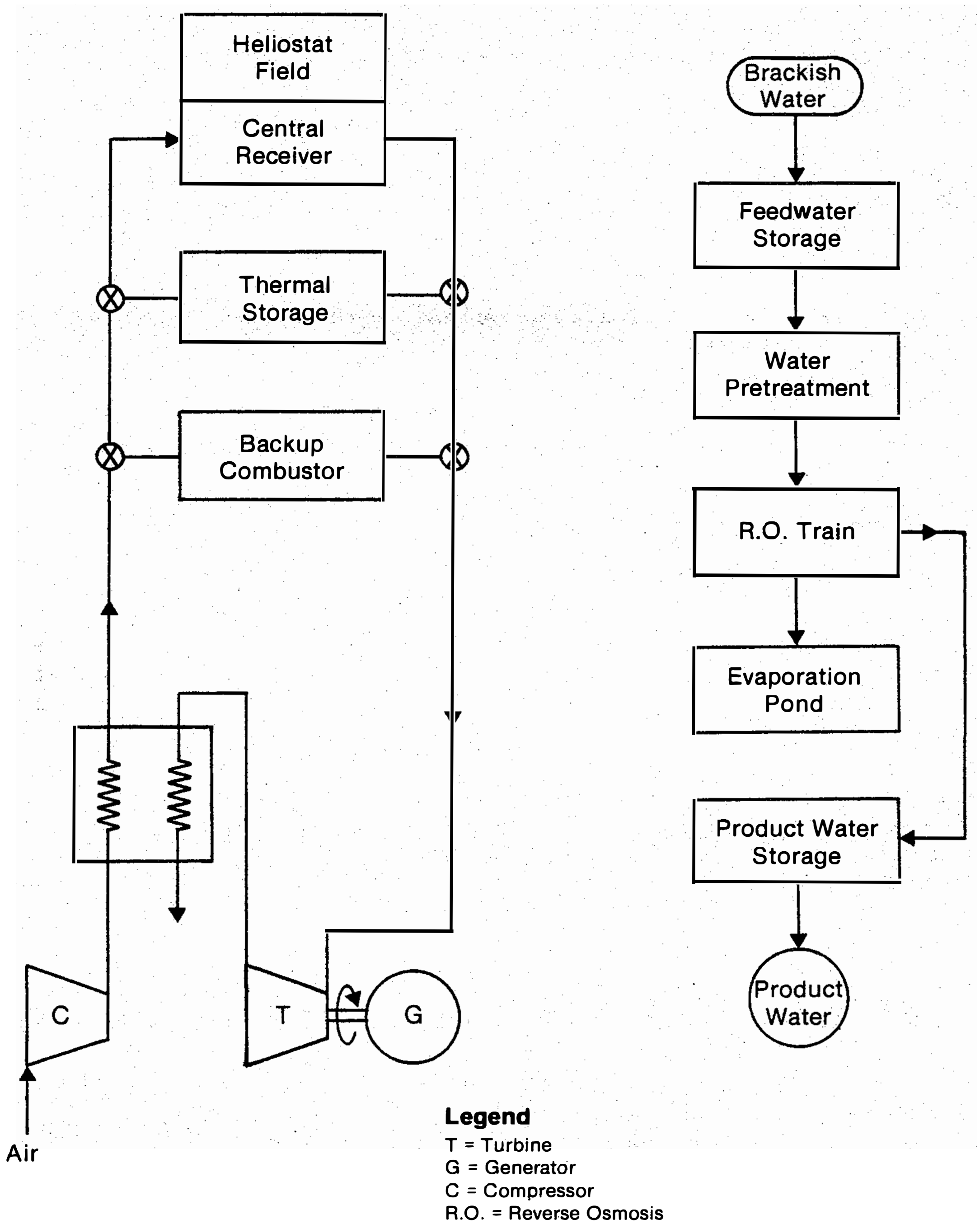

Figure 4. Block Diagram of the Boeing System

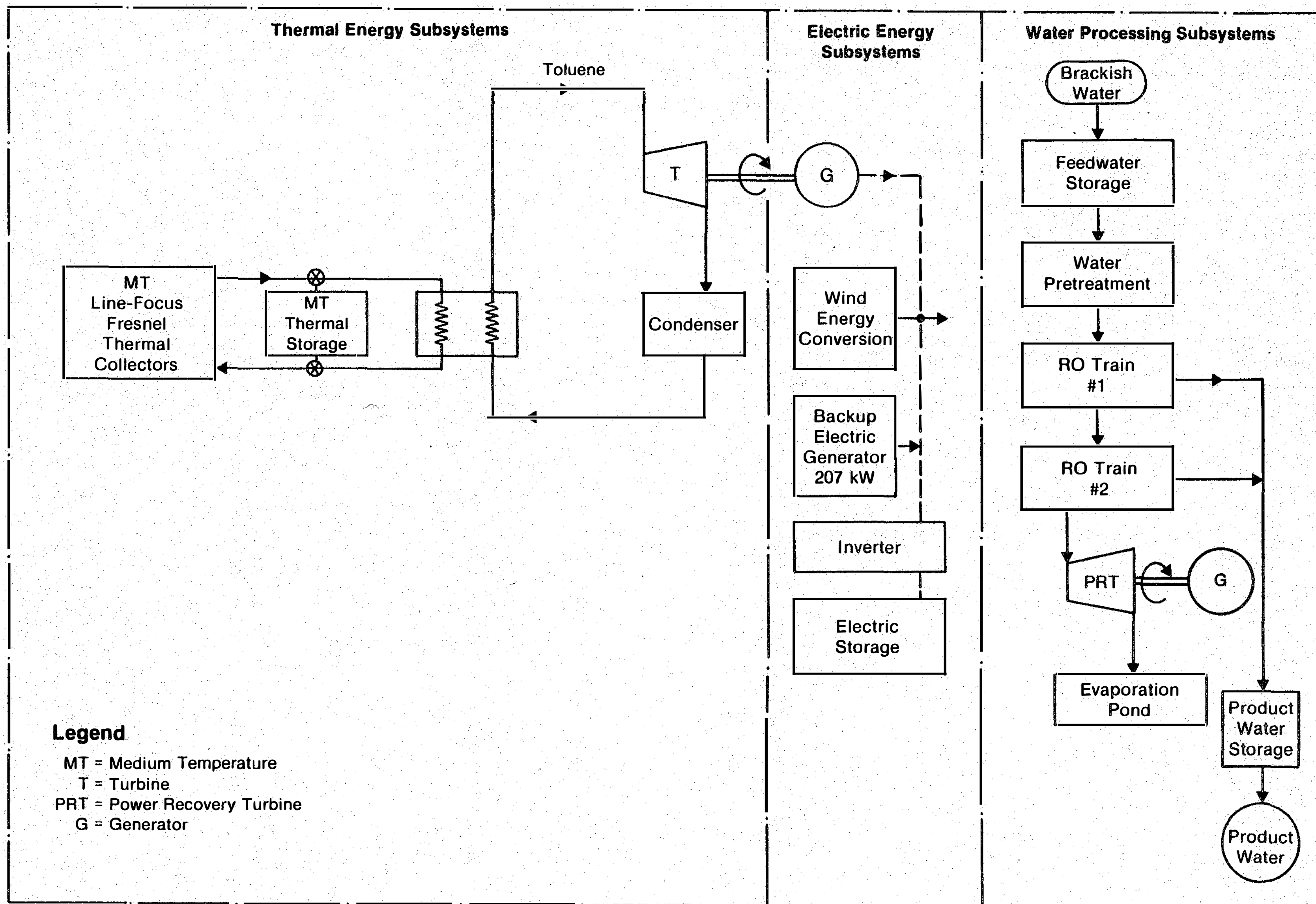

Figure 5. Block Diagram of the Catalytic System

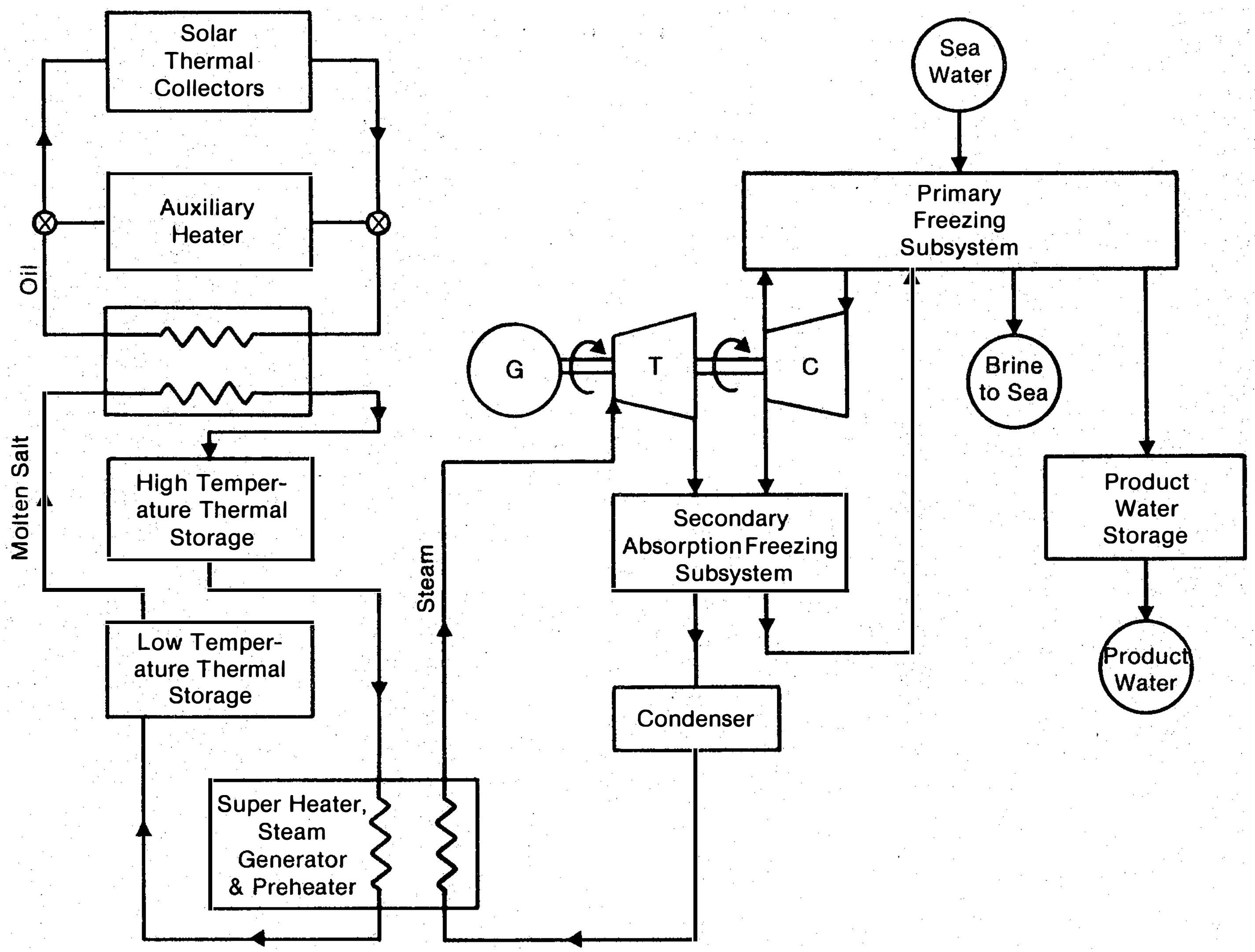

Figure 6. Block Diagram of the Chicago Bridge & Iron System

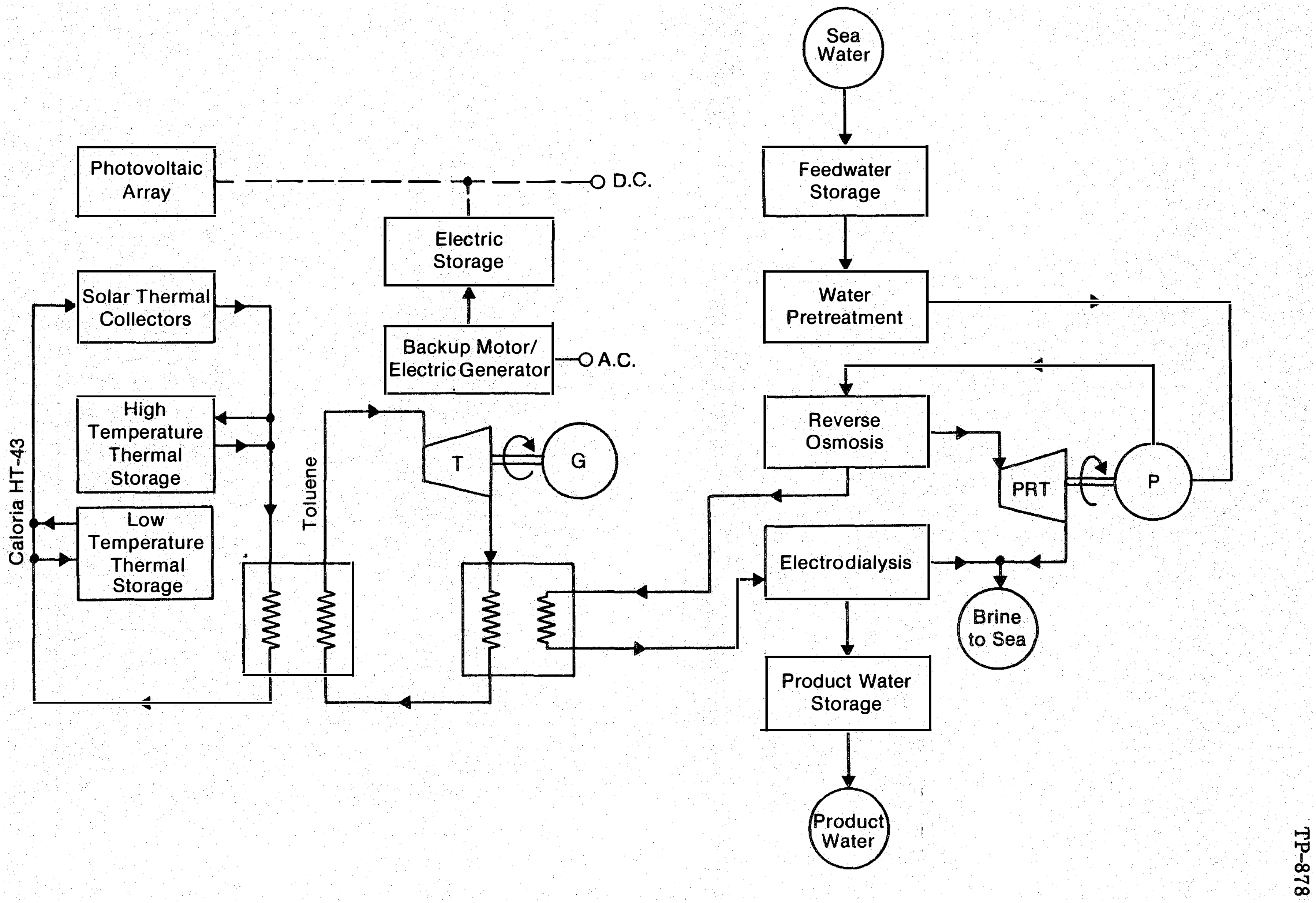

Figure 7. Block Diagram of the DHR System

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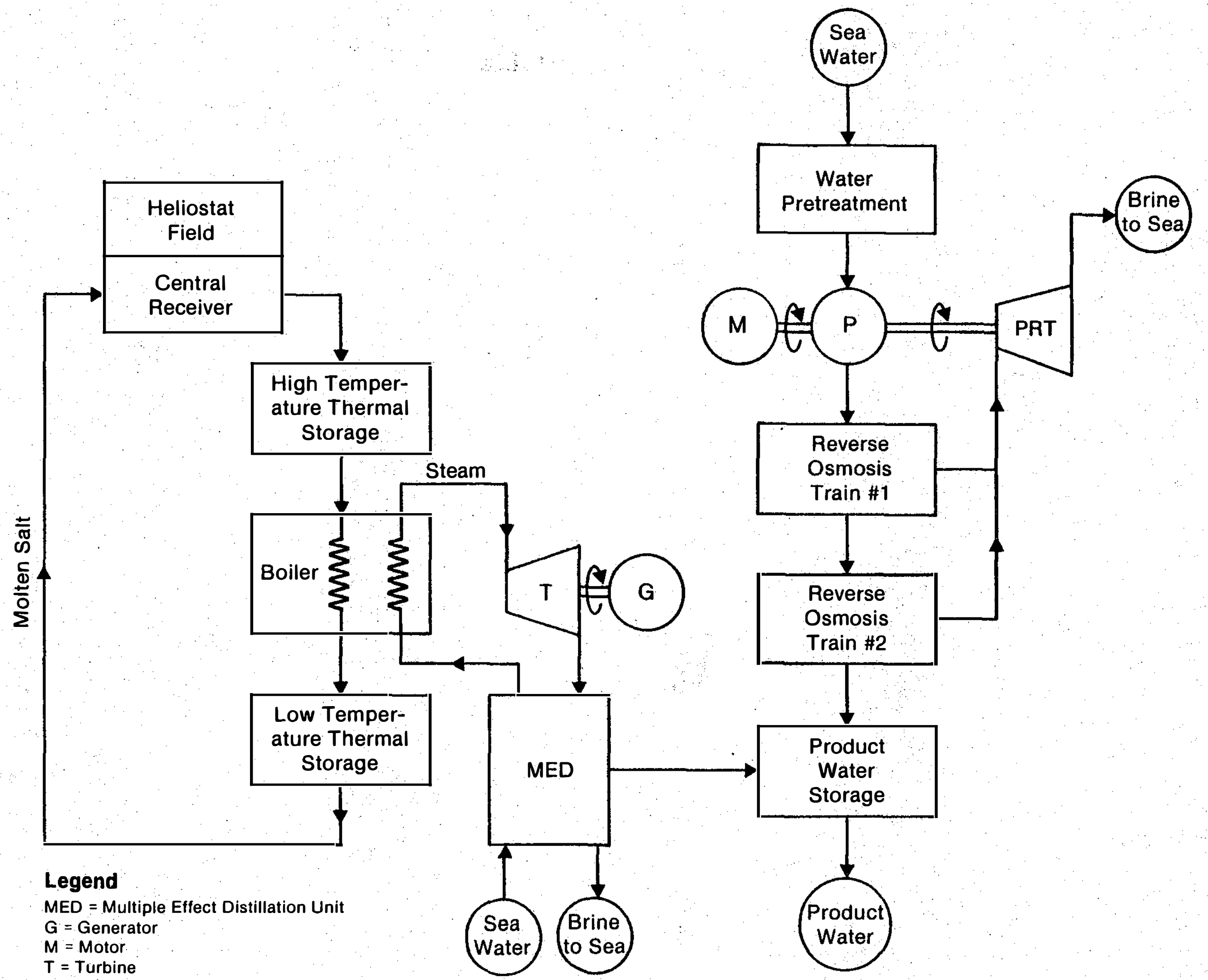

Legend
