195

PROSPECTS OF SOLAR POWER PLANTS IN INDIA

M. M. Shah

Central Mechanical Engineering Research Institute
Durgapur
India

Abstract

Besides discussing the theoretical and practical aspects of solar power plants, an assessment is made in this article of the feasibility of building such plants in India. It is concluded that under present Indian conditions of materials' availability, fabrication facilities etc, building of solar power plants would be advantageous only in a few special cases.

Introduction

During the last two decades, there has been considerable interest in the possibilities of utilising solar energy for power generation in India. Many laboratories and institutions in India have spent much time and money in investigating these possibilities. Though none of them achieved much success, many foreign and Indian experts still advocate further research and development in this field as they consider solar power to hold much promise for India.

To examine the validity of their view, projects were undertaken to study the theoretical aspects of the problem and to analyse the available technical data in the light of Indian conditions. Simultaneously, some practical experience of the related engineering problems was attempted by erecting and testing a solar reflector made from locally available materials.

This paper discusses the theoretical and practical backgrounds of the problem. The endeavour of the author is to give to the scientists and engineers who are presently considering the feasibility of building solar power plants in India, a comprehensive view of this field so that more money and labour are invested only after the objections raised in this paper have been satisfactorily answered.

It is to be noted that this paper deals only with the conversion of solar to mechanical energy. Direct conversion of solar to electrical energy is not covered by this paper.

Field of application

It is well established that solar power plants are unpractical for urban and industrial areas. The very size of the plant necessary due to low solar intensity, makes them untenable for such applications. Further, wherever power can be had from large conventional central power generating plants, these are again uncompetitive. However, at the moment there are more than 5 lakh villages in India which are unelectrified. In most of these, it is not economical to supply power through central power grids due to low load factors and large distances separating the consuming areas from the generating plants. On the other hand, the Government is keen to improve the economic condition in such rural areas by encouraging the use of power for driving agricultural implements and in cottage and small scale industries. For these purposes two types of power plants would be needed: (*i*) Small independent plants of up to 10 kw for driving irrigation pumps, small agricultural machines etc; and (*ii*) Small scale central plants of up to 100 kw to serve groups of villages.

For such applications, solar plants may be considered along with the more conventional types. The solar plant has the advantage of having free driving energy available locally. If other aspects are also found favourable, solar plants should naturally be preferred.

Ideal power plants for rural areas

We are considering applications in remote backward areas where communications are inadequate and skilled labour generally not available. Hence the plant should be very simple to operate and maintain, requiring the minimum of spare parts or replacement materials.

Even more important is the first cost. It should be as low as possible as capital is scarce, specially so in the rural areas. The argument that the plant will make up for the additional cost in five or ten years is unlikely to be convincing as there may simply be no additional capital for investment,

Basic principle of solar heat engine

The most efficient engine is a reversible engine which takes in all its heat at the highest temperature and rejects all the heat at the lowest cycle temperature. The Carnot cycle fulfils these requirements and it has the maximum possible efficiency for an engine.

$$\text{Carnot efficiency} = \frac{t_1 - t_2}{t_1} \quad \ldots \quad \ldots \quad (1)$$

where, t_1 is the temperature of heat addition, and t_2 is the temperature of heat rejection.

Due to well-known reasons, Carnot cycle is not practicable. However, Ericsson and Stirling cycles also theoretically satisfy the conditions of maximum efficiency, and hence their efficiency is the same as that of Carnot cycle. These cycles have been used in practical engines, though not with any great success.

An important cycle used for most heat engines employing vapours as working medium is the Rankine cycle. Theoretically, it can also be made reversible but its efficiency is lower than that of Carnot engine as it does not receive all its heat at the highest temperature. The efficiency of a Rankine engine working on saturated vapour is given by

$$\text{Rankine efficiency} = \frac{t_1 - t_2 \left(1 + \frac{L_1}{t_1}\right) - t_2 \log_e \frac{t_1}{t_2}}{(t_1 - t_2) + L_1} \quad \ldots \quad (2)$$

where, t_1=temperature at which vapour evaporates, ie temperature of heat addition; t_2=temperature at which vapour condenses, ie temperature of heat rejection; and L_1=Latent heat of vapour at temperature t_1.

It is obvious that for high engine efficiency, t_1 should be as high as possible and t_2 should be made as low as practicable. In practice, the choice of t_1 and t_2 may depend on other factors besides the engine efficiency, as discussed later.

Choice of heat collecting device

It has been noted that for high engine efficiency, high heat collection temperatures are necessary. This rules out the use of flat plate collector as this device is not economical for high collection temperatures due to large re-radiation surface provided by it. Hence some concentrating device is necessary. Of the various concentrating devices like parabolic reflector, lens concentrator, conical reflector, parabolic cyclindrical reflector, the last-named is the most suitable for a plant of any size but the smallest. The lens concentrator is too expensive and fragile. The parabolic and conical reflectors require constant adjustment along two axes if reasonable amount of radiation is to be collected. This results in great complications and high cost. Besides, the whole structure being comparatively unstable requires strong supports for withstanding strong winds, etc. The parabolic reflector, on the other hand, can intercept a large amount of available radiation with adjustment along one axis only. The structure is robust and can withstand storms more easily. The skill required for its fabrication is also less than for the other types. It is, hence, not surprising that the majority of solar power plants built till date have used this type of reflector. In further discussions, therefore, only the parabolic reflector will be considered.

Choice of operating temperatures

In most cases, the only heat sink available is atmospheric air and hence the heat rejection temperature is decided by the ambient temperature. Further, from practical considerations of heat exchanger design, the actual heat rejection temperature is likely to be 30°F above the ambient.

For deciding the heat addition temperature, the efficiencies of both the collector and the engine are to be considered. While the engine efficiency increases with increasing temperature, the collector efficiency goes down due to increased heat losses at elevated temperatures. Hence, the optimum temperature is that at which the combined efficiency of engine collector system is maximum.

The energy balance of a parabolic solar collector having an uncovered absorber may be written as[1]

$$H_D.A.r.\gamma.\alpha = h_w.A_x\,(T-T_a) + \sigma.\epsilon.A_x\,(T^4-T_e^4) + q_n \quad .. \quad (3)$$

where, H_D=Direct solar radiation normal to aperture, BTU/hr/sq ft; A=Aperture of the reflector, ft; r=Specular reflectivity of reflecting surface; γ=Shape factor (reflected radiation intercepted by receiver/radiation specularly reflected by reflector); α=Absorptivity of receiver for solar radiation; q_n=Rate of useful energy gain per foot of length of reflector, BTU/hr; h_w=Coefficient for convection loss to air, BTU/sq ft (hr) (°F); A_x=Area of receiver tube per foot of length, ft^2; T=Receiver surface temperature, °R; σ=Stefan-Boltzmann constant; ϵ=Emissivity of the solar energy absorbing surface; and T_e=Effective sink temperature, °R.

