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TECHNICAL AND ECONOMIC ASSESSMENT OF SOLAR DISTILLATION FOR LARGE SCALE PRODUCTION OF FRESH WATER

FINAL REPORT

PREPARED FOR

SANDIA LABORATORIES
LIVERMORE, CALIFORNIA

BY
BECHTEL CORPORATION
RESEARCH AND ENGINEERING OPERATION
DECEMBER 1977

CONTRACT NO. 87-9814
BECHTEL JOB NO. 12610

BECHTEL

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ABSTRACT

This report presents an assessment of solar distillation plant performance attainable with presently implementable technology. A review of existing technology provides the basis for selection of the design for a 5 million gallon per day solar distillation plant. The cost of distilled water from this plant is compared with the cost of water from an oil fired distillation plant of the same installed capacity.

For present day plant construction and annual fuel escalation rates below 10.5 percent, water obtained from a solar driven distillation plant is more expensive than that obtained from conventional oil driven distillers.

For plants constructed in the future, the continued escalation of fuel oil cost at annual rates exceeding 5 percent will make the cost of water from solar driven and oil driven distillers equal within 15 years.

CONTENTS

CONTENTS (Cont'd)

ILLUSTRATIONS

Section 1

INTRODUCTION

In many arid or remote locations, fresh water for human consumption is provided by the distillation of salty or brackish waters. The rising cost of fossil fuel is increasing the cost of such water and it is to be expected that at some time in the future water obtained from solar distillation will become cheaper than that obtained from fossil fuel driven processes.

This assessment of the present status of solar distillation is presented with the hope that it will provide a realistic context for estimating the future potential of solar distillation in a period of rising fuel costs. Present solar distillation technology is defined by first reviewing the literature and by subsequently selecting a candidate solar distillation design for a 5 million gallon per day sea water conversion plant. The cost of water produced by this plant is compared with the cost of water obtained from a conventional oil fired distillation plant, for a range of fuel escalation rates, and with both plants based on presently implementable technology. This brief assessment of solar distillation is concluded with a discussion of areas of future conceptual evolution for the large scale production of fresh water.

The work reported here was conducted under contract No. 87-9814 to Sandia Laboratories, Livermore, California. Supplementary input provided by a parallel study of solar distillation conducted with Bechtel in-house funding has been incorporated into this report.

Section 2

SUMMARY AND CONCLUSIONS

2.1 LITERATURE SURVEY

The survey of the literature provided performance and cost information for:

- basin type single-effect solar stills
- multi-effect solar stills
- solar driven conventional distillation units

2.1.1 Single-Effect Solar Stills

Actual solar still costs and associated labor rates reported for stills built from 1959 to 1969 averaged:

- $1.88/ft^2 and $.49/hour for developing countries, and
- $2.65/ft^2 and $4.00/hour for industrial countries.

The corresponding water costs, based on 8 percent interest, 20 years amortization and 10 hour/1,000 ft^2-year maintenance, are:

- $7.85/1,000 gallons for developing countries.
- $12.40/1,000 gallons for industrial countries.

The literature does not provide an estimate of current solar still water costs which accounts for the effect of the marked inflation of the last several years. Costs pertaining to the present time frame would require a detailed audit and updating of the construction and operating records for existing facilities. Based on information in the literature, a cost of approximately $10/1,000 gallons for solar distilled water in most developing countries appears likely at the present time.

2.1.2 Multi-Effect Solar Stills

A few references were found in the literature describing multi-effect solar stills. Although in principle these stills can produce a high yield of distillate per 1,000 Btu of solar heat input, they are complex and expensive. The technology has not progressed beyond the laboratory scale, and no economic data are available for a full evaluation.

2.1.3 Solar Driven Conventional Distillation Units

A number of investigators have recommended the driving of conventional distillation with solar heat. The designs of these investigators are based upon use of the shallow pond collector and the parabolic trough collector as solar heat sources. Distillation equipment advocated includes multi-stage flash units, vertical tube evaporator units and a humidification cycle. Projected water costs for these conceptual designs, reported over the 1953-1973 time span, range from $1.00/1,000 gallons to $6.50/1,000 gallons, and are based on collector costs considerably lower than those which presently pertain.

2.2 CANDIDATE CONCEPT

Using a 5 million gallon per day plant capacity as representative of present day large scale water production, a candidate solar distillation concept was selected for comparison with an oil-fired distillation plant of equal installed capacity. The selected system, based on presently implementable technology, consists of a field of parabolic trough collectors which heats distillate quality water from 250 F to 300 F. The 300 F water is stored in tanks in sufficient quantity to permit 24 hour operation of the plant. Steam is generated as required for operation of a 19-effect vertical tube evaporation (VTE) distillation unit, by flashing of stored 300 F water to 250 F. The plant is assumed to be located at a seaside, 30 degree latitude site with 25% annual cloud cover.

2.3 WATER COST

Water costs were estimated for the candidate solar VTE distillation concept and for an identical VTE distiller driven by an oil fired boiler. The influence of fuel escalation rate on water cost for both plants was evaluated. Using a current fuel oil price of $2 per million Btu, the water costs of Figure 2-1 were obtained.

The figure shows the effect of fuel escalation on the cost of water from solar and oil driven distillation plants constructed in 1977. The levelized cost of water from an oil driven distiller is markedly influenced by the escalation of fuel prices over the 30 years plant life. The cost of water from a solar driven distiller is subject to a much smaller increase, which is due solely to the dependence of pumping costs on the price of fuel oil generated electricity. For 1977 plant construction (using current collector field costs of $18 per sq. ft.) and annual fuel escalation below 10.5 percent, water obtained from a solar driven distillation plant is more expensive than that available from oil driven distillers.

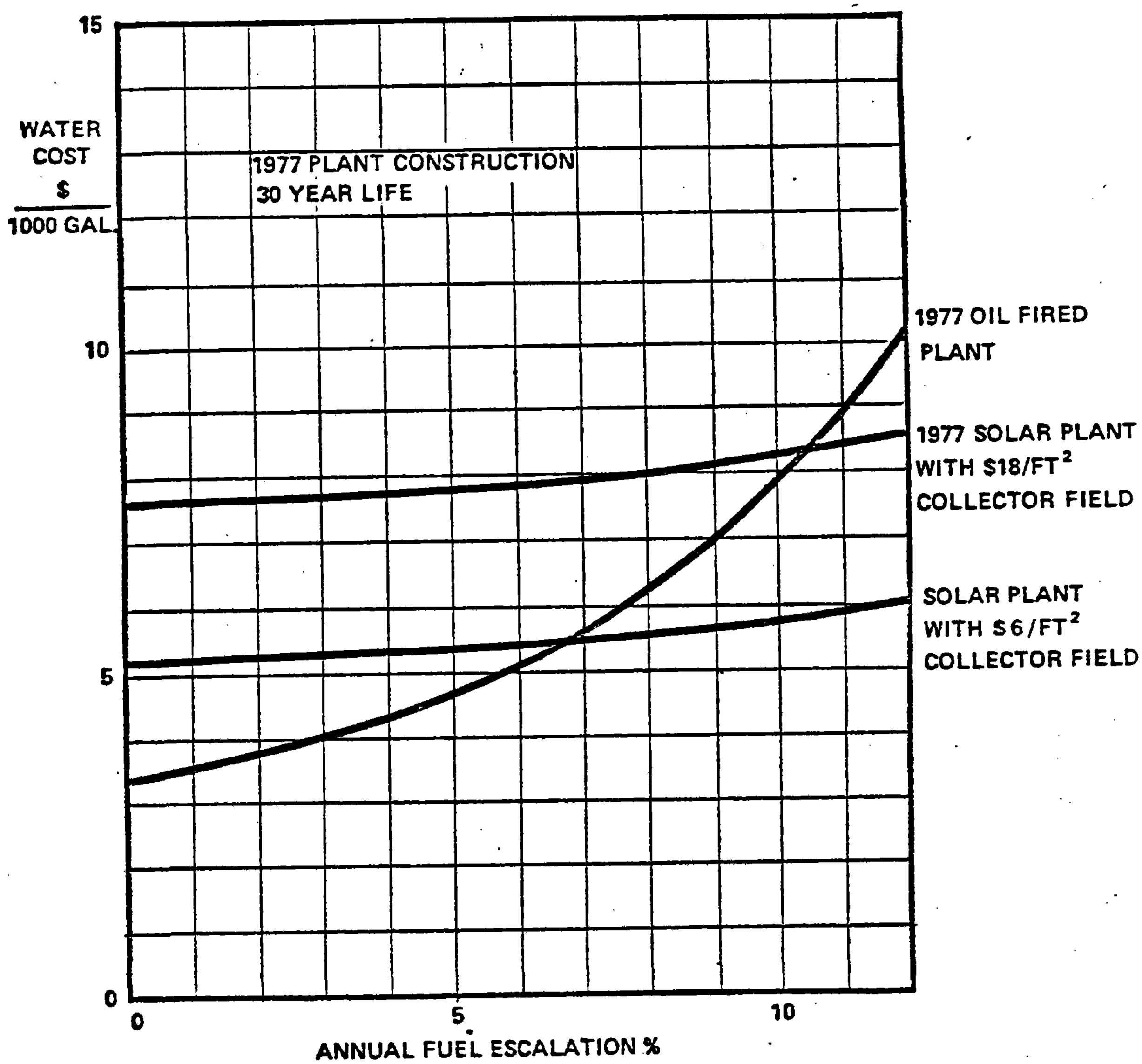


FIGURE 2 – 1 INFLUENCE OF FUEL (OIL) ESCALATION ON DISTILLED WATER COST

The influence of fuel escalation on the cost of water from solar and oil driven distillation plants constructed in the future is indicated in Figure 2-2. Thus, for example, while a fuel escalation rate of over 10 percent is required to make solar distillation competitive with oil driven distillation for plants constructed in 1977, a fuel escalation rate of only 5 percent will make solar distillation competitive 15 years from now in 1992. The escalation rate of Figure 2-2 applies from 1977 to the indicated plant construction date and for the subsequent 30 years of plant operation. The curve is based on $18/ft^2 collector field costs representative of 1977 solar collector technology for parabolic trough collectors. Although it is not possible to predict future solar collector field costs, some substantial reduction of the $18/ft^2 figure is expected. The projections of Figure 2-2 are therefore conservative. Accounting for some improvement in solar collector costs, it is concluded that solar distillation will be competitive with oil driven distillation within 15 years.

Nevertheless, to place this discussion into perspective, it must be recognized that distilled water costs are approximately an order of magnitude greater than the cost of water from normal domestic sources. This limits the use of distilled water primarily to human consumption at remote or arid locations. While competition between solar distillation and oil fired distillation is impending, this is of limited relevance because most new large scale distillation plants presently under construction are designed to operate with power plant waste heat. However, where oil fired units are in use, competition from solar driven distillers can occur within the next 15 years.

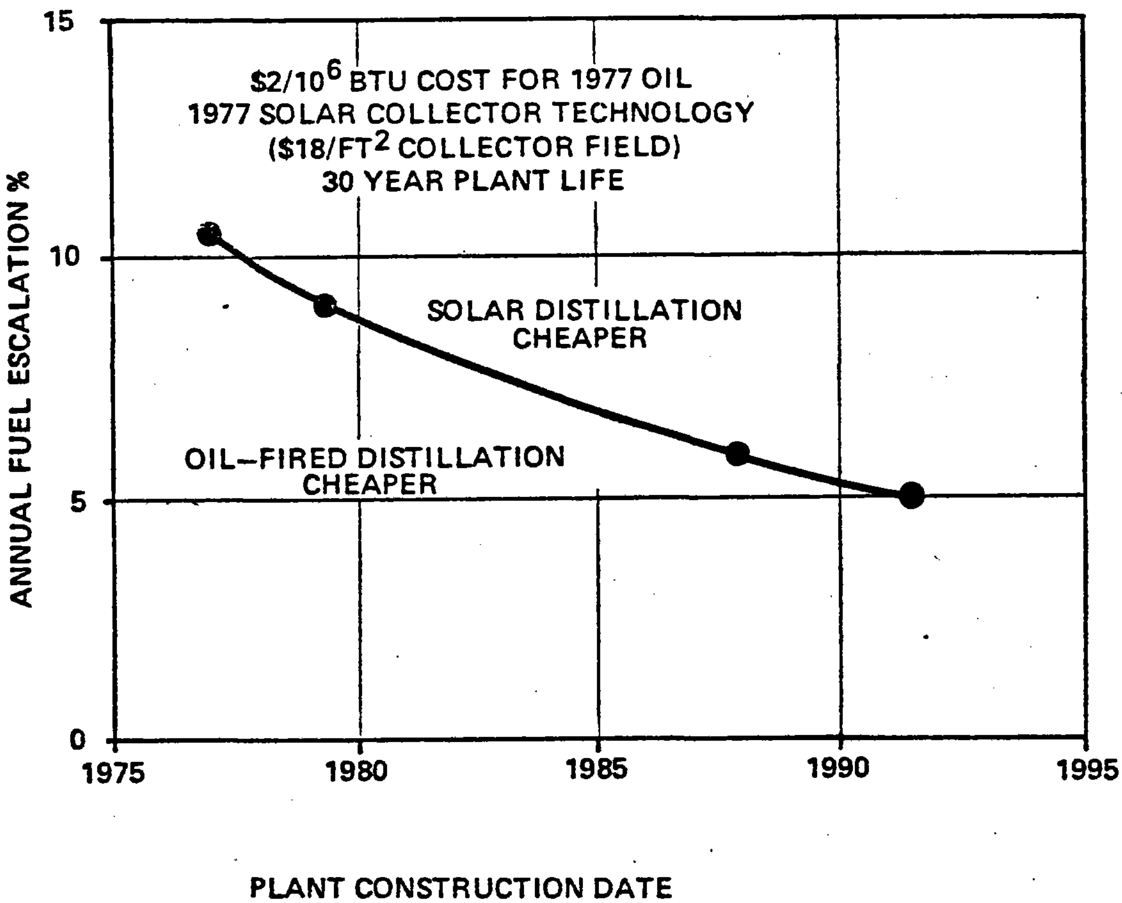


FIGURE 2-2 ANNUAL FUEL ESCALATION REQUIRED TO MAKE SOLAR AND OIL-DRIVEN DISTILLATION COSTS EQUAL

2.4 CONCLUSIONS

Conclusions of this report are:

- The cost of water from a solar driven VTE distillation unit will become competitive with that from oil fired distillation within the next 15 years if annual escalation of fuel cost remains in excess of 5 percent.
- A comparative assessment of competing solar collector designs should be conducted to identify the economic choice of solar energy collection system for a distillation plant.
- The performance of distillers operating with solar power plant waste heat should be evaluated.
- Cost of water from solar stills in some developing countries may be competitive with solar driven and oil fired conventional distillers. An audit of existing facility costs adjusted to the present time frame is needed.

