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COLLECTORS FOR INTERMEDIATE TEMPERATURE APPLICATIONS

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1.- INTRODUCTION

Solar thermal technology for intermediate temperatures is one of the most extensive ways of applying solar energy, since it is possible to use it for different purposes such as air-conditioning, industrial process heat, power for irrigation pumping and electric power generation. In all theses cases it can work in conjunction with conventional plants as fuel saver (hybrid or co-generation).

The present state of art allows to affirm that the feasibility of converting solar energy into heat useful for the different applications mentioned before by means of several kinds of collectors has been demonstrated, and that for a large scale use, the only developments required are those appropriate to reduce the cost of the systems. It should be emphasized that the required technology is not complex, specially when compared against nuclear technology, and that it is within reach of countries with an average degree of technological development such as some of the Latin American countries.

The present work will briefly describe the different solar collectors suitable for the intermediate-temperature range between aproximately 100 and 500°C, including some of their more oustanding characteristics. Some examples of systems in construction or operation around the world, as well as their present and projected costs are also presented.

2.- SOLAR ENERGY PHOTOTHERMAL CONVERSION SYSTEM

In general, the system that allows the collection of solar energy and its conversion to thermal energy consists of the following major subsystems (see Fig. 1):

a) Collectors field subsystem, which includes the collectors, their foundations, piping, pumps, heat transfer fluid (working fluid), the field control unit;

b) storage subsystem which includes the heat storage medium, heat exchanger, foundations, control unit;

c) steam generation or fluid heater, in which the heat from the storage or from the collectors field is transferred to the applications(electricity production, industrial process heat, air conditioning, etc).

In many cases it is possible to identify three heat loops:

a) The first loop extracts low temperature working fluid from the storage, circulates it through the collectors field, and returns it at high temperature to the storage subsystem;

b) in a second loop a working fluid is heated taking energy from the storage (it could be the same fluid used in the first loop or a different one), discharges the thermal energy to the fluid heater, and returns the cooled-down fluid to the storage;

c) the third loop is the connection between the steam generation or fluid heater and the application.

3.- COLLECTORS AND COLLECTORS FIELD

The collectors field is the most important part of the solar energy application system and its cost exceeds in many cases 40 or 50 % of the overall cost. Special emphasis therefore has to be given to the collector selection.

3.1 Definition of parameters

Before beginning the description in detail of the different kinds of collectors, we shall discuss the principal parameters that characterize the photothermal conversion systems.

For most of the intermediate temperature applications, some means of concentrating solar radiation is necessary. The concentrator "aperture" area is that plane area through which the direct incident solar radiation (or the direct solar radiation plus some diffuse) passes. The "receiver" area (in which the absorber is placed) is the one designed to receive the concentrated solar radiation. A "working fluid", which may be a liquid, vapor or gas, is used to remove energy from the absorber. The "angle of acceptance" δ is the angle such that all radiation incident within it on the concentrator aperture, arrives at the receiver, upon being reflected.

The sense in which the term "concentration" is used must be clearly understood. We will follow the definition given in Ref. 1. The "local concentration factor" is defined as the ratio of the intensity $I_r(x)^{(+)}$ incident on a given point of the receiver plane and the intensity of direct solar radiation (or direct plus some diffuse):

$$C(x) = I_r(x)/I_b \quad , \qquad (3.1)$$

where x is a coordinate in the receiver plane, normal to the concentrator's focal line and such that x = 0 is the coordinate of the receiver center. In practice, the optical parameter of interest is the average of the local concentration factor over the receiver width w_r. Thus, the "mean concentration factor" is defined as

$$\begin{aligned} \bar{C}(w_r) &= (1/w_r)\int_{-w_r/2}^{w_r/2} C(x)dx = \\ &= (1/I_b\, w_r)\int_{-w_r/2}^{w_r/2} I_r(x)dx = \bar{I}_r/I_b \quad , \end{aligned} \qquad (3.2)$$

where $\bar{I}_r$ is the average radiation intensity incident onto the receiver.

It is usual to use the "geometric concentration factor" C_g which is defined as the ratio of the concentrator aperture area (A_c) and the receiver area (A_r):

$$C_g = A_c/A_r \quad . \qquad (3.3)$$

It is related to the mean concentration factor $\bar{C}(w_r)$ by:

$$\begin{aligned} \bar{C}(w_r) &= C_g\ (1-p_t(w_r))\ (1-p)\cos i \\ &= C_g\ \eta_o \cos i \quad , \end{aligned} \qquad (3.4)$$

where $p_t(w_r)$ stands for the "total geometric losses", i.e. that fraction of the energy incident onto the concentrator aperture which does not incide on the receiver:

$$p_t(w_r) = 1 - (1-p_c)\ (1-p_g(w_r)) \quad . \qquad (3.5)$$

(+) We must remember that intensity is the density of the energy flux through the receiver plane (W/m^2).

Here the "concentrator losses" p_c are the fraction of the energy incident onto the concentrator aperture which is not reflected towards the receiver plane (these losses include absortion and dispersion on the mirror, as well as screening in faceted concentrators), and the "geometrical losses in the receiver" $p_g(w_r)$ are the fraction of the energy incident onto the receiver plane which does not incide on the receiver proper:

$$p_g(w_r) = 1 - \frac{\int_{-w_r/2}^{w_r/2} I_r(x)\, dx}{\int_{-\infty}^{\infty} I_r(x)\, dx} \quad ; \qquad (3.6)$$

p takes into consideration possible additional losses, such as reflection on the receiver cover and "i" is the angle of incidence, made by the incident rays with the normal to the aperture plane. Finally,

$$\eta_o = (1-p_c)(1-p_g(w_r))\,(1-p) \qquad (3.7)$$

is defined as the optical efficiency.

As it is clear from equation (3.4), C_g is, en general, only an upper bound of $\bar{C}(w_r)$.

An important relation exists between the mean concentrator factor and the angle of acceptance. As is shown in Ref. 2, the second law of thermodynamics implies that for two dimensional concentrators (or systems with linear focus) the maximum or ideal possible concentration for a given angle of acceptances is

$$\bar{C}_{max} = 1/\sin\,(\delta/2) \quad \text{with } p_g(w_r) = 0 \;, \qquad (3.8)$$

whereas for three dimensional concentrators (or systems with a point focus) it is

$$\bar{C}_{max} = 1/\sin^2\,(\delta/2). \qquad (3.9)$$

The smallest angle of acceptance is the angular aperture of the solar disk as seen from the collector (32 minutes); consequently the maximum theoretical $\bar{C}(w_r)$ are respectively

$\bar{C}_{max}$ two dimensional concentrator = 215 with $p_g(w_r) = 0$ (3.10)

$\bar{C}_{max}$ three dimensional concentrator = 46.000 . (3.11)

For two dimensional concentrators it is possible to have[3]) a local concentration factor $C(x)$ bigger than the limit given in equation (2.10), namely 273 if the direct solar radiation is considered to be uniformly emmitted from the solar disc.

The thermal perfomance of concentrating collectors is characterized by their efficiency. If, for simplicity, we assume the receiver and the ambient air to be at homogeneous temperatures T_r and T_a respectively, its thermal efficiency for the conversion of solar energy into thermal energy is given by

$$\eta_{th} = \alpha - \frac{\varepsilon\sigma\ (T_r^4 - T_a^4) + (h+K)\ (T_r - T_a)}{\bar{I}_r} , \qquad (3.12)$$

where:

$\bar{I}_r$ is the average intensity incident on the receiver, W/m^2;

α and ε are, respectively, its characteristic absorptance and emittance;

σ is the Stefan-Boltzmann constant $5,669710^{-8}$ $W/m^2 °K^4$);

h is the convective loss coefficient ($W/m^2 °K$);

K is the conduction loss coefficient ($W/m^2 °K$).