If a transparent cover is arranged over the absorber, τ being its transmissivity and ϵ_1 its emissivity, the heat balance becomes

$$H_D.A.r.\tau.\gamma.\alpha = h_w.A_c\,(T_1-T_a) + \sigma.\epsilon_1.A_c\,(T_1^4-T_e^4) + q_n \quad .. \quad (4)$$

where, T_1=Surface temperature of the transparent cover, °R; A_c=Area of cover per unit length of reflector, ft^2; and T_1 is given by the relation,

$$q_e = C.A_x\,(T-T_1)^{5/4} + \frac{1}{1/\epsilon + \frac{1}{\epsilon_1} - 1}\cdot A_x.\sigma\,(T^4-T_1^4)$$

$$= h_w.A_c\,(T_1-T_a) + A_c.\epsilon_1.\sigma\,(T_1^4-T_e^4) \quad .. \quad .. \quad (5)$$

q_e being the heat loss from the absorber; and C the conduction-convection heat transfer coefficient governing heat transfer between the absorber and the cover.

Now, the collector efficiency may be defined as

$$E = \frac{100\,q_n}{H_D.\,A} \quad .. \quad .. \quad .. \quad .. \quad .. \quad (6)$$

Hence, the efficiency of the collector system with an uncovered absorber may be found by combining equations (6) and (3), and may be written as

$$E = 100\left[r.\alpha.\gamma - \frac{A_x}{H_D.A}\left\{h_w\,(T-T_a) + \sigma.\epsilon\,(T^4-T_e^4)\right\}\right] \quad .. \quad (7)$$

For a collector having an absorber with transparent cover, the efficiency is found by combining equations (4) and (6) as follows

$$E = 100\left[r.\gamma.\tau.\alpha - \frac{A_c}{H_D.A}\left\{h_w\,(T_1-T_a) + \sigma.\epsilon_1\,(T_1^4-T_e^4)\right\}\right] .. \quad (8)$$

Thus knowing all other factors, collector efficiency can be determined for various values of tube surface temperature, T. The corresponding Carnot or Rankine engine efficiency may be calculated from equations (1) and (2) by assuming the heat to be added at the temperature of tube surface and heat rejected at the ambient temperature. The practical efficiency of the engine could later be determined by multiplying this ideal efficiency by a suitable factor derived from practical experience. The overall plant efficiency may be found by multiplying collector efficiency by the engine efficiency. The most suitable tube surface temperature would be that at which this overall efficiency is maximum.

Choice of working cycle and working medium

The basic question is whether to use gas or vapour as the working medium. The choice has to be made in consideration of the thermodynamic and practical aspects.

The two important hot air engine cycles which have been used in practice are the Ericsson and Stirling cycles. The Ericsson cycle is completely obsolete now, while efforts are being made to revive the Stirling cycle through researches at Phillips of Holland and General Motors of USA. Theoretically, both these cycles are reversible and have the same efficiency as the Carnot cycle. However, it is difficult to devise a simple engine which would reproduce these cycles to any reasonable extent. Phillips of Holland in cooperation with General Motors of USA, has been trying to develop closed cycle Stirling engines[2]. Though the development is giving encouraging results (the engines surpassing Otto engines in efficiency and even equalling diesel engines), the engines developed so far are by no means simple and are definitely more costly than conventional engines. Further, these engines are designed for fairly high operating temperatures which, as shall be shown later, are not economical for solar installations. Hence, it is clear that no commercially available hot air engine could conveniently be adapted for this purpose. Developing a new, simple, efficient, hot air engine specially for this application would be an extremely ambitious project which is unlikely to meet with much success within reasonable time. A close study of the Stirling and Ericsson cycles would clearly show how difficult it is to make an engine to fulfil the thermodynamic requirements of these cycles. The heart of these cycles is the regenerator which should be 100 per cent efficient. The poor heat transfer properties of air and most gases make the job even more difficult. The same difficulty is faced in heat addition and rejection. The prospect of excessive pressure and heat losses makes it necessary to have an intermediate heat transfer medium between the solar heater and the engine. This complicates the system besides adding to the irreversibilities. Low heat transfer properties of air necessitate large and expensive heat exchangers.

The vapour engines work on the Rankine cycle. Innumerable steam engines and turbine plants are operating all over the world. Hence, a great deal of knowledge and experience of vapour engines is today available, and it may even be possible to modify an existing engine to suit the requirements of a solar plant. The heat addition is done by boiling the working medium and this is inherently a high heat transfer rate process. Heat rejection is through condensing of vapour, again a high heat transfer process. Thus compact, inexpensive heat exchangers can be devised with minimum temperature difference and thus causing minimum irreversibility. The power stroke is an adiabatic expansion process which can closely be approximated in practice and allows design of high speed

engines. The pumping of liquid is an adiabatic compression process which can also be approached in practice.

Fig 1 shows the Rankine cycle on temperature-entropy diagram. Fig 2 shows the essential components of a solar plant operating on Rankine cycle.

From the foregoing discussions, it may be concluded that at least for the present and in the near future, vapour engines working on Rankine cycle appear to be the most suitable for use in conjunction with solar heat collectors.

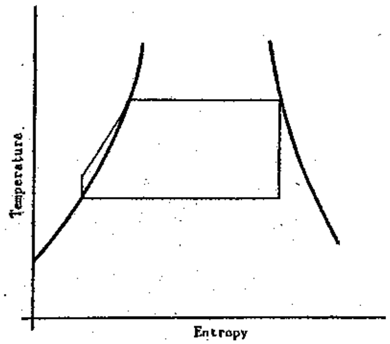

Fig 1
Rankine cycle on temperature-entropy diagram. Saturated vapour used

The ideal vapour should have the following qualities: (*i*) Easy availability and low cost; (*ii*) Non-toxic, non-explosive, non-corrosive, stable; (*iii*) Positive but moderate pressures at heat addition and rejection temperatures; (*iv*) A positive slope at the vapour-mixture boundary on the temperature-entropy diagram so that expansion does not result in moisture deposition. Thus, need for superheating is