MED = Multiple Effect Distillation Unit
G = Generator
M = Motor
T = Turbine
PRT = Power Recovery Turbine
P = Pump

Figure 8. Block Diagram of the Exxon System

Table 5. SUBSYSTEMS SUMMARY

Subsystem	Contractor				
	Boeing	Catalytic	Chicago Bridge & Iron Co.	DHR, Inc.	Exxon
Feed-water pretreatment	Yes	Yes	None	Yes	Yes
Feed-water storage	24,000 m^3	18,000 m^3	None	None	None
Solar energy collection	20,448-m^2 heliostats and central receiver (815° C)	12,800-m^2 linear Fresnel thermal collectors and 20 wind generators (4 MW)	43,801-m^2 distributed point focus collectors with 2-axes tracking	56,000-m^2 60X line-focus collectors and 5,000-m^2 flat-plate photovoltaics	22,800-m^2 heliostats & central receiver (566° C)
Energy storage	Magnesia bricks 227-788° C, 130 MWh	33.8-MWh liquid 204-302° C thermal storage, and 500-kWh electric storage	Partherm molten salt 260-400° C, 142 MWh	Caloria HT-43 141-MWh two-tank thermal storage and 600-kWh electric storage	HITEC molten salt 288-566° C, 100 MWh, 2-tank
Energy conversion	Brayton gas turbine with 0.8-MW generator	Steam turbine with 650-kW generator and power recovery turbine	2 MW steam turbine with 560-kW generator and primary refrigeration compressor (1200 kW)	3 Toluene turbines with 3(600) kW AC generators, and 7 power recovery turbines with 160-kW generators each	Steam turbine with 1200-kW generator and power recovery turbine
Waste disposal	Evaporation ponds (578,000^2)	Evaporation ponds (452,000 m^2)	None	None	None
Backup power generator	Combustor and diesel-generator set	Diesel motor with 207-kW generator	6-MW boiler	Diesel motor with 200 kW generator	Diesel motor with generator

The desalination subsystem consists of a single-stage reverse osmosis unit operating at 2.9 MPa. The feedwater is pretreated and stored in one 24,000 m^3 reservoir. The brine is disposed in one evaporation pond having a surface area of 578,000 m^2. The water recovery ratio is 0.72.

