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A SCHEME FOR LARGE SCALE DESALINATION OF SEA WATER BY SOLAR ENERGY

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Abstract : A scheme is proposed to desalinate sea water using solar energy for the Thar Desert of India. The scheme has been using solar energy for the Thar Desert of India. The scheme has been designed to produce about 5.25 x 10 m^3/yr (13860 MG/yr) of fresh water with 11.52 km^2 (4.5 $miles^2$) of collector area. The solar collectors are rectangular concrete tubes, half buried in the ground, through which sea water flows and is heated by solar energy. The heated sea water is then flash evaporated in a multi-stage flash evaporator (MSF) unit to yield fresh water. Pumping of the sea water to the site and through the MSF unit is powered by 415 wind turbines each of 200 kW capacity. Economic analysis of the scheme shows that it compares favorably with the existing fossil fuel fired desalination plants of the equivalent capacity.

1. INTRODUCTION

Solar distillation units have been extensively studied [1, 2] and deployed on a moderate scale [3], but little effort has been done on scaling them up for greater). The reasons for this are not difficult to see, they being; (1) Cost of the units – On an average roof type solar distillation units cost \$ 35-40/m^2 of basin area, thus making large scale deployment economically unattractive compared to other means of desalination. (2) Difficulty in maintenance because of breakage of glass, flushing of the basins and flow of distillate to a centralized location.

The above reasons have therefore prompted some investigators [4, 5] to propose alternative ways of utilizing solar energy in conjunction with conventional distillation plants, but the solar energy collection systems in these schemes have been conventional collectors which have again made the scheme economically (because of high cost of collector) and technically (because of corrosion problems and breakage of plastic cover [5]) unattractive. Thus the existing large scale (capacity greater than 4000 m^3/day) desalination plants all over the world are fossil fuel fired, and 80 per cent of them are multi-stage flash evaporation (MSF) type. With the world water demand increasing because of rising population and industrialization and with fossil fuel prices spiraling up, it becomes imperative to look at new methods of solar distillation. These systems should be able to have the ruggedness of the fossil fuel fired plants, should be economically attractive, and, above all, should work on renewable sources of energy.

With this in mind a scheme is, therefore, outlined in the present paper for large scale desalination of sea water using solar energy for the coastal desert of India. The technical and economic feasibility of the scheme has been studied, and the thrust has been to present an

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[1] This paper was published when the author was a graduate student in the Mechanical Engineering Department (Solar Energy Lab.) of University of Florida, Gainesville, USA.

overall objective rather than detailed design and cost calculations. Thus, an attempt has been made to present only the results of preliminary design and cost calculations.

2. **THAR DESERT**

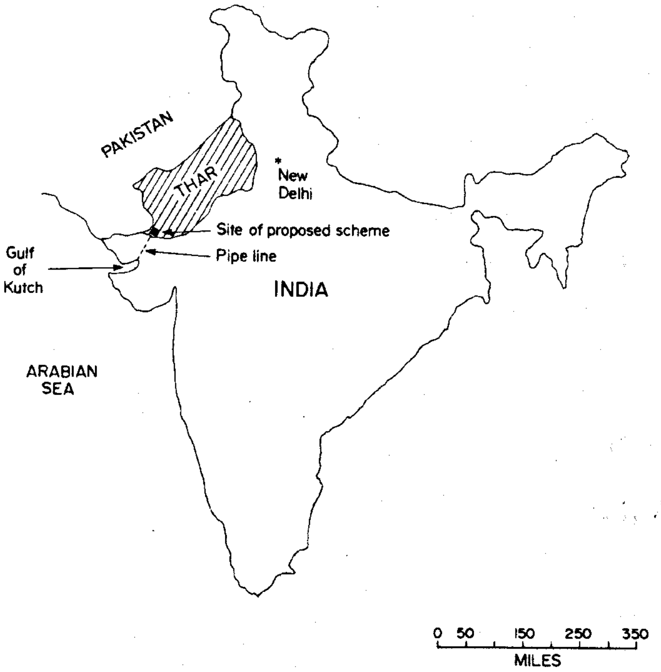

Fig. 1. Map of India and the site of the proposed scheme.

The northwest region of India is covered with a large desert known as the Thar Desert, which occupies an area of about 200,000 sq.m. [6]. Figure 1 shows the location of this desert and the proposed site for the desalination unit. The desert is inhabited by about 3 million people, most of whom eke out a modest existence through subsistence agriculture [7]. The average annual precipitation is about 150 mm, the monsoon months being from late July to early September; most of the deep wells are saline; and the water table is very low, in some places as deep as 100-200 m. In some locales it has not rained for the past 80 yr [8]. There is always the threat of famine in this area resulting in great loss of animal and human life. Nevertheless, through the ages local population has been able to identify and use some of the wild plants that grow in this area [9]. These plants grow with very little water available during the monsoon months, and it is hoped that if adequate water is available in this region then the quantity of such food together with other staple foods like *Bajra* can be greatly increased. Such optimism is also borne by the past history of the region, which indicates that, the confluence of man and nature has turned this rich area of flourishing Harrappian culture into desert [10].

