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STUDY OF THE POTENTIAL FOR USING LIQUID CARBON DIOXIDE FOR FRESHWATER PRODUCTION AT AQUATRAIN COAL TRANSPORT PIPELINE TERMINUS SITES

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16. ABSTRACT

In this study, the Bureau of Reclamation investigated the technical and economic feasibility of using energy both from the expansion of liquid CO_2 (carbon dioxide) planned for use as a transport medium in the proposed Aquatrain coal slurry pipeline and from salt-gradient solar ponds to produce freshwater at pipeline terminus sites in Utah and southern California. An analysis is provided of a combined freeze/RO (reverse osmosis) plant, which would be used to desalt waste saline waters collected from the Colorado River Basin, also planned for transport in the slurry pipeline. Desalting would be achieved in two stages: first, by an RO process powered by a solar-pond-coupled ORC (organic Rankine cycle) heat engine, and secondly, by a freeze process using vaporizing CO_2 directly to freeze RO reject brine. For comparison, an analysis is provided for a similar desalting system, without the freeze process, which would use liquid CO_2 as a direct heat sink for the ORC.

A cost comparison of the two desalting systems is provided: first, with solar ponds as the source of power, and secondly, assuming a coal-fired steam plant, which is the most likely alternate source of power. Freshwater produced using the solar-pond-coupled RO process without freeze desalination was found to be the most cost effective, with product water costs ranging between $2.02 and $2.30 per kgal (1982 dollars). Water costs using coal-fired steam as the power source and RO alone were the next competitive, between $2.42 and $2.67 per kgal. The higher unit cost of water for the combined system is due to the disproportionately larger capital costs and parasitic power requirements associated with the freeze process.

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STUDY OF THE POTENTIAL FOR USING LIQUID CARBON DIOXIDE FOR FRESHWATER PRODUCTION AT AQUATRAIN COAL TRANSPORT PIPELINE TERMINUS SITES

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September 1984

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INTRODUCTION

This report presents the results of a study that evaluated the potential for using liquid CO_2 (carbon dioxide) for freshwater production employing selected desalination processes at Aquatrain coal transport pipeline terminus sites. The Saline Water Transport and Use Office has proposed the use of liquid CO_2 as a medium for transporting coal through a slurry pipeline from sources in Colorado and Wyoming to powerplants in Utah, Nevada, and southern California. The same or a parallel pipeline would be used to transport waste saline waters collected from selected salinity control sites in the Colorado River Basin for disposal in either Sevier Dry Lake, Utah, or at a location near Blythe, California. It is estimated that 34,000,000 tons of coal and 120,000 acre-feet of saline water could be transported annually. This study assesses the potential for using available resources (saline water, liquid CO_2, and solar energy) at a terminus site to economically recover freshwater using existing technology.

Funding for the study was provided by the Colorado River Water Quality Office in support of the Saline Water Use and Disposal Opportunities Unit. Current information on the Aquatrain Project can be found in [1]*.

SUMMARY

Preliminary thermodynamic and economic assessments are presented for a combined freeze/RO (reverse osmosis) desalting plant that uses both liquid CO_2 and a solar-pond-coupled ORC (organic Rankine cycle) heat engine as energy sources. Saline water from the slurry pipeline or other local source would be desalted in two stages: first, by an RO process powered by the solar-pond-coupled ORC, and secondly, by a freeze process using vaporizing CO_2 directly to freeze RO reject brine. The freeze process melter would provide a subambient temperature heat sink for the ORC engine, thereby increasing its thermodynamic cycle efficiency by 30 to 40 percent over that obtained in a typical solar-pond-coupled system. The freeze plant would also support the solar pond by supplying concentrated reject brine for storage layer maintenance. Assuming an initial feedwater concentration of 3000-mg/L TDS (total dissolved solids), it is estimated that a product water recovery of 96 percent could be achieved for the combined desalting stages. Estimates for the total production and cost of freshwater are provided for a conceptual system located near Blythe, California.

For comparison, an analysis is provided for a similar desalting system, without the freeze process, which would use liquid CO_2 as a direct heat sink for the ORC engine.

The most significant conclusions drawn from this study are:

- Aquatrain and its coal slurry transport medium (liquid CO_2) matches well with the organic Rankine power module because it provides a lower condensing temperature, and therefore a higher (30 to 40 percent) thermodynamic cycle efficiency than typically achieved with a solar-pond-coupled system.
- The amount of liquid CO_2 available at the proposed Aquatrain terminus site near Blythe, California should be sufficient to accommodate freeze and/or RO desalination plants with a total capacity of 2.5 to 3.0 Mgal/d.
- Despite its advantages in theoretical desalting energy efficiency, freeze desalination requires so much parasitic power for recirculating slurry that it is less favorable than RO for desalting brackish waters.
- Freshwater (500-mg/L TDS) produced as described herein would cost (1982 dollars) between \$2.60 and \$2.88 per kgal using a solar-pond-coupled freeze/RO system, and between \$2.02 and \$2.30 per kgal using solar-pond-coupled RO alone. Water costs using coal as the conventional power source range between \$3.00 and \$3.25 per kgal for the combined system, and between \$2.42 and \$2.67 per kgal for the RO system alone. The higher unit cost of water for the combined system is due to the disproportionately larger capital costs associated with the freeze process, which are first or second plant costs as opposed to *nth* plant costs for the RO equipment.

ENERGY SOURCES

Liquid Carbon Dioxide

Large quantities of CO_2 at subambient temperatures could be available from solid-gas coal separators at deslurrying points along the proposed pipeline to drive freeze desalination processes. Based on preliminary information regarding the expected thermodynamic state of CO_2, just before and after coal separation, it is estimated that nearly 100 Btus could be absorbed during the vaporization of each pound of liquid CO_2: enough to freeze approximately 0.7 lb of water per lb of CO_2. Little information is available on the planned design and operation of the separators. However, it is known that one process consideration is to supply heat during separation to permit isothermal expansion near the critical temperature of 80°F, as shown by line 1-2-3-4 on figure 1. These

* Numbers in brackets refer to entries in the bibliography.