By introducing the expressions (3.2) and (3.4) into (3.12) one gets

$$\begin{aligned} \eta_{th} &= \alpha - \frac{\varepsilon\sigma\ (T_r^4 - T_a^4) + (h+K)\ (T_r - T_a)}{\bar{C}(w_r)\ I_b} = \\ &= \alpha - \frac{\varepsilon\sigma\ (T_r^4 - T_a^4) + (h+K)\ (T_r - T_a)}{C_g\ \eta_o\ \cos i\ I_b} \end{aligned} \qquad (3.13)$$

The total "instantaneous" efficiency is the product of the thermal and optical efficiencies:

$$\eta = \eta_{th}\ \eta_o = \eta_o\ \alpha - \frac{\varepsilon\sigma\ (T_r^4 - T_a^4) + (h+K)\ (T_r - T_a)}{C_g\ I_b\ \cos i} \qquad (3.14)$$

and it is defined as the ratio of useful energy extracted from the receiver to the solar energy passing through the concentrator aperture:

$$\eta = \frac{\dot{m}\ C_p\ \Delta T}{A_c\ I_b\ \cos i} , \qquad (3.15)$$

where:

$\dot{m}$ = mass flow rate of fluid;

C_p = specific heat of fluid;

ΔT = IN/OUT temperature differential.

From Eq. (3.14) it is possible to express η in a similar way as the efficiency of the flat-plate collector:

$$\eta = \eta_o' - U\ (T_r - T_a)/C_g\ I_b \cos i \quad , \tag{3.16}$$

where U represents the total heat losses, that is to say conduction, convection and radiation losses, and it is a rather complex expression. In the case of a collector field, it is necessary to subtract a term that takes into account the heat losses of the piping due to conduction, convection and radiation.

It is important to call the attention to the fact that both, the optical efficiency η_o as well as the thermal efficiency η_{th} depend of the receiver width w_r but in opposite way

$$\begin{aligned} \eta_o &= (1-p_c)\ (1-p_g(w_r))\ (1-p) \\ \eta_{th} &= \alpha - \frac{\varepsilon\sigma\ (T_r^4 - T_a^4) + (h + K)\ (T_r - T_a)}{\bar{C}(w_r)\ I_b} \end{aligned} \tag{3.17}$$

This is shown in Fig. 2, where the geometrical losses in the receiver and the mean concentration factor are plotted as a function of the width of the receiver. In order to obtain the maximum total efficiency η it is neccesary to select carefully the receiver width.

3.2 Brief description of the generic types of concentrators and their general characteristics

We divide solar energy concentrators into two groups, depending on whether the collector system is formed by a great number of units in each of which the conversion is produced (distributed conversion), or whether the solar energy is collected on a large surface and concentrated onto a single central receiver (centralized conversion). Within each one of these groups, we shall classify the collectors depending on whether they need seasonal adjustment or have one or two degrees of continous movement. Figure 3 shows schematically the different types of concentrating collectors that are under active development. For each movement type, they are placed in increasing order of maximum theoretical concentration factor (i.e. increasing optical quality).

The systems of distributed conversion, as already mencioned, convert solar into thermal energy at the location that each of the collectors occupies in the collection field, being it necessary to transport the above mentioned thermal energy to a receptacle near the place where it will be utilized. This requires a transport system with a high degree of thermal insulation. The centralized conversion systems, on the other hand, collect solar radiation and transmit it by optical means (they reflect it) to a point where it is converted into thermal energy, generally close to the place where this energy will be used.

In general these systems can only use direct radiation althoug, in the case of the fixed CPC type concentrator, a fraction of the diffuse radiation is also converted.

With increasing concentration factor, it is possible to extract useful energy from the collector at a progressively higher temperature without sacrificing efficiency. In Fig. 4, the effect of the concentration factor on the absorber temperature is given for several collectors. The advantage of an increase in the temperature of the delivered energy is accompanied by an increase in the required accuracy to track the sun position and, to a certain degree, a growing complexity of the collector's system of movement.

Receiver thermal losses can be reduced by using a selective coating on the absorber, and consequently increase the thermal efficiency of the system. Selective surfaces have high solar absorptance and low infrared emittance. It is possible to write equation (3.13) for the case in which only radiation losses are considered:

$$\eta_{th} = \alpha \left(1 - \frac{\sigma(T_r^4 - T_a^4)}{F_s \, \bar{C}(w_r) \, I_b}\right), \qquad (3.17)$$

where we call $F_s = \frac{\alpha}{\varepsilon}$ the selective factor. Therefore, in order to increase the thermal efficiency when higher temperature energy delivery is required, we will have an important economic competition between the increase of the mean concentration factor or the use of more sophisticated, but also more expensive, selective sufaces with high selective factor. Increasing the selective factor F_s from 5 to 10 at $\bar{C}(w_r)$ = 20 is comparable to double the mean concentration factor from 20 to 40 at F_s = 5.

However, it is important to call the attention on the fact that in all cases a coating with high solar absorptance is necessary. In addition, it can be shown that, depending on the mean temperature of the receiver, from a certain value of $\bar{C}(w_r)$ upwards a coating with high absorptance is enough, and no selective surface is necessary (see Fig. 5, where equation (3.17) has been plotted[3])). For a thermal efficiency of about 80 % and a temperature of 200°C, a selective surface is not needed for $\bar{C}(w_r)$ bigger than 40. At T = 300°C this holds for $\bar{C}(w_r) > 75$, at T = 400°C for $\bar{C}(w_r) > 140$, and at T = 500°C for $\bar{C}(w_r) > 250$.

A large number of materials have been used in concentrating collectors. The reflective surfaces are made, in general, of second surface silvered glass but, in order to reduce the cost, in some cases electropolished aluminium or metalized film have been used. For Fresnel lenses acrylic is used.

The absorbers are normally metallic covered with a black coating of high solar absorptance or with a selective surface. The receiver is parcially or totally enclosed in a glass envelope, depending on its shape.

3.3 Concentrator description

Let us now describe the different collectors according to Fig. 3.

A. *Compound parabolic concentrator*

There is a variety of concentrators with seasonal or daily adjustment which allow to obtain geometric concentration factors which go from somewhat more than 1 up to 10. The most simple ones are formed by a pair of V shaped mirrors. The best C_g is obtained using the compound parabolic concentrator (CPC) or Winston concentrator. Figure 6 shows a CPC and its principal parameters.

The concentration factor of the CPC is given by $\bar{C} = 1/\sin(\delta/2)$, where δ is the angle of acceptance. As said above, the CPC can concentrate direct radiation and a fraction $1/\bar{C}$ of the diffuse radiation. All the radiation that reaches the aperture area with an angle of incidence i equal to or less than the semiangle of acceptance will arrive to the receiver.

The bigger the concentration factor, (smaller acceptance angle), less is the diffuse radiation used and, furthermore, more frequently the inclination of the aperture plane has to be modified. On the other hand, the area of the reflector per unit of required aperture also increases when $\bar{C}$ increases, which is significant from the practical and economical points of view. Figure 6 shows the concentration factor of the compound parabolic concentrator as a function of the ratio between the length of the reflectors and the aperture, for different value of $\delta/2$. At is possible to see from this figure, a truncated PCP with practical reflector sizes, can be built without losing too much concentration factor.

B. Fresnel lens

Each concentrating unit is made up by a Fresnel lens with linear or point focus and with its facets oriented towards the receptor, as shown in Fig. 7. The lenses, of the order of 7 - 10 mm in thickness, are usually made of acrylic in order to keep costs as low as possible. The transmission of the acrylic Fresnel lenses is of the order of 85 %. Experiments made with acrylic sheets show[5]) that the transmission only drecreasses by 11 % after having been exposed to atmospheric conditions for 17 years.

If geometric concentration factors bigger than 10 ($C_g > 10$) are aimed at with linear focus lenses two axes tracking is necessary.

C. Fixed concentrator with faceted mirror

The fixed concentrator with faceted mirror is formed by an assembly of flat, narrow and long mirrors, arranged in such a way that its longitudinal axes of symmetry are on an imaginary cylinder of reference. One of the specular strips is tangent to the mentioned cylinder of reference and the rest form angles which are prefixed with respect to the tangent mirror. As is shown in Fig. 8, if the angular position of mirror n with respect to the tangent mirror is θ, the angle between the planes that contain the tangent mirror and mirror n is $\theta/4$. It is possible to demonstrate[6]) that, for any direction of a parallel bundle of incident rays, the system has a linear focal zone located on the reference cylinder and that the successive positions of the latter (due to the apparent movement of the sun), are also located on the same cylinder. Furthermore, the receiver of the concentrated energy can be made up by a tube supported by arms with their center of rotation located on the axis of symmetry of the reference cylinder.