Several schemes for watering this area have been proposed, but most of them have proven to be economically unfeasible. Among one of the schemes that is being actively pursued by the Government of India is the construction of a huge canal known as the Rajasthan Canal. This canal, when completed, will be able to irrigate a substantial portion of the northern part of the desert, but the scheme has been bogged down by rising cost of the canal and the lowering of the level of the Sutlej River, the source of this canal.

Other schemes that have been proposed are the desalination of sea water by fossil fuel and nuclear energy, but the rising cost of fuels and their shortages have shelved most of these schemes. The best possibility, then, of achieving the goal of supplying fresh water rests with desalination of sea water using solar energy.

3. SCHEME

The scheme envisages bringing about 2.16 x $10^5 m^3$ (57.0 MG) of sea water every hour in three 3.05 m (10 ft) diameter concrete pipes to the location of the "solar field". The proposed location of this field in the Thar Desert is at about 80 km (50 miles) from the Arabian Sea and at an elevation of 45.7 m (150 ft) from sea level. The sea water passes through the heat exchanger tubes of a 20 stage multi-stage flash (MSF) evaporator where it is heated from 15.5^{0}C (60^{0}F) (the inlet temperature) to about 54.4^{0}C (130^{0}F) at 2 pm on a typical June day, as a result of the vapor condensing on the outside of the tubes. Figure 2 shows the general flow diagram on the multistage flash evaporation process and the "solar field". As the heated sea water leaves the desalination plant, it is pumped through the "solar field" which heats it to 60^{0}C (140^{0}F). The "solar field" consists of tubular concrete collectors. The cross section of one such collector is shown in Fig. 3. There are 9600 of these collectors on each side of the desalination unit with the length of each being 609.6 m (2000 ft).

A scheme for large scale desalination of sea water

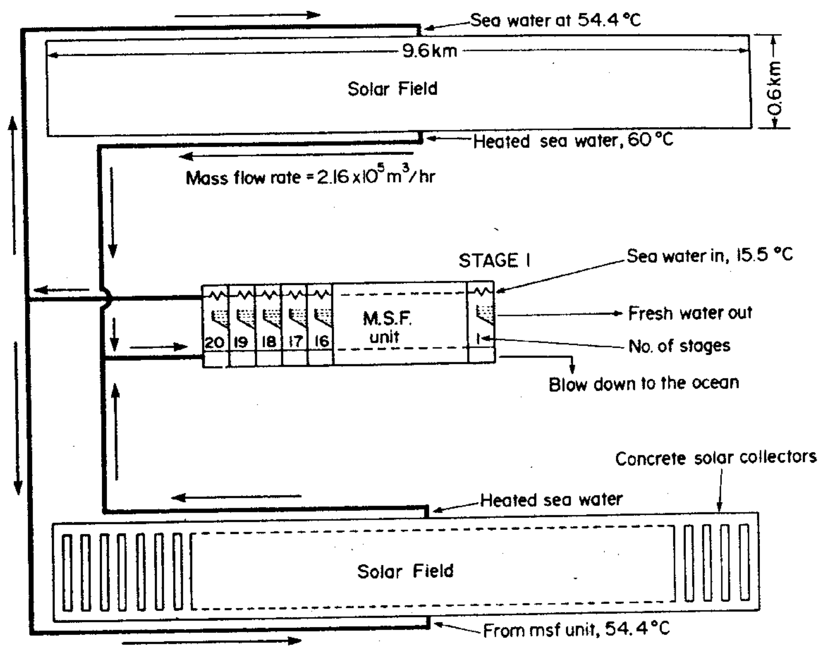

Fig. 2. Flow diagram of the MSF process and the "solar field".

The heated seawater in the collector travels at a velocity of 0.04 m/s (0.14 ft/sec), thus taking 4 hr to traverse the "solar field". Water at 60^{0}C (140^{0}F) is then flash evaporated in the desalination unit to yield 1.36 x $10^4 m^3$/hr (3.6 MG/hr) of fresh water for a typical day in June at about 2 p.m. The pumping of the sea water to the site through the solar collectors and through the desalination unit is powered by wind turbines. The effluents from the plant are allowed to run by gravity back to the sea.

Below are given the details of the design and the cost of the system.

Solar field

This is the most important component of the system since it provides the energy to effect desalination. Thus the need for right choice of solar collector cannot be underestimated. For the present scheme the solar collectors should meet the following criteria: (1) Ease of fabrication and maintenance; (2) Cost effectiveness; (3) minimum corrosion with sea water; (4) Durability and ruggedness to last the life of the plant.