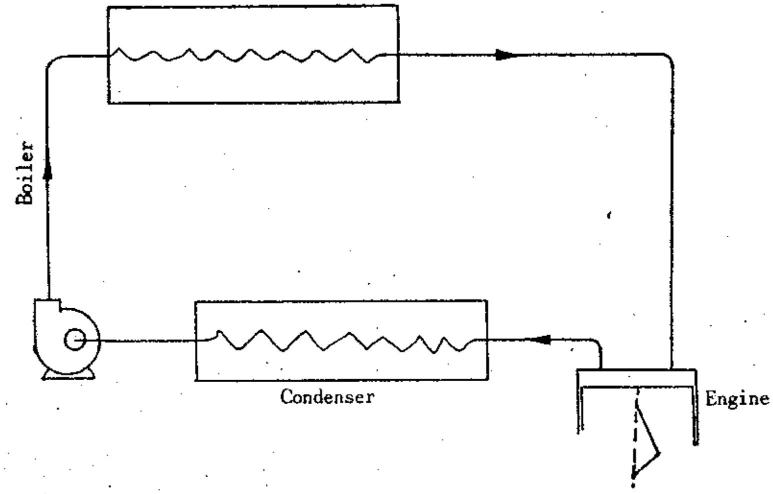

Fig 2
Essential components of a condensing Rankine engine

eliminated and blade erosion due to liquids is avoided; (*v*) If the engine is to be a small turbine, high molecular weight is desirable as it results in higher efficiency; (*vi*) Commercial engines working on that medium should preferably be available.

The vapours which have been used or proposed for solar engines are water, sulphur dioxide, ammonia, ether, freons, monochlorobenzene, etc. Of these, sulphur dioxide and ammonia are highly toxic, even explosive under certain conditions. Ether is combustible and expensive. Freons are non-toxic, non-explosive and non-corrosive, but costly. Water, universally available at negligible cost, is non-toxic and non-explosive. It, however, does not satisfy any of the other requirements. For high efficiency, the low side of the plant would have to run under high vacuum. Superheating is necessary as expansion of saturated steam results in moisture deposition causing well-known difficulties. However, water is the only medium which is freely available even in a remote rural area.

Monochlorobenzene is the vapour used in Israel for solar engine and satisfactory results are reported[3]. It is cheap, has a positive slope at vapour-mixture boundary and has high molecular weight.

Of all these vapours, only water is being presently used in commercial engines. None of the other vapours have so far been used to any great extent in practice. Hence, if it is decided to use a vapour other than water, the engine development has to start from the very beginning. Besides, in the remote areas that we are considering, supply of these mediums in case of leakage etc would pose serious problem.

Therefore, though vapours like monochlorobenzene are ultimately desirable, any assessment of prospects for immediate application of solar plants has to be based on the use of water as the working medium.

Objectives for the solar plant designer

It has been discussed that the possible field of application for solar power plants is the remote rural areas where the important requirements of a power plant are low first and operation costs, simplicity of operation and maintenance, and independence from external supply sources. It has also been shown that the most suitable solar plant would use a parabolic cylinder type heat collector and a vapour engine. The following may, therefore, be laid down as the objectives which the plant designer should aim at.

1. Operation and maintenance should be simple. The reflector should be stationary and the absorber reflector assembly should be hermetically sealed under an inert atmosphere to prevent any deterioration due to atmospheric forces.
2. The engine-generator (or turbine-generator) set should also be hermetically sealed so that shaft seal leakage and maintenance problems may not occur. The assembly should have the reliability of a sealed refrigeration compressor which normally runs unattended for 10 years or more.
3. The liquid pump-motor assembly should also be hermetically sealed.
4. Every care should be taken to keep the first cost low. This could be achieved by improving plant efficiency, using low cost materials and using mass production techniques wherever possible.
5. The efficiency of the plant should be sufficiently high to ensure that cost of power generation is lower than that run with conventional generators.

If all these objectives could be achieved, solar power plants would naturally be given preference.

Of the well-known attempts to develop solar heat engine plants, viz, Ericsson hot air engine (1883), Pasadena Ostrich Farm plant (1901), Shumen-Boys plant (1913) and the work done at the National Physical Laboratory of India and the National Physical Laboratory of Israel, only the last-named organisation aimed at design objectives similar to those laid above. Though the Israeli plant is yet to reach a commercial stage, it would be useful to make a brief study of the same.

Israeli solar plant[3,4,5]

For more than ten years, the National Physical Laboratory of Israel has been engaged in developing solar power plants.

The heat collector is a low concentration parabolic cylindrical reflector with a triangular absorber. The reflector is made from inflated transparent and weather-resistant plastic. The lower half of the circumference of this cylinder is aluminised to form the reflecting surface. The triangular absorber has a selective black surface which has high absorptivity for short wave radiation but low emissivity for long wave radiation, thus substantially reducing radiation losses. Due to the low concentration factor of reflector, selective absorber and the transparent plastic covers, it becomes possible to attain fair efficiency even when reflector is stationary. The whole structure is light but very strong and requires only weekly adjustments to compensate for the changes in solar declination.

The working fluid is monochlorobenzene, a high molecular weight compound. A high speed turbine has been developed which gives high efficiency, reported value being 15 per cent, presumably between the temperature limits of 300 °F boiling and 80 °F condensing. The efficiency of the ideal Carnot cycle between these temperatures is 29 per cent. Hence the efficiency ratio exceeds 50 per cent which is very good for a small unit. It is now being attempted to make the turbine, generator and liquid pump as fully hermetic.

Thus, it will be seen that the Israeli effort has been based on very sound principles. Reduction of first cost has been attempted through use of plastic reflectors. Reduction in maintenance cost has been tried by using reflecting surface and absorber enclosed in weatherable plastic and also by making the turbine-generator set as a hermetically sealed unit. Still, after more than ten years work and access to the highly developed US plastic industry, the plants have not reached commercial stage. The first cost is still too high to encourage wide application.

Plants that can be made at present in India

In India, a plant similar to the Israeli plant cannot be made at present mainly because of the lack of know-how, materials and technology. Plastic industry is still underdeveloped in the country, as such plastic reflectors cannot be made. Plants for providing selective surfaces for heat absorbers are non-existent, and in absence of selective surfaces, it becomes necessary to have high concentration ratio and glass envelope over the absorber. High concentration ratio necessitates constant orientation of reflector to the sun thus making plant operation and maintenance difficult. Glass tubes of the required specifications have to be imported and they are very costly. No turbines have ever been built in India according to local designs. All the experience available of hermetic units is that with small refrigeration compressors which are presently being built in India with foreign collaboration. Hence, hardly any hope of developing a hermetic turbine-generator set can be entertained. Without hermetic units, the problem of leakages becomes serious. Therefore, the only medium that can be considered is water. Thus, any solar plant development in India would presently have to be based on open reciprocating steam engines only.

Keeping these facts in mind, let us now work out the outlines of a solar power plant which can be developed within a short period using the locally available materials and technology.

The set-up

Fig 3 shows the working cycle and basic components of the plant.