The Catalytic solar energy collection subsystem consists of solar thermal collectors having a total area of 12,800 m^2. The collectors are medium-temperature line-focus Fresnel thermal collectors. In addition, 20 wind generators provide a total of 4 MW of electric power.

Thermal energy storage is provided by multiple tanks containing Syltherm 800 liquid with a temperature range of 204-302° C. The total capacity for the thermal storage system is 33.8 MWh. The electric storage capacity is 500 kWh.

Energy conversion is obtained through an organic Rankine-cycle Toluene turbine with a 650 kW electric generator and through the use of a power recovery turbine. Backup power is obtained through a diesel motor with a 207 kW electric generator.

The brackish water is pretreated and uses 18,000 m^3 storage tanks. The desalination subsystem consists of two stages of reverse osmosis units in series, operating at 2.9 MPa and 5.6 MPa. The brine is disposed in 452,000 m^2 surface area evaporation ponds. The water recovery ratio is 0.90.

The Chicago Bridge and Iron system uses 380 distributed point-focus thermal collectors with two axes tracking, each collector having an area of 113 m^2 for a total collector area of 43,801 m^2 Energy storage is obtained through two tanks containing Partherm 430 molten salt operating over a temperature range from 253-378° C and having a capacity of 142 MWh. The desalination is obtained through freezing. The primary freezing unit is driven by a compressor and is augmented by an absorption freezing unit.

The energy conversion subsystem uses a 2 MW steam turbine with a 560 kW electric generator and a 1,200 kW primary refrigeration compressor. Backup power is obtained from a 6 MW boiler, and a 500 kW diesel generator. There is no waste disposal subsystem as the brine is rejected directly into the sea. The water recovery ratio is 0.37.

The DHR system achieves the solar collection by using 56,000 m^2 of 60 power line-focus thermal collectors and 5,000 of flat-plate photovoltaics. Thermal energy storage is provided by four tanks of 141 MWh capacity and using Caloria HT-43 as a heat transfer medium. The storage temperature range is 215°-300° C. Energy conversion is obtained from 3 Toluene turbines with 600-kW-each electric generators and through the use of 7 power recovery turbines each being connected to 160-kW electric generators. Backup power is obtained from a motor with a 200 kW generator.

The desalination subsystem provides for feedwater storage and pretreatment and uses a one-stage reverse osmosis system in series with an electrodialysis unit. There is no waste disposal subsystem as the brine is discharged directly into the sea.

The Exxon system uses a 22,800 m^2 heliostat field with a central receiver operating at a heat medium temperature of 566° C. Energy storage is obtained through sensible heat storage in two thermal storage tanks having a capacity of 100 MWh and operating over the temperature range from 288°-566° C.

The energy conversion is obtained through a noncondensing steam turbine with an inlet steam temperature of 538°C and a 10.34 MPa inlet pressure and a 296 kPa exhaust pressure with a 1200 kW electric generator and through the use of a power recovery turbine. The thermal-to-electric energy conversion efficiency is 22%. Backup power is provided by a motor with a generator.

The desalination is achieved through a two-stage reverse osmosis unit producing 3476 m^3/day product water with 800 mg/L total dissolved solids and having a water recovery ratio of 0.50 in parallel with a 24-effect distillation unit providing 2520 m^3/day water with essentially zero total dissolved solids and having a water recovery ratio of 0.35. There is no waste disposal subsystem as the brine (88 g/L) is directly discharged into the sea.