Several collectors and materials, which would meet the above criteria, were looked into, and finally concrete was chosen as the collector material. Apart from meeting all of the above criteria, there is an added advantage for picking it as the collector material. The clay (a necessary ingredient of concrete) content of the Thar soil is high (15 per cent), and thus it has been felt that local raw materials can be used effectively in making these collectors, thereby reducing the cost. Figure 3 shows the cross section of the collector used in the present scheme. The present configuration was decided from strength considerations of concrete together with the need to maximize the surface area exposed to solar radiation.

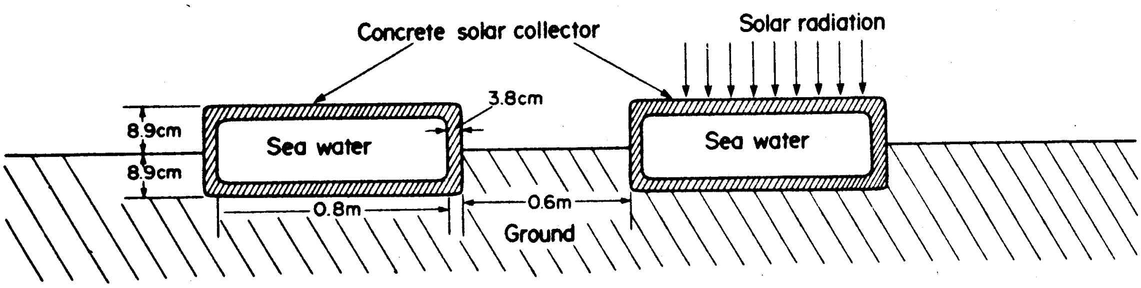

Fig. 3. Cross section of the solar collector.

Simple heat transfer analysis has been done for the collector in order to get the temperature of the outlet seawater. Instantaneous heat balance has been done over the cross section of the collector for length $\Delta L = 5$ cm, as shown in Fig. 4.

Heat balance at a time t, for the surface of the collector yields,

$$\propto_{cb} q''(t)\, A_0 = h_{c+r}\, A_0 \{T_0(t) - T_\infty(t)\} + (k_c/t_c)\, \underline{A_0} \{T_0(t) - T_1(t)\} \tag{1}$$

And the heat transfer to the liquid flowing in the collector is,

$$(k_c/t_c)\, \underline{A_0} \{T_0(t) - T_1(t)\} = h_1\, A_i \{T_1(t) - T_{mm}(t)\} \tag{2}$$

Where h_i = heat transfer coefficient inside the collector and T_{mm} (t) is the mixed mean temperature of the fluid.

Similarly heat gain from the bottom of the collector is :

$$(k_c/t)\, \underline{A_b} \{T_b(t) - T_2(t)\} = h_1\, A_i \{T_2(t) - T_{mm}(t)\} \tag{3}$$

Finally we can also write the total heat gain to the fluid as :

$$m\ c_p\ \{T_{out}(t) - T_{in}(t)\} = h_1 A_i \{T_1(t) + T_2(t) - T_{mm}(t)\} \tag{4}$$

and,

$$T_{mm}(t) = [T_{out}(t) + T_{in}(t)]/2.0 \tag{5}$$

It should be noted that steady state calculations have been made for the heat flow in the collector from the top. There will be a thermal lag in the heat transfer to water because of absorption of heat by the pipe during the warm-up period in the morning. This heat gain will have a tendency of being lost during the afternoon cooling-off period. However, the internal heat transfer coefficient h_i inside the pipe is about 448 $W/m^2 - {}^0C$ as compared to external heat transfer coefficient, h_0 of 33.6 $W/m^2 - {}^0C$ and thus most of the energy absorbed in the walls of the pipe is transferred to the water.

The base temperature T_b (t) is calculated after knowing the soil surface temperature T_s (t). Following the method outlined in [15] we find that the diurnal variations of the temperature dies down after about 0.8 m below the surface and is a constant 12.7^0C (55^0F).

Hence the sand surface temperature in the desert is given by the following equation for per unit area,

$$\alpha_{sand}\ q''(t) = h\,[T_s(t) - T_\infty(t)] + (k_{sand}/\Delta X)\,[T_s(r) - 12.7] \tag{6}$$

Where $\Delta X = 0.8$ m.

Knowing q'' (t) and T_∞ (t) one can calculate T_s (t) easily. There is a time lag between the maximum surface temperature and the maximum temperature 8.9 cm (3.5 in.) below the surface and is given by [15],

$$\xi = (l/2)\,[24/(\Pi A)]^{1/2} \tag{7}$$

Where l = depth below the surface and $A = K_s/(C_p\rho)_s$. For the present case ξ is 3.7 hrs. Also the maximum temperature T_b is given by

$$T_{b,\,max} = T_{s,\,amp} \exp\{-l\,(\Pi/A) \times 24]^{1/2}\}, \tag{8}$$

Where T_s amp is the amplitude of the diurnal variation of soil surface temperature. For a typical day in June the top surface temperature, T_s and T_b are shown in Fig. 5. Table 2 lists the property values used in the calculations above.