The most convenient orientation for the FCFM is East to West. In order that the losses at the ends of the receiver may be neglected, the ratio[6]) between the length of the concetrator and its radius should be greater than 50. The concentration factor is a function of the ratio between the width of the mirrors and the radius of the reference cylinder (w/r), and also of the angle of incidence of the radiation.

It is possible to increase the concentration factor substituting[7]) the flat mirrors by cylindrical ones. In the limit, when w/r is approaching zero, both concentration factors coincide.

Typical dimensions of fixed concentrators with faceted mirror are:

the diameter of the cylinder of reference is about 4 m, the width of each flat mirror ~ 4 cm, the number of mirrors is ~ 70 and the module length ~ 50 m (we call one module the several mirror units that is possible to drive with one motor).

D. *Concentrator with multiple concave rotating mirrors*

The concentrator is formed by an assembly of concave rotating mirrors which are narrow and long, the rotation axes of these being arranged on a plane[8]) or on a cylinder[9]). Both the supporting plane or cylinder as well as the rotation axes are fixed. The mirrors can be of equal or variable width, being positioned in such a way that, when rotating, all of them have the same angular velocity for tracking the apparent movement of the sun, the concentration zone remaining permantently fixed. Figure 9 shows, for incidence of the rays normal the longitudinal axes of symmetry of the mirrors, the inclination needed for each mirror in order to obtain a sharp focus.

In general, the aperture width of each mirror is about 25 - 30 cm, the number of mirrors 7 - 10, and the focal length 2.5 m.

E. *Central receiver system with linear focus*

As mentioned in Section 3.2, the basic idea of centralized conversion systems is that of concentrating by optical means in a relatively small area (several square meters) the solar energy incident on a large surface of the Earth (1 - 2 km^2). In the case of the central receiver systems with linear focus, this is achieved by means of an assembly of rows of concave rotating mirrors with their longitudinal rotating axes oriented in the East-West direction. The central receiver could be located at one of the ends of the field of mirrors as is shown in Fig. 10.

In principle the system is similar to that of case D, but with a different scale.

F. *Parabolic trough concentrator*

In order to obtain a well defined focus in the parabolic trough or cylindrical-parabolic concentrator, it is neccesary that at all times the radiation incident on it coming from the Sun's center, projected onto the plane perpendicular to the axis of symmetry of the cylinder, be parallel to the axis of symmetry of the parabola (Fig. 11a). This is equivalent to say that this radiation should be contained in planes parallel to the plane normal to the aperture and which contains the axis of symmetry of the cylinder, as is showing on Fig. 11b. This can only be achieved by rotating the cylinder about an axis parallel to the focal axis, following the Sun as it moves.

According to the orientation of the axis of movement, we can specifiy three cases:

1.- North-South direction, inclined with respect to the horizontal at an angle close to the latitude of the location (Polar orientation);

2.- North-South direction in horizontal position;

3.- Eath-West direction and horizontal position.

It is possible to use the parabolic trough employing two axes tracking for orientation in azimuth and elevation in order to maximize daily energy collection. However, before selecting this possibility it is necessary to perform a detailed analysis of the annual energy outputs of collector fields with two axes and one axis mountings, taking into account the different daily energy collection as well as the different heat losses of the pipings.

The several systems on the market have an aperture width ranging from 1,5 m to 3 m, a focal length from 0,4 m to 0,9 m, a rim angle from 70° to 90°, and a module length from 20 to 30 m. The diameter of the receiver depends on the concentration factor but is in the order of 5 cm.

G. *Semispherical fixed concentrator (Spherical bowl)*

Basically, each semispherical fixed concentrator, or concentrator with a distributed focus, is made up by a section of a fixed sphere with its axis of symmetry inclined at an angle which is a function of the location. As can be seen in the Fig. 12, the focal region is distributed and, given the finite size of the Sun, has a conical shape with the angle of the cone equal to the angle subtending the solar disk (32'). Any ray which falls upon the aperture area of the concentrator, after being reflected one or two times reaches the region of the receiver included between R and R/2, where R is the radius of the sphere.

The conical receiver moves during the day in such a way that its axis of symmetry is always on the line determined by the center of the Sun and the center of the sphere. The focal area is controlled to track the Sun using a two-axes motion. The shape of the focal region is independent of the time of day during which different sections of the semisphere are used.

As an example of the sizes, the proof of concept version now in operation in France (Mini-Pericles) has a 10 m diameter bowl. The full scale plan for Pericles calls for a 30.8 m diameter bowl with an aperture area of 745 m^2.

The project at Crosbytown, USA, in operation since 1981, has a bowl with a diameter of 20 m which is a prototype for a plant with a 61 m diameter bowl.

H. *Central receiver system with point focus*

In the central receiver system with point focus, also called the central tower system, the concentration is carried out by means of an assembly of flat or curved mirrors which are appropriately distributed and which reflect the solar radiation towards a receiver located at the highest point of a tower. The mirrors are mounted on heliostats. The radiation concentrated in this way can be converted into thermal energy at the same point or retransmitted by optical means to another point located at ground level. The tower can be installed in the center of the mirrors field or at one of its ends. Figure 13 shows a diagram of the system described. The receiver has been proposed with a cavity shape and acting like a black body.

The size of the mirror area for each heliostat ranges from 20 to 40 m^2. For a power plant of 500 kW_e the total reflective surface area of the heliostat field is of ~ 3,500 m^2, with a tower of ~ 40 m of high.

I. *Parabolic dish concentrator*

The shape of the mirrored surface of a parabolic dish is that of a paraboloid of revolution; i.e., a cross section of the dish in any direction conforms to the same parabola. The parabolic dish concentrates radiant solar energy falling upon a surface of several square meters (the aperture area of the concentrator) in a small area (the focus of the parabolic dish) where it is converted into thermal energy. Since, in order to keep a sharp focus, the solar radiation should incide parallel to the axes of symmetry of the paraboloid of revolution, it is necessary to be able to rotate the latter according to two degrees of freedom (Fig. 14). For example, the frame supporting the mirror rotates about a vertical axis for alignment in the azimuthal direction, and the mirror and receiver assembly rotate about a horizontal axis for adjustment of the elevation.

For this type of concentrator, the parabolic mirrors have an overall diameter ranging from 4 to 13 meters and a focal length from 5 to 6 meters.

3.4 Examples of $\bar{C}$ and η_t for linear focus concentrators

As an example of the mean value of the theoretical concentration factor $\bar{C}$, we consider the cases of five linear focus concentrators[10]: fixed concentrator with faceted mirror (whit flat or cylindrical facets); concentrator with multiple concave mirror (rotation axes arranged on a plane or on a cylinder) and parabolic trough. In Fig. 15 the $\bar{C}(w_r)$ is plotted as a function of the standard deviation of the error of the normal to each mirror surface element respect to its ideal position according to a Gaussian distribution. All the concentrators are oriented in East-West direction with their aperture plane with a slope equal to the latitud. The receiver widths (w_r) are selected in each case in order to keep the geometric losses in the receptor $p_g(w_r)$ below 10 %. Two different cases are presented: 1) for the equinox at solar noon and 2) for the solstice at three hours respect to solar noon.

The parabolic trough has the higher concentration factor, followed by the concentrators with multiple concave mirrors. In these, the concentrador with rotation axes arranged on a cylinder is better than the concentrator with the axes on a plane. Finally, the concentrator with lowest $\bar{C}$ is the fixed concentrator with faceted mirror. The case with cylindrical facets is better than that with plane mirrors, but in some cases the advantage is not too relevant as compared to the complexity of constructing cylindrical mirrors instead of flat mirrors.

Fig. 16 shows measured efficiency data (equation 3.16) for five concentrators with line focus tested[11] at Sandia laboratories.

3.5 Yearly average performance of the principal solar concentrators

Instantaneous efficiency test will provide data on collector performance under standard clear sky conditions. For practical applications it is necessary to know the long term average energy delivered by a real system, taking into account such effects as variable cloudiness and varying incidence angles. First of all, no such data are available for a sufficiently long period for all the concentrators and, secondly, the measured collector output for different kinds of collector have been taken under different conditions.

As a simple alternative, design tool calculation procedures have been developed which are useful in selecting, sizing and optimizing solar equipment for specific applications. Collares-Pereira and Rabl[12] have proposed a generalized and simplified model of the utilizability approach of Liu and Jordan, which is directly applicable to concentrating collectors.