SECTION 3

REVIEW OF THE LITERATURE

The literature on solar distillation is devoted primarily to investigation of the simple single-effect solar still, in which production is limited to one pound of water for each 1,000 Btu's of solar heat absorbed. A few investigators have reported on multi-effect solar stills which, by means of multiple evaporation-condensation processes, attempt to produce more than one pound of water for each 1,000 Btu's of solar heat absorbed. Another small group of investigators has suggested that solar distillation can be accomplished most economically by solar heating of conventional distillation processes.

The review of the literature which follows reports on single-effect stills, multi-effect stills and solar heating of conventional distillation processes, in that order.

The bibliography on the subject of solar distillation, presented at the end of this report, is based on the large bibliographies contained in References 3-1 and 3-2.

3.1 SINGLE-EFFECT SOLAR STILLS

3.1.1 Basin Type Stills

Existing Basin Stills. The key reference on single-effect solar stills is the "Manual on Solar Distillation of Saline Water" (Ref. 3-2) published in 1970 by the U.S. Department of the Interior. It is a compendium of physical performance and cost data for all of the major solar stills in existence. It also summarizes most of the work and conclusions of solar still investigators prior to 1970. The listing of major solar stills presented in Table 3-1 is based on data from References 3-2 and 3-3. Typical configurations for these stills are illustrated in Figure 3-1.

The elements of a basin type solar still are the basin, the basin liner, the glazing and the distillate collection troughs. The basin contains a 1 to 6 inch depth of supply water. Solar energy passing through the glazing is absorbed by the water and by a black basin liner. This heats the basin water above the temperature of the glazing thereby causing water vapor to condense on the glazing. Gravity and surface tension forces convey this condensate to collection troughs which channel the distillate to storage. An additional function of the basin liner is to prevent leakage of water into the soil beneath the still. Dry foundation soil is needed to minimize heat loss to the ground. Proper functioning of the still requires effective sealing of the basin vapor space to prevent vapor leakage from the still. Equally important is the construction of leak-free condensate collection troughs to prevent loss of condensate back into the basin.

Basin Still Performance. The average productivity of the major stills listed in Table 3-1 is 0.068 gal/ft^2- day or about 25 gal/ft^2- yr. The actual value achieved is very site dependent. The stills which report 0.055 gal/ft^2- day in Australia could produce possibly .09 gal/ft^2- day if located in the Chilean highlands. But the 25 gal/ft^2- yr is a commonly used figure for evaluating

TABLE 3-1 MAJOR SOLAR STILLS

COUNTRY	LOCATION	DATE BUILT	SIZE FT^2	PRODUCTION GAL/DAY	PRODUCTIVITY GAL/FT^2-DAY	GLAZING	REMARKS
AUSTRALIA	MURESK I	1963	4000	220	.055	GLASS	REBUILT
	MURESK II	1966	4000	220	.055	GLASS	
	COOBER PEDY	1966	34000	1680	.049	GLASS	
	CAIGUNA	1966	4000	205	.051	GLASS	
	HAMELIN POOL	1966	6000	320 (E)	.053	GLASS	
	GRIFFITH	1967	4450	240	.054	GLASS	
CAPE VERDE ISLANDS	SANTA MARIA	1965	8000	560 (E)	.070	PLASTIC	
CHILE	LAS SALINAS	1872	48000	3900 (E)	.081	GLASS	ABANDONED
	QUILLAGUA	1968	1076	106	.099	GLASS	
GREECE	SYMI I	1964	2920	2000 (E)	.069	PLASTIC	REBUILT
	SYMI II	1968	28030			PLASTIC	DISMANTLED
	AEGINA I	1965	16060	1120 (E)	.070	PLASTIC	REBUILT
	AEGINA II	1968	16020			PLASTIC	ABANDONED
	SALIMIS	1965	4180	290 (E)	.069	PLASTIC	ABANDONED
	PATMOS	1967	92710	6900	.074	GLASS	REBUILT 1969
	KIMOLOS	1968	27040	2000	.074	GLASS	
	NISYROS	1969	21610	1600	.073	GLASS	
	FISKARDO	1971	23710			GLASS	
	KLONLON	1971	25870			GLASS	
	MEGISTI	1973	27250			GLASS	
INDIA	BHAVNAGAR	1965	4060	220	.054	GLASS	
MEXICO	NATIVIDAD IS. BAJA CA.	1969	1024	100 (E)	.098	GLASS	
PAKISTAN	GWADAR I	1969	3300			GLASS	
	GWADAR II	1972	97800			GLASS	
SPAIN	LAN MARINAS	1966	9350	680 (E)	.073	GLASS	
				592	.063	GLASS	
TUNISIA	CHAKMOU	1967	4730		.030	GLASS	
	MAHDIA	1968	14000		.079	GLASS	
UNITED STATES (DAYTONA BEACH, FLA)	DEEP BASIN I	1959	2450	140 (E)	.057	GLASS	REBUILT
	DEEP BASIN II	1961	2650	150 (E)	.057	GLASS	ABANDONED
	INFLATED PLASTIC	1959	2330	100 (E)	.069	PLASTIC	ABANDONED
	INFLATED PLASTIC	1963	1600	160 (E)	.100	PLASTIC	ABANDONED
U.S.S.R.	BAKHARDEN, TURKMENIA	1969	6450	430 (E)	.067	GLASS	
WEST INDIES	PETIT ST. VINCENT	1967	18400	1300	.071	PLASTIC	
	HAITI	1969	2400	200 (E)	.083	GLASS	

(E) denotes estimated production

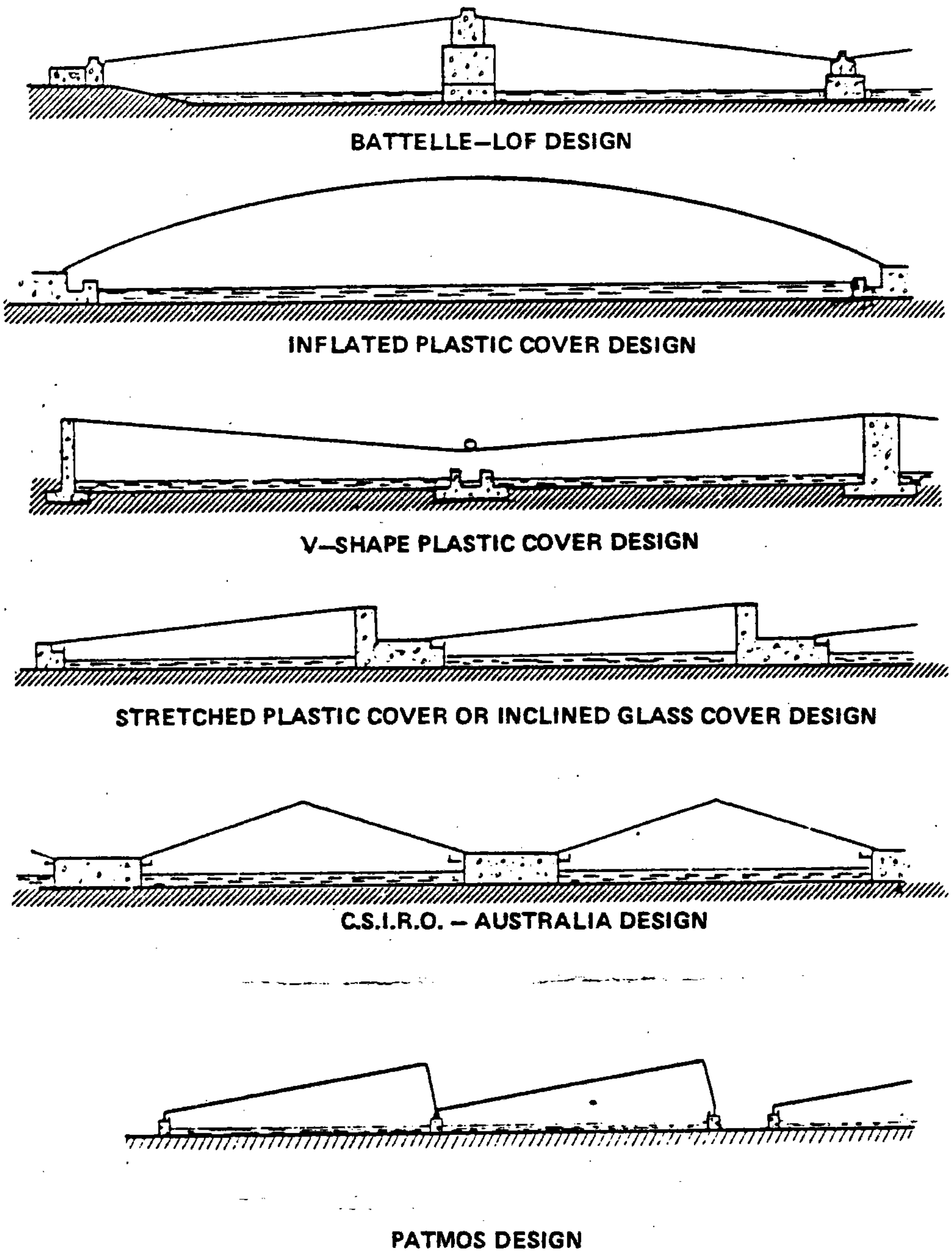


Figure 3–1 TYPICAL BASIN STILL CONFIGURATIONS

the economics of the typical solar still. It represents performance that is good for most locations where solar distillation would be considered.

The performance level cited above should be expected from a well built still in new condition. All stills have some tendency to produce at a declining rate, however. A number of small factors, such as discoloration of the basin lining, and major factors, such as vapor leakage through hardened or cracked glazing seals and deterioration of distillate collection troughs leading to leakage at the seams, can combine to create serious loss of production. Deterioration as great as 10 percent per year has occurred in the Australian stills (Ref. 3-4). Similar results, reported by Tleimat (Ref. 3-5), are shown in Figure 3-2.

The thermal cycling which all stills experience tends to open cracked glazing seals. Openings caused by storm damage sometimes go undetected or unrepaired. Such conditions can lead to a major loss of performance particularly in the winter when vapor production is lowest.

Leakage from distillate collection troughs can cause equally serious loss of performance. A small leak can return large portions of the collected distillate to the basin water. Collection rates are small enough to make trough leaks difficult to detect.

Maintenance of still performance requires particularly effective glazing seal and distillate collection trough design. It also requires a diligent program of inspection and repair. Morse and coworkers (Ref. 3-4) report that required maintenance for the Australian stills ranges from 10 to 60 man-hr/1,000

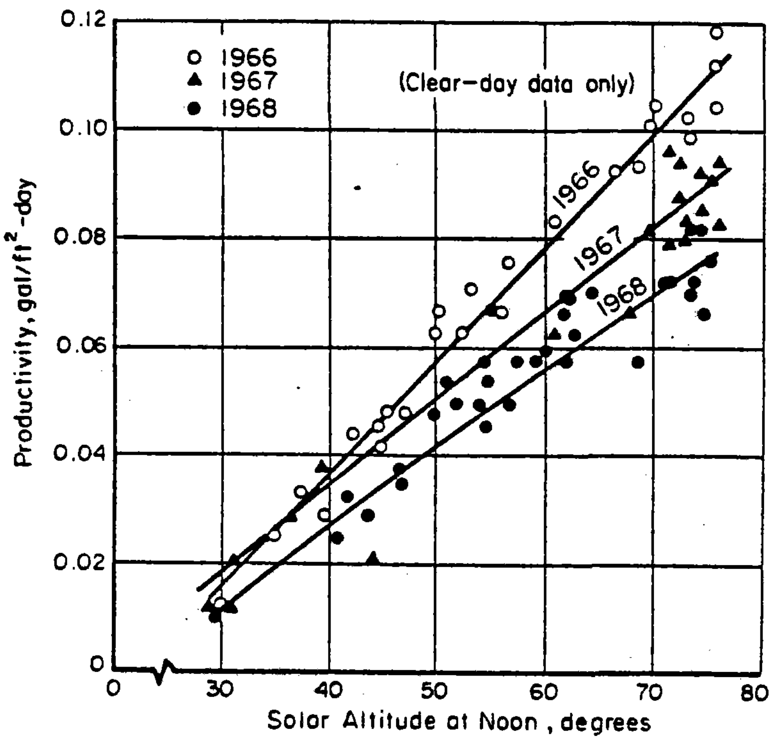


Figure 3 – 2 PRODUCTION DECLINE OF STILL NO. 55 (UNIVERSITY OF CALIFORNIA)

ft^2- year. They suggest a realistic target for essential maintenance of 10 man-hr/1,000 ft^2-year. This target is certainly a lower bound to actual required maintenance. Monthly inspection for fault detection alone could account for 1/2 man-hour per 1000 ft^2, or 6 man-hr/1,000 ft^2- year.

The simple solar still is a single-effect device, which is to say it involves but one evaporation and condensation process. As a consequence, solar stills of this type are subject to a theoretical limit of approximately one pound per 1000 Btu of solar heat. The typical 20% to 40% solar still efficiencies illustrated in Figure 3-3 result in solar still water production of less than 1/2 pound per 1000 Btu's. Proponents of the solar still try to compensate for this basic limitation in performance by striving for extremely low construction and operating costs. The minimal structures so obtained sometimes contribute to the performance degradation and the greater than expected maintenance and repair discussed above.

Basin Still Costs. Single-effect solar still construction costs reported in References 3-2 and 3-6 are presented in Table 3-2. The \$1 to \$5/ft^2 range of construction costs is considerable as would be expected for installations in countries with widely differing wage rates. Considering only the reported "actual" costs of Table 3-2, the average reported still cost for the industrial countries (USA and USSR) during the 1959 to 1969 time period is \$2.65/ft^2. The associated labor rate is about \$4.00 per hour. The average of the remaining actual costs reported in Table 3-2 for the developing countries of Spain, Greece, India and the West Indies, is \$1.88/ft^2. The associated labor rate is around \$0.49 per hour.