Thus knowing the bottom temperature T_b (t), eqns (1) - (5) have been solved to yield the temperature of the outlet water from the solar collector. T_{out} (t) from eqn (4) then becomes T_{in} (t) for the next section of the collector, and thus the calculations proceed for the total length of the collector. For a typical day in June the outlet temperature from the solar collector is shown in Fig. 6. The inlet temperature to the solar field is a function of the outlet

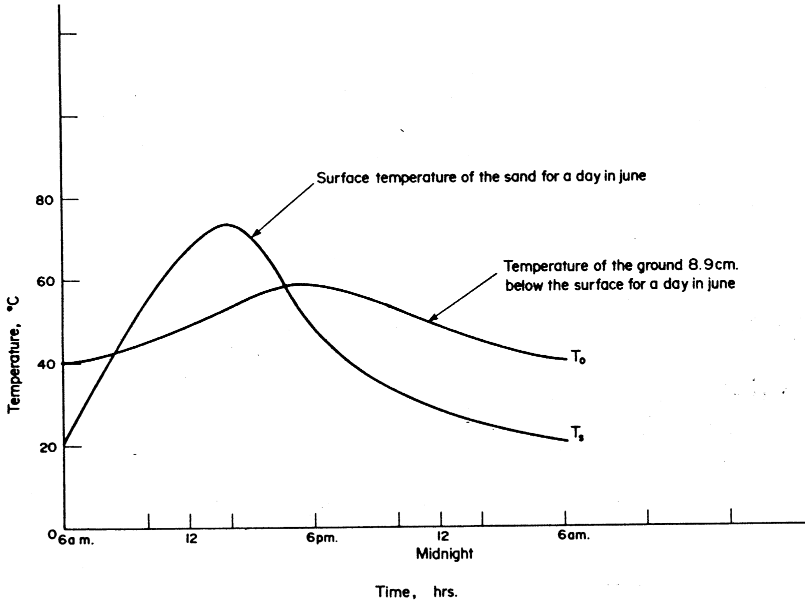

Fig. 5. Temperature profiles for surface of the sand and ground 8.9 cm below.

temperature. This relationship, shown in Fig. 7, can be calculated by making an enthalpy balance on the distillation unit [16]. In the above calculations it is assumed that the bottom of the collector temperature is the same as that of sand at depth of 8.9 cm, but which is exposed to solar radiation directly. In actual practice the bottom of the collector will be cooler than the adjacent sand because of shading. However, heat loss calculations from the collector to sand using temperature of 49^0C (120^0F) for a typical day in June at 2 p.m. yield heat flow of about 480 W/m^2 . This heat loss is about 240 W/m^2 less than that from the collector bottom, which is shaded. The above heat flow was estimated assuming the same type of temperature profile of the sand parallel to collector, as that of the ground. Corrections for the above profile were made since the heat is conducted from both ends of the collector. The above heat loss translates into loss of distillate output of 10 per cent which is within the accuracy of most heat transfer calculations. This then justifies the assumption of T_b. Naturally, the above loss sets the upper limit on the heat flow to the sand and at other times it will be much less and consequently the distillate loss will be much lower.

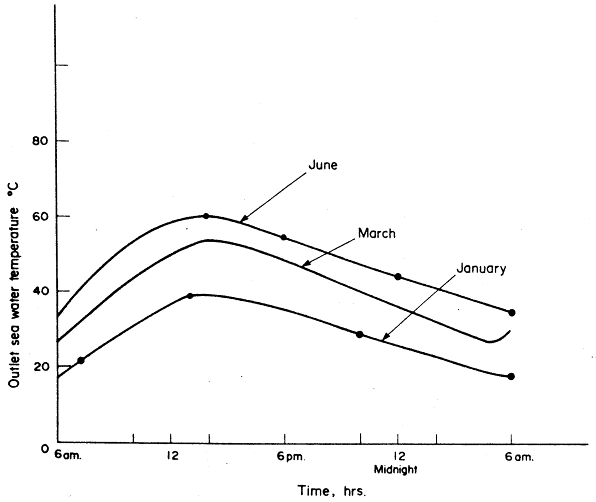

Fig. 6. Outlet temperature profile from the solar field for the months of January, March and June.

The above set of calculations have been done for a typical day in January (the coldest month) and for March, and the outlet temperature-time history is shown in Fig. 6.