The result is a plot of collector yearly average energy delivery ($\bar{Q}_{year}$) versus difference between fluid temperature and ambient temperature. Recently Rabl[13]) developed a set of graphs from which the yearly total energy deliverable by the principal collector types can be read directly. As an example, in figure 17 we show for several typical collectors a direct comparison between the yearly average energy delivery versus operating temperature for two different yearly average direct insolations. The yearly total energy deliverable is important when the total cost of different collectors must be compared using the cost per energy criterion, or the annual capacity cost (total system capital cost against annual energy output).

4.- STORAGE OF ENERGY

Because solar radiation is intermittent, conventional back-up or energy storage must supply the energy needs at night or during periods of cloud cover. From the economic point of view, it is debatable if, in order to compensate for the hours without insolation, it is more advantageous to carry out storage of energy or to use a conventional back-up. In any way, at least some short-term storage is necessary in order to have continuity during the short periods of cloud cover.

We shall only mention, without discussing them, the different methods proposed[14,15]) in different projects and classify them into two large groups:

1.- Systems which can be utilized making direct use of thermal energy:

a) Sensible heat storage media

Raising the temperature of a solid or liquid in insulated tanks.

Example: Water; molten sal as Hitec; oil as Therminol, Caloría; liquid metal as Na.
Rock; SiO_2; MgO; Al_2O_3; Fe.

b) Latent heat of phase change

High energy storage densities over a narrow temperature range.

Example: $CaCl_2$(52) -NaCl(48); Na_2CO_3(56) -K_2CO_3(44); KCl(50) -Na_2CO_3(50); NaOH; $NaNO_3$; KF(58) -NaF(35) -MgF_2(7).

c) *Reversible chemical reactions*

The thermal energy is stored as the bond energy of a chemical compound. The energy storage density by reversible chemical reactions is generally higher than heat-of fusion transitions.

Example: $NH_4F(s) \longleftrightarrow NH_3(g) + HF(g)$

$NH_4HSO_4(l) \longleftrightarrow NH_3(g) + H_2O(g) + SO_3(g)$

$SO_3 \longleftrightarrow SO_2 + 1/2\ O_2$

2.- System which before storage require a transformation of thermal energy into another form of energy:

a) *Liquid Hydrogen;*

b) *flywheels;*

c) *batteries;*

d) *superconductor magnets;*

e) *pumped hydroelectric storage power stations.*

5.- APPLICATIONS, EXAMPLES AND PRESENT EXPERIENCES

Several experimental plants have been planned and realized in the world, mainly in order to gather practical experience in design, construction and operation of the different types of systems.

For the cases of solar industrial process heat and water pumping applications using concentrating collectors, most of these projects have been made in the USA. In Table I we list some of the principal applications of solar process heat in industrial processes, in operation or under construction, as well as some of the principal data of these plants. The Solar Energy Research Institute of Denver, USA, has analyzed[19]) the operating data for some of these plants. The analysis showed a number of positive results but also demonstrated the necessity of further improvements on systems and components. Present annual average system efficiencies represent only 25-50 % of the predicted performance. Among the problems which cause this poor performance are mentioned: a) the not fully utilization of the solar system, principally due to lack of matching between the solar plant and the requirements and operational characteristics of the industrial process and b) the excessive thermal losses. Surprisingly, the solar systems were available at least 90 % of the demand time.

In Table II three examples of solar thermal irrigation systems in operation are shown. The largest system, 150 kW_e, began operation in October 1979 on a farm south of Coolidge, Arizona, USA. The system supplies enough electricity to drive three water pumps for irrigating 65 hectares of farmland devoted to cotton growing. The water pumps lift approximately 5300 liters of water per minute from a well 91 meters deep. A tank of 113,500 liters of stratified temperature oil permits thermal energy storage for about 6 additional hours.

Finally, in Table III we give a list of the principal applications of photothermal conversion of solar energy into electricity, in operation or in construction. Some of the projects using a central tower collecting system are in the limit of what we call intermediate temperature applications but we include them in order to give an idea of the experimental plants built in the electricity field, using concentrators.

6.- ECONOMIC ANALYSIS AND PROJECTIONS

The solar industrial process heat (SIPH) systems currently can only be considered as fuel savers. Due to the intermittent nature and variability of sunshine and to industry's need for a reliable energy supply, solar industrial process heat systems must have complete back up and reduce conventional boiler capacity requirements only if they include elaborate storage systems.

Theoretically, SIPH systems and fossil fired boilers will be economically equivalent if equal specific cost of energy will be reached during the lifetime of the systems. Practically, SIPH systems will be come competitive if they demonstrate reliable operation and reach commercially attractive pay back times of about 5 to 10 years due to the fuel saved.

Solar units costs are conveniently expressed in dollars per square meter of collector area (or by the total cost of the complete system per square meter of collector aperture). However, this measure gives no information on the differences among the characteristics of the various types of solar systems, for example the efficiency of the collector. Moreover, equal SIPH systems will give different quantities of thermal energy per year according to the solar radiation intensity which is a function of the geographical location. Finally, to obtain the so called "end-use matching", one must know the amount and temporal distribution of insolation and ambient temperature as well as the load distribution of the process.

Therefore, in order to compare the energy cost from different solar collector systems taking into account the end-use matching, a more accurate unit of cost has been developed by Kreith and Kearney[20] and applied to the SIPH market by Brown et al[19,21]. This is the "unit capacity cost", i.e. the total solar system capital cost against annual energy delivered by the solar system, in dollars per million Wh per year. In other words, this is the average number of investment dollars required to purchase the capacity to produce an average annual thermal energy output of 1 MWh according with the necessity of the particular industrial process heat considered.

In Fig. 18 we show the present average annual energy capacity cost, in 1980 dollars per MWh year for different solar industrial process heat systems being operated in the USA[22]. Also shown is the extrapolated average energy capacity cost for the same solar systems, assuming the greatest efficiency of the collectors in their class from the field data[22], standard construction methods, and full utilization. The total installed system unit cost in dollars per square meter of active collector aperture is between 500 and 700 U$S (in 1980 dollars). We also plot the average energy capacity cost estimated for the operational SIPH units of a second generation system of 10,000 m^2 size given in Ref. 22, for which this source gives total system cost of 350-450 U$S/$m^2$.

In the same figure we plotted the energy capacity cost obtained by us from the data given by Feustel[16] versus the annual production rate of collectors (m^2 per year) and the nominal power in MWh installed per year. The average cost per square meter of collector installed as well as the cost of the total installed system per m^2 of collector aperture is shown for each point. Feustel considers that the presently high investment cost of SIPH systems can be lowered on the basis of intensified research and development, optimization, operational experience and application of mass production methods.

Finally, we give the average energy capacity cost for central tower systems presented recently by Laurence and Hildebrand[23]. It is given for a cost of m^2 of heliostats corresponding to a production rate per year of 2,500 and 250,000 heliostats which is equivalent to 10^5 and 10^7 m^2 per year (40 m^2 per heliostat).

Both, the projected energy capacity costs for 1995-2000 obtained from the Feustel analysis as well as from the analysis given by Laurence and Hildebrandt, are in agreement with the estimate by Kreith and Davenport of the price (180 U$S/MWh-year) which would allow solar industrial process heat to find wide application in many industries. The last authors assumed that in the future the cost of solar collectors can be the same as the cost of other mass-produced items as lawn mowers, automobiles, refrigerators, etc, which cost is 4.40-6.60 U$S/Kg. The weight of solar collectors is approximately 25 Kg per m^2 of aperture. Assuming that by appropriate design of the collector the mass can be reduced by 30 % and another 20 % can be saved by selection of inexpensive materials, they obtain a collector cost of 50 U$S/$m^2$.

Concerning solar thermal conversion to electricity for irrigation pumping, we reproduce the data presented by LL.O.Herwing[24]). In Fig. 19 the installed collector cost and the total installed system cost (collectors, storage and organic rankine turbine/generator) in U$S/$m^2$ are plotted versus time. We see that for 1990 the cost for collectors is similar to the cost given for solar industrial heat process (Fig. 18). In Fig. 20 the annualized cost of solar thermal and diesel electricity generation are presented for a range of total solar system cost and for two inflation rates of diesel electricity generation. As we can see, for the high inflation rate diesel generation, the solar system could be competitive about 1985 and for the low inflation rate in 1990.