5.0 COST PROJECTIONS

The primary criterion by which the projected performance will be judged is the levelized product-water cost. The levelized cost is the price per unit of product-water consistent with producing revenue that equals the sum of the system costs, expressed in present value terms. That is, the levelized cost includes capital, maintenance, and operation costs over the life of the system divided by the amount of product water that is produced over that time. To ensure that this levelized cost is being calculated properly by the various contractors, a specific methodology is being imposed [6]. Some of the parameters specified are a system operating lifetime of 20 years with a capital recovery factor of 0.1064 corresponding to 8.6% rate of return in capital over 20 years. These numbers result in a present value of Sum-of-the-Years-Digits depreciation of 0.6376.

There is a basic difference between the seawater desalination systems and those for brackish water in that the former requires neither feed-water storage nor brine disposal ponds. These factors should tend to reduce the product water cost for seawater systems. On the other hand, the seawater plants must desalt water having seven times higher salinity than the brackish water systems.

Projected energy requirements, water costs, and plant costs for the five systems under development are given in Table 6. The energy requirements for these systems can be compared to the minimum theoretical energy required to desalt seawater having a salinity of 34,400 mg/L as shown in Fig. 9 [7].

Table 6. PROJECTED SOLAR ENERGY WATER DESALINATION SYSTEM ENERGY REQUIREMENTS AND COSTS

Company	Water Type[a]	Solar Collector Area (m^2)	Solar Collector Cost ($/$m^2$)	System Energy Requirements (kWh/m^3)	System Energy Requirements (MJ/m^3)	Water Cost ($/$m^3$)	Commercial Plant Cost (M$)
Boeing	B	24.5×10^3	200	10.2	36.7	3.18	30
Catalytic, Inc.	B	9.3×10^3 (Wind)	1500/kW				
		12.8×10^3 (Th)[b]	230	19.6	70.6	4.61	45
Chicago Bridge & Iron Co.	S	43.8×10^3	194	49.3	177.5	2.83	39
DHR, Inc.	S	56×10^3 (PV)[c]	-				
		5.0×10^3 (Th)	178	30.5	109.8	6.80	55
Exxon	S	22.8×10^3	-	18.8	67.7	2.02	19.5

[a]B = Brackish water, S = Seawater
[b]Th = Thermal
[c]PV = Photovoltaics

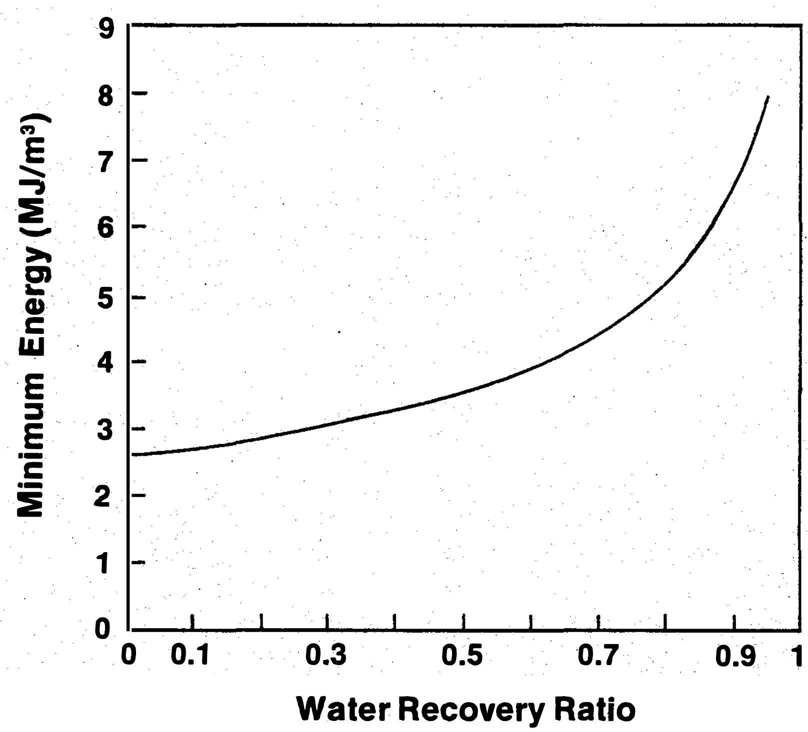

Figure 9. Theoretical Minimum Energy Required for Deslination of Seawater as a Function of Water Recovery Ratio

The cost projections for the two brackish water desalination projects are in the range of \$3.18-\$4.61/m^3 of product water. The projected water costs for the three seawater systems vary widely from \$2.02 to \$6.80. In part, the cost difference is attributed to initial undersizing of the solar collection field for some contractors and less energy efficient systems or inherently more costly systems in other cases. A more detailed cost analysis by subsystem for each contractor's system is in progress. At the conclusion of this study, more reliable cost data should be available.