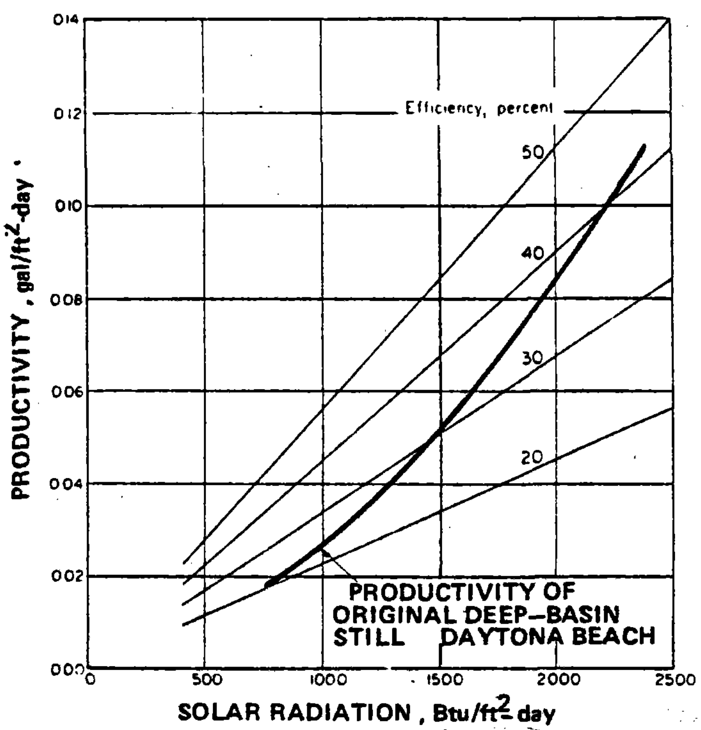


Figure 3 – 3 SOLAR STILL EFFICIENCY

TABLE 3-2

SOLAR STILL CONSTRUCTION COSTS

COUNTRY	LOCATION	YEAR	GLAZING	LABOR RATE $/hr	Cost $/Ft^2	REMARKS
U.S.A.	Daytona					
	Inflated Plastic	1959	Plastic	4.00	0.80	Actual, .075 MH/ft^2
	Deep Basin I	1959	Glass	4.00	5.00	Actual
	Deep Basin II	1961	Glass	4.00	2.04	Actual
					2.30 (a)	Actual
Greece	Patmos	1967	Glass	0.50	1.64	Actual
	Kimolos	1968	Glass	0.50	2.26	Actual, 1.08 MH/ft^2 (Concrete Slab Basin)
	Aegina	1965	Plastic	0.50	1.87	Actual
Spain	Las Marinas	1966	Glass		1.56	Actual
					1.05	Estimated
West Indies	Petit St Vincent	1967	Plastic	0.45	2.13	Excluding Auxiliaries
					3.13	Total
India	Bhavnagar	1965	Glass	(b)	0.80	Actual
U.S.S.R.	Turkmenia	1969	Glass	(b)	2.64	Actual

All costs from Reference 3-2 except as noted.

(a) Reported in Ref. 3-5 in 1968

(b) No data

Basing operating costs on the 10 man-hr/1,000 ft^2- year maintenance target previously cited, \$0.49/hr labor in developing countries and \$4/hr labor in industrialized countries, yields overall operating costs of:

- \$0.005/ft^2- year in developing countries
- \$0.040/ft^2- year in industrialized countries

The approximate water costs in \$/gallon are obtained from the following expression:

$$\frac{\text{CRF } (\$/ft^2) \text{ Construction} + (\$/ft^2\text{-yr}) \text{ Operation}}{(gal/ft^2\text{- year})}$$

The capital recovery factor (CRF) for 20 year amortization at 8% interest is 0.10185. Typical still productivity cited earlier is 25 gal/ft^2- year. These assumptions lead to the following average costs for solar still water.

- \$7.86/1,000 gal. in developing countries
- \$12.40/1,000 gal. in industrial countries

Some incidental cost elements are neglected. Since both solar stills and conventional distillers are generally municipally owned and not profit making installations, the consideration of taxes is unnecessary.

These figures are an indication of average cost of water from solar stills in the 1959 to 1969 time frame. The widely quoted \$3 to \$4/1,000 gallon water cost presented as typical in Reference 3-2 is actually based on lowest reported still costs (\$1/ft^2).

Considering the marked inflation of the last several years, it is clear that the cost data discussed above do not provide a reasonable indication of solar still water costs for the present 1977 time frame. Accurate assessment of present solar still water cost would require a detailed audit and updating of the construction and operating costs for facilities presently in operation.

This study is limited to the gathering of costs that are available in the literature. Updated cost for basin type stills are not in the literature and will take considerable time to gather. Therefore only a rough indication of the present cost of solar still water is possible. Some guidance is provided by the following points of reference. First, the cost of heat tempered 1/8 inch glass in multi-million square foot quantities is presently about $.43/ft^2 compared to the $.25/ft^2 quoted in Reference 3-2 for a 1,000,000 ft^2 still. Additionally, the costs for shallow solar pond collectors which are similar in design to the plastic solar stills, is presently estimated (Refs. 3-7, 3-8) at between $4.65 and $5.60/ft^2. From this it might be inferred that present cost for a large scale solar still is considerably greater than the $1 to $3/ft^2 reported for the 1959-1969 time frame in Table 3-2.

From the preceeding discussion it can only be surmized that the cost of water from basin type solar stills in most developing countries is probably in excess of $10/1,000 gallons. Until the facts are known, however, there remains a possiblity that lower costs may pertain in some countries with very low labor rates.

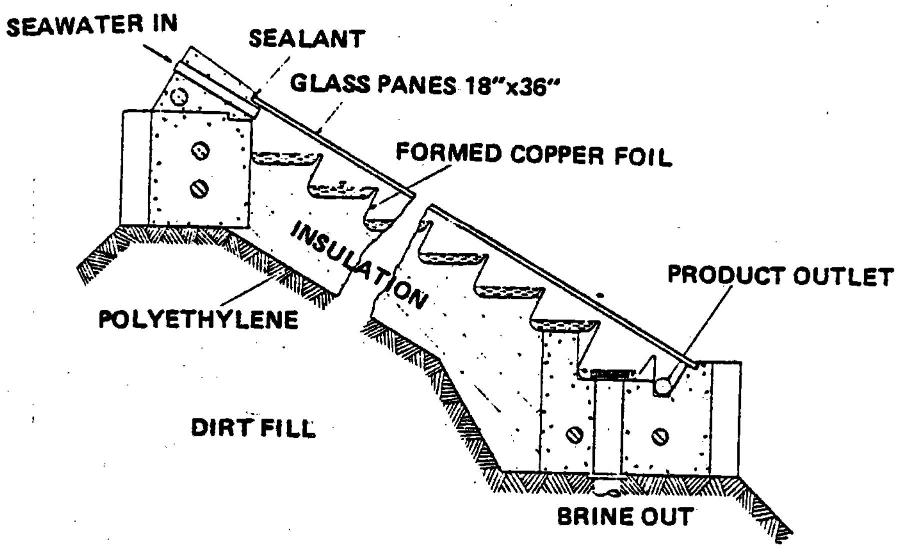
3.1.2 Tilted Still Configurations

Two tilted still configurations are shown in Figure 3-4. They are the inclined tray and the tilted wick stills. These stills out-produce the basin type still, particularly in the winter when they intercept considerably more solar radiation due to a more direct angle of incidence. Annual production of these stills is about 50% above that of the basin type still. The production of durable wicks for the tilted wick stills has proven difficult. The relatively high cost of construction has so far prevented significant application of either of these tilted still designs.

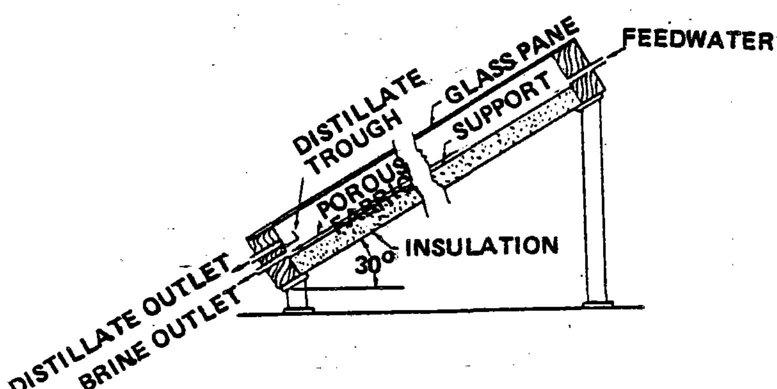
A number of small laboratory scale experimental units have been built and tested (Refs. 3-3 through 3-13). None of the designs tested so far have shown an economic advantage over the basin type still. As a result, there are no production-scale facilities in operation which make use of the tilted still configuration.

3.2 MULTI-EFFECT SOLAR STILLS

The multi-effect solar still designs of Selcuk (Ref. 3-14) and of Cooper and Appleyard (Ref. 3-15) are presented in Figures 3-5 and 3-6, respectively. The multi-effect still uses sunlight to provide the heat of evaporation to the first effect. Then the heat of condensation from the first effect is used to provide the heat of evaporation in the second effect. This is repeated for subsequent effects, with the final effect rejecting its heat of condensation to the environment. The number of effects that can be practically utilized is limited by the available temperature difference between the evaporator of the initial effect and the ambient heat sink.



INCLINED TRAY STILL



TILTED WICK STILL

Figure 3 — 4 TILTED STILL CONFIGURATIONS

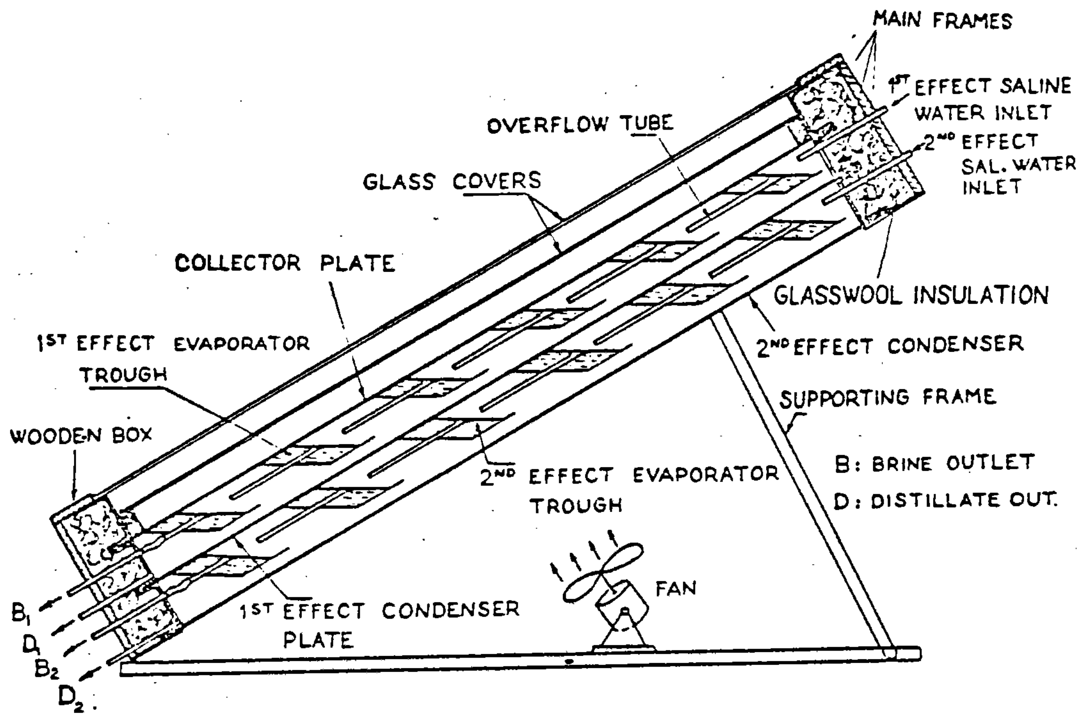


Figure 3 – 5 TWO–EFFECT STILL OF SELCUK

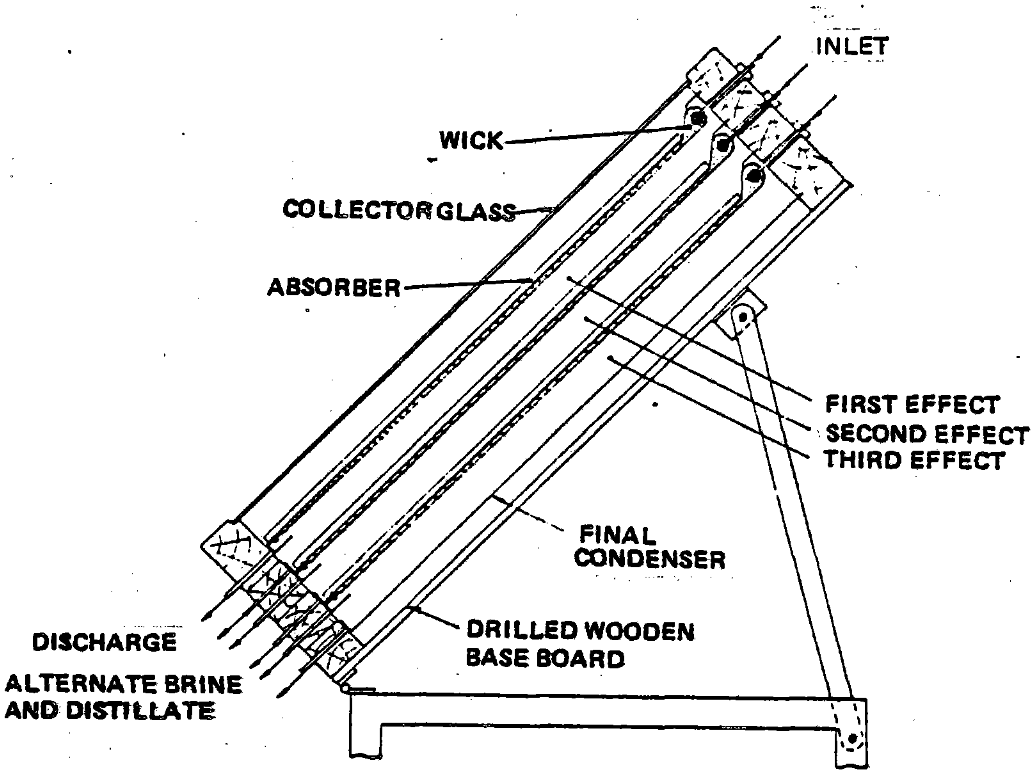


Figure 3 – 6 THREE – EFFECT STILL OF COOPER AND APPLEYARD

The gained output ratios achieved in multi-effect stills are shown in Table 3-3. The values shown in the table are not all directly comparable. Those values of Telkes (Ref. 3-9), obtained with electric heat, do not account for the reflection, reradiation and convective losses of an external solar heat collector.

Although the multi-effect solar still design can substantially increase the still productivity, it also substantially increases construction costs. The added construction costs have so far deterred significant application of the multi-effect solar still. The laboratory scale stills tested to date have been complex and expensive. As a result there are no production scale facilities in operation which make use of the multi-effect solar still.

3.3 SOLAR HEATING OF CONVENTIONAL DISTILLATION PROCESSES

A number of investigators have advocated the use of solar heat for driving conventional multi-effect distillation equipment. Grüne (Ref. 3-16) and Hodges (Ref. 3-17) developed a packed tower humidification process. Howe and Tleimat (Ref. 3-18) analyzed a vertical tube expansion distiller driven by a shallow pond solar energy collection system. Brice (Ref. 3-19), Eibling (Ref. 3-20), and Weihe (Ref. 3-21) each analyzed multi-stage flash distillers driven by the solar pond or the parabolic trough type of solar collectors.