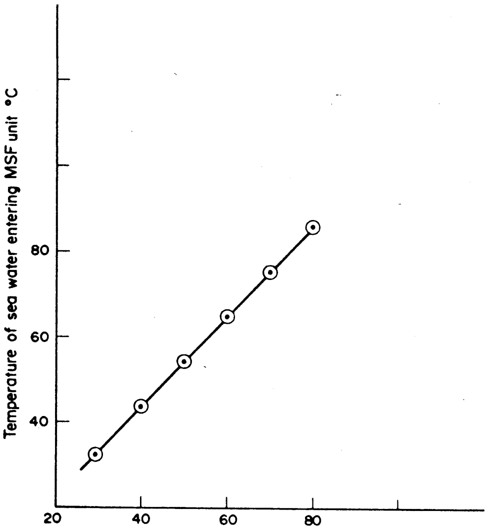

Fig. 7. Relationship between the temperature of sea water entering MSF unit and leaving it.

Desalination unit

The heated seawater from the "solar field" goes to the desalination unit for production of fresh water. The desalination unit is the regular multi-stage flash evaporation (MSF) type. Normally, these MSF units are used for brine temperatures of approximately 100^0C (212^0F) and thus would seem inappropriate at a first glance, for our scheme where the maximum brine temperature is 60^0C (140^0F). Nevertheless, in the absence of any other viable desalination technology we have used this system. We do, however, feel the need of better and more efficient systems for evaporation of sea water, which would ultimately bring down the cost of the scheme. It will be seen later than the MSF unit is one of the costliest item in the whole scheme and thus the need of a better unit.

The MSF unit for the present scheme is a 20-stage evaporator with terminal temperature difference (TTD) of 1.67^0C (3^0F). The present design is simply an extrapolation on the design by Brice *et al.* [5] for the production of about 1.36 x 10^3m^4/hr (3.6 MG/hr) of fresh water. Table 2 gives the various parameters of the unit. As can be expected the output from the desalination unit depends upon the brine temperature entering in it. For different months the output of the unit has been calculated. The method for calculating the output is very well known [16] and those methods have been used in the present case.

The distillate output starts as soon as the outlet temperature from the "solar field" reaches 32.2^0C (90^0F). Thus for the month of June the scheme operates for 24 hr while for the month of March it works for 19 hr and for the month of January only 9 hr.

Figure 8 shows the output for various months. There is no output during the months of July, August and half of September since in these months the sky is mostly cloudy [7]. More over these months can be used for yearly maintenance, if any. The integration of Fig. 8 than gives us the yearly output of 5.25 x 10^7m^3 (13860MG) of fresh water.

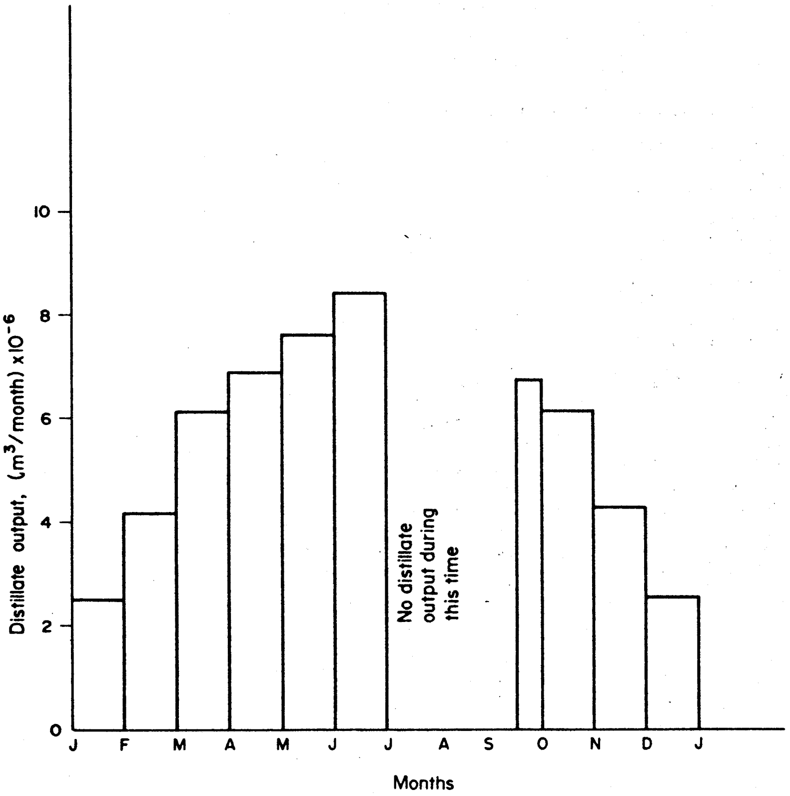

Fig. 8. Distillate output for different months.

In most of the existing desalination plants with MSF units, scale build up is quite a major problem requiring large clean-up operations thereby shutting down the plant and use of costly chemicals for reducing it. The scale problem becomes more acute after temperatures if 71.1^{0}C (160^{0}F) while below this temperature the severity of this problem is substantially reduced. Thus, in the present scheme since the maximum brine temperature is 60^{0}C (140^{0}F), the scale problem is minimized. This is one of the major advantages of operating at low temperatures.