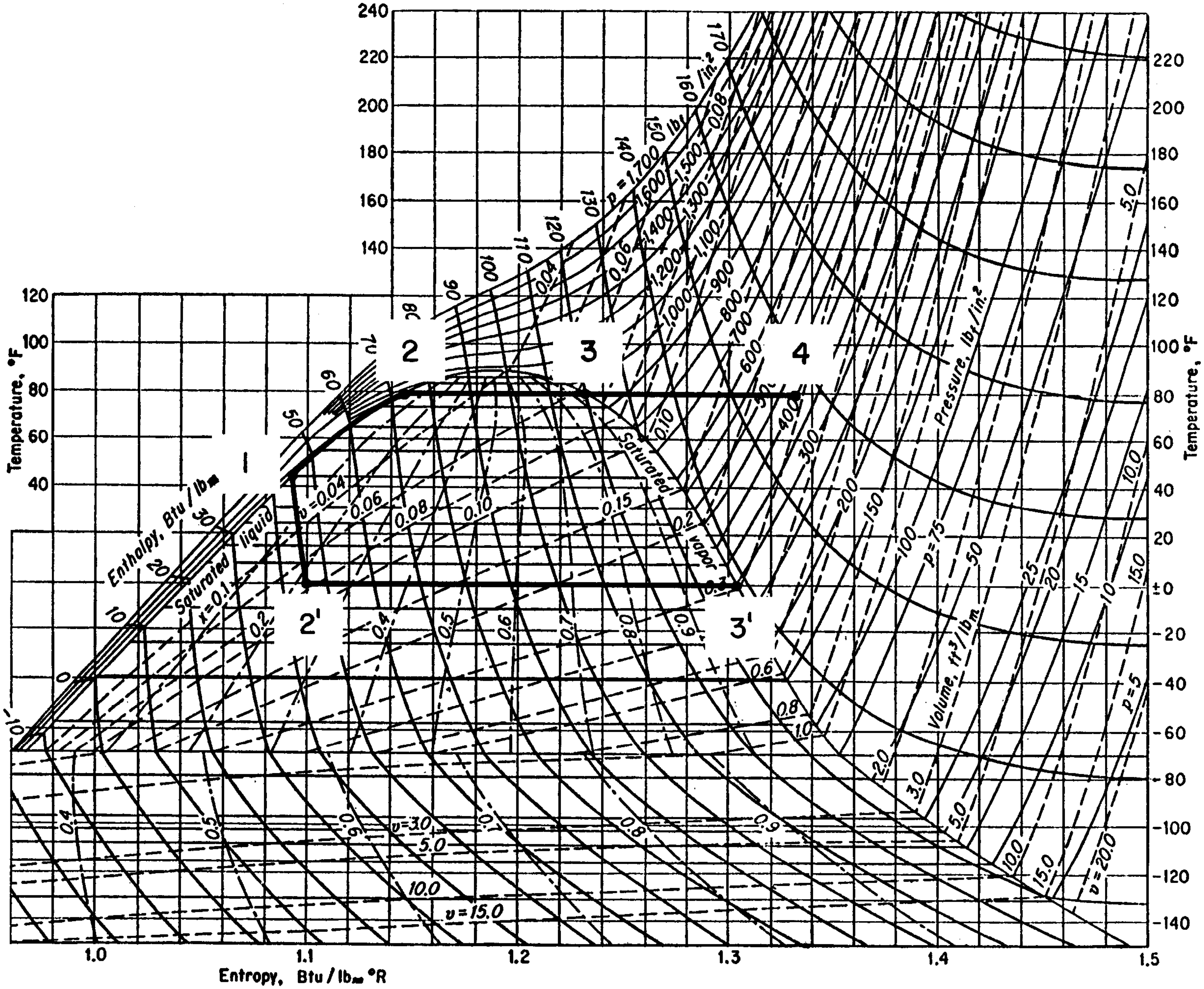

Figure 1. – Temperature-entropy diagram for carbon dioxide.

operating conditions offer little potential for desalting. If, however, the separation were to proceed along path 1-2'-3' [adiabatic expansion to a temperature near 0°F to provide a driving force for freezing saline water, followed by an isothermal expansion to between 300 and 400 lb/in^2 (abs)], nearly 100 Btu/lb would be available for heat exchange with saline water, which would be sufficient to keep the separator at a constant temperature without supplemental heat input. The effluent gas pressure in either method would be roughly the same.

Salt-gradient Solar Pond

Briefly, a salt-gradient solar pond is a shallow body of saline water, generally between 2 and 5 m deep, that functions like a flat-plate solar collector. It is constructed, as shown on figure 2, in three distinct layers or zones.

- ***Upper convecting zone*** – a thin, top layer of low-salinity water, containing vertical convection currents caused by wind and evaporation.
- ***Nonconvecting or salinity-gradient zone*** – an intermediate layer, in which the concentration of salt increases with depth to about 20 percent by weight.
- ***Lower convecting zone*** – a bottom layer of uniformly high salt concentration, which is used for heat storage.

The salinity-gradient zone acts as a thick layer of insulation by inhibiting convective heat losses from the storage zone. With these losses suppressed, a considerable amount of the solar radiation absorbed throughout the storage layer is trapped, enabling storage temperatures to increase substantially. Energy can then be extracted from the pond by recycling the hot storage layer brine through a heat exchanger, as shown on figure 3. Typically, pond storage temperatures range between 160 and 212°F (70 to 100°C) with pond thermal conversion efficiencies ranging from 15 to 20 percent.

The solar radiation intensity at the pond site and the thermodynamic cycle efficiency of the ORC are two of the more important variables that determine the unit electric energy output (W/m^2 of pond area) for the solar pond system. The amount of solar radiation on the pond surface determines the amount of thermal energy that can be collected and extracted from the pond. The available solar radiation at Blythe, California is among the highest in the United States; the annual average is approximately 245 W/m^2. The ORC