Finally, for the small solar thermal electric power systems, the capital cost of all the prototypes mentioned in Table III, ranks from 10,000 to 30,000 U$S per kW_e installed. In several cases (or probably in all) these costs inclued the costs of research and development. To identify the most likely options for long-term commercialization of small solar thermal electric power systems, the Department of Energy of the USA requested the Solar Energy Research Institute, Batelle Pacific Northwest Laboratories, and the JET Propulsion Laboratory to produce a comparative analysis[25]) of the major generic solar thermal electric systems. This study considered plants with rated capacities from 1 to 10 MW_e for utilities, operating with different capacity factors, and from 0.1 to 1 MW_e for industrial and other non-utility applications. The capacity factors, as used in this report, represent the total amount of electrical energy produced during the full year, divided by the amount of energy that the plant would produced if operated at rated capacity for the entire year. They studied all the collectors described in this paper as well as shallow solar ponds in combination with different kinds of cycles (Brayton Rankine, and Stirling). The cost estimates for each technology and the resulting energy cost have been obtained using costs that can reasonably be achieved by the mid-1990s, expressed in dollars of 1978. As an example of this study we will give the cost for a distributed system formed by parabolic dishes with Stirling engines mounted at each focal point. The collector cost for 1990 were considered to be about 110 u$S/m^2.

The Table IV presents the data for systems with rated capacities from 0.1 to 1 MW_e and two capacity factors (0.7 and 0.4) for industrial or other non-utility applications with diesel generator or with the network as back-up capacity. The systems can yield electrical energy for industrial use at less than 100 mills/kWh, a cost that is competitive with the rate that small industrial users often paid in 1980, which was between 60 and 90 mills/kWh. In Table V we present the costs for systems with rated capacities from 1 to 10 MW_e and capacity factors of 0.7 and 0.4 which will be used by utilities to inject electricity to the network . Sensitivity studies indicate that if concentrator costs are reduced and engine efficiency increased, a busbar energy cost as low as 75 mills/kWh could be achieved. These concentrator and engine developments are beyond those considered likely by 1990 in that study and would require vigorous component and system development.

As mentioned in the paper[25]), because capital markets of utilities are under pressure to support expansions, it is critical that solar thermal power systems, while providing low busbar energy costs, do not exceed acceptable levels of capital cost in order to be able to compete for that capital.

Acknowledgement

I express my appreciation to Dr. Walter Scheuer for critically reading the manuscript and contributing to improvement of its content.

The original report was typed by Susana Lires to whom I express my gratitude.

TABLE I

APPLICATION OF SOLAR PROCESS HEAT IN INDUSTRIAL PROCESSES

EXAMPLES OF SYSTEMS IN OPERATION OR IN CONSTRUCTION

COMPANY AND LOCATION	APPLICATIONS	COLLECTOR DATA			STATUS
		TYPE	PROCESS TEMP. °C	FIELD SIZE m²	
CAMPBELL SOUP CO. SACRAMENTO, CALIFORNIA, U.S A.	CAN WASHING	P.T.	80 - 90	680	OPERAT 11/77
YORK BUILDING PRODUCTS INC. HARRISBURG, PENNSYLVANIA, U.S.A	CONCRETE-BLOCK CURING	M.C.R.M.	80	860	OPERAT 9/78
WEST. POINT-PEPPERELL INC. FAIRFAX , ALABAMA , U.S.A.	TEXTIL DRYING	P.T.	160	700	OPERAT 12/78
HOME LAUNDRY PASADENA, CALIFORNIA, U.S.A.	LAUNDRY PROCESSING	P.T.	130	600	OPERAT 9/78
DOW CHEMICAL CO. DALTON, GEORGIA, U.S.A.	LATEX MANUFACTURING	P.T.	185	920	OPERAT 11/81
BLEYLE TEXTILE SHENANDOAH, GEORGIA, U.S.A.	STEAM AND ELECTRICITY (400 KWE)	P.D.	400	4,500	CONSTR OR OPERAT 1982
SOUTHERN UNION CO. HOBBS, NEW MEXICO, U.S.A.	PRODUCE REFINERY MAIN STEAM	P.T.	190	910	CONSTR
ORE-IDA FOODS CO. ONTARIO, OREGON , U.S.A.	STEAM FOR POTATOE FRYING	P.T.	214	890	OPERAT 1980
LONE STAR BREWING CO. SAN ANTONIO, TEXAS, U.S.A.	PROCESS STEAM FOR BREWERY	P.T.	178	880	CONSTR
JOHNSON AND JOHNSON SHERMAN, TEXAS, U.S.A.	GAUZE BLEACHING	P.T.	175	1,070	OPERAT 1/80
RAM, DAIRY FACTORIA LACTARIA CASTELLANA ALCORCON, MADRID, SPAIN	PRESTERILIZATION OF MILK	P.T.	150	580	OPERAT 6/81
CONSERVAS ESPAÑOLAS S.A. SPAIN	STERILIZATION OF CONSERVE MEAT	P.T.	170	1,120	CONSTR
THEMIS TARCASONNE, FRANCE	MELTING OF STORAGE SALTS	P.D.	320	825	OPERAT TEST

P.T : Parabolic Trough: M.C.R.M.: Multiple Concave Rotating Mirror .
P.D.: Parabolic Dish.

From Refs. 16-18.

TABLE II

SOLAR THERMAL IRRIGATION SYSTEMS

EXAMPLES OF SYSTEMS IN OPERATION

LOCATION	POWER	COLLECTOR DATA			STATUS
		TYPE	FIELD SIZE m^2	OUTLET TEMP. °C	
WILLARD ALBUQUERQUE NEW MEXICO U.S.A.	19 kW	PARABOLIC TROUGH	625	216	OPERATION
GILA BEND ARIZONA U.S.A.	36 kW_e	PARABOLIC TROUGH	550		OPERATION 77
COOLIDGE ARIZONA U.S.A.	150 kW_e	PARABOLIC TROUGH	2,130	290	OPERATION 10 / 79

TABLE III

APPLICATION OF PHOTOTHERMAL CONVERSION OF SOLAR ENERGY INTO ELECTRICITY

EXAMPLES OF SYSTEMS IN OPERATION OR IN CONSTRUCTION

Location	Power	Collector Data			Status
		Type	Outlet Temp. °C	Field size m^2	
White Cliffs - Australia	25kWe	P.D.		275	Operat. 81
Perth - Australia	35kWe	P.T.	300	300	Operat. 82
Meekatharra - Australia	50kWe	P.T. two axes	300	960	Constr.
Corsica - France	100kWe	F.C.F.M.	250	1,176	Constr. and Test
Kuwait	100kWe	P.D.	400	1,000	Constr. and Test
Almeria - Spain (IAE)	500kWe 500kWe	P.T. one axis two axes C.T.	295 530	2,674 2,688 3,655	Operat. 9/81
Nio - Japan	1MWe 1MWe	C.T. C.S.L.F.	249 530	12,912 11,160	Operat. Test 10/81
EURELIOS - Sicilia - Italia (EEC)	1MWe	C.T.	510	6,216	Operat. 5/81
CESA I - Almeria - Spain	1MWe	C.T.	520	11,400	Constr.
THEMIS - Targasonne - France	2,5MWe	C.T.	450	10,740	Operat. 3/82
SOLAR ONE - Barstow-Ca.-U.S.A.	10MWe	C.T.	510	72,700	Operat. Test 4/82

P.D.: Parabolic Dish; P.T.: Parabolic Trough; C.T.: Central Tower;
F.C.F.M.: Fixed Concentrator Faceted Mirror .
C.S.L.F.: Central System Linear Focus.

TABLE IV

CAPITAL AND ELECTRICITY COST FOR INDUSTRIAL SYSTEMS.

POWER (MWE)	CAPACITY FACTOR	CAPITAL COST U$ / KWE	BUSBAR ENERGY COST MILLS / KW_EH
0,1	0.7	3380	92
	0.4	2100	93
0,3	0.7	3100	88
	0.4	1700	90
1,0	0.7	2950	85
	0.4	1600	84

TABLE V

CAPITAL AND ELECTRICITY COST FOR UTILITY SYSTEMS

POWER (MWE)	CAPACITY FACTOR	CAPITAL COST U$ / KWE	BUSBAR ENERGY COST MILL / KW_EH
1	0.7	3600	104
	0.4	2200	111
5	0.7	3340	98
	0.4	2000	101
10	0.7	3280	96
	0.4	1950	99

COST FOR 1990 IN 1978 DOLLARS.