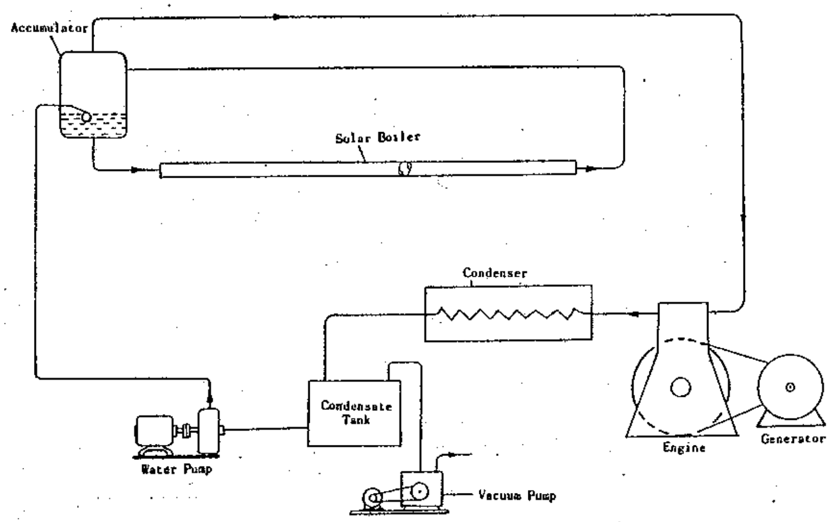

Fig 3
Working cycle and essential components of solar plant using steam

Steam condensate from the condensate tank is pumped into an accumulator through a float valve which maintains the water level there. The accumulator is kept at a higher level than the absorber and hence water flows by gravity into it, gets heated and boils. The other end of the absorber tube is also connected to the accumulator by a pipe. Steam produced is collected above the water level in the accumulator and is then led to the steam engine where it expands and produces power (for the first estimates we are eliminating the necessary superheater). The spent steam from engine is led to a condenser which may be water cooled if the engine is used for water pumping or abundant water supply is available. Steam condenses and the water thus formed collects in the condensate tank for repeating the cycle. For any reasonable engine efficiency, as shall be shown later, it becomes necessary to expand steam to well below the atmospheric pressure. This makes an air purging device essential and hence a vacuum pump has to be connected to the condensate tank for constantly removing air and other non-condensibles. In the figure, the engine is shown driving an electric generator. For most applications, this would be the best arrangement as power is also needed for driving vacuum pump, condenser fan, reflector aligning motor, etc.

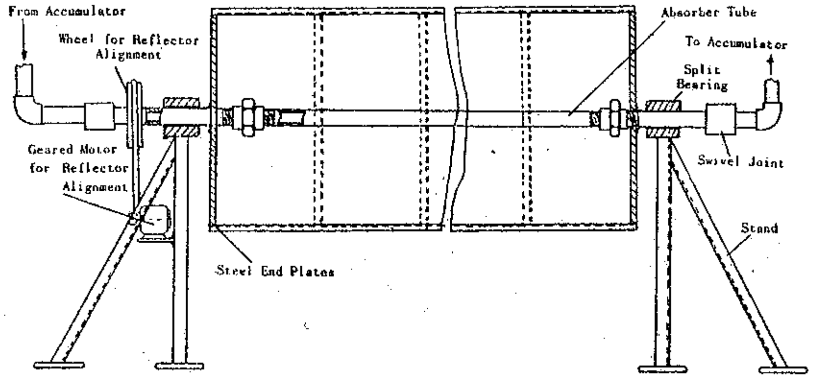

Fig 4a
Reflector assembly shown with reflector in early morning position

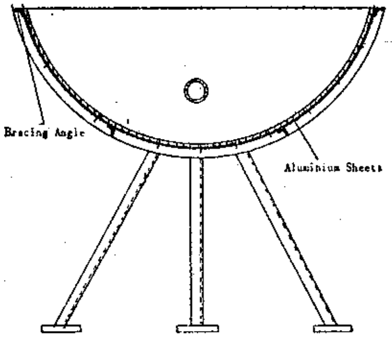

Fig 4b
Sectional side view of reflector

Figs 4a and 4b show some constructional features of the proposed reflector. The parabolic trough is formed by bending steel angles and the assembly strengthened by longitudinal bracing angles. Polished aluminium sheets are screwed to this trough to form the reflector. Thick steel plates are welded to the ends of the trough. Two thick hollow steel pipes are welded to the ends of these plates to serve as the passage of water as well as the support for the whole assembly. The absorber tube is attached to these end pipes through unions. The whole reflector is supported on two split bearings at the two ends held in two strong tripods fabricated from steel sections. A pulley is fixed at one end and is connected to a geared motor for keeping the reflector aligned to sun. The axis of rotation is a horizontal N-S line. The end pipes are connected to the accumulator through pressure tight swivel joints. The absorber is a copper tube having a black coating over it. Depending upon its length, additional supports may be necessary to prevent sagging. Glass envelope over the absorber is very useful for improving its efficiency but is omitted due to its high cost, fragility, difficulties in execution, cleaning and other maintenance problems.

Obviously, this plant does not satisfy the requirements of simple operation and minimum maintenance. With so many motors, generator, engine, fans, seals, etc maintenance even by a skilled technician may be difficult.

Performance

The basic equations governing the engine and heat collectors have already been presented. The efficiency of the plant is now worked out giving realistic values to the various terms.

The mean hourly solar radiation falling on a normal surface between sunrise and sunset on a clear day is about 240 BTU/hr/sq ft for most parts of India. The intensity is much higher in the noon hours and, naturally, a higher value can be adopted if it is intended to operate the plant only during the noon hours. Usually, however, it would be desired to operate the plant during the greater part of day and hence it is more realistic to consider the mean radiation between sunrise and sunset. For a reflector having adjustment only about one horizontal N-S axis, roughly 15 per cent radiation is lost due to the surface being not fully normal to the sun's rays. Hence a value of $H_D=200$ BTU/hr/sq ft may be taken as effective for the reflector in question. The value of convective heat transfer co-efficient due to wind may be taken as 2 BTU/hr/sq ft/°F. The reflectivity of aluminium sheets available in India is about 70 per cent under normal conditions of maintenance. The absorptivity and emissivity of the black coated absorber may be taken as 0·95. The ambient temperature may be assumed to be 90°F. The radiation sink temperature can be fairly low under clear sky conditions, but for simplicity it is assumed to be equal to the ambient temperature. The shape factor mainly depends on accuracy of fabrication. The value of 0·926 quoted by Lof et al[1] for their reflector of similar design is adopted here because it can be realised in practice. For the same reason, the physical dimensions of their reflector have been used for computation. The values of the various terms in equation (7) are therefore

$H_D=200$, $r=0{\cdot}7$, $\alpha=0{\cdot}95$, $\epsilon=0{\cdot}95$, $T_a=550°R$, $T_e=550°R$, $\gamma=0{\cdot}926$, $A=6{\cdot}19$ ft, $A_x=\pi\times2{\cdot}375$ sq in (tube dia being 2·375 inch) and $h_w=2$ BTU/hr/sq ft/°F.