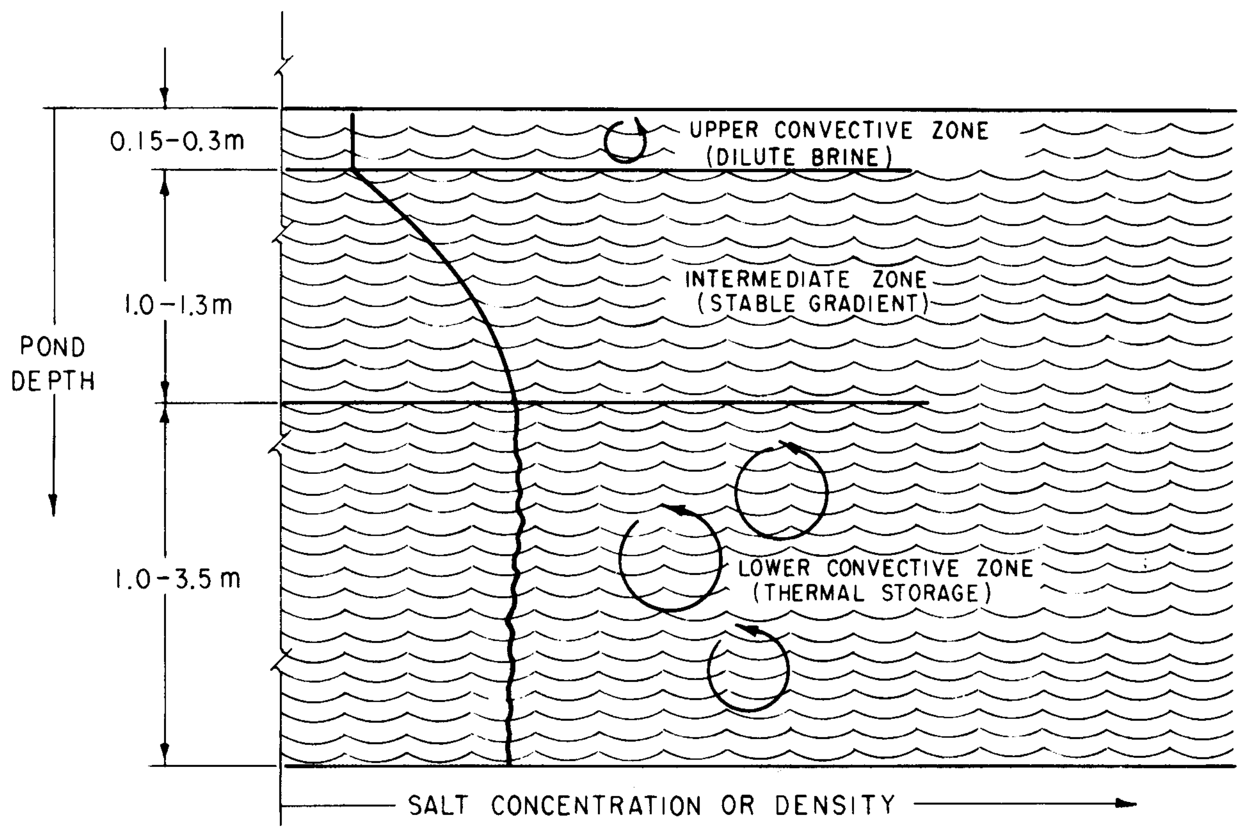

Figure 2. – Solar pond cross section.

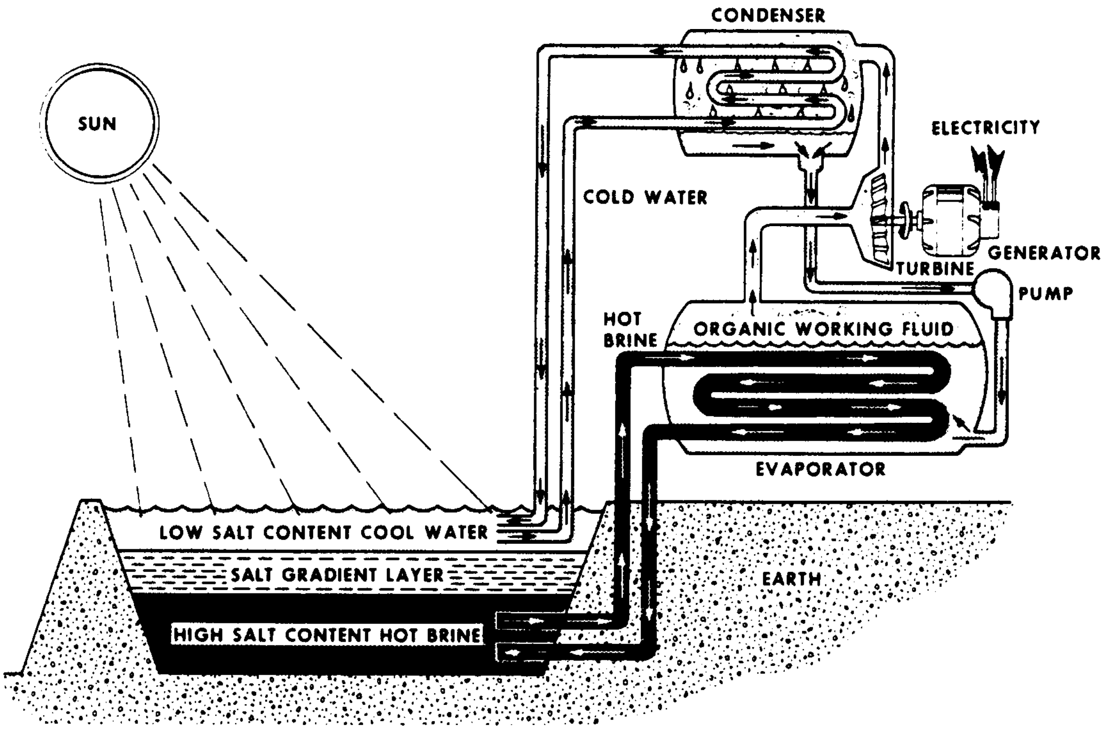

Figure 3. – Solar pond power generation concept.

thermodynamic cycle efficiency is directly proportional to the difference between the maximum cycle temperature and minimum condensing temperature, which for this study are 176 and 44°F, respectively. This temperature difference, which is achieved by using the vaporizing CO_2 as a heat sink, yields a unit electric energy output between 30 and 40 percent greater than can be obtained by using an ambient temperature cooling source.

SYSTEM DESCRIPTION AND TECHNICAL EVALUATION

Two process cases are considered in this report: the first involving combined freeze/RO desalting, and the second desalting by RO alone.

Case 1 – Combined Freeze/Reverse Osmosis Desalting

The first system evaluated, in which liquid CO_2 is used as a coolant source to drive a freeze desalination process, is shown schematically on figure 4. In this system two desalination stages are used. In the first stage an RO unit provides an initial 70-percent product water recovery (process feed water was assumed for this study to have a concentration of 3000 mg/L TDS). In the second stage the RO reject brine at about 12 000 mg/L is used as the feed to a freeze desalting plant, driven by expanding CO_2, which would concentrate the RO reject brine to about 70 000 mg/L. The combined recovery for both stages is approximately 96 percent. Electric energy needed for the two desalting plants and other pumping would be provided by an ORC heat engine operating from a solar pond as the heat source on the boiler side and the freeze process melter as the heat sink on the condenser side. Solar pond surface flush and brine makeup would be supplied, as shown on figure 4, by process feed water and concentrated freeze reject, respectively. Process flow data for this system are presented in table 1.

The following is a brief discussion of each of the major system components shown on figure 4.

- ***Separator heat exchanger*** – Because of the uncertainty associated with the planned design and operation of the separator, some liberty was taken in conceptualizing the extraction of "cold Btu's." It was assumed that a heat exchanger within the separator would transfer energy by a two-phase NH_3 (ammonia) cycle to the freeze heat exchanger. The freeze desalination plant capacity, 0.68 Mgal/d, was determined by the available Btu's from the CO_2 expansion. Thermodynamic state conditions for the NH_3 cycle are shown in table 1 (points 32 and 33). The separator heat exchanger area required to transfer 40.0 MBtu/hr was calculated to be 10,000 ft², assuming an overall heat transfer coefficient of 210 Btu/hr-ft²-°F.