The humidification process reported by Hodges (Ref. 3-17) was shown to be feasible in laboratory scale tests conducted at the University of Arizona. A 5,000 gallon per day plant was subsequently built in 1963 and operated, in cooperation with the University of Sonora, at Puerto Penasco in Sonora, Mexico. This project involved considerable engineering analysis and testing.

TABLE 3-3

GAINED OUTPUT RATIOS ACHIEVED

IN MULTI-EFFECT SOLAR STILLS

EFFECTS	LB/1000 BTU	REMARKS
2	.24	Selcuk (Ref. 3-14)
3	.74	Cooper (Ref. 3-15)
3	1.2	Telkes (Ref. 3-9) Electric Heat
4	2.0	Telkes (Ref. 3-9) Electric Heat
5	2.25	Telkes (Ref. 3-9) Electric Heat
10	2.5	Telkes (Ref. 3-9) Electric Heat

A flow schematic of the Puerto Penasco distiller is shown in Figure 3-7 and cross-sections of two collector configurations considered for use are shown in Figure 3-8. The two glazing collector actually used is very similar in design to the shallow solar ponds of the current DOE-SOHIO project (Ref. 3-7 and 3-8).

The cycle operates by inserting 150 F heated sea water at the top of a packing column. Counter flowing air is humidified by the hot sea water, and deposits its moisture while flowing downward in the adjacent condenser. A blower returns the air to the bottom of the packing tower.

The 5,000 gpd peak output was obtained with a solar collector area of 10,400 ft^2. The resulting productivity of 0.481 gal/ft^2- day is approximately seven times that of a single-effect solar still. A plant construction cost of $56,870 leads to fixed capital charges amounting to $1.80/1,000 gallons based on peak water production and the 30 year life and 4% interest rate used by Hodges. Annual water costs of the facility were not reported. Total annual water production was also not reported. The shallow pond solar collector produces sufficient 150 F energy to drive the distiller for only 8 or 9 months of the year as can be seen from Figure 3-9. Accounting for reduced winter production and for operating charges, it can be surmized that the annual cost of water at Puerto Penasco may have been about double the fixed capital charge identified above, that is, $3 to $4/1000 gallons.

Hodges projected water costs of $1.53/1,000 gallons for a 1,000,000 gallon per day plant.

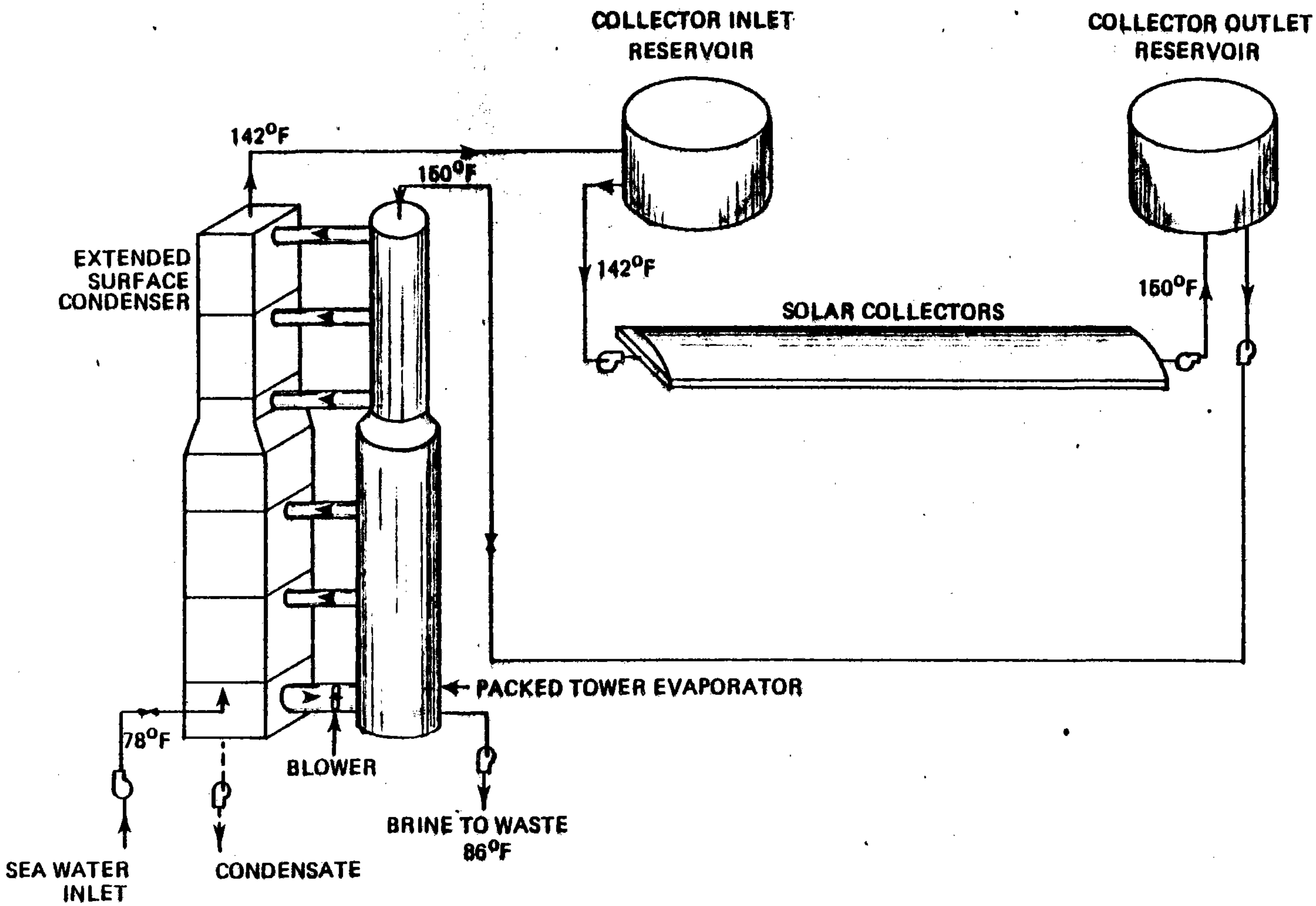


Figure 3–7 FLOW SCHEMATIC – PUERTO PENOSCO PILOT PLANT

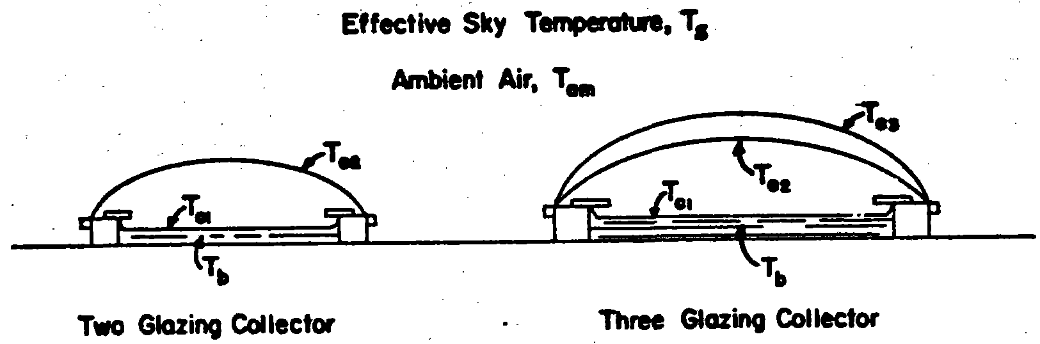


Figure 3 – 8 TWO AND THREE GLAZING SOLAR COLLECTOR CROSS–SECTIONS

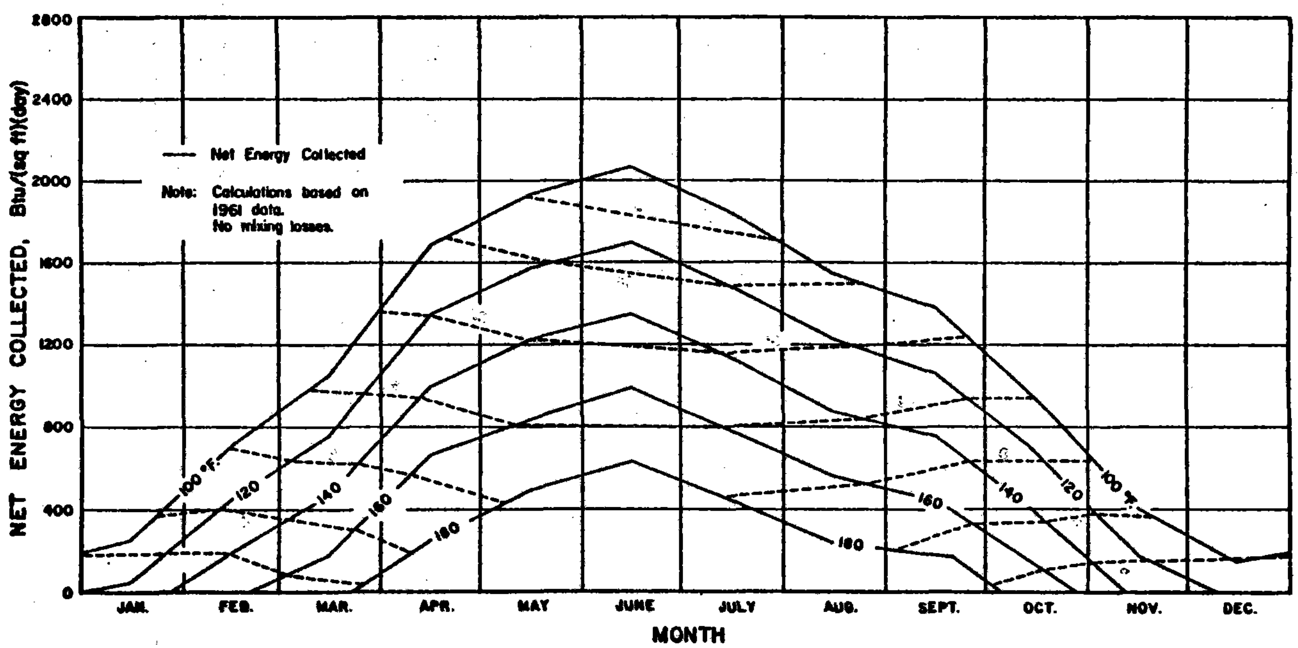


Figure 3-9 THEORETICAL PERFORMANCE OF TWO GLAZING SOLAR POND COLLECTOR

Although these 1966 cost figures no longer apply, the design construction and operation of the Puerto Penasco Pilot Plant was a significant achievement. It provides an excellent point of reference for the present study.

The vertical tube expansion distiller analyzed in 1973 by Howe and Tleimat (Ref. 3-18) was also driven by a shallow pond solar collector. The flow diagram for their distiller is shown in Figure 3-10. The 10,000 gallon per day distiller was assumed to be at a 30 degree latitude site where solar insolation of 2,000 Btu/ft^2-day exists for 300 days per year (i.e., 18% cloud cover). Using solar collectors costing \$.75 to $\$1.00/ft^2$, a 6% interest rate and a 20 year operating life, water costs of \$4.52 to \$6.45/1,000 gallons were calculated.

The design was based on use of a solar pond producing 160 F water. No discussion of reduced performance for the solar pond during winter months was included.

The multiple stage flash distillation analysis of Brice (Ref. 3-19), also using the shallow solar pond collector, did acknowledge that the plant would be idle for two months each winter. His proposed plant operated with sea water heated to 140 F. The 1963 analysis concerned a plant with 16.5×10^6 gallon per day peak summer capacity and an annual production of $3,450 \times 10^6$ gallons. Forty percent of the 26 million dollar capital expenditure was required for the collector field. This amounts to $\$0.42/ft^2$ for a shallow pond collector with the multi-faceted plastic glazing illustrated in Figure 3-11. Brice calculated a water cost of \$1.02/1,000 gallons.

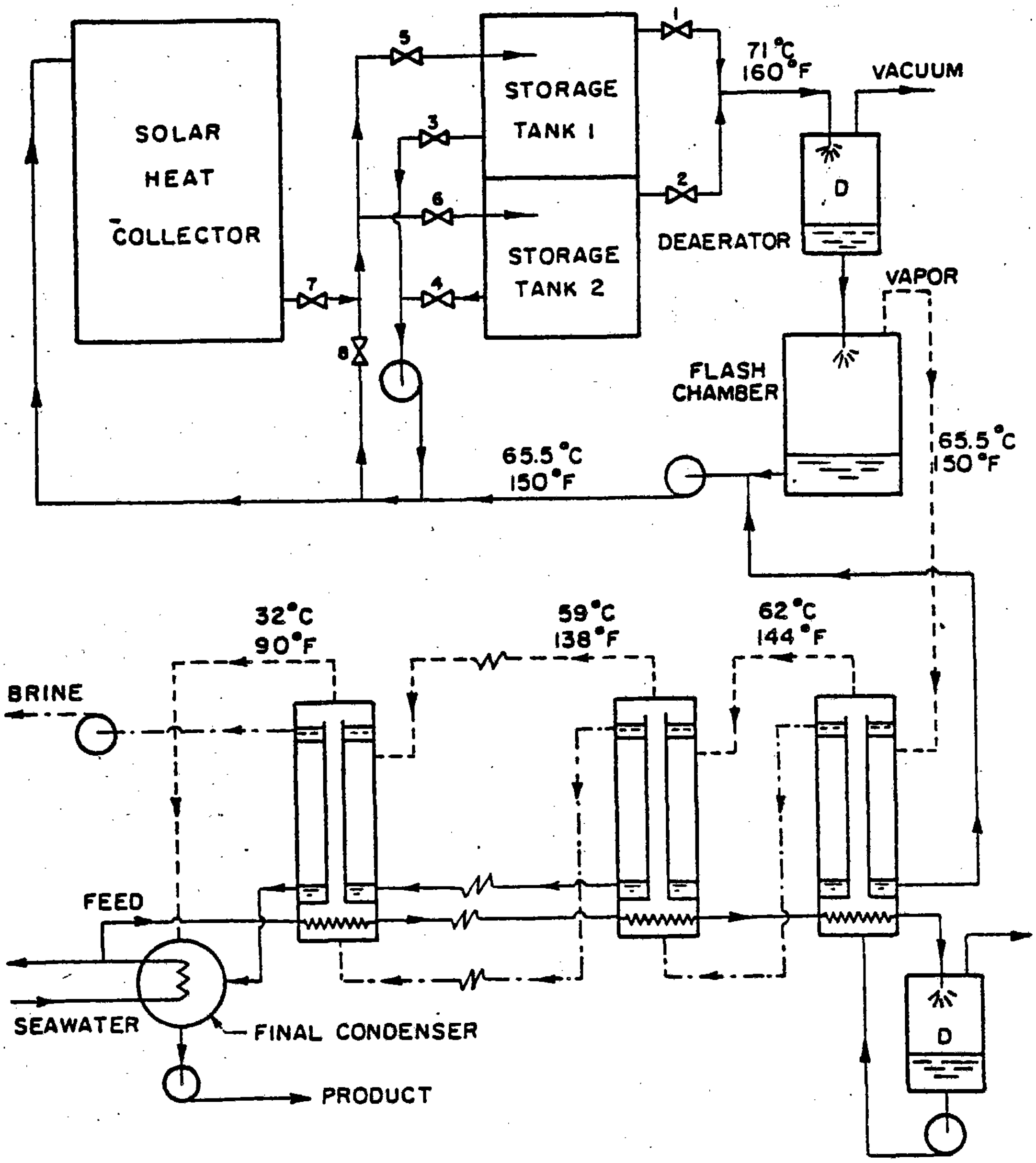


Figure 3–10 Ten-Effect Upflow Vertical-Tube Distillation Plant with Solar Heat Collector Steam Generation (Schematic Flow Diagram)