Substituting these values in eqn (7), the efficiency of solar collector for different values of *T*, the surface temperature of absorber tube, are calculated, and are shown in Fig 5. Fig 6 shows the efficiencies of ideal Carnot engine and a saturated steam-operated Rankine engine with various heat collection temperatures, sink temperature being 90°F in both the cases.

Multiplying the corresponding values of engine and reflector efficiencies (from Figs 5 and 6), the overall efficiency of a power plant employing this reflector and an ideal Rankine engine may be calculated. These values of overall plant efficiencies are shown in Fig 7, curve 1. From this curve, it is evident that the maximum efficiency attained by this Rankine engine and reflector combination is about 4·2 per cent at a collection temperature of 640°R or 180°F. As the boiling point of water at atmospheric pressure is 212°F, the whole plant has to run under vacuum and a purging device becomes necessary as has been stated earlier.

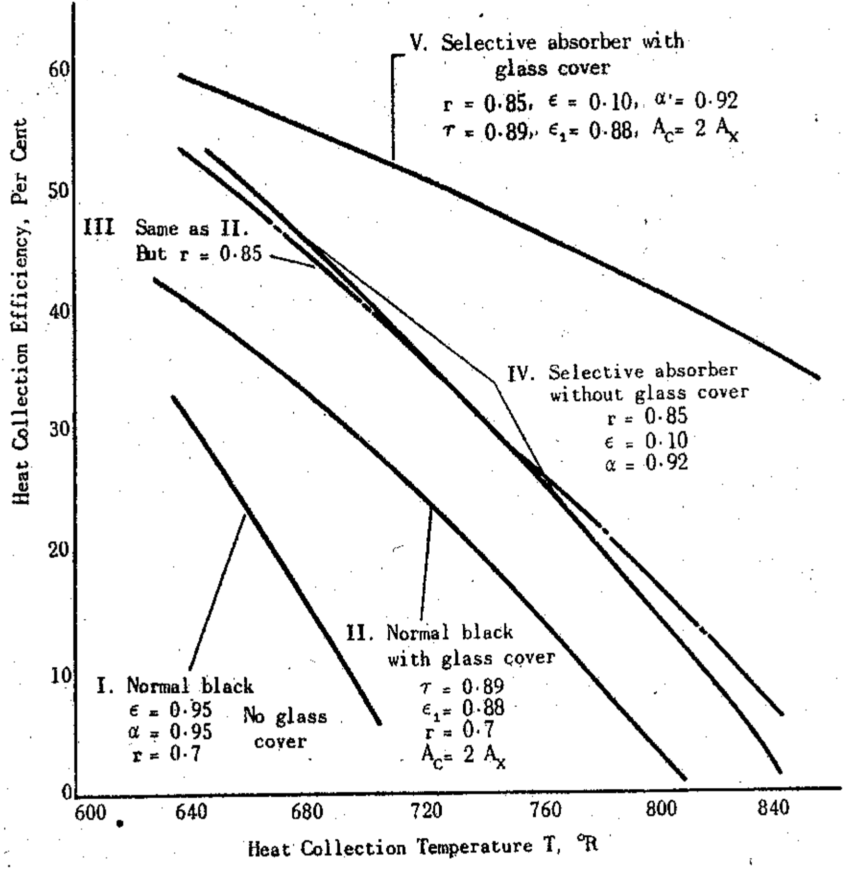

Fig 5
Variation of collection efficiency with collection temperature and different types of absorber tubes. Parabolic cylinder has horizontal N-S axis of rotation. $H_D=200$, $h_W=2$, $A=6{\cdot}19$, $\gamma=0{\cdot}926$, $A_X=\pi\times2{\cdot}375$, $A_C=2A_X$, $T_a=550$ and $T_e=550$°R

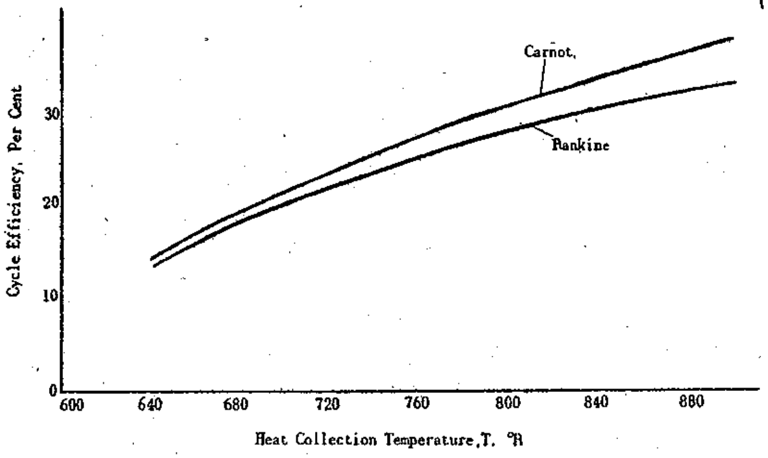

Fig 6
Efficiencies of ideal Carnot and Rankine cycles. Saturated steam used for the Rankine cycle. Heat sink temperature 550°R

Fig 7 is based on the ideal Rankine engine. In practice, the thermal efficiency of an engine would be only a fraction of the ideal engine efficiency. The efficiency ratio has to be found from practical data.

However, none of the present engines works on low pressures. From historical records, we find that the Shuman engine which used low pressure steam had an efficiency ratio of about 35 per cent of the ideal Carnot engine[6]. Modern high pressure steam engines achieve figures of up to 75 per cent and even higher. However, we cannot expect such high figure for our engine as not much developmental work has been done on low pressure steam engine. Still, we may reasonably hope to surpass the figure for Shuman engine due to the overall advancements in all branches of mechanical engineering. We are arbitrarily assuming, therefore, that the efficiency ratio would be 0·4 as compared with the ideal Rankine cycle. The mechanical efficiency of engine may be taken as 85 per cent.