Pumping requirements

The seawater has to be pumped from the Arabian Sea to the desalination site, which is 80 km (50 miles) from it and at an elevation of 45.7 m (150 ft) from the sea level. The pumps, hence, should be large enough to overcome the pressure loss in the feed pipes and the elevation. The feed pipes are three in number and are 3.05 m (10 ft) in diameter. They are made of concrete and are 10.16 cm (4 in.) thick and will be buried in ground so as not to be heated. Table 3 shows the results of calculations for power required in this section of the plant.

In addition to the above requirements, pumps are also needed to effect desalination. Thus in the MSF unit, they should be able to overcome the pressure loss in heat exchangers as well as be able to create enough suction for flash evaporation. For the pumping in the MSF plant we have extrapolated on the design given by Brice *et al.* [5] to suit our requirements. Table 3 shows the power required for MSF unit.

The effluent from the MSF, it is proposed, will be allowed to flow by gravity back to the Arabian Sea in a canal 11.9 m (39 ft) wide and 0.91 m (3 ft) deep, at a velocity of 6.4 km/hr (4 m.p.h.).

The average wind velocity in this area is about 32 km/hr (20 m.p.h.) and sometimes goes as high as 28 km/hr (80 m.p.h.). Thus, it is quite logical to use wind turbines to pump the sea water. The wind turbines used in the present scheme are the 200 kW each capacity machines which are being actively experimented by the Department of Energy (DOE) for large scale deployment in the 1980's. The machines will be staggered throughout the length of the feed pipes and in the solar field. In the feed section they will be arranged in such a manner so that each machine just overcomes the pressure loss and the elevation head equivalent to its capacity. At the same time there will be one elevated storage tank attached to each machine, which will be filled up when the wind velocities go above 32 km/hr. Thus during the "wind lean" periods the steady flow rate in the feed section will be maintained. The exact analysis on the size of these tanks and their location has not been done since it is beyond the scope of this paper.

Disposal of effluents

In the present scheme, the rejected seawater is on an average about 2.03 x $10^5 m^3$ (53.0 MG) per hr, and it is but natural to inquire if we cannot use this brine to extract salts like NaCl, KCl, and others. However, the effluents have a salt concentration of only 3.7 per cent, which is still 96 per cent pure water and is not sufficiently shown to be, in general, an economically viable feed stock. Nevertheless, the decision on whether to extract the salts from this brine have to be made, taking into consideration many local, national, and economic factors that it is again beyond the scope of the present paper.

In such a large scale desalination plant study, it is also worthwhile to look at the effect of effluents on the marine environment. Very little work has been done on this aspect, but the studies do indicate [10] that there is very little or negligible effect on the marine environment. Specifically, in our case, since we are operating at very low concentrations of salts and at the same time, very near to the feed water temperature of 15.5^0C (60^0F), the harmful effects will be negligible to the environment.

4. **COST ANALYSIS**

In any project of the magnitude and complexity like the present scheme, the calculations for the cost of water can at best be an approximation. There are a multitude of local conditions that have to be taken into account for the final figures. In the absence of any such data, like the cost of water in this region, cost of other alternatives and the payback mode for a desalination plant, it is appropriate that a simple minded cost calculation based on the capital and running cost of the system should be sufficient. The capital cost includes the cost of wind machines, the cost of 20 stage MSF unit and the cost of concrete tubes. Also included in the capital cost is the labor, which has been taken arbitrarily to be 20 per cent of the capital cost. The running cost includes the maintenance and the chemicals for scale reduction. Based on the existing technology for such plants [12], the maintenance cost has been taken to be 7 per cent of the capital cost.

The cost of the wind machines is based upon the projected cost by DOE for the 1980's [13] which is $2500 kW. For concrete collector tubes the existing market price of $12.50/ton has been taken. We do believe that large scale production of concrete locally will be much cheaper than this price. The MSF desalination technology is quite developed and thus the cost of such plants has been extensively surveyed [12]. Based on such cost figures, the desalination unit cost has been calculated. Brice *et al.* [5] have given detailed costs for a MSF desalination unit operating at 60^0C (140^0F) brine temperature. We have interpolated on this design for condensing area requirements and cost for the present scheme. Table 4 gives the various costs for the system. Assuming that present plant will provide water for 290 days in a year, the cost of water per 3.79 m^3 (1000 gal.) is :

$$\text{Cost of water } \$/3.79\ m^3\ (\$/1000\ \text{gal.}) = \frac{\text{Capital cost x } (1.1)^{\eta\ -1}\ \text{x } 1000}{13860\ \text{x}\ \eta} \qquad (9)$$

where η = number of years.