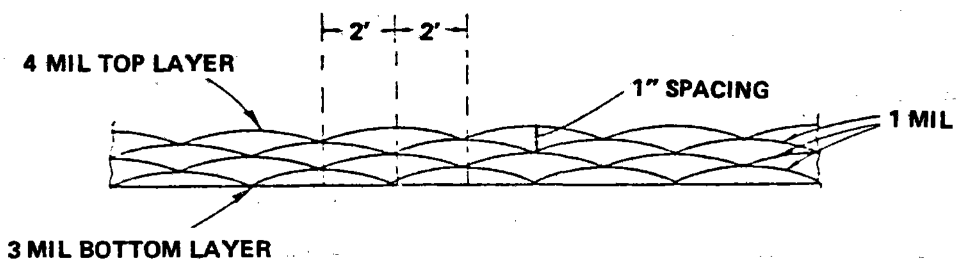


Figure 3 — 11 CROSS-SECTION OF FIVE LAYER GLAZING

The multi-stage flash distillers analyzed by Eibling (Ref. 3-20) in 1953 and by Weihe (Ref. 3-21) in 1972 each operate from heat collected by parabolic trough solar concentrators.

Eibling's distiller, analyzed in 1953, had a capacity of 40,000 gallons per hour. A 35 degree north latitude site was assumed. The solar collectors produced 5 psig, 226 F steam. No thermal storage was provided. The day-light production of the plant was calculated to be 100,000,000 gallons per year. This was based on 2,500 hours of operation per year which, at 8 hours per day, corresponds to 312 operating days per year (equivalent to 15% cloud cover). The cost of the solar collectors, aligned in a north-south orientation, was $\$4.30/ft^2$. Water costs were calculated at $3.25/1000 gallons using a fixed annual capital charge of 5% and a 30 year plant operating life.

Weihe's (Ref. 3-21) proposed multi-stage-flash distiller is driven by parabolic trough collectors aligned in a north-south orientation. The distiller capacity is 6,336 gallons per day. Thermal storage at 212 F to 230 F is provided in the one-tank arrangement shown in Figure 3-12 where warm water and hot water are separated by means of thermal stratification. Weihe's 1969 analysis did not calculate water cost directly but instead compared alternative distiller power sources on a basis of installed cost per kilowatt and operating cost per kilowatt-hour. His results showed the solar energy source to be cheaper than oil, comparable to nuclear energy and more expensive than hydroelectric power.

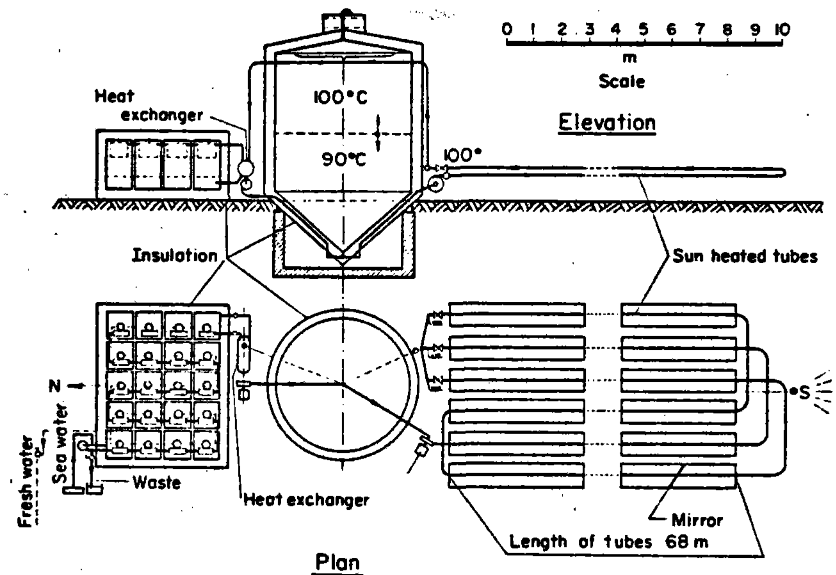


Figure 3 – 12 MULTI – STAGE FLASH DISTILLER OF WEIHE

Section 4

SOLAR DISTILLATION CANDIDATE CONCEPT

The purpose of this section is to select from the literature a candidate solar distillation concept that is capable of near term cost-effective implementation. The candidate should represent as well as possible what is presently attainable.

The estimates of current single-effect solar still water costs presented in Section 3.1 do not encourage selection of the single-effect solar still as the candidate concept. Also, as discussed in Section 3.2, multi-effect solar stills appears to be complex and expensive, and the technology is still in the experimental stages. Present technology does not provide an economically competitive multi-effect solar still. Attention is therefore directed to concepts which use solar heat to operate conventional distilation processes; i.e., to those systems discussed in Section 3.3. This type of concept relies on a combination of conventional distillation, solar collector and thermal storage technologies. Proven technological capabilities exist in all three areas, and sufficient cost data exist for a meaningful economic assessment.

The capacity selected for the candidate solar distillation plant is 5 million gallons per day. This capacity is representative of a current large scale distiller. A seaside site is selected because sea water conversion is the predominant application for distillation plants. Since the cost of distillation is relatively independent of the dissolved solids content, the results of this study are generally applicable to distillation of brackish water as well. The site is arbitrarily at 30 degrees latitude. The annual cloud cover is assumed to be 25 percent. The considerations of distillation process selection, solar collector choice and the role of thermal storage require discussion.

4.1 DISTILLATION PROCESS

The distillation process associated with a solar heat source must be efficient to minimize solar collector area. It should be easily controlled and adapt well to diurnal and seasonal variations in heat input. All distillation processes gain efficiency by adding effects. However, this reduces the temperature drop per effect, and can make the system difficult to control. The discussion in Section 6 identifies the vertical tube evaporation process as both more efficient and more controllable than the multi-stage flash process. The humidification process discussed in Section 3.3 is least efficient of the conventional distillation processes considered. Distiller efficiency directly affects the required size of the solar collector field, and as is shown in Section 7, collector field cost dominates the solar distillation plant cost. These considerations led to the selection of the vertical tube evaporation (VTE) distiller for use in the candidate solar distillation plant.

In Section 6, the VTE distillation unit is also selected for the non-solar distillation unit. In a time of rising fuel cost the same logic regarding selection of an efficient distillation unit applies to the fuel driven distiller.

The fact that the candidate solar and non-solar plants each use a VTE distillation unit helps to simplify comparison between the two. The comparison would be further simplified if both distillation units operated at identical conditions at peak-output. This is possible since conventional distillers do not heat sea water above 250 F. Unacceptable precipitation of calcium sulfate occurs at higher temperatures so sea water distillers are usually driven by steam at temperatures from 225 F to 275 F, a range easily attained by some of the solar collectors discussed below.

4.2 SOLAR COLLECTOR

Solar collectors identified in the solar distillation literature include the shallow solar pond and the parabolic trough. Other collectors deserving consideration include the evacuated tube collector, the compound parabolic concentrator (CPC), the tracking segmented mirror and the fixed segmented mirror. A discussion of the physical and performance characteristics of these collector configurations is available in Reference 4-1. Representative costs and collection efficiencies for these collectors are presented in Table 4-1.

The table shows all of the solar collectors to be potentially acceptable drivers of a solar distillation unit. But not all of the collectors can be considered within the restraints of this study. The primary restraint for solar collector selection is that the collector design must be presently implementable. This means it must be a field-proven design that is available in large quantities for installation in a distillation plant now.

The segmented mirror, evacuated tube and compound parabolic concentrator (CPC) designs do not meet this requirement. While it is expected that large quantities of evacuated tube and CPC collectors will be available in the

TABLE 4-1

COLLECTOR COSTS AND PERFORMANCE (a)

(1977 COSTS)

COLLECTOR	$/Ft^2 INSTALLED	O&M $/Ft^2- YEAR	COLLECTION EFFICIENCY (%) 150 F		300 F	
			MORN.	NOON	MORN.	NOON
Shallow Solar Pond (b)	4.65 (Ref. 3-8)	.060 (c)	12	52	--	
Parabolic Trough	15.85	.075	57	60	43	57
Evacuated Tube	5.52 (d)	.050	42	53	10	45
Compound Parabola (3/1)	8.00 (d)	.160	42	53	10	45
Articulated Segmented Mirror	9.93-11.55	.037-.056	63	66	51	65
Fixed Segmented Mirror	6.79-11.76	.050	53	54	46	53

(a) All values based on Reference 4-1 unless otherwise noted.

(b) Summer performance; incapable of operating distiller in winter.

(c) O&M cost assumed same as for single-effect basin type solar still (Section 3.1.3).

(d) Future cost potential. Not available on domestic market. Present experimental units cost $18 to $25/ft^2.

future, they are currently available only in small quantities (at \$18 to \$25/ft^2) for evaluation in select government sponsored programs.

The articulated and fixed segmented mirror collectors have been built and tested in small quantities only. They have not been produced nor field tested in quantity. These collectors designs are not presently implementable in a large scale distillation plant.

The shallow solar pond is implementable. It has been field tested in the past (Ref. 3-17) and is being field tested now (Refs. 3-7, 3-8). Although the economics of a shallow solar pond driven distiller may possibly be competitive with other solar distillers, it does not seem appropriate to select a system that does not provide a year round source of water as the candidate solar distillation concept. It was observed in Section 3.3 that a distiller driven by the shallow solar pond must be inactive for 2 to 3 months each year.

The parabolic trough collector is selected as the heat source for the candidate concept because it best satisfies the requirement of being presently implementable. It is available on the domestic market and over 10,000 ft^2 of collector area are currently in operation (Ref. 4-2, 4-3, 4-4).

Also, choice of the parabolic trough collector permits operation of the VTE distillation units for the solar and non-solar plants at identical conditions; i.e., with 250 F, 15 psig steam. The 250 F steam is obtained from the solar energy collection system by heating water from 250 F to 300 F and routing the 300 F water to a flash tank to provide a 250 F mixture of water and steam. The 250 F steam is sent to the distiller. The 250 F water from the flash tank and 250 F condensed steam from the distiller are then returned to the storage tank and subsequently to the collector field. This process is explained in further detail in Section 5.

4.3 THERMAL STORAGE

Thermal storage capability for 24 hour plant operation is provided in the candidate concept for practical reasons. It prevents short term heat input variation due to passing clouds; it also minimizes diurnal variation in distiller heat input, thereby contributing to ease and reliability of plant control. Additionally, it eliminates the need for daily shutdown and startup of the distiller, which is not considered a practical operating procedure. It often takes many hours to bring a distillation train on line and to full rated output.

No economic comparisons of solar distillation systems with and without thermal storage are available from the literature. It can be reasoned, however, that addition of thermal storage involves the simultaneous tripling of the water output (from 8 to 24 hours of daily operation) and collector system costs, while incurring a less than proportionate increase in cost of the balance-of-plant. The net result is an improvement in system economics.

The literature provides no thermal storage system design tailored to the solar distillation plant discussed here. The direct storage of the 300F, 52 psig water in tanks provides the most compact storage of solar energy for night operation of the distillation unit. The volumetric heat capacity for water storage is 57 Btu/ft^3-F, compared to 31 Btu/ft^3-F for a thermal storage oil such as Caloria HT43, or 33 Btu/ft^3-F for a mixture of Caloria HT43 and rocks.

For the purpose of this assessment of solar distillation, a conservatively designed non-optimized water storage system was assumed. It is expected that a more lengthy and detailed design analysis could justify some reduction in cost of the resulting thermal storage system based on the use of water storage or possibly a mixture of Caloria HT43 and rock.

4.4 CANDIDATE CONCEPT SUMMARY

The candidate solar distillation concept consists of a parabolic trough solar energy collection system driving a vertical tube evaporation distiller. Sufficient thermal storage for 24 hour plant operation is provided.

A peak plant capacity of 5 million gallons per day is selected to represent the large scale distillation potential of a presently implementable concept. A sea level site at 30° latitude with 25% average annual cloud cover is assumed.

The distillation unit, described in Section 6, contains nineteen effects and is designed for a gained output ratio of 12.5 pounds of water per 1,000 Btu's. The solar driven plant is compared to an identical distiller operated on fuel oil generated steam. Both plants are energized by 250 F, 15 psig steam.

SECTION 5

SIMPLIFIED CONCEPTUAL DESIGN OF CANDIDATE PLANT

5.1 SYSTEM DESCRIPTION

A flow schematic for the candidate solar distillation plant is presented in Figure 5-1.

The solar collector field heats a circulating flow of distillate quality water from 250 F to 300 F. The heated water is stored in tanks with sufficient capacity to run the plant from stored energy for 16 hours. The plant is driven by energy directly from the collector field for the remaining 8 hours of each day. The thermally stratified tank arrangement stores 300 F water in the top portion of the tanks and 250 F water occupies the lower portions. At the end of the day, the tanks are entirely filled with 300 F water.

300 F water at a pressure of 52 psig flows from the storage tanks to a flash tank where a mixture of steam and water at 15 psig, 250 F is formed. The flash tank provides the 250 F steam that drives the distiller. 250 F flash tank water is returned to the bottom of the thermal storage tanks as is the condensed steam from the distiller.