With these figures, the overall plant efficiency comes to $4{\cdot}2\times0{\cdot}4\times0{\cdot}85 = 1{\cdot}53$ per cent. Hence, with the effective solar intensity of 200 BTU/hr/sq ft, the surface area required for one hp generation comes to 835 sq ft. This means that for a plant generating 100 hp, 83500 sq ft of collector area would be needed. A rough estimate shows that only the

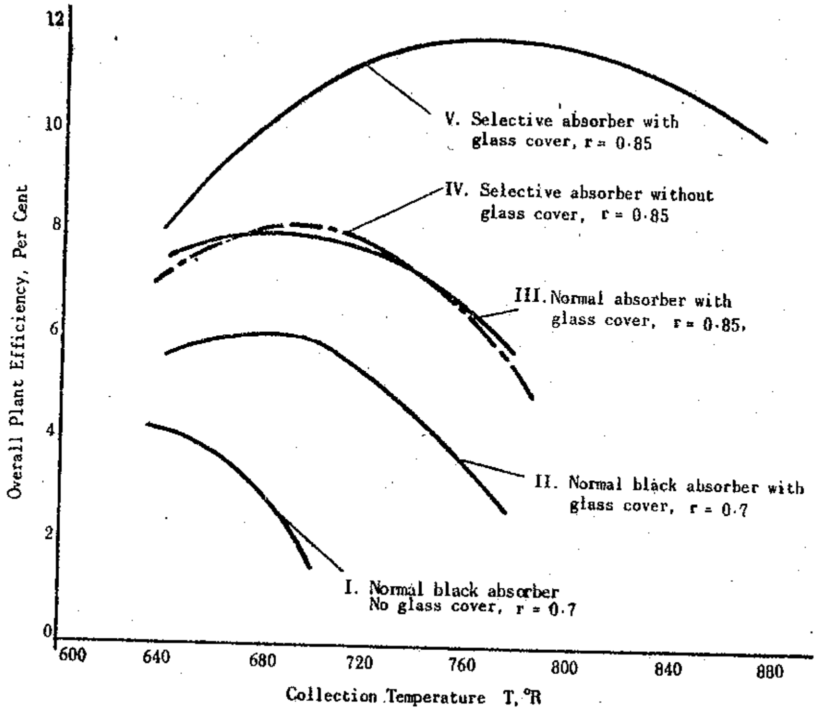

Fig 7
Overall efficiency of a plant with ideal Rankine engine using saturated steam and different types of absorbers. $H_D=200$, $h_w=2$, $A=6{\cdot}19$, $\gamma=0{\cdot}926$, $A_x=\pi\times2{\cdot}375$, $A_C=2A_x$, $T_a=550$ and $T_e=550°R$. Heat sink temperature 550°R

raw materials needed for making collectors for such a plant would cost more than 10 lakh rupees. The fabrication cost will also be very high as most of the job would have to be done at site. Added to it are the costs of engine, generator, condenser, vacuum pumps etc. Thus the first cost of this plant is unlikely to be lower than rupees 30 lakhs.

It may, therefore, be concluded that the solar plant built with the present-day indigenous materials and local technology is unfeasible due to very high first cost and difficulties in operation and maintenance. Let us now see if improvements could be brought about through further research and development.

Possible improvements

By using aluminised Mylar films attached to the parabolic curvature,

a durable reflector with reflectivity as high as 0·85 may be obtained. Further, temperature resistant glass with high transmittance and low emissivity could be used as an envelope over the absorber tube to decrease heat losses, though it would make fabrication and maintenance complicated. These developments, which could be effected in a comparatively short period, would result in reflector efficiency as shown by curves 2 and 3 of Fig 5. The combined collector-Rankine engine efficiencies are shown by curves 2 and 3 of Fig 7. It will be seen that by using a glass cover over the absorber and by increasing reflectance to 0·85, the overall efficiency of the plant reaches 8·45 per cent at 700°R. Hence with these two modifications, the collector area required would be reduced to 535 sq ft/hp.

Selective radiation absorbing surfaces have already been developed in Israel[8]. Thus, it is possible to have an emissivity of only 0·10 with absorptance as 0·92. Using such an absorber with 0·85 reflecting surface, the collector efficiency attainable is shown in curve 4 of Fig 7. Thus a maximum efficiency of about 8 per cent is achieved at a collection temperature of 700°R. By applying transparent glass cover over absorber, this figure reaches 11·82 per cent at 780°R collection temperature and the collection area required reduces to about 320 sq ft/hp.

Further improvements are possible through application of insulation over absorber, addition of more glass layers, and improving the efficiency of engine. If the engine efficiency ratio could be increased to 0·75 and mechanical efficiency to 0·9, the reflector area would be reduced to about 160 sq ft/hp. Further increase in number of glass layers is difficult but insulation of absorber may be possible. Hence, for areas with a normal incidence of 240 BTU/hr/sq ft, it would appear that the minimum reflector area required even after intensive development would not be less than 150 sq ft/hp.

Though this reduction in surface area would reduce the first cost substantially, yet the plant would not be practical as it does not satisfy the requirement of simple operation and minimum maintenance. Hence we will have to go over to the Israeli design of stationary reflector and hermetic power unit. With the reflectors stationary, the radiation intercepted would be less, being about 65 per cent of that on a surface normal to the sun. Thus with normal irradiation as 240 BTU/hr/sq ft, that on the horizontal stationary reflector would be about 180 BTU only. Fig 8 shows the computed efficiency of these stationary collectors combined with ideal Carnot engine as given by Tabor et al[8]. It will be seen that the plant reaches its maximum efficiency of about 11 per cent at 160°C.

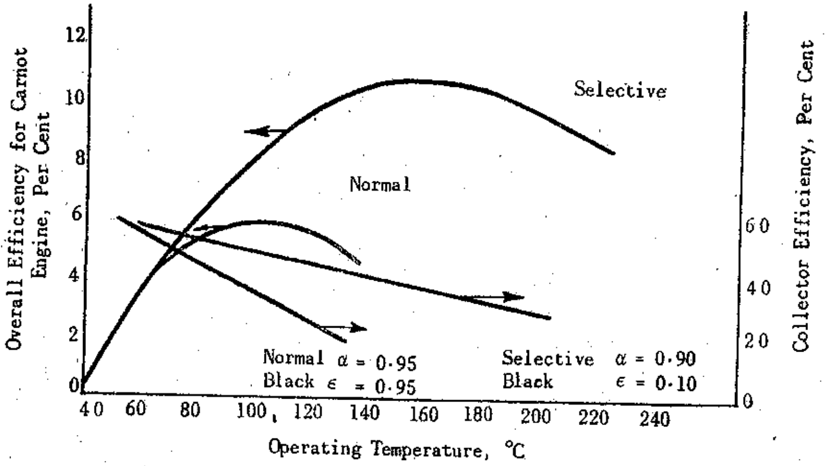

Fig 8
Relative computed efficiency of mirror collector operating ideal Carnot engine condensing at 40°C[8]. Concentration factor 3, reflectance 0·85 of cylindrical receiver with glass cover