Figure 9 shows the cost of water with time. Naturally, this cost should be compared with the cost of water obtained from an alternative supply of water. The alternatives available in this region are (a) a canal from one of the rivers in North India and (b) another desalination plant running on fossil fuels. As for alternative (a), very little or no data is available and thus no meaningful cost calculations can be done. Hence, we can only compare the cost of water with alternative (b) of the equivalent capacity. For such fuel fired MSF plants data is available [12]. Table 6 shows the various cost parameters involved in such a plant. The cost of water for 3.79 m^3 (1000 gal.) is given by :

$$\text{Cost } (\$) = \frac{2.88}{\eta}\ \text{x } (1.1)\ )^{\eta\ -1} + 4.74\ (1.1)\ )^{\eta\ -1} \qquad (10)$$

where η = number of years.

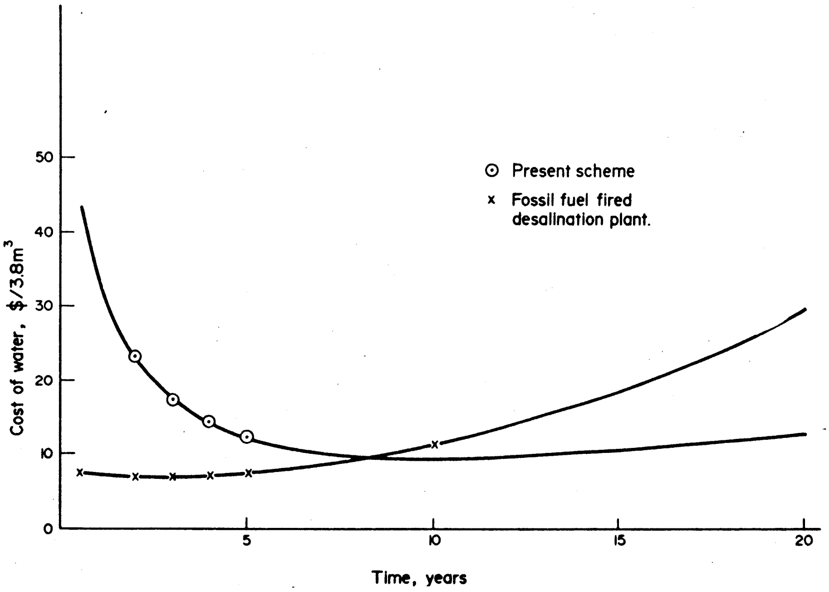

Fig. 9. Cost of water.

Figure 9 shows the comparison of the cost of water available from both the solar plant and fuel powered MSF plant. The point of intersection of the two curves is at about 8 yr, which means that the water from the solar system becomes economically cheaper than that obtained from the fossil fuel fired desalination plant after about 8 yr.

Though the cost calculations done above are justified for the sake of completeness of the study there are other things, which sometimes are given priority, than cost, to make the scheme work. In an area where the level of poverty is unimaginable and where a small amount of water together with the will and determination of these people will bring wonders to the land, it can be argued from the philosophical point of view that the water is priceless. Thus, a scheme of this nature and magnitude can only be funded by the government as a part of the social commitment to the people.

5. **CONCLUSIONS**

The purpose of this study has been to look at technical and economical feasibility of a scheme to desalinate sea water using solar energy for Thar Desert in India. Based upon this study the following conclusions can be drawn :

1. An area of 11.52 km^2 (4.5 miles) of desert will be sufficient to produce $5.25 \times 10^7 m^3$ (13860 MG) of fresh water every year.
2. The pumping requirements for the whole scheme will be met by 415 wind machines each of 200 kW capacity.
3. The cost of water from the present scheme compares favorably with that from a fuel fired MSF plant, the crossover taking place at about 8 yr (Fig. 9).

Finally, it is realized that the technological implications are staggering, but the impact on the national economy, the welfare and employment of the local rural population and the effect on the environment in terms of converting this desert into a great developmental area, appear to be favorable and thus warrant further development and evaluation of the present scheme.

Acknowledgement :- The author wishes to thank Dr. C. C. Oliver for his many helpful suggestions and critical comments.

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Table 1. Heat transfer results for collector for a typical day in June at 2 p.m.

Brine flow rate	11.25 m^3/hr (2970 gallons/hr)
Solar radiation	849 W/m^2 (294 BTU/ft^2-hr)
Absorptivity of paint	0.9
Average ground temperature (8.9 cm. below the surface)	49^0C (120^0F)
Average ambient temperature	51.6^0C (125^0F)
Wind velocity	32 km/hr (20 mph)
Outside heat transfer coefficient	33.6 W/m^2–^{0}C (6 BTU/ft^2–hr-^{0}F)
Inlet brine temperature (to the solar field)	54.4^0C (130^0F)
Outlet brine temperature (from the solar field)	60^0C (140^0F)
Residence time for the brine in solar field	4 hrs.