The projected costs for the solar energy water desalination systems should be compared to product-water costs from conventionally powered plants shown in Table 7 [3, 8].

Table 7. PRODUCT WATER COSTS FOR VARIOUS CONVENTIONAL DESALINATION PROCESSES IN \$/m^3

Process	Plant Capacity (m^3/day)	Product Water Costs (\$/m^3)	Reference[a]
Distillation	3,800	1.69 - 1.45	8
	190,000	0.72	3
	380,000	0.57 - 0.75	8
Freezing	190,000	0.42	3
Reverse osmosis	380 - 19,000	1.14 - 1.73	8
Seawater	190,000	1.00	3
Reverse osmosis	4,000 - 95,000	0.25 - 0.36	8
Brackish water	190,000	0.26	3
(2,000-5,000 mg/L)			
Electrodialysis	190,000	1.10	3
Seawater			
Electrodialysis	4,000 - 90,000	0.16 - 0.25	8
Brackish water	95,000	0.19 - 0.35	3
(2,000-5,000 mg/L)			

[a]3, in 1978 dollars; 8, in 1979 dollars

Table 8. THERMAL ENERGY STORAGE SUBSYSTEM DATA

Company	Medium	Temperature (°C)	Capacity (MWh)	Capacity (GJ)	Capacity (hrs)
Boeing	3 tanks magnesia bricks (1.68 million kg)	227-788	130	468	39
Catalytic, Inc.	Multi-tank Syltherm 800 Liquid	204-302	33.8	122	10
Chicago Bridge & Iron	2-tank Partherm 430 molten salt	253-378	142	511	13
DHR, Inc.	2-tank Caloria HT-43	215-300	141	508	16
Exxon	2-tank molten salt (60%, $NaNO_3$/40% KNO_3)	288-566	100	360	24

Table 9. SOLAR ENERGY WATER DESALINATION SYSTEM PERFORMANCE DATA

	Contractor				
Parameter	Boeing	Catalytic	CB&I	DHR	Exxon
Effective collector area (10^3 m^2)	20.5	9.3 (w) 12.8 (th)	43.8	56.0 (th) 5.0 (e)	22.8
Total incident energy on collectors (MWh/yr)[g]	—	38,300 (w)[a] 54,700 (th) 93,000	—	— 11,400 (e)[c]	—
Total incident energy on collectors (MWh/m^2-yr)[g]	—	4.12 (w) 4.27 (th)	—	2.28 (e)[f]	—
Direct incident energy on collectors (MWh/yr)	44,658	—	133,260	135,000 (th)[b]	68,720
Direct incident energy on collectors (MWh/m^2-yr)	2.18[d]	—	3.04[b]	2.41 (th)[e]	3.01[d]
Total energy collected at 100% system availability (MWh/yr)	22,374	19,900 (w) 23,000 (th) 42,900	95,460	64,400 (th) 1,030 (e) 65,430	41,285
System availability	0.91	0.82	0.93	0.90	0.82
Total energy collected at system availability (MWh/yr)	20,360	16,300 (w) 18,900 (th) 35,200	88,778	57,960 (th) 927 (e) 58,887	33,854
Collection efficiency (1) = total energy collected at 100% availability divided by total incident energy[g]	—	0.52 (w) 0.42 (th)	—	— 0.090 (e)	—
Collection efficienty (2) = total energy collected at 100% availability divided by direct incident energy	0.50	—	0.72	0.48 (th)	0.60
Product water output at system availability (10^6 m^3/yr)	2.0	1.8	1.8	1.93	1.8
Total incident energy per unit product water (kWh/m^3)	22.3	51.7	74.0	75.8	38.2
Total collected energy at system availability per unit product water (kWh/m^3)	10.2	19.6	49.3	30.5	18.8

[a]w = wind
[b]th = thermal
[c]e = electric
[d]2 axix tracking
[e]1 axis tracking
[f]no tracking
[g]direct and diffused

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