5.2 SOLAR HEAT INPUT

5.2.1 Collector Field Orientation

As mentioned in Section 4.2, the parabolic trough collector was selected for the candidate plant. Approximate clear day heat capture for a para-

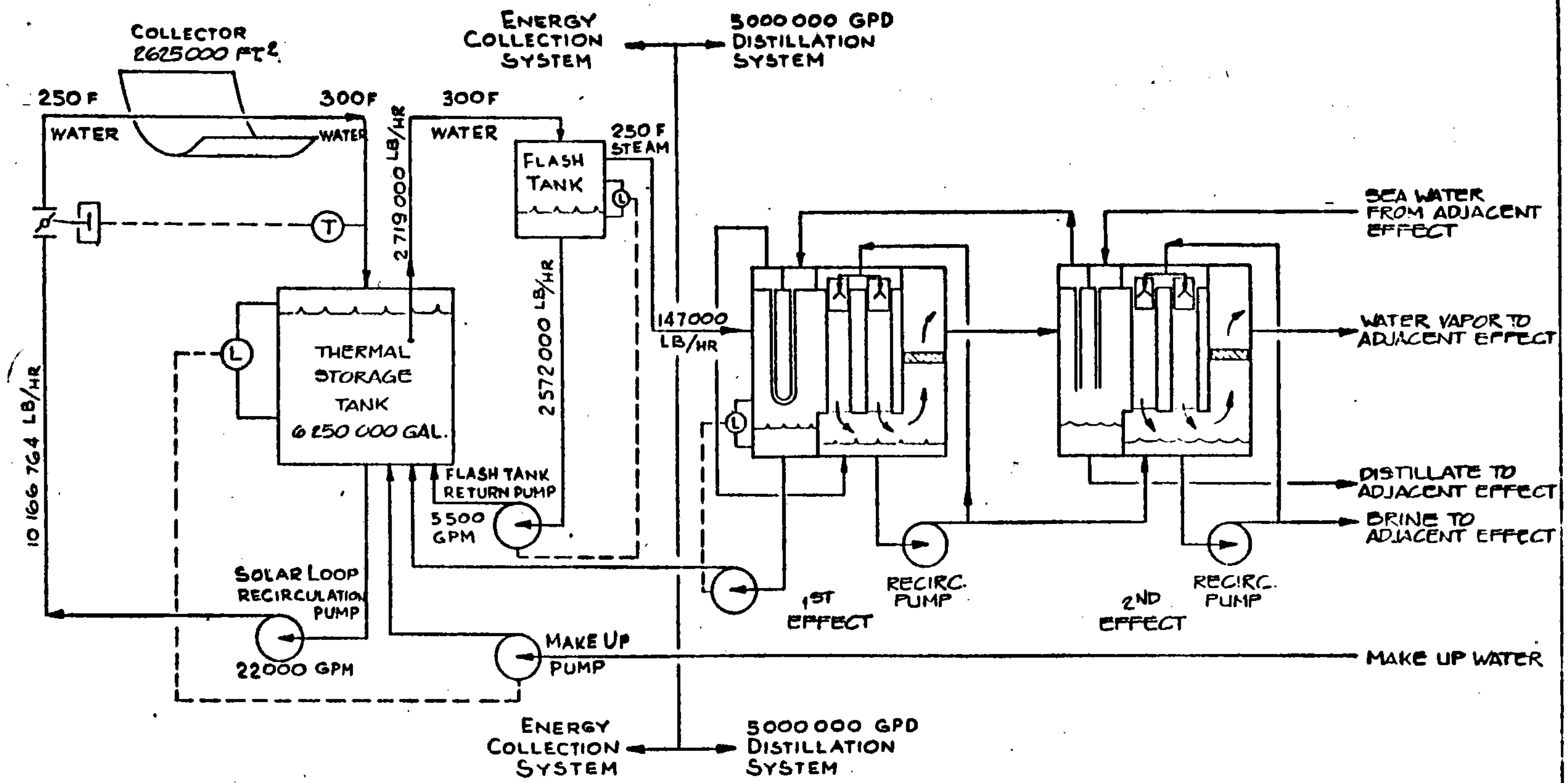


FIGURE 5-1 CANDIDATE SOLAR DISTILLATION PLANT FLOW DIAGRAM

NOTE: ADDITIONAL DISTILLATION UNIT DETAILS IN FIGURES 6-1 AND 6-2 bolic trough collector is shown for both north-south and east-west collector axis alignments in Figure 5-2. Although the north-south collector alignment annually delivers 12% more energy than the east-west orientation, it matches typical water consumption patterns very poorly, delivering only 25% of its peak output in winter. The east-west collector alignment produces 70% of its maximum capacity in winter and provides a much better match of normal water consumption patterns such as that shown for Los Angeles in Figure 5-2. The east-west orientation was selected for this reason. Upon further examination it was found to be the economic choice as well.

The north-south oriented collector field requires only 70 percent as much collector area as an east-west oriented field to drive the distiller at its full capacity on a maximum insolation day (June 15, Figure 5-2). As is shown in Section 7, however, the collector field cost is slightly more than half of the total plant cost. The calculated cost of a plant with a north-south collector field was therefore found to be 82 percent of that for a plant with east-west oriented collectors.

However, the annual water production obtained from a distillation plant with northsouth collectors was found to be 77 percent that obtained with an eastwest field. This is due to the extremely low energy gathering capability associated with a north-south collector field during the winter months.

Switching from an east-west collector field to a north-south collector field therefore results in 77 percent as much water delivered at 82 percent as much cost; or an increase in water cost of about 7 percent.

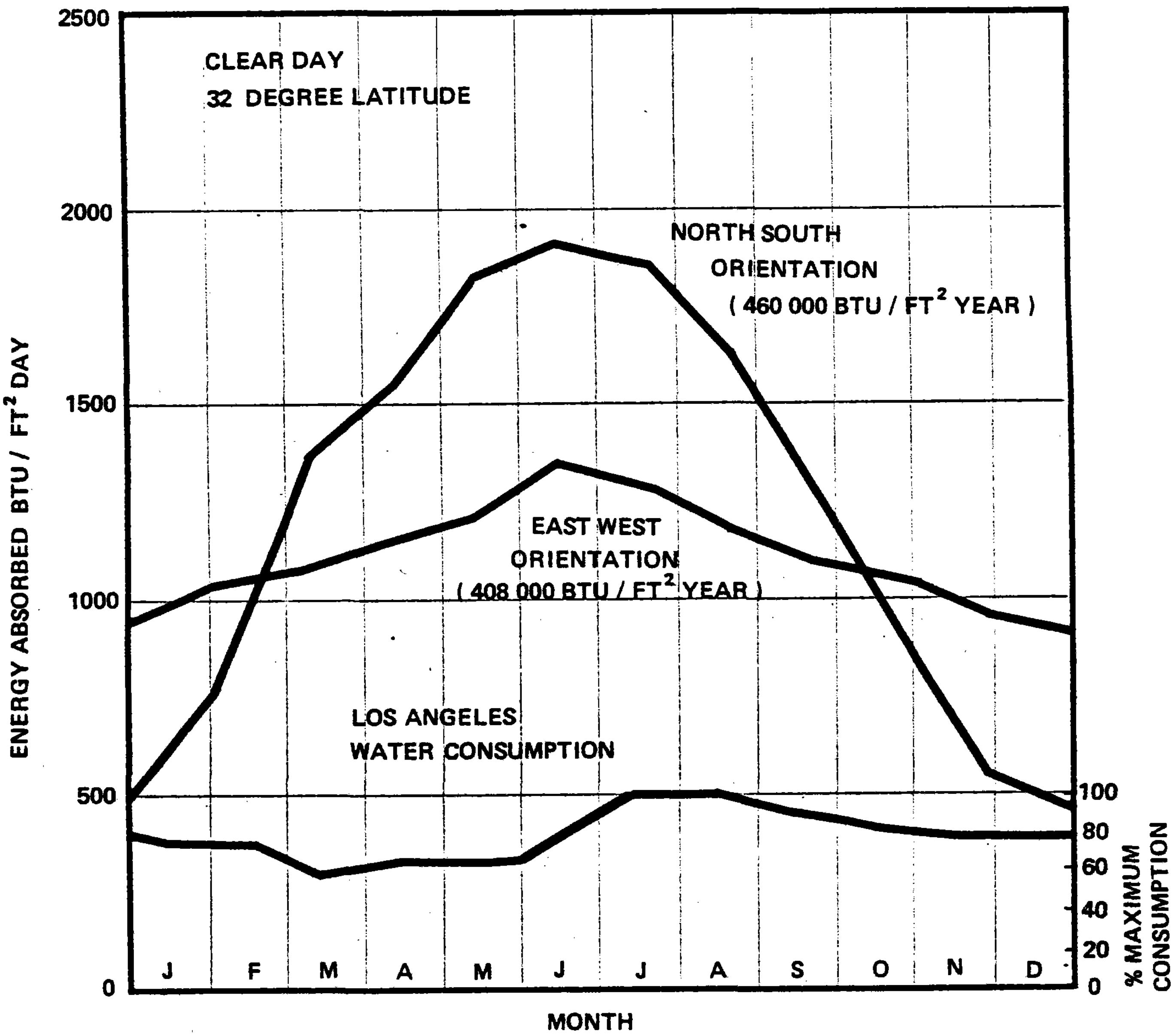


FIGURE 5–2

PARABOLIC TROUGH DAILY ENERGY CAPTURE

5.2.2 Solar Collector Area

The required heat input needed to produce 5,000,000 gpd with a distiller gained heat ratio of 12.5 pounds of distillate per 1,000 Btu is 3332×10^6 Btu/day. For a peak summer collector heat capture of 1,330 Btu/ft^2 day (Figure 5-2, east-west collector orientation, June 15) the required collector field aperture area is 2,500,000 ft^2. Adding 5% for thermal storage loss gives a final collector area of 2,625,000 ft^2.

5.3 THERMAL STORAGE

Storage required for 16 hours of plant operation is two-thirds of the daily heat input or $2,332 \times 10^6$ Btu, including a 5 % storage loss. Each pound of 300 F water flashed to 250 F releases 51.14 Btu, hence the required storage capacity is 45.6×10^6 lb, or 6,250,000 gallons storage capacity, including a 5% ullage allowance. This storage requirement can be satisfied by forty-six 24 ft diameter tanks, each 40 ft tall with 0.75 inch wall thickness.

SECTION 6

NON-SOLAR DISTILLATION PLANT

6.1 INTRODUCTION

A fuel driven non-solar distillation plant representative of present practice is described here for comparison with the candidate solar distillation concept defined in Section 4 and described in Section 5. The same distillation process is used for both the solar and non-solar plants. Each plant is to operate with 250 F steam. The choice of distillation process is discussed below.

6.2 DISTILLATION PROCESSES

At present, over 600 million gpd of sea water desalting capacity is installed worldwide. Of this, the bulk is provided by distillation processes, namely, multistage flash, multi-effect vertical tube evaporation (VTE), or vapor compression evaporation. The multistage flash process, comprising over 70% of the installed distillation plant capacity in the world, has found widest acceptance in the Middle East where the demand for desalted water is extremely high and where the cost of energy is still at a low level. In the United States, the development of advanced VTE distillation processes has been shown (Ref. 6-1, 6-2, 6-3) to provide substantial cost benefits without appreciable loss of plant reliability. In addition, research work sponsored by the U.S. Government Department of Interior, Office of Saline Water (Ref. 6-3, 6-4) has indicated that further advantages, particularly in the area of thermal economy, are yet to be gained. While the VTE distillation process is slightly more complex than the multistage flash evaporation process, it appears to be more appropriate for use with a solar heat source and for use in the United States primarily because of its greater inherent economy. In addition, the VTE is better equipped to handle a varying heat input (Ref. 6-1) as might be experienced from a solar heat source with diurnal and seasonal variations in the heat input rate.

6.3 DESCRIPTION OF THE VTE DISTILLATION PROCESS

The process selected for comparison of solar driven and conventional oil-fired distillation plants is illustrated in Figure 6-1. Additional details are shown in Figure 6-2.

This unit is a 19 effect VTE distillation plant with a nominal product capacity of 5 million gpd. As shown in these figures, sea water first enters the condenser where it serves to remove the heat from the process and condense steam from the evaporator last effect. Each of the evaporator's identical 19 effects contains an evaporating tube bundle (evaporator), a feed water preheater tube bundle, a brine-vapor disengagement zone, and a mist entrainment eliminator (demister). The evaporating tubes typically used in a modern VTE distillation plant are axially corrugated (double fluted), usually 2 inches in diameter, and 15 - 30 feet long. Preheated brine or sea water to be evaporated is pumped into the top of the tubes on the inside, with each tube equipped with a distributor nozzle. The sea water then flows down the inside of the tube in a thin film. Heating of the tube is accomplished by the condensation of boiler steam or vapor from the previous effect on the outside. With the axial corrugations, the heat transfer film coefficients on both the inside and the outside are substantially enhanced, and overall heat transfer coefficients twice as high as for smooth tubes are not unusual.