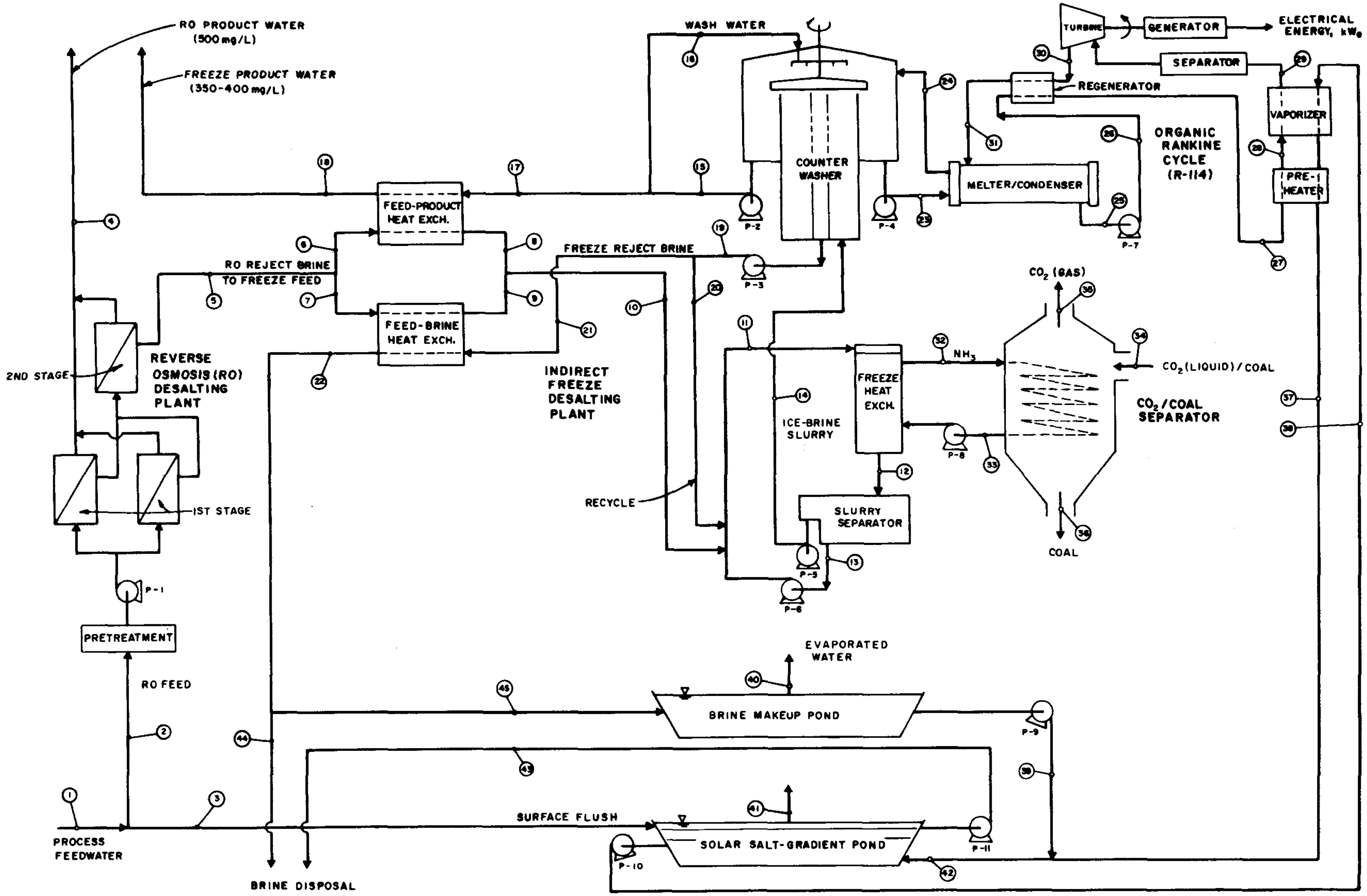

Figure 4. – Process flow diagram for Case 1 – combined freeze/reverse osmosis desalting. Note: circled numbers refer to process monitoring points shown in table 1.

Table 1. – Process flow data for Case 1 – combined freeze/reverse osmosis desalting.

Point	Flow		Temp	Composition (wt %)			TDS
	lb/hr x 10^{-3}	gal/min	°F	H_2O-solid	aqueous sol'n	H_2O-liquid	%
1	1,058	2,110		0	100	99.7	0.30
2	923	1,840		0	100	99.7	0.30
3	135	268		0	100	99.7	0.30
4	646	1,290		0	100	99.95	0.05
5	277	550		0	100	98.89	1.11
6	228	453		0	100	98.89	1.11
7	48.7	96.7		0	100	98.89	1.11
8	228	453	36.0	0	100	98.89	1.11
9	48.7	96.7		0	100	98.89	1.11
10	277	550		0	100	98.89	1.11
11	23,200	44,100	25.2	0	100	93.13	6.87
12	23,200	44,100	25.0	1.1	98.9	93.06	6.94
13	21,600	41,000	25.0	0	100	93.06	6.94
14	1,620	3,080	25.0	15.0	85.0	93.06	6.94
15	385	768	33.0	0	100	99.96	0.04
16	149	298	33.0	0	100	99.96	0.04
17	236	471	33.0	0	100	99.96	0.04
18	236	471		0	100	99.96	0.04
19	1,390	2,630	25.1	0	100	93.1	6.90
20	1,340	2,550	25.1	0	100	93.1	6.90
21	41.4	78.5	25.1	0	100	93.1	6.90
22	41.4	78.5	77.0	0	100	93.1	6.90
23	3,600	7,180	33.0	0	100	99.96	0.04
24	3,600	7,180	43.0	0	100	99.96	0.04
37	4,590	7,820	174	0	100	79.4	20.6
38	4,590	7,820	185	0	100	79.4	20.6
39	8.4	13.9		0	100	78.3	21.7
40	18.1	36.0		0	100	100	0.00
41	97.0	194		0	100	100	0.00
42	4,600	7,840		0	100	79.4	20.6
43	45.8	88.6		0	100	95.16	4.84
44	14.9	28.4		0	100	93.1	6.90
45	26.3	50.1		0	100	93.1	6.90