Table 2. Property values used in equations (1) to (8)

α_{cb}	0.9^a
h_{c+r}	33.6 W/m^2 – ^{0}C (6 BTU/ft^2 –hr- ^{0}F)
k_c	1.82 W/m- ^{0}C (1.05 BTU/hr – ft – ^{0}F)^a
h_i	448.0 W/m^2 – ^{0}C (80 BTU/ft – hr - : F)
k_{sand}	0.347 W/m - ^{0}C (0.2 BTU/hr – ft ^{0}F)^a
α_{sand}	0.82^a
p_{sand}	1518.5 kg/m^3 (94.8 1b/cu. ft.)^a
$C_{p\ sand}$	816 KJ/kg ^{0}C (0.195 BTU/1b ^{0}F)^a

a : Values taken from Standard Handbook for Mechanical Engineers Seventh Edition (1967).

Table 3. Calculations for MSF unit (for a typical day in June)

Area of condensing surface	1.41 x $10^6 m^2$ (15.2 x $10^6 ft^2$)
Outside diameter of the condensing tube	2.54 cm (1 inch)
Material of the tube	Cu/Ni Alloy
No. of stages	20
Terminal Temperature Difference (TTD)	1.67^0C (3^0F)
Total pump power required (to overcome pressure loss in heat exchanger and to create suction)	4.47 x 10^4 kW (6 x 10 H.P.)
Distillate produced	1.36 x $10^4 m^3$/hr (3.6 MG/hr).
Maximum temperature of sea water in	60^0C (140^0F)
Temperature of condensing water	15.5^0C (60^0F)
Temperature of water going to solar field	54.4^0C (130^0F)
Temperature of blow down brine	26.6^0C (80^0F)
Product water temperature	25.5^0C (78^0F)

Table 4. Pumping requirements

Section	Pipe Size, ID (m)	No. of Pipes	Length (m)	Pressure Loss (N/m^2)	Total Pump Capacity Required (kW)
Feed*	3.05	3	80,000	6.39×10^5	3.84×10^4
Solar Field	0.71 m x 0.1 m	9600	610	47	

* The total pumping requirement for feed section includes power required to pump water to an elevation of 45.7 m.

Table 5. Cost calculations

Item	Quantity	Cost (Millions of Dollars)
Concrete*	2.4×10^6 tons	40.6
Wind Machines	415	207.0
Desalination Unit	1	190.0
Labor (20% of capital cost)		118.0
Maintenance (7% of the capital cost)		41.3
Annual interest rates = 10%		
Plant life = 20 years		

* Total concrete required for feed pipes, solar collectors, and canal

Table 6. Cost of MSF Unit (Fossil Fuel Operated)

Item	Quantity	Cost (Million $)
Desalination Plant	1	40
Fuel @ $12/bbl	60×10^6 litres/annually (16.4×10^6 gallons)	54
Electricity @ 0.05 /kWh	207 x 10 kWh (annually)	11.86
Capacity of plant	1.44×10^5 m^3/day (38 MGD)	
Interest rate (annual) = 10%*		
Fuel price increase/yr = 10%* (14)		

* The above interest rates are not relative to inflation.

NOMENCLATURE

A_0	Outside area of the concrete collector, m^2 (ft^2).
A_0, A_b	Average areas of the top surface and bottom surface of the collector respectively, m^2 (ft^2).
A	Thermal diffusivity of sand k /
A_i	Inside area of the collector, m^2 (ft^2).
C_{ps}, C_p	Specific heat of sand and water respectively, W_s/kg k (Btu/lb.R).
h_{c+r}	Outside heat transfer coefficient for convection and radiation, W/m^2 (Btu/ft^2 hr F).
h_i	Inside heat transfer coefficient for water flowing in the collector, W/m^2 C (Btu/ft^2 hrF).
k_c, k_s	Conductivity of concrete and sand respectively, W/m k (Btu/ft hr F).
l	Depth of ground below the surface eqn (7), m (ft).
m	Mass flow rate of sea water in the collector, kg/hr (lb/hr).
$q''(t)$	Incident solar insolation at time t, W/m^2 (Btu/ft hr).
$T_{b,\,max}$	Maximum temperature of the ground 8.9 cm below the surface, ^{0}C (^{0}F).
$T_{s,\,amp}$	Amplitude of the surface temperature in eqn (8), ^{0}C (^{0}F).
T_1, T_2, T_0, T_b, T_{mm}, T_m T_{out} ,	Temperatures shown in Fig. 4.
T_∞, T_s	Temperatures of the ambient and surface of sand respectively ^{0}C (^{0}F).
t_c	Thickness of the concrete collector, m (ft).
ΔX	Depth of the ground, eqn (6).
α_s	Solar absorptivity of sand.
α_{cb}	Solar absorptivity of blackened concrete.
ξ	Time lag between the maximum temperature of the surface of sand and that at 8.9 cms below, hr.
ρ_s	Density of sand, kg/m^3 (lb/ft^3).

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