As shown, heating steam either provided by a fossil fueled boiler or by the flashing system from the solar heat source, is introduced into the steam

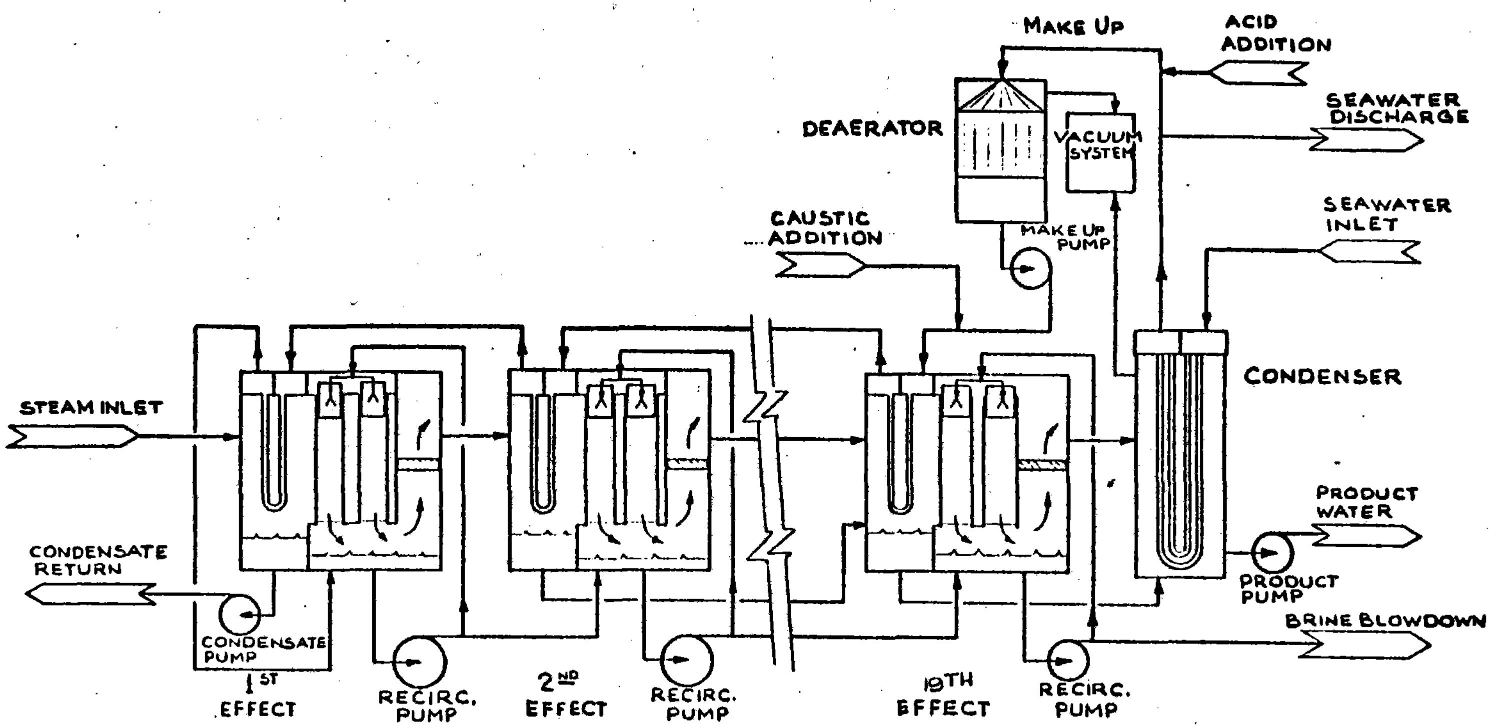


FIGURE 6-1 SCHEMATIC DIAGRAM
VTE DISTILLATION UNIT

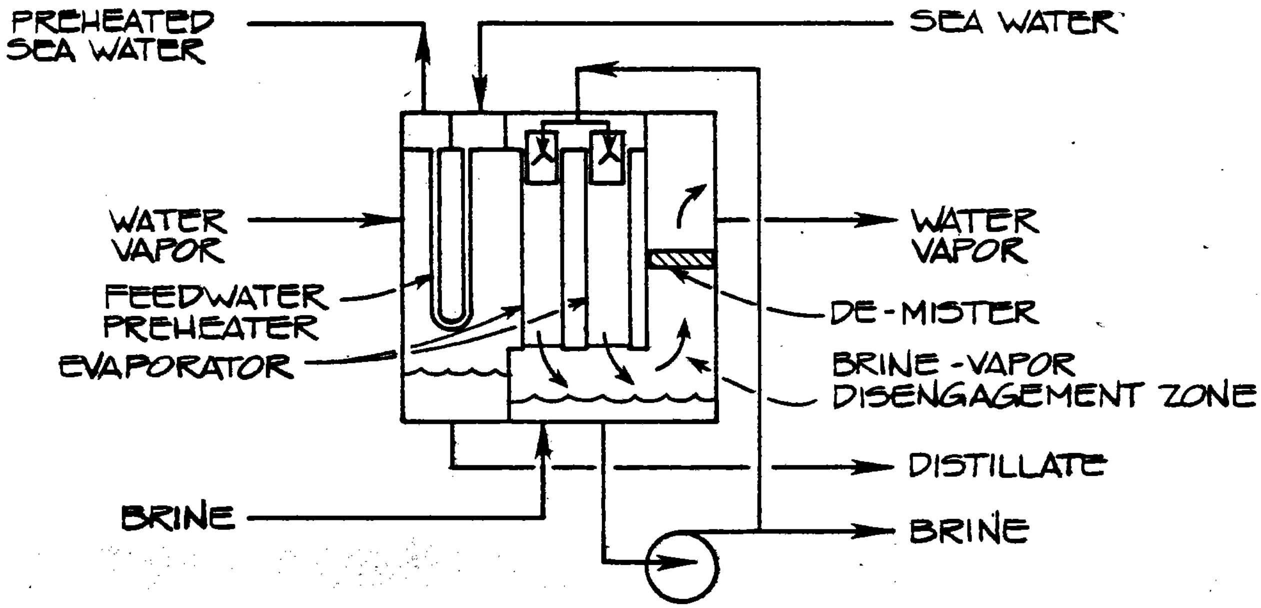


Figure 6–2 TYPICAL VTE EFFECT

side of the first effect. Here, heat is transferred to both the evaporating tubes and to the feed water preheater tubes. Vapor produced in the boiling side of the first effect goes through a mist entrainment eliminator and into the vapor side of the second effect where it condenses, heating sea water on the inside of the tubes there. This process is repeated in series in each effect, giving very efficient utilization of the energy. In the system described, the plant produces 12.5 pounds of product for every 1000 Btu's of heat input to the first effect steam chest. Plants of this type and thermal economy have already been built in sizes up to 2.5 million gpd and are now part of the water supply system in the U.S. Virgin Islands.

As shown in the process diagram in Figure 6-1, sea water which is used for distillation, is first acidified and then sent to a vacuum degasifier for the removal of carbon dioxide. This prevents scaling of calcium carbonate in the evaporator tubes. Caustic soda is added to adjust the sea water pH just above 7 to prevent any possibility of increased corrosion to the tubes. The sea water then is pumped through the preheater tubes which are mounted in the vapor spaces of each effect. In so doing, the sea water traverses each of the 19 effects and is brought up to the operating temperature of the first effect (approximately 240 F). The sea water is then pumped, with the recirculation pump, into the tubes of the first effect and also transferred into the second effect, and so on down the line, until it is finally removed from the 19th effect and discharged back to the ocean along with waste cooling water. Product water collected in each effect is flashed from effect to effect and finally pumped out to storage. Steam that is with waste cooling water. Product water collected in each effect is flashed from effect to effect and finally pumped out to storage. Steam that is condensed in the first effect is transferred back to the heat source, either solar or non-solar.

All dissolved solids entering the distiller are discharged with the blowdown brine. Distillers of this type are generally not used for reclaiming minerals from saline or brackish waters.

6.4 ADAPTABILITY TO VARIABLE OPERATING CONDITIONS

The VTE concept is particularly well suited to varying heat input conditions and varying capacity which would be typical of a solar heat source. In addition, it may be desirable to adjust operating capacity for seasonal supply requirements. Figure 5-2 shows the variation in water consumption for a large metropolitan area of Southern California. This figure shows that there is approximately a 40% difference between maximum and minimum water consumption between the months of July and August versus January, February, and March. For a solar distillation plant, this should coincide closely with the variation in insolation.

Previous studies (Refs. 3-17 and 6-5) have considered the possibility of linking a solar heat source with multistage flash distillation. In both of these studies, the heat for evaporation is applied directly to the sea water circulating through the multistage plant. The heated sea water then is introduced into the flash vessels where conversion to product water takes place with the attendant recovery of some heat, as is typical in a multistage flash plant. In each of these cases, however, operating costs are expected to be much higher due to the lower cost-effectiveness of multistage flash distillation. In addition, the inability to handle varying loads, which is inherent in the multistage flash design, makes this combination much less desirable than the chosen VTE concept.

SECTION 7

ECONOMIC COMPARISONS

7.1 COMPARISON BASES

A comparison is made here between the presently implementable candidate solar distillation concept as described in Section 5 and a conventional non-solar distillation plant, as described in Section 6, operating under similar conditions. The intent is to provide an approximate indication of the relative competitive positions of solar and fossil energized distillation plants for the 1977 time frame. This point of reference will provide a basis for the assessment of the future potential of solar distillation.

The common bases for comparison of the the solar and conventional distillation plant are:

- 5 million gallon per day capacity
- Vertical tube expansion distiller for both plants
- Gained output ratio of 12.5 pounds of distillate per 1,000 Btu's of thermal input into the first effect
- 70 F sea water supply
- Seaside site at 30 degrees latitude
- 25% annual cloud cover

7.2 COST ESTIMATING BASES

The costs for this study are based on information taken from the literature and assessed for validity based on Bechtel cost information. The scope of the study neither intends nor permits a detailed or highly documented cost analysis. It does require a reasonable first order estimate of plant costs in order to assess the relative competitive positions of large scale solar and fossil driven distillation plants for the 1977 time frame.

The cost estimate for the solar collection system is based on information in the current literature with some adjustment to account for the large collector area required. The distillation equipment costs are based largely on Bechtel cost information. Some specific criteria are presented below.

- Costs are based on 30 year amortization and the assumption that the plant is a non-profit, nontaxable, publicly owned enterprise
- Fixed annual charge on investment, based on 8% interest and a 30 year plant life, is 0.08883 x invested capital
- Annual charge for operation and maintenance:

  solar collection system at $0.15/ft^2 - year

  remainder of plant 2% at of invested capital
- Administration and general expense at 25% of operation and maintenance
- 1977 Fuel Costs:

  Oil at $2.00/10^6 Btu
- Fuel Escalation Rates:

  0%, 6%, 9% and 12%
- Cost of Electric Energy

  $$\$/\text{kWh} = .010 + \frac{F}{100}$$

  F = fuel cost in dollars per million Btu.

- Land cost is neglected (amounts to about \$.01/1,000 gallons for \$1,000/acre land).

7.3 COSTS FOR NON-SOLAR DISTILLATION PLANT

The cost of the VTE desalting plant selected is shown in Table 7-1. This includes not only equipment costs, but costs for intake and outfall and buildings. In the distillation plant only, the capital cost, including engineering and construction management, interest during construction, and a 10% contingency, totals approximately \$20.5 million. This is equivalent to approximately \$4.10 per installed gpd of capacity. Recent surveys of plant awards for large desalination complexes throughout the world show an average installed cost of less than \$3.00 per gallon day capacity. However, since most of these complexes are in the Middle East, and will reflect lower thermal economy, the plants are somewhat less expensive than anticipated for this study.

Table 7-2 shows annual costs for the non-solar distillation plant. As can be seen, cost of fuel, which was estimated at \$2.00/million Btu's, represents half of the total yearly cost. Since the total equipment was amortized over a 30 year period, the fixed charges on capital are approximately one-third of the total yearly cost. The resultant overall cost for water based on operating at full capacity 330 days per year, was estimated to be \$3.31/1,000 gallons. If reduced capacity for the lower water demands anticipated for the winter months is taken into account, the actual average water cost will be higher.

TABLE 7-1

CAPITAL COST DATA

FOR OIL-FIRED DISTILLATION PLANT

Distillation Plant, Installed	5 Mgd Capacity 12.5/1 Gained Output Ratio Vertical Tube-Expansion
ITEM	Cost, 1977 $
Evaporator Bodies (including tubing)	7,788,000
Pumps and Motors	2,549,000
Valves and Piping	2,124,000
Chemical Equipment	425,000
Instrumentation	283,000
Electrical	779,000
Deaerator and Vacuum System	212,000
Distillation Equipment, Subtotal	14,160,000
Site Preparation	500,000
Intake and Outfall	750,000
Buildings	125,000
Total Direct Capital, Distillation Plant	15,535,000

Steam Supply System	200,000 #/Hr, Package Unit Oil Fired
ITEM	Cost, 1977 $
Steam Generator, Burners, Fans & Stack	980,000
Deaerator and Feed Pumps	35,000
Fuel Storage and Handling	147,000
Steam Supply Equipment, Subtotal	1,162,000
Site Preparation	37,000
Total Direct Capital, Steam Supply	1,199,000

TABLE 7-1 (Cont'd.)

Capital Estimate Summary

ITEM	Distillation Plant Only	Distillation Plant w/Boilers
Total Direct Capital	15,535,000	16,734,000
Engineering and Construction Management[a]	1,942,000	2,092,000
Interest During Construction[b]	1,310,000	1,412,000
Contingency[c]	1,748,000	1,826,000
Total Capital Cost	20,535,000	22,064,000

(a) 12.5% of direct capital

(b) 7.5% of capital and engineering

(c) 10% of capital and engineering

TABLE 7-2

CAPITAL AND ANNUAL COSTS - OIL-FIRED PLANT

Capital Investment	$22,064,000
Annual Costs	
Fixed Charge on Capital @ 8%, 30 yr. (.08883)	1,960,000
Operation & Maintenance @ 2% of Capital	441,000
Administration & General Expense @ 25% of O&M	110,000
Electric Energy (Levelized) [a]	202,000
Fuel (Levelized) [b]	2,749,000
Total Annual Cost	$5,462,000
Annual Water Production	1,650 x 10^6 gallons [c]
Water Cost	$3.31/1000 gallons

(a) Based on $.03/kWh electric energy and no fuel escalation.

(b) Based on $2/10^6$ Btu and no fuel escalation.

(c) Based on operation of 330 days per year. Down time of 35 days per year is to allow for scheduled and unscheduled maintenance.

7.4 COSTS FOR SOLAR DISTILLATION PLANT

Costs for parabolic trough collectors are available from the current literature. MITRE (Ref. 4-1) presents representative installed cost and operating cost for a number of collector types. These costs were discussed earlier and are displayed in Table 4-1. Acurex (Ref. 7-1) gives a complete installed cost for a 43,200 ft^2 collector field of $22.70 per square foot. Table 7-3 tabulates representative costs for a 2,625,000 ft^2 collector field and those reported for Acurex's 43,200 ft^2 collector field. The installed cost of $18.00/$ft^2$ for the 2,625,000 ft^2 field represents approximate cost reduction associated with the larger field size and is based on information from collector suppliers. The slight reductions in foundation and piping costs are arbitrary reductions assumed for a considerably larger collector field.

Table 7-3

REPRESENTATIVE COLLECTOR FIELD COSTS

	43,200 Ft^2 FIELD	2,625,000 Ft^2 FIELD
Collectors (Installed)	$16.66	$12.50
Foundations	4.38	4.00
Piping	1.66	1.50
Total Cost per ft^2	$22.70	$18.00

Representative operating costs for parabolic trough collector fields are given in Reference 4-1 as $0.075/$ft^2$-year. An operating and maintenance cost of double that number, or $0.15/$ft^2$-yr, is used here to account for the several reflector resurfacings that are expected to be needed during the 30 year plant life.

No costs directly applying to thermal storage of 300 F water were found in the literature. Nicholson and Cahn (Ref. 7-2) report a tank cost of $.43 per gallon for storage of 500 F oil at atmospheric pressure. The Public Service Electric and Gas Company of New Jersey (Ref. 7-3) estimates tank costs of $3.38 per gallon for 420 F, 300 psig storage of power plant feed water. The thermal storage cost for 300 F, 52 psig water used here is based on tanks 24 ft dia x 40 ft tall with 0.75 inch wall thickness. The cost of one such tank installed with insulation is about $2 per gallon without quantity discount. Since approximately forty-six such tanks are required to provide the required 6,250,000 gallon storage, a unit cost reduction to $1.92 per gallon is assumed, giving a total storage system cost of $12,000,000.

The costs discussed above provide the basis for the solar distillation plant and water costs shown in Table 7-4.