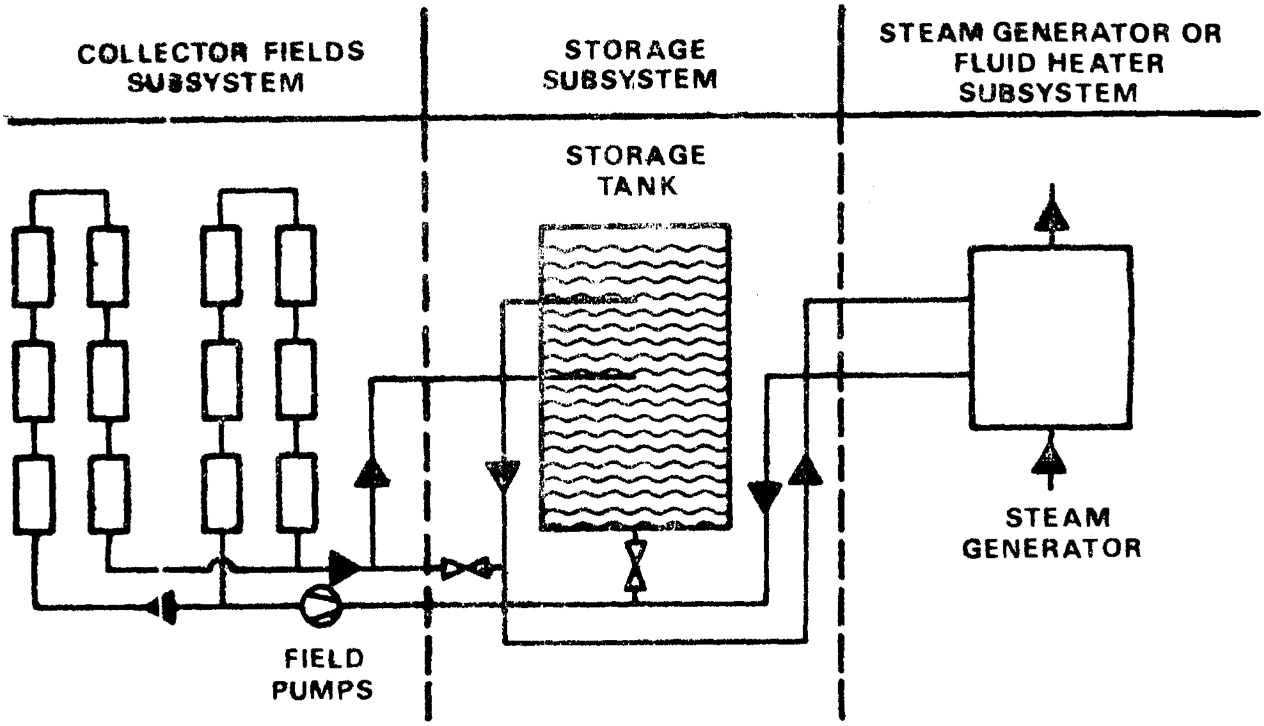


Fig. 1: Major subsystems that form, in general, a solar energy photothermal conversion system.

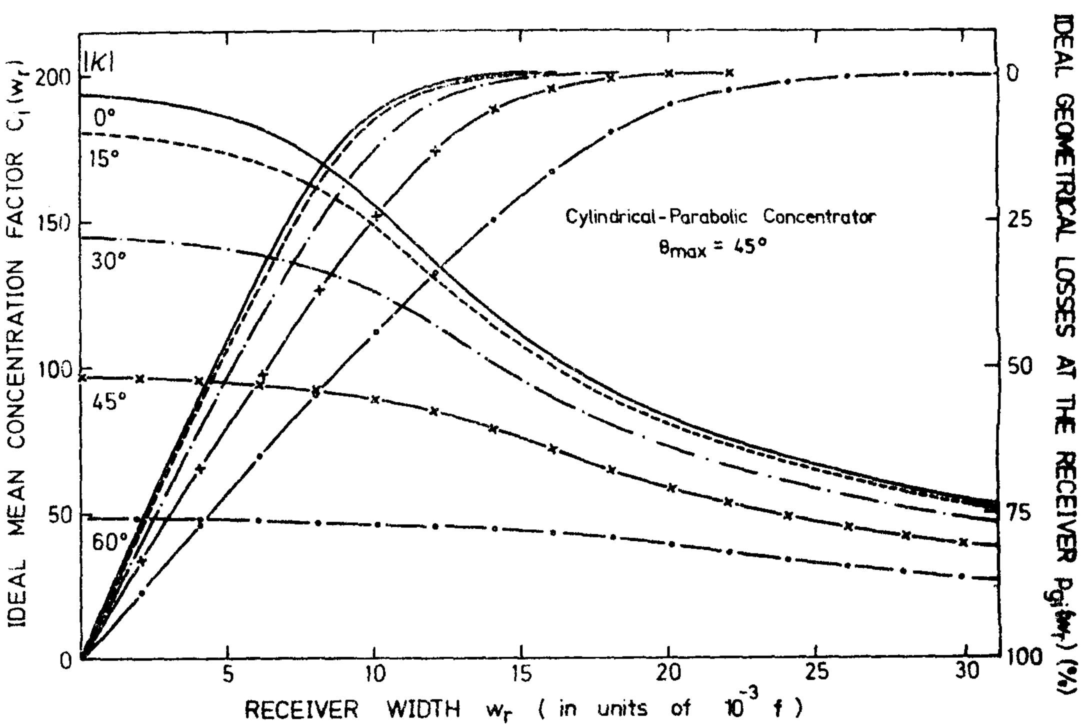
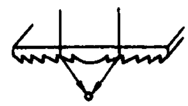
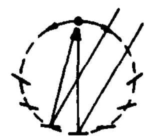
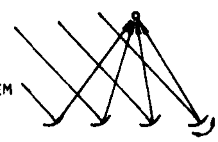
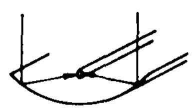
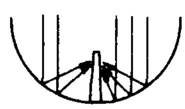
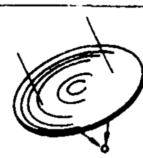
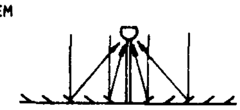


Fig. 2: Mean concentration factor and geometrical losses in the receiver as a function of its width for a cylindrical-parabolic concentrator with flat receiver. The focal length is indicate by f. From Ref. 1.

MOVEMENT TYPE	COLLECTOR TYPE		CONVERSION TYPE
SEASONAL ADJUSTMENT	COMPOUND PARABOLIC CONCENTRATOR (CPC) $C_G = 1.5 - 10$		DISTRIBUTED
MOVEMENT AROUND TWO AXES (LINEAR FOCUS)	FRESNEL LENS $C_G = 10 - 40$		
MOVEMENT AROUND ONE AXIS (LINEAR FOCUS)	FIXED CONCENTRATOR WITH FACETED MIRROR $C_G = 20 - 60$		
	MULTIPLE CONCAVE ROTATING MIRRORS CENTRAL RECEIVER SYSTEM WITH LINEAR FOCUS $C_G \simeq 20 - 80$		CENTRALIZED
	PARABOLIC TROUGH* $C_G = 20 - 100$		DISTRIBUTED
MOVEMENT AROUND TWO AXES (POINT CONCENTRATORS)	SPHERICAL BOWL $C_G = 100 - 300$		
	FRESNEL LENS $C_G = 100 - 1000$		
	CENTRAL RECEIVER SYSTEM OR CENTRAL TOWER $C_G = 100 - 1,000$		CENTRALIZED
	PARABOLIC DISH $C_G = 100 - 5,000$		DISTRIBUTED

(*) Some times used with two axes movement

Fig. 3: Generic types of concentrators.