Point	Fluid	Flow lb/hr x 10^{-3}	Pressure lb/in² (abs)	Temp °F	Liquid Phase %	Vapor Phase %
25	R-114	595	16.4	44	100	0
26	R-114	595	16.4	44	100	0
27	R-114	595		78	100	0
28	R-114	595	134	176	100	0
29	R-114	595	134	176	0	100
30	R-114	595		97	0	100
31	R-114	595		55	0	100
32	NH_3	72.2	47.2	19.0	0	100
33	NH_3	72.2	47.2	19.0	100	0
34	LCO_2	400	300	0	79.8	20.2
35	GCO_2	400	300	0	0	100

- ***Indirect freeze desalination process*** – Technical data used for the freeze desalination plant were obtained from the test results of a 6,000 gal/d indirect freeze desalination pilot plant developed by CB&I (Chicago Bridge and Iron) [2]. The developmental work and testing, sponsored by the Office of Water Research and Technology, has concentrated on the design of a new vertically installed shell-and-tube freeze heat exchanger, which uses electropolished stainless steel tubes. The heat exchanger has overcome many of the problems associated with past designs, particularly ice fouling of the heat exchanger surfaces. The normal heat flux and overall *U*-value achieved during testing were 1400 Btu/hr-ft^2 and 250 Btu/hr-ft^2-°F, respectively. The optimum freeze heat-exchanger operating salinity was determined to be between 7 and 8 mass percent TDS to avoid ice fouling of the exchanger tubes (see points 11 through 14 in table 1). Product water recovery and concentration, based on the use of RO brine reject as feed, are approximately 85 percent and 350 to 400 mg/L, respectively.

- ***Reverse osmosis desalination process*** – A two stage RO unit was assumed, operating at a product water recovery of 70 percent with a feed and product water salinity of 3000 and 500 mg/L TDS, respectively. The RO unit was sized (rated product water capacity of 1.86 Mgal/d) just large enough to provide a brine reject stream to feed the freeze plant. Because the feed water characteristics are unknown, accurate information regarding actual pretreatment cannot be developed. Later, in the economic analysis, a "typical" cost for pretreatment was assumed based on data from the Yuma Desalting Test Facility and other operating RO plants.

- ***Organic Rankine cycle*** – The ORC heat engine, using Refrigerant 114 as the working fluid, was sized so that the heat released in the condenser matched that required for melting ice. The calculated electric generating capacity of 1.57 MWe (gross continuous) turned out to be within a few percent of satisfying the requirements of all the component systems shown on figure 4; i.e., no residual electric energy would be produced. The assumed heat engine would operate at a maximum cycle temperature and minimum condensing temperature of 176 and 44°F, respectively, as shown in table 2. The working fluid would vaporize before entering the turbine at 176°F, using thermal energy supplied by the solar pond at 185°F. To help improve the cycle efficiency, a regenerator (heat exchanger) was used to recover energy in the fluid leaving the turbine by the transfer of heat from the low-pressure vapor to the high-pressure fluid. The low cycle condensing temperature of 44°F was obtained by circulating cooling water at 33°F, produced in the melter of the freeze desalination loop, through the condenser. This resulted in a thermodynamic cycle efficiency (neglecting mechanical losses) of 13.2 percent based on the component performance data shown in table 2. This table summarizes the thermodynamic and heat transfer conditions for both the ORC and NH_3 systems.

- ***Salt-gradient solar pond*** – The solar pond parameters used for this study were assumed to be the same as those determined for an earlier report dealing with solar pond development at Danby Dry Lake in southeastern California [3]. The average storage layer temperature and unit thermal output for the pond are estimated to be 185°F and 50.0 W/m^2, respectively. As with the previous systems, the solar pond was sized just large enough to provide the thermal energy required by the ORC. At a brine recirculation rate of 4.59x10^6 lb/hr and ΔT of 11°F (across the vaporizer and preheater of the ORC – see lines 37 and 38 on fig. 4), the pond would be sized at about 0.23 km^2 for a total thermal output of 11.3 MW. As noted earlier, the surface flush and brine makeup required to support the solar pond would be supplied by process feed water and concentrated freeze reject, respectively.

The expected power generation and associated system energy requirements for Case 1 are summarized in table 3. Also shown are the assumed desalination plant capacities and unit energy consumptions. In the case of RO, the values represent a compromise between the predictions made in the *Desalting Handbook for Planners* [4] and available operating data for existing commercial systems [5, 6]. Parasitic energy requirements for the freeze plant were assumed to equal 75 percent of the actual energy consumption measured for the CB&I pilot plant. The 75 percent scaling factor was agreed on by the CB&I engineering staff.

Case 2 – Reverse Osmosis Desalting Alone

For comparison, an analysis is provided for a system similar to that in Case 1, but without the freeze process. This system would use liquid CO_2 as a direct heat sink for the solar-pond-powered ORC (see fig. 5). Without the intervening freeze process the energy transfer between the separator and condenser (see lines 32 and 33 of table 4) is increased by about 10 percent, which contributes to corresponding increases in the ORC and solar pond capacities. Otherwise, the operation of the ORC, NH_3 loop, and solar

Table 2. – Selected thermodynamic and heat transfer data for Case 1.

	Hot Brine (to ORC vapor./preheater)	Cooling Water (to ORC condenser)
Water Subsystem		
Inlet temperature, °F	185	33
Outlet temperature, °F	174	43
Flowrate, lbm/hr x 10^{-3}	4590	3600
NH_3 Subsystem (to freeze heat exchanger)		
Temperature, °F	19	
Pressure, lb/in² (abs)	47.2	
Heat of vaporization, Btu/lbm	554	
Flowrate, lbm/hr x 10^{-3}	72.2	
Separator heat exchanger (LCO_2/coal)		
Thermal duty, MBtu/hr	40.00	
Overall heat transfer coefficient, Btu/hr-ft²-°F	210	
Surface area, ft²	10,000	
ORC Working Fluid (R-114)		
Flowrate, lbm/hr x 10^{-3}	595	
Boiling temperature, °F	176	
Boiling pressure, lb/in² (abs)	134.2	
Condensing temperature, °F	44	
Condensing pressure, lb/in² (abs)	16.4	

	Vaporizer	Condenser	Preheater
ORC Heat Exchangers			
Water inlet temperature, °F	185	33	178
Water outlet temperature, °F	178	43	174
Working fluid temperature, °F	176	44	—
Corrected LMTD, °F	4.7	11.5	24.3
Thermal duty, MBtu/hr	26.03	35.97	15.39
Overall heat transfer coefficient, Btu/hr-ft²-°F	300	250	150
Surface area, ft²	18,500	12,600	4,300

		Liquid	Vapor
Regenerator			
Inlet temperature, °F		44	97
Outlet temperature, °F		78	55
Corrected LMTD, °F	14.6		
Thermal duty, MBtu/hr	4.15		
Overall heat transfer coefficient, Btu/hr-ft²-°F	10		
Surface area, ft²	28,500		

Table 3. – System power generation/energy consumption.