7.5 EFFECT OF FUEL COST ESCALATION

The major cost of the non-solar distillation plant is the cost of fuel. Fuel costs also impact the annual operating expense for the solar plant due to its consumption of electric energy for pumping. The levelized annual cost of fuel over the plant's 30 year operating life is controlled by the annual fuel cost escalation rate and the assumed 8 percent interest rate. Levelized fuel oil costs for several escalation rates are shown below:

TABLE 7-4

CAPITAL AND ANNUAL COSTS - SOLAR PLANT

	5 Mgd Capacity Solar Distillation Plant
Capital Investment	
Distillation Plant	$20,535,000
Solar Energy Collection Field @ $18/ft^2	47,250,000
Thermal Storage System	12,000,000
Total Capital Investment	$79,785,000
Annual Costs	
Fixed Charge on Capital @ 8%, 30 yr. (.08883)	7,087,000
Operation & Maintenance	
Solar $.15/ft^2 - yr	394,000
B.O.P. @ 2% of Capital	411,000
Administration & General Expense	
@ 25% of O&M	201,000
Electric Energy (Levelized) (a)	380,000 (a)
Total Annual Cost	$ 8,473,000
Annual Water Production	1,102.3 x 10^6 gallons (b)
Water Cost	$7.69/1,000 gallons

(a) Based on $.03/kWh electric energy and no fuel escalation. The higher cost compared with the oil-fired plant reflects a higher auxiliary power requirement for the solar plant.

(b) Based on operation 265 days per year and reduced insolation during winter. Down time is due to 25 percent annual cloud over and maintenance.

Escalation Rate	0%	6%	9%	12%
Levelized Fuel Cost per million Btu	$2.00	$4.04	$6.17	$9.84

The water costs of Tables 7-2 and 7-4 are based on 0% escalation of fuel cost for the next 30 years. The potential impact of fuel escalation on water costs is shown in Table 7-5.

7.6 COST COMPARISONS

The same information, presented in Figure 7-1, indicates that for 1977 construction solar distillation is not presently competitive with fuel driven distillation if the annual fuel oil escalation rate is less than 10.5 percent for the thirty year plant life. Figure 7-2, showing the comparison between solar and oil driven distillation plants constructed in the future, indicates that for a fuel escalation rate as low as 5 percent solar distillation will become competitive with oil driven distillers by 1992 even if solar collector technology remains at its present state. Since marked improvement in solar collector technology is expected, solar distillation should become competitive with oil-fired distillation within the next 15 years.

The estimate of lower bound water costs for future solar distillation plants, shown in Figure 7-1, is based on the assumption that cost of the solar collection field is reduced to $\$6/ft^2$; one-third of the presently estimated collector field cost. This gives a reduction in water cost of $2.54/1,000 gallons.

TABLE 7-5

INFLUENCE OF FUEL (OIL) ESCALATION ON WATER COST

Full Escalation Rate	Solar Plant	Non Solar Plant
	$/1,000 gal	$/1,000 gal
0%	$7.69	$ 3.31
6%	$7.92	$ 5.09
9%	$8.17	$ 6.96
12%	$8.58	$10.16

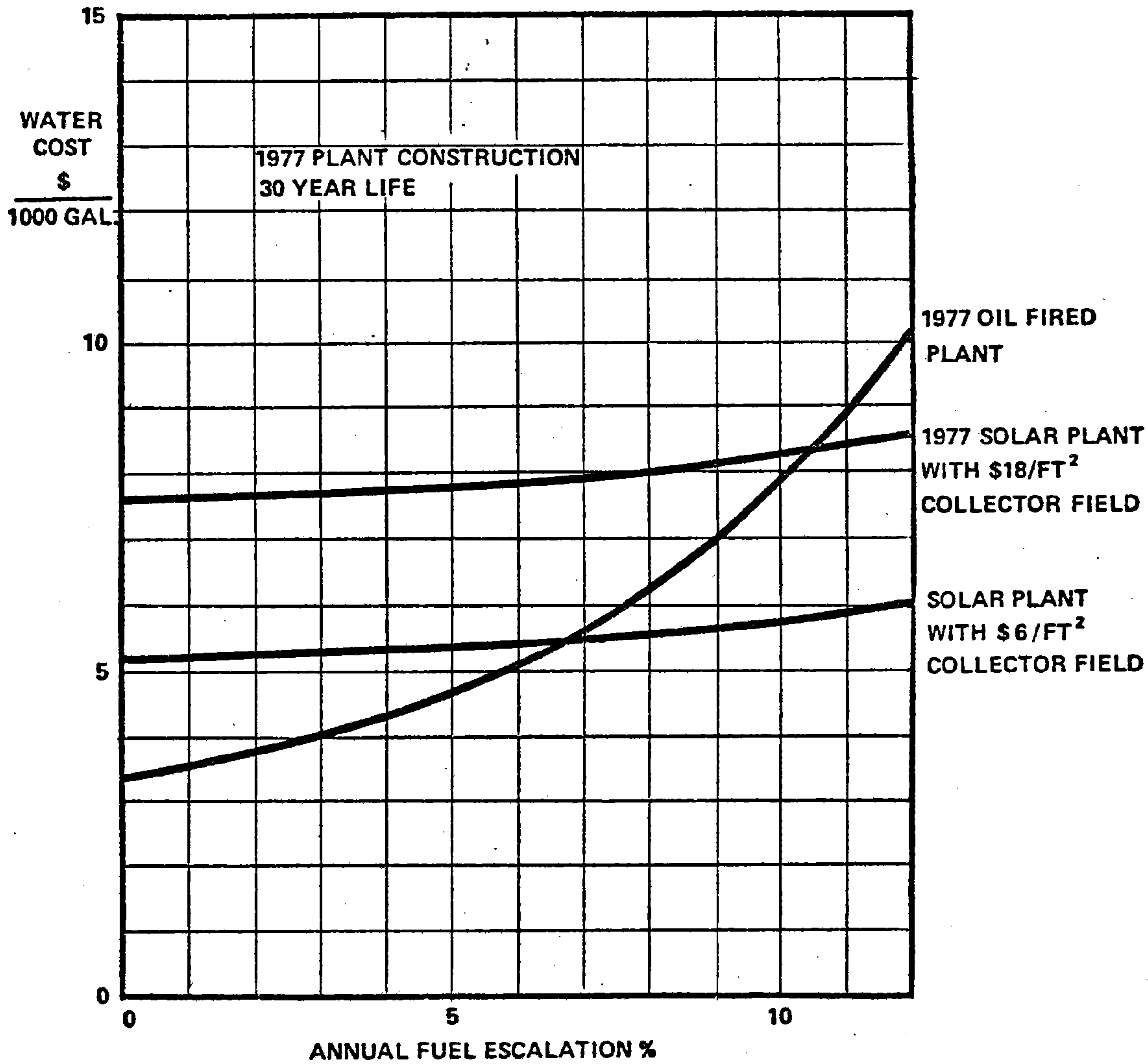


FIGURE 7 – 1 INFLUENCE OF FUEL (OIL) ESCALATION ON DISTILLED WATER COST

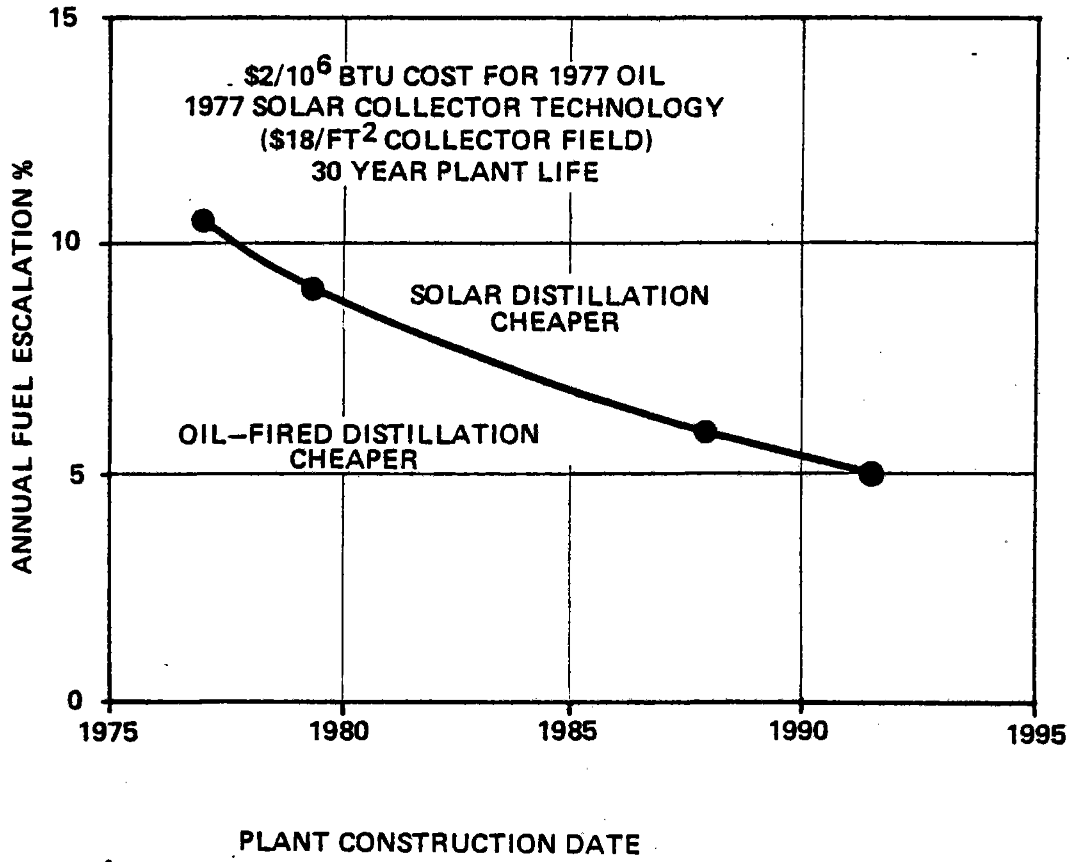


FIGURE 7–2 ANNUAL FUEL ESCALATION REQUIRED TO MAKE SOLAR AND OIL-DRIVEN DISTILLATION COSTS EQUAL

Section 8

POTENTIAL OF CONCEPTS NOT SELECTED AS CANDIDATE

Concepts not selected as the candidate in this study include the single-effect solar still, the multi-effect solar still, and solar driven conventional distillers involving different solar collector concepts or a different distiller concept.

The current cost for single-effect solar stills is not firmly established by this study. It appears that such stills may have the potential to compete with oil and solar driven distillation processes only in some developing countries where labor costs are low. The real potential of single-effect solar stills cannot be realistically assessed with information currently in the literature. Many questions remain unanswered. For example: are stills currently in operation really constructed well enough to give a reasonable operating life?; are operating costs given really adequate to cover rebuilding and repair required by storm damage as well as prevent performance degradation?; how cheaply can a still be built today in a developing country? Answers to these questions might be obtained by an up to date detailed survey of the experience at Patmos (Greece) and Gwadar (Pakistan) and in Australia. The real potential of the solar still is presently indeterminate.

The multi-stage flash distiller could have been used as the reference process for this study but, being less efficient than the VTE process, its future potential in a period of increasing fuel costs should diminish rather than improve with the passage of time.

Several collector concepts were identified which appear to have a potential for solar distillation applications which may exceed that of the parabolic trough. Included are the fixed and articulated types of segmented mirror collectors, and possibly the compound parabolic concentrator (CPC) or the evacuated tube collector. Each of these may be deserving of further consideration. It is doubtful however, if any of them can improve upon the water costs indicated in Figures 7-1 for the $6/ft^2 collector in the near future.

Section 9

AREAS FOR FUTURE CONCEPTUAL EVOLUTION

Areas of future conceptual evolution include (1) the identification of preferred solar collector designs for the driving of conventional distillation units, and (2) evaluation of the merits of operating distillation units with waste heat from a solar power plant. A definitive assessment of present single-effect solar still construction and operating costs is also needed to determine whether solar stills are a competitive means for large scale production of fresh water in developing countries.

9.1 PREFERRED SOLAR COLLECTOR DESIGNS FOR DRIVING A CONVENTIONAL DISTILLATION UNIT

The parabolic trough solar collector was selected as the solar driver for the candidate solar distillation plant of this study. It was selected primarily because it is the only high temperature collector design which meets the criterion of being presently implementable for a large scale plant, were construction to start today. The resulting solar distillation plant is one that could be assembled with equipment that is currently available in quantity production and that is presently operating in a number of field installations.

There are a number of alternate solar collector designs, now being developed and tested in small quantitites, which may soon be implementable. Each has a different performance characteristics and a different cost structure. One or more of these alternate designs may be superior to the parabolic trough for the driving of a distillation unit. What is really needed is the cheapest source of 300 F solar energy.

Reliable performance data for the alternate collector designs are currently available. Available cost data are tentative, but a general range of collector costs for each design is known.

Alternate collector designs which should be evaluated as distillation unit drivers are

- Shallow pond collector
- Evacuated tube collector
- Compound parabolic concentrator (CPC)
- Fixed segmented mirror concentrator
- Articulated segmented mirror concentrator
- Linear focusing central receiver
- Point focusing central receiver

The end result of each evaluation would be annual average water cost, in dollars per 1000 gallons.

9.2 DISTILLATION UNIT OPERATION USING SOLAR POWER PLANT WASTE HEAT

This approach parallels what is currently taking place in conventional distillation unit applications where power plant waste heat is being substituted for more expensive primary heat obtained from the combustion of fuel. A definitive evaluation of the merits of this use of solar waste heat is warranted. The evaluation must include a screening of various ways for utilizing the waste heat and an assessment of the most promising methods.

9.3 COST OF WATER FROM SINGLE-EFFECT SOLAR STILLS IN THE PRESENT TIME FRAME

The available literature does not provide a satisfactory base for accurate estimation of the cost of water which might now be obtained by the construction and operation of a large scale solar still. Costs which are reported are old, generally optimistic and often incomplete. Uncertainty as to present costs is amplified by the marked inflation of the last several years.

A tentative lower bound water cost of $7.85/1000 gallons for single-effect solar stills in developing countries was set forth in Section 3. This figure is based on $1.88 per square foot construction costs, 10 hours maintenance per year for each 1000 square foot of still, and $0.49 per hour labor. These assumptions are plausible for underdeveloped countries but are undocumented for the present time frame.

Determination of the present cost for large scale production of fresh water from single-effect solar stills in developing countries requires a survey and evaluation of experience accumulated at the major solar still facilities presently in operation. At a minimum the survey should include the worlds largest still, Gwandar II, in Pakistan; and the stills in Greece and Australia. The survey must gather the original still cost breakdowns and adjust them to reflect presently available material cost and labor rates at each facility location. This, plus an accurate tally of actual manhours spent on routine maintenance, repair and rebuilding will permit the calculation of the cost of water obtainable from new solar stills constructed today.

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