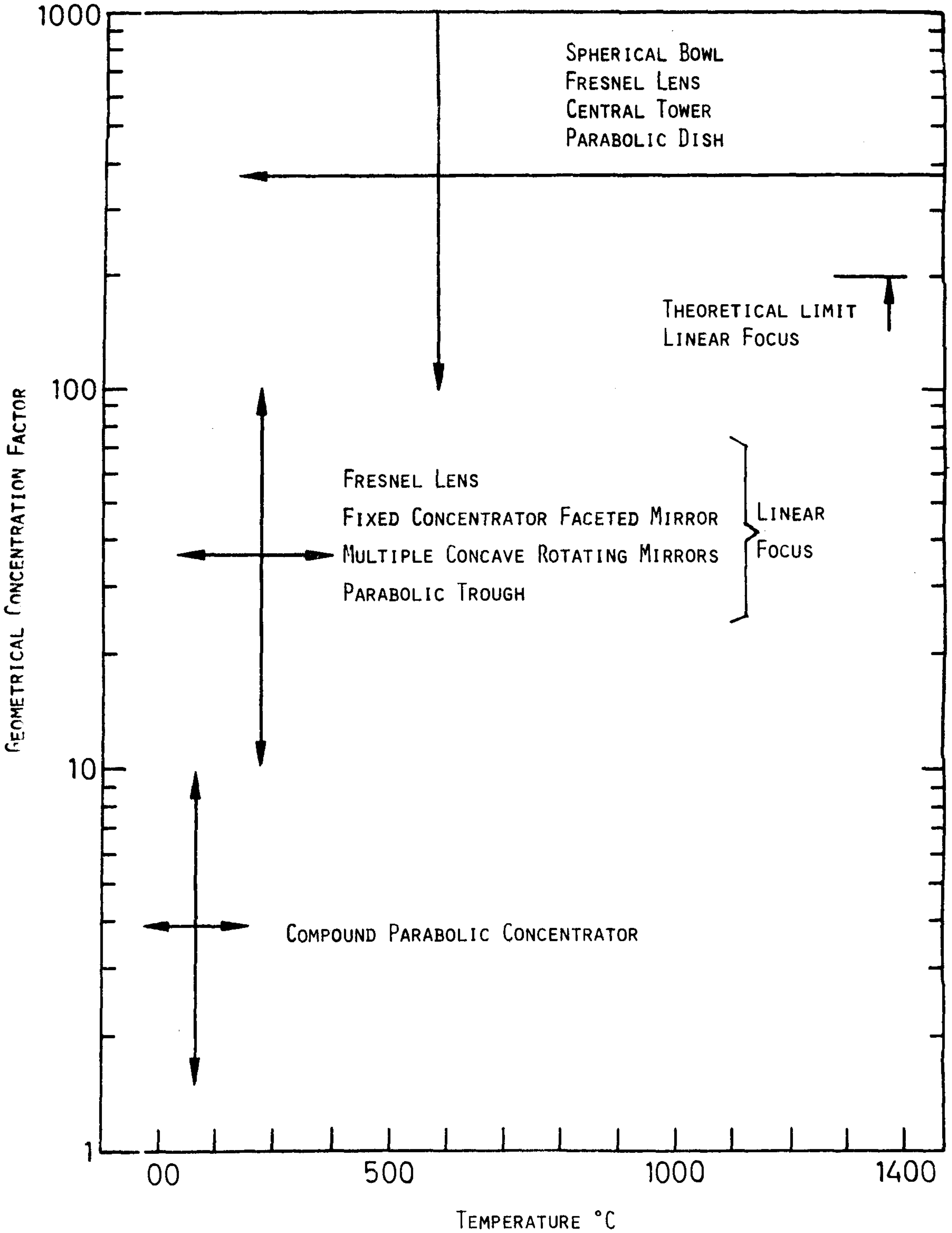


Fig. 4: Concentration factor versus temperature for several collectors.

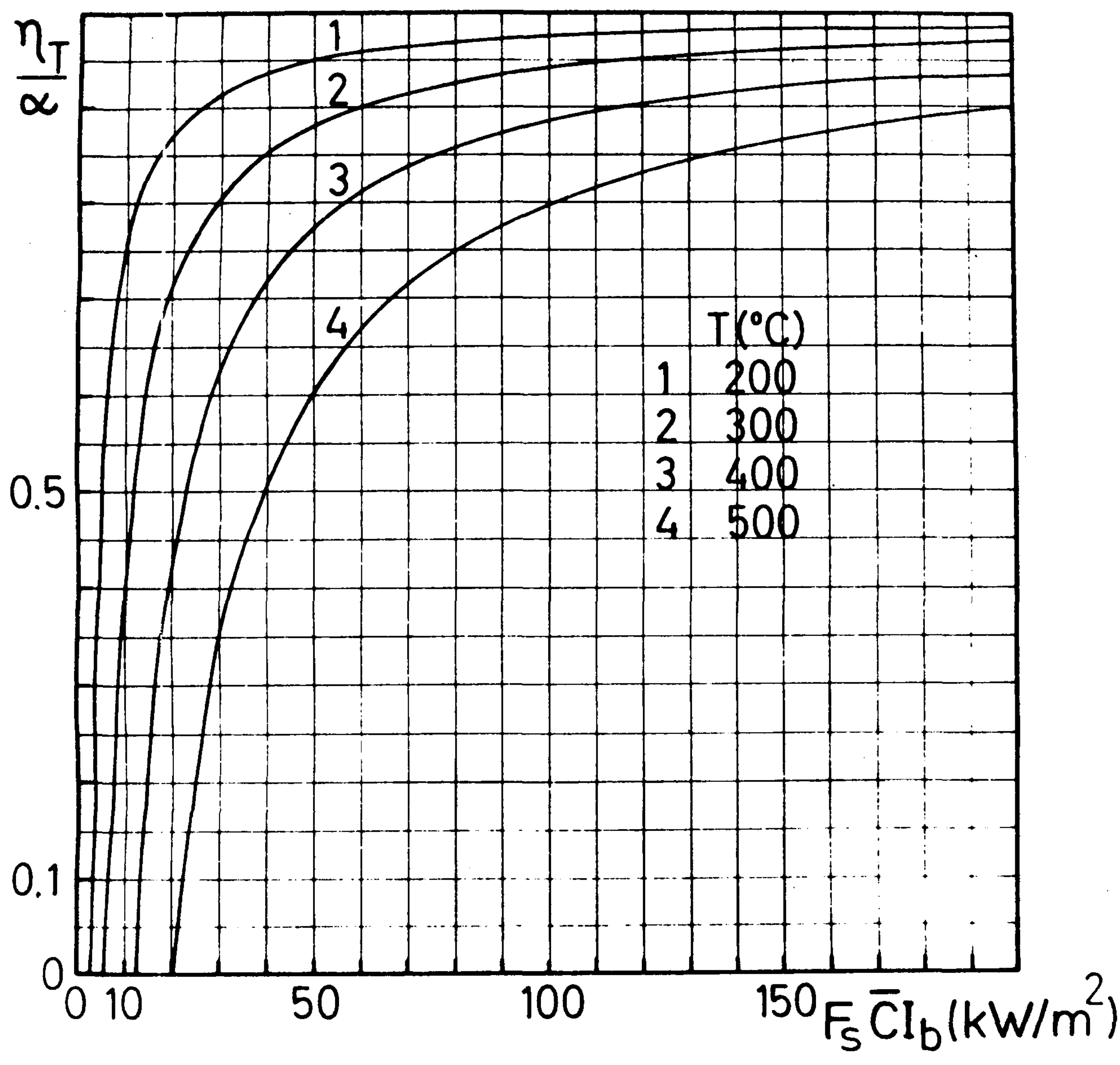
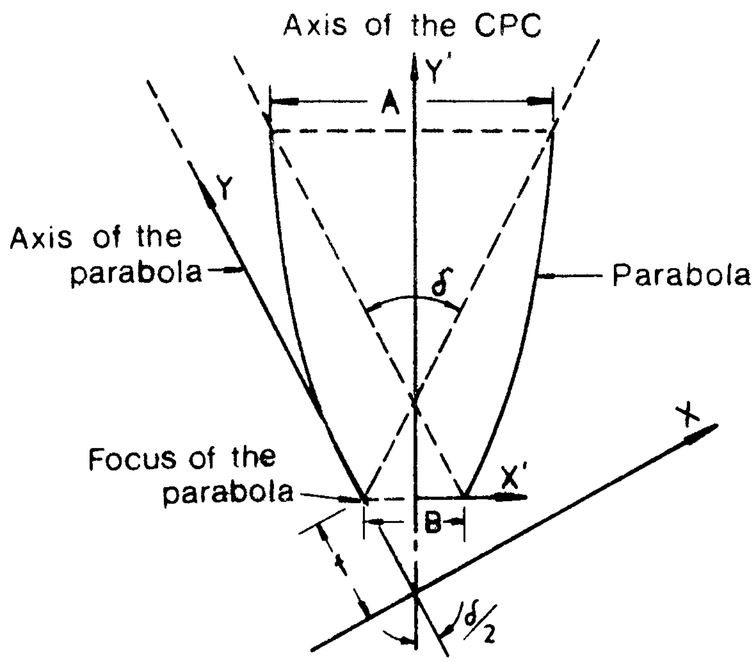


Fig. 5: Thermal efficiency divided by the absorptance as a function of the product of selective factor (Fs), mean concentration factor ($\bar{C}$) and direct solar radiation (I_b) for different temperatures.