	Case 1 (including freeze desalination)	Case 2
Rated ORC capacity, kWe	1683	1869
Gross continuous power, kWe (93 percent plant factor)	1565	1738
ORC losses (10 percent)[1/]	-157	-174
Net continuous ORC power, kWe	1408	1564
Solar pond losses (7.5 percent)[2/]	-117	-130
Pump P-8 losses	-5	-5
Net continuous electric power available for desalting, kWe	1286	1429
Freeze plant requirement, kWe	-353	0
RO plant requirement, kWe	-957	-1429
Residual electric power, kWe	-24	0
Pond thermal output, MWt[3/]	11.3	12.6
Solar pond area required, km^2[4/]	0.23	0.25
Evaporation pond area required, km^2	0.05	0.09
Freeze plant rated capacity, kgal/d	678	—
Freeze plant average capacity, kgal/d	631	—
Freeze plant energy consump., kWh/kgal	13.4	—
RO plant rated capacity, kgal/d	1858	2774
RO plant average capacity, kgal/d	1728	2580
RO plant energy consump., kWh/kgal[5/]	13.3	13.3

1/ Includes feed pump energy requirements, mechanical losses (seals, bearings, etc.), and equipment pressure drop.
2/ Includes brine recirculation, makeup, and surface flush pump energy requirements.
3/ $\dot{m}_{brine}$ = 4.59 x 10^6 and 5.11x10^6 lb/hr in the brine recirculation line for cases 1 and 2, respectively; C_p = 0.82 Btu/lb-°F; ΔT = 11°F.
4/ Assumes a unit thermal output equivalent to that at Danby Dry Lake of 49.98 MWt/km^2 [2].
5/ 3000 mg/L feed water

pond are the same as in Case 1. Process flow and selected thermodynamic and heat transfer data for the ORC and NH_3 loop are summarized in tables 4 and 5, respectively.

Because the size of the RO plant is not dictated by the freeze plant feed requirements, its rated capacity of 2.77 Mgal/d was determined by the amount of energy available from the ORC, after other system parasitic requirements had been met (see table 3). RO brine reject is used initially as surface flush for the solar pond and again, after concentration, as brine makeup.

ECONOMIC ANALYSIS

A brief economic analysis was performed to determine the capability of the Case 1 and Case 2 systems to produce low-cost water. This was done by comparing the cost of water ($/kgal of product) using solar ponds as the source of power with the cost of water using a coal-fired steam plant, the most likely alternate source of power for this application. The economic assumptions used in the analysis are listed in table 6.

The energy costs shown in table 7 are based on the results of earlier USBR (Bureau of Reclamation) studies [3,7], which investigated the performance, operation, and cost of solar-pond-coupled power generation systems. Those studies were performed in accordance with the planning guidelines then in effect for Federal water resource development projects [8]. These guidelines required the calculation of power generation costs using the Federal discount rate and projected values (in real terms) for the cost of fuel.

The results of the economic analysis are plotted in the form of bar graphs on figure 6. These graphs show that the unit cost of product water from the combined freeze/RO system (Case 1) is greater than that for the RO system alone (Case 2). This is primarily due to the disproportionately larger capital costs associated with the freeze process, which are first or second plant costs as opposed to *nth* plant costs for the RO equipment. The Case 2 system desalination costs are also less because of the improved ORC engine performance that is achieved as a result of being able to use the separator heat exchanger as a direct heat sink for the engine.

Table 4. – Process flow data for Case 2 – reverse osmosis desalting alone.

Point	Flow lb/hr x 10^{-3}	Flow gal/min	Temp °F	Composition (wt %) H_2O-solid	Composition (wt %) aqueous sol'n	Composition (wt %) H_2O-liquid	TDS %
1	1380	2750		0	100	99.7	0.30
2	236	469		0	100	98.89	1.11
3	178	353		0	100	98.89	1.11
4	966	1930		0	100	99.95	0.05
5	414	822		0	100	98.89	1.11
37	5110	8710	174	0	100	79.4	20.6
38	5110	8710	185	0	100	79.4	20.6
39	9.1	15.2		0	100	78.3	21.7
40	32.5	64.9		0	100	100	0.00
41	105	210		0	100	100	0.00
42	5120	8730		0	100	79.4	20.6
43	81.5	158		0	100	95.16	4.84
44	39.9	77.1		0	100	95.16	4.84
45	41.6	80.4		0	100	95.16	4.84

Point	Fluid	Flow lb/hr x 10^{-3}	Pressure lb/in² (abs)	Temp °F	Liquid Phase %	Vapor Phase %
25	R-114	662	16.4	44	100	0
26	R-114	662	16.4	44	100	0
27	R-114	662		78	100	0
28	R-114	662	134	176	100	0
29	R-114	662	134	176	0	100
30	R-114	662		97	0	100
31	R-114	662		55	0	100
32	NH_3	72.2	47.2	19.0	0	100
33	NH_3	72.2	47.2	19.0	100	0
34	LCO_2	400	300	0	79.8	20.2
35	GCO_2	400	300	0	0	100

In regards to the solar versus fossil-fuel comparison, the bar graphs show that the solar-pond-coupled systems are more economical. They also show that water costs are not significantly affected by solar pond construction costs or, in the case of coal, by the fuel escalation rate.

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Table 5. – Selected thermodynamic and heat transfer data for Case 2.

	Hot Brine (to ORC vapor./preheater)		
Brine Subsystem (to ORC vaporizer/preheater)			
Brine inlet temperature, °F	185		
Brine outlet temperature, °F	174		
Flowrate, lbm/hr x 10^{-3}	5110		
NH_3 Subsystem (to ORC condenser)			
Temperature, °F	19		
Pressure, lb/in^2 (abs)	47.2		
Heat of vaporization, Btu/lbm	554		
Flowrate, lbm/hr x 10^{-3}	72.2		
Separator heat exchanger (LCO_2/coal)			
Thermal duty, MBtu/hr	40.00		
Overall heat transfer coefficient, Btu/hr-ft^2-°F	210		
Surface area, ft^2	10,000		
ORC Working Fluid (R-114)			
Flowrate, lbm/hr x 10^{-3}	662		
Boiling temperature, °F	176		
Boiling pressure, lb/in^2 (abs)	134.2		
Condensing temperature, °F	44		
Condensing pressure, lb/in^2 (abs)	16.4		
	Vaporizer	Condenser	Preheater
ORC Heat Exchangers			
NH_3 inlet temperature, °F	—	19	—
NH_3 outlet temperature, °F	—	19	—
Brine inlet temperature, °F	185	—	178
Brine outlet temperature, °F	178	—	174
Working fluid temperature, °F	176	44	—
Corrected LMTD, °F	4.7	30.2	24.3
Thermal duty, MBtu/hr	28.96	40.00	17.12
Overall heat transfer coefficient, Btu/hr-ft^2-°F	300	250	150
Surface area, ft^2	20,600	5,300	4,700
		Liquid	Vapor
Regenerator			
Inlet temperature, °F		44	97
Outlet temperature, °F		78	55
Corrected LMTD, °F	14.6		
Thermal duty, MBtu/hr	4.62		
Overall heat transfer coefficient, Btu/hr-ft^2-°F	10		
Surface area, ft^2	31,700		

Table 6. – Economic assumptions.