Allowing 90 per cent mechanical efficiency of turbine and taking the efficiency ratio as 0·5 (computed from turbine performance figures given by Yellot[3]), the overall plant efficiency comes to ·9×·5×·11 or about 5 per cent. Then with normal solar radiation at 240 BTU, the required collector area is about 280 sq ft/hp. It is very difficult to estimate the cost of these plastic collectors as neither are such plastics made in India nor ever have such collectors been made here. The figures given for the Israeli plant in various references are rather conflicting, which suggests that it has not been possible to fully estimate the production cost of these units. According to Yellot[3], the whole plant including the collectors may be erected for about 1000 dollars/kw, 80 per cent of the plant cost being accounted for by the collectors which in turn cost about 2 dollars per sq ft. But according to more recent information[5] the cost of a 4 kw plant is estimated to be about 4000 dollars without the solar collectors. If we accept that 80 per cent of plant cost is due to collectors, the cost of collectors for a 4 kw plant comes to 16000 dollars and if 280 sq ft of collector area is needed for one hp generation, the cost of collectors per sq ft turns out to be 10·65 dollars per sq ft. Considering the low concentration ratio of these reflectors, the surface area of the absorber tube will be pretty high and due to the high inside pressure and triangular configuration, the thickness of metal would also be high. The most suitable material for high heat transfer is copper which has rather low mechanical strength. Thus the weight of copper needed would be fairly high and the cost of collectors would appear to be nearer to the higher figure. Thus taking cost of collectors as 10 dollars or 75 rupees/sq ft, the collector cost for a 100 hp plant comes to 2,250,000 rupees. The cost of the remaining components of the plant is given as 4000 dollars for a 4 kw plant. The cost of the turbo generator and other components may later be reduced through mass production to say half of this figure. So assuming 500 dollars/kw cost, the rest of the 100 hp plant costs dollars 37,000 or rupees 296,000. Thus the total cost of 100 hp plant comes to rupees 2,546,000. In a recent letter to the author, Dr H. Tabor, Director of NPL, Israel has stated that the present power plants in Israel are of about one hp and use flat plate collectors. The collectors cost 2000 dollars and the turbo generator 5000 dollars. These figures lead to plant costs higher than those given in the foregoing paragraphs.

As the collectors are unlikely to last more than 20 years, assuming 5 per cent interest rate, and operation of 10 hours a day on 330 days a year, the cost/kwh comes to slightly more than one rupee. This is a very high figure. In comparison to this, a standard diesel-generator set which costs about 50,000 rupees, gives power at rupee 0·30/kwh at current diesel prices assuming the same plant life, rate of interest and yearly power generation. In fact, it can generate more energy per year and is more reliable, power being available at any time—day or night.

Thus, it is seen that if for reducing maintenance, simplifying operation and increasing reliability, stationary low concentration reflectors are used, the first cost of the plant becomes high due to lower radiation interception, resulting in larger collector area requirement and larger size and weight of the costly copper heat absorber. The collector area requirement may be reduced by using higher concentration, and constant adjustment collectors using smaller size of absorber tube. But operation and maintenance may become unpracticable in the rural areas.

Concluding remarks

It has been shown that even if India immediately obtains the best available know-how in the world, the cost of energy from a solar plant would be more than rupee 1/kwh and the first cost about 50 times that of a diesel-generator plant. No doubt improvements in this field may be possible through research and the above figures may be reduced to some extent. But as we have no past experience, intense efforts over a very wide field would be needed. The following are some of the fields in which research and development would have to be carried out:

- (*i*) Hermetic engine-generator development.
- (*ii*) Development of selective absorber surfaces.
- (*iii*) Low cost, strong, weatherable, temperature resistant plastics to be developed.
- (*iv*) Development of high reflecting, low cost and long life reflecting surfaces.

In all these fields, we shall have to start from the very beginning, and even take up routine production. It not only requires a full-fledged laboratory working for at least a decade, but simultaneous investment and development in connected industries also. In short, vast amount of resources has to be invested with no returns during the first 10 years or so. In the present state of our economy, it is very difficult to invest in costly long-term projects unless some very substantial gains are assured. Such an assurance cannot be given for this work. The basic difficulty for solar plants is the low intensity of solar radiation which necessitates large collector areas. Unless some quite unexpected breakthrough occurs, it is difficult to considerably reduce the cost figures worked out here.

An argument generally given in favour of solar plants is that fossil fuels are being exhausted at a fast rate and new sources of power should be found. As far as India is concerned, our coal deposits are sufficient for at least another few hundred years. Therefore, it would be more fruitful to develop low maintenance, self-contained coal or wood burning engines for rural areas. The experiments with Phillips Stirling engine and the history of the hot air engines would indicate that it is not an impossible target. Besides, we have huge deposits of thermonuclear materials which may provide very low cost energy from nuclear reactors thus compensating for the cost of transmitting power to remote areas.

Thus, it appears to the author that conversion of solar energy to mechanical energy is not a promising field, at least as far as India is concerned. It may be more fruitful to concentrate on coal and wood burning engines. However, it is not to be inferred that solar energy utilisation in general is being declared as unpracticable. For low temperature applications like domestic water heating, small-scale water purification plants, house heating, etc solar energy has already been well established and we in India could also profitably work on such applications.

Appendices

Appendix I gives a brief report of some tests on a parabolic solar collector carried out at CMERI in 1964-65.

In appendix II, some salient features of a few solar power plants built in different parts of the world are given.

References

[1] G. O. G. Lof, D. A. Fester and J. A. Duffie, 'Energy Balances on a Parabolic Cylinder Solar collector', *Journal of Engg for Power*, January 1962, p 24.

[2] Gregory Flynn et al, 'GMR Stirling Thermal Engine', *SAE Transactions*, Vol 68 p 665 (1960).

[3] John I. Yellot, 'Solar Energy Progress Report—1961', *Journal of Engg for Power*, **84** (2) 213-220 (1962), Series A.

[4] John I. Yellot, 'Solar Energy Progress Report—1963', *Journal of Engg for Power*, **86** (4) 475-484 (1964) Series A.

[5] John I. Yellot, 'Solar Energy Progress Report—1965', *Journal of Engg for Power*, **88** (3) 221-231 (1966) Series A.

[6] Nathan Robinson, 'A report on design of solar energy machines', UNESCO/NS/AZ/141/1953, p 10.

[7] R. C. Jorden, 'Conversion of solar to mechanical energy', **Introduction to the utilization of solar energy,** McGraw-Hill Book Co, USA, p 129.

[8] H. Tabor et al, 'Further studies on selective black coatings', Proceedings of the UN Conference on New Sources of Energy, Rome (1961) pp 1-13.