Federal discount rate	7⅞ percent	
Fuel cost escalation rate	0-4 percent[1]	
	Combined Freeze/ RO Desalination	**Reverse Osmosis**
Desalination Plant		
Rated plant capacity, Mgal/d	2.54	2.77
Plant factor, percent	93	93
Service life, years	30	30
Operating conditions:		
Feed salinity, mg/L	3000	3000
Product recovery, percent	96	70
Product water conc., mg/L	[2]460-470	500
Electric power consumption, kWh/a x 10^{-6}	11.5	12.5
Powerplant (Solar pond with and without liner, and coal-fired steam)[3]		
Rated plant capacity, MWe	1.68	1.87
Plant factor, percent	93	93
Service life:		
Powerplants, years	30	30
Solar pond, years	90	90
Land area:		
Solar pond, m^2 x 10^{-3}	230	250
Evaporation pond, m^2 x 10^{-3}	50	90

[1] Based on DOE (Department of Energy) cost data published in January 1980 [9] and updated in May 1981, which project a coal price escalation rate of approximately 4 percent per year through 1995. Current prices indicate the rate is closer to 2 percent than 4 percent.
[2] Achieved by blending 500 mg/L product water from the RO plant with 350-400 mg/L product from the freeze process.
[3] For this analysis, lined solar pond refers to the use of an elastomeric liner; unlined denotes compacted earth only.

Table 7. – Cost summary (1982 dollars).

Cost Component	Installed Cost $\$ \times 10^{-3}$	Fixed Charge Rate [1]	Annual Cost $\$ \times 10^{-3}$	Water Cost \$/kgal
Case 1 – Combined Freeze/RO				
Capital costs:				
Freeze desalination equipment	[2] \$6,500	.0878	\$ 570	\$ .66
RO desalination equipment	[3] 3,800	.0878	330	.38
CO_2/coal separator heat exch.	[4] 200	.0878	20	.02
Power generation equipment	[5] 1,160	.0878	100	Included in
Solar pond				energy costs
– unlined at \$5.00/m²	1,400	.0788	110	shown below
– lined at \$7.50 – \$12.50/m²	2,100-3,500	.0788	170-280	
Brine disposal	N/C	.0788	—	—
Annual costs:				
Interim replacement				
– freeze system at 2%	—	—	135	.15
– RO system incl. membranes	—	—	180	.21
O&M (labor, chemicals, supplies, and administrative expenses)	—	—	500	.58
Energy costs (baseload):	mills/kWh [6]			
Solar pond				
– unlined at \$5.00/m²	45		520	.60
– lined at \$7.50 – \$12.50/m²	53-66		610- 760	.71- .88
Conventional coal-fired steam (0 to 4% fuel escalation)	75-94		860-1080	1.00-1.25

Total costs for Case 1: w/unlined solar pond = \$ 2.60
w/lined solar pond = 2.71-2.88
w/coal-fired steam = 3.00-3.25

Cost Component	Installed Cost $\$ \times 10^{-3}$	Fixed Charge Rate [1]	Annual Cost $\$ \times 10^{-3}$	Water Cost \$/kgal
Case 2 – Reverse Osmosis				
Capital costs:				
RO desalination equipment	[3] \$5,700	.0878	\$ 500	\$ .53
CO_2/coal separator heat exch.	[4] 200	.0878	20	.02
Power generation equipment	[5] 1,290	.0878	110	Included in
Solar pond				energy costs
– unlined at \$5.00/m²	1,700	.0788	130	shown below
– lined at \$7.50-\$12.50/m²	2,600-4,300	.0788	200-340	
Brine disposal	N/C	.0788	—	—
Annual costs:				
Membrane replacement	—	—	270	.29
O&M (labor, chemicals, supplies, and administrative expenses)	—	—	550	.58
Energy costs (baseload):	mills/kWh [6]			
Solar pond				
– unlined at \$5.00/m²	45		560	.60
– lined at \$7.50-\$12.50/m²	53-66		660- 830	.71- .88
Conventional coal-fired steam (0 to 4% fuel escalation)	75-94		940-1180	1.00-1.25

Total costs for Case 2: w/unlined solar pond = \$ 2.02
w/lined solar pond = 2.13-2.30
w/coal-fired steam = 2.42-2.67

1/ Federal discount rate plus depreciation (sinking fund factor); interim replacement not included.
2/ Based on cost data obtained from M. Hussain, Chicago Bridge and Iron, September 1983.
3/ Based on cost data compiled by E. Ewoldsen, Bureau of Reclamation, May 1981.
4/ 10,000 ft² surface area at \$20/ft².
5/ \$600/kWe plus 15 percent for contingencies.
6/ Based on the busbar energy costs presented in [3] for staged construction, corrected to account for the improvement in ORC conversion efficiency resulting from the lower condensing temperature provided by the liquid CO_2. This amounts to cost savings of between 30 and 40 percent for the solar system and between 5 and 10 percent for the system powered by coal-fired steam.

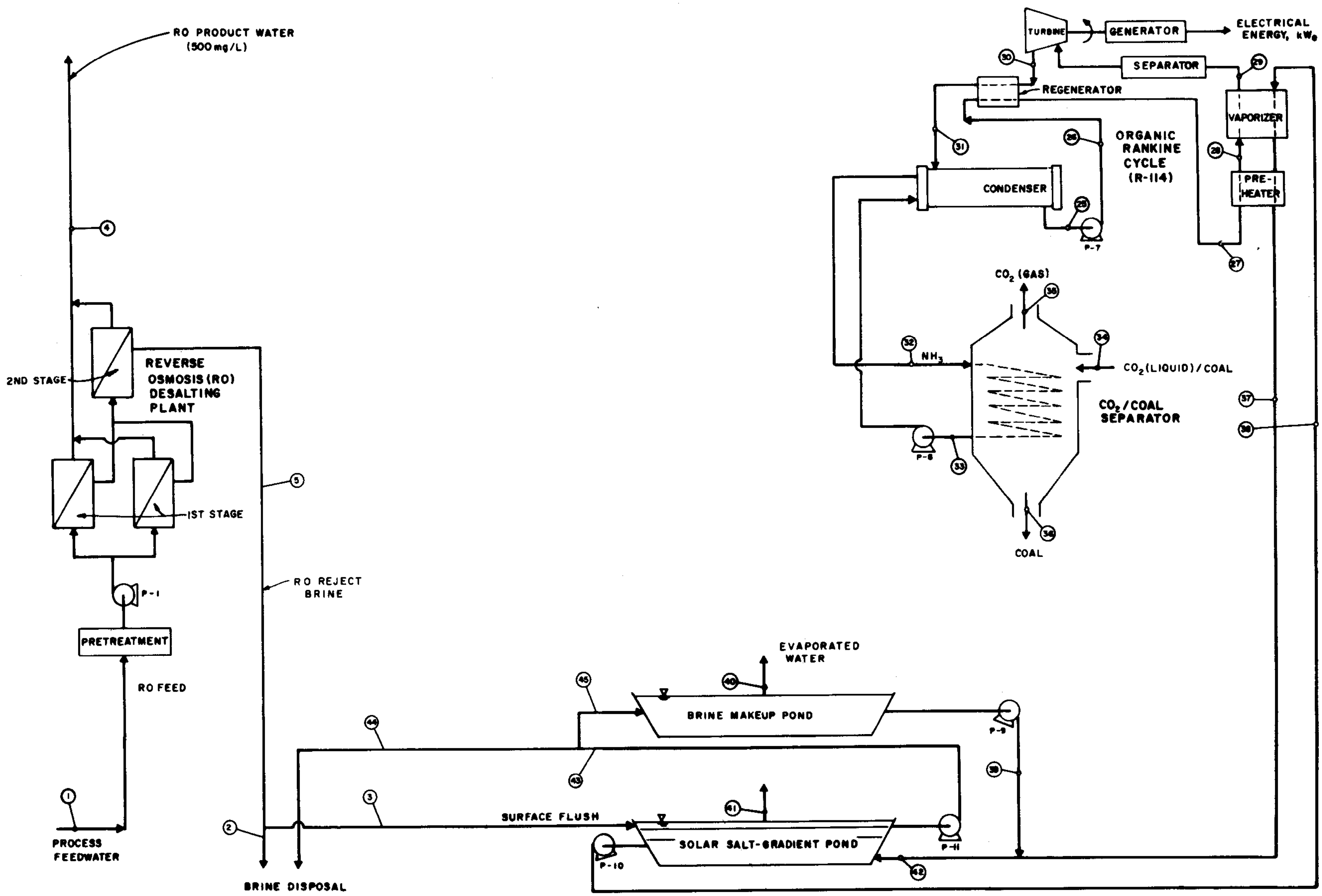

Figure 5. – Process flow diagram for Case 2 – reverse osmosis desalting only. Note: circled numbers refer to process monitoring points shown in table 4.

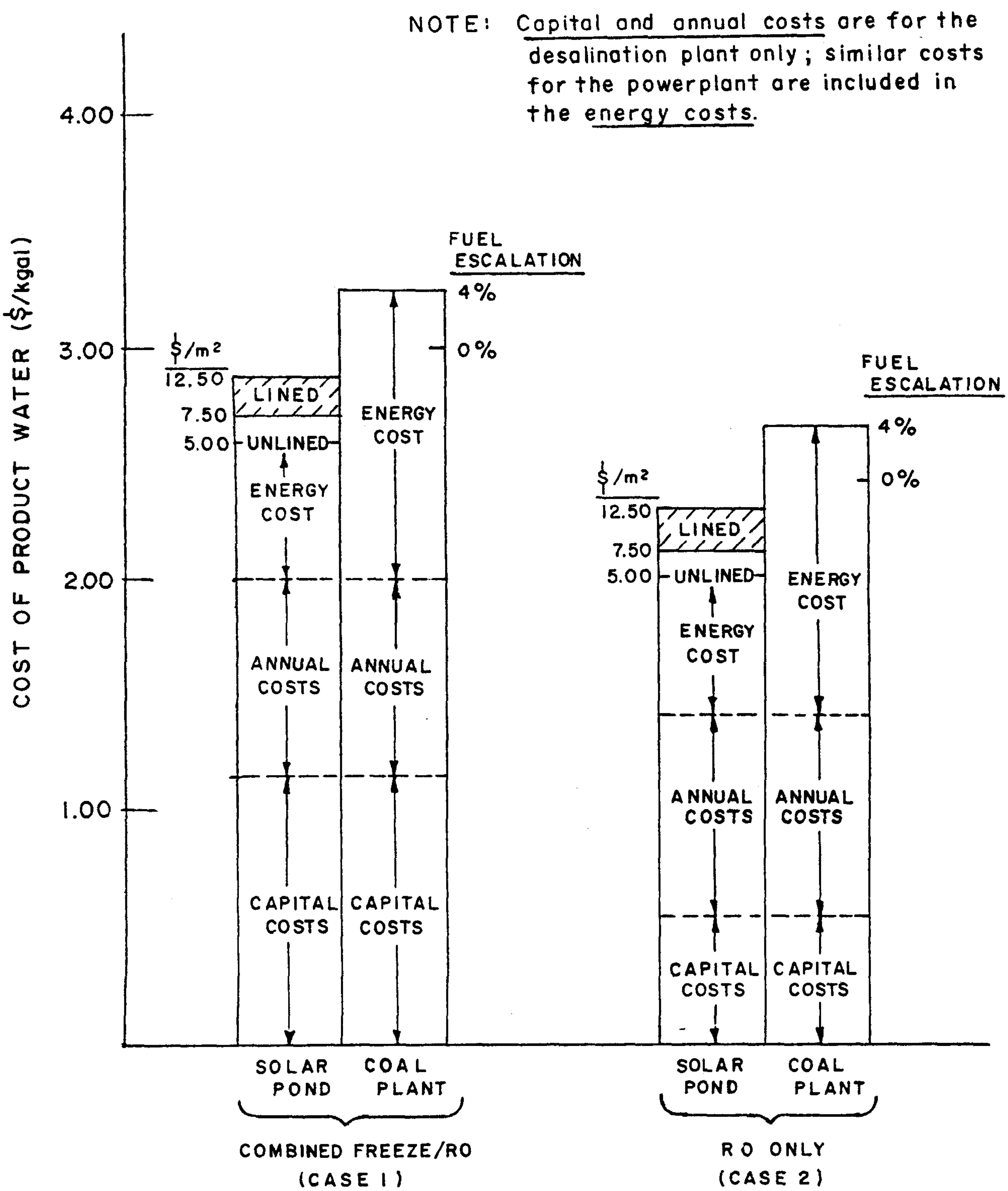

Figure 6. – Desalination costs with baseload power.

GPO 845-947

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

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