APPENDIX I

Experimental work done at CMERI

A solar energy collector, probably the largest of its kind so far made in India, was designed and fabricated (Fig A1) at the Institute in 1964. Some interesting experiments were conducted with it, and some useful practical data were obtained.

The reflector was a parabolic cylinder with a focal length of 2·5 ft. Aperture was 6 ft and length 30 ft. As the investigations aimed at, were of preliminary nature, the framework was made from hardboard to keep the cost to a minimum and to expedite fabrication. 1 inch thick hardboard supports were given after each 4 ft of length. On each board,

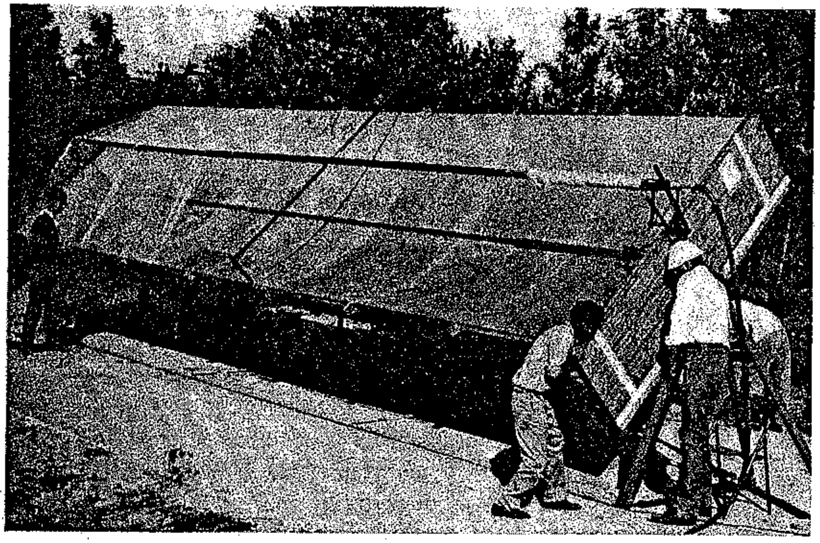

Fig A1
The experimental solar reflector designed and fabricated at CMERI

the parabolic profile was carefully cut and the framework completed by adding longitudinal hardboard members. 16 gauge polished aluminium sheets, 4 ft × 8 ft size, were screwed on to the parabolic profile. The result was a fairly accurate reflector. Two flanged rods were bolted to the two ends of the assembly and these rods were supported on rough split bearings at the two ends. These bearings were welded on two heavy section steel tripods which supported the weight of the reflector. These bearings were intentionally kept rough and undersized to act as brakes. The heat absorber was a two-inch tube fixed at the focus of the reflector. A number of supports were given to the absorber to prevent sagging. GI and copper tubes were alternatively used as absorbers and their surfaces were coated black with a lead sulphide-gelatin emulsion. For alignment to sun, a very simple arrangement was used which was found to be quite effective. Holes of $\frac{1}{2}$ inch dia were drilled into the end plates of the reflector at 1 inch interval. After each alignment, a bolt was inserted into the hole nearest to the end support. For keeping the focus on the absorber, adjustments at approximate intervals of 10 minutes were found necessary.

In the first set of experiments, a GI tube without glass envelope was used. A centrifugal pump drew water from an insulated tank, circulated it through the absorber and then deposited it back to the tank. Suitable temperature and flow measuring instruments were incorporated into this closed circuit. It was found that the maximum rise in temperature was 45° to 50°F above ambient with a heat absorption rate of about 70 BTU/min at the highest temperature.

The GI tube was next replaced by a copper absorber and a 4 inch pyrex glass tube was fitted over it using cork plugs for support between glass and copper tubes. Considerable improvement in performance was evident. On a day in June with an ambient temperature of 97°F, starting at 9 AM, steam began to form at about 1·30 PM and continued till around 4·30 PM. During these four hours, steam was produced at the rate of 4 to 5 lbs/hr at a pressure of 3 to 5 psig.

An insulated accumulator with a float valve was next fixed on an elevated platform near one end of the absorber. Fresh water was pumped into the accumulator through the float valve from where it flowed down into the absorber tube through gravity. The other end of the absorber was also connected to a closed insulated tank. The idea was that water from accumulator would flow down into absorber and boil. Steam thus formed could collect above the water in the other tank from which it could be drawn out for use. This arrangement was not successful, steam production falling down appreciably. The reason was considered to be the small dia and long length of boiler tube which did not allow easy passage of steam. A better design of absorber allowing easy steam collection was obviously needed.

The following are considered to be some of the more useful information obtained through these experiments:

(*i*) The reflectivity of aluminium sheets available in India is between 70-75 per cent. After exposition to rain, white dull spots tend to form on the surface and the average reflectivity reduces. The same can be restored by buffing the surface but it is a fairly tedious process, specially difficult for the middle portions of the reflector. However, aluminium can be considered to be a long life reflecting material as even now, after 4 years of weathering, it is possible to polish the aluminium reflector back to a reflectivity of about 70 per cent.

(*ii*) The black coating used on the absorber had a tendency to chip off. This presented great difficulty while fixing glass cover over it. Black dust collected into the tube which was difficult to remove.

(*iii*) The use of glass envelope is essential with simple black coatings if any reasonable performance is to be obtained. However, this is very difficult to execute in practice. A number of tubes were broken during fixing to absorber tube and it was found very difficult to completely seal the annular space between glass and copper tubes. The cleaning of glass tube from inside caused great hardship and in fact resulted in most of the breakages. For any practical installation, a transparent plastic cover sealing the whole reflector absorber tube is essential.

(*iv*) The only near-transparent plastic film available in India is polyethylene. The commercial product was found to have poor transmittance and in actual trials resulted in considerable decrease in heat output.

APPENDIX II

Salient features of some earlier plants

It would be useful to study the records of various solar machines made by various experimenters. An excellent description of early solar machines may be found in Dr Nathan Robinson's "A Report on the design of solar energy machines", UNESCO/NS/AZ/141, 1953. Here the salient features of a few machines are given.

(*a*) Shuman-Boys plant at Meadi, Egypt (1912)—Parabolic cylinder reflector made from small plane mirrors arranged on a trough. Irradiated surface 13,000 ft^2, concentration ratio 4·5. Absorber covered with glass. 100 hp engine used. Developed 50 to 60 hp continuously for a 5-hour period[7].

(*b*) University of Dakar solar pump—Flat plate collectors, vapour as medium, 3 hp hermatically sealed turbo-alternator. 3,100 sq ft collector area needed[5].

(*c*) Somor water pump—Used vapour as medium, flat plate collector. Well water used for condensing. Details not available. It is claimed that in hot areas 30 m^2 collector area is sufficient for generating 2 hp.

(Revised manuscript received December 28, 1967)