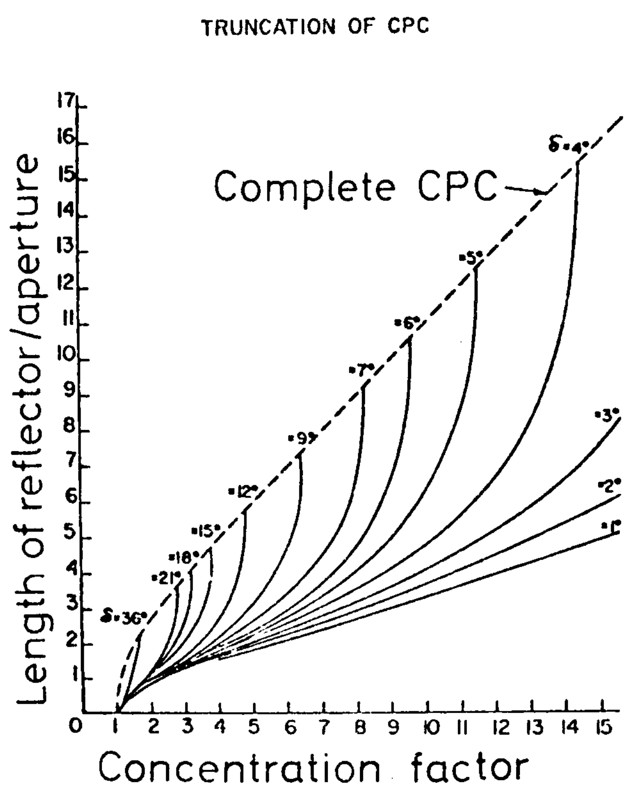


Fig. 6: Upper part: Profile of compound parabolic concentrator. A is the aperture of the concentrator, B the width of the receptor and δ the acceptance angle. Lower part: Concentration factor of the δ compound parabolic concentrator as a function of the ratio between the length of the reflectors and the aperture, for different values of δ/2. From Ref. 4.

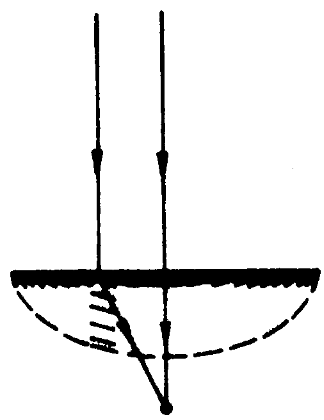


Fig. 7: Diagram of a Fresnel lens.

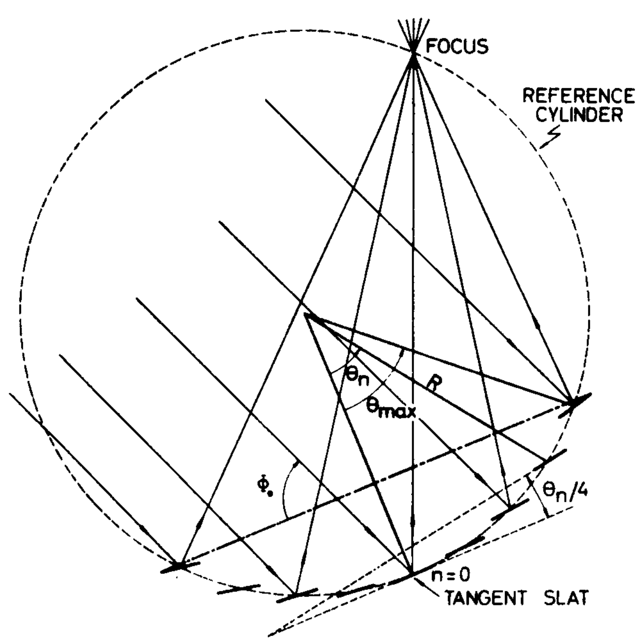


Fig. 8: Fixed concentrator with faceted mirror.

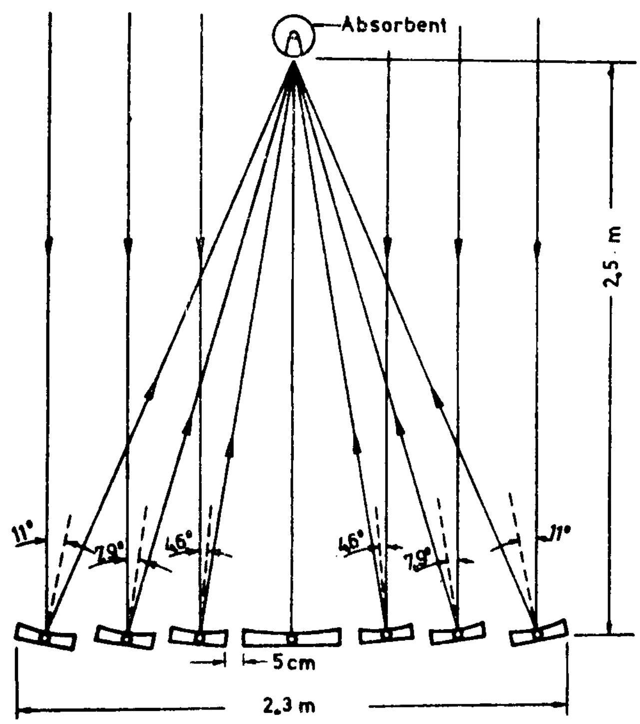


Fig. 9: Concentrator with multiple concave rotating mirrors. All of the mirrors have their rotating axes in one plane. In the figure is indicated, for normal incidence, the inclination of each mirror needed to have a sharp focus. When rotating all mirrors at the same angular velocity in order to track the apparent movement of the Sun, the fixed sharp focus is maintained.

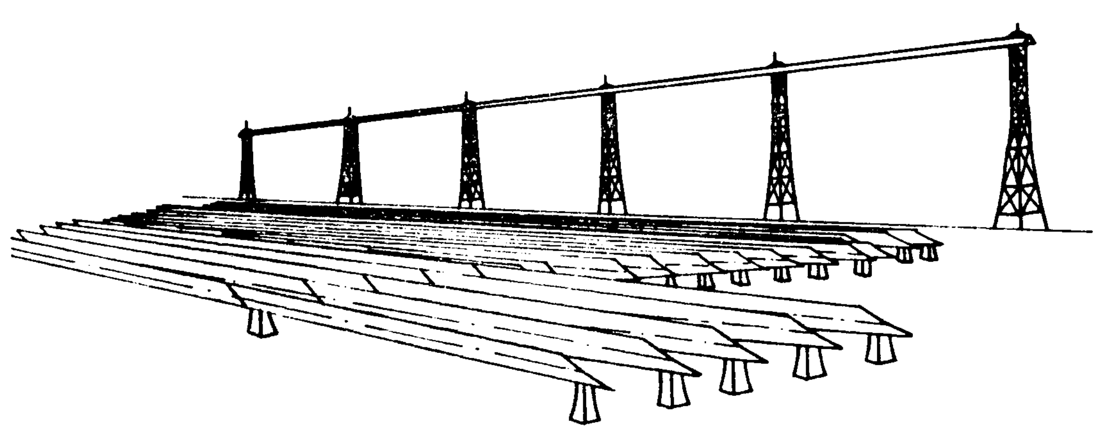


Fig. 10: System of central receiver with linear focus having a receiver at one end of the field of mirrors. The receiver and the rows of mirrors are oriented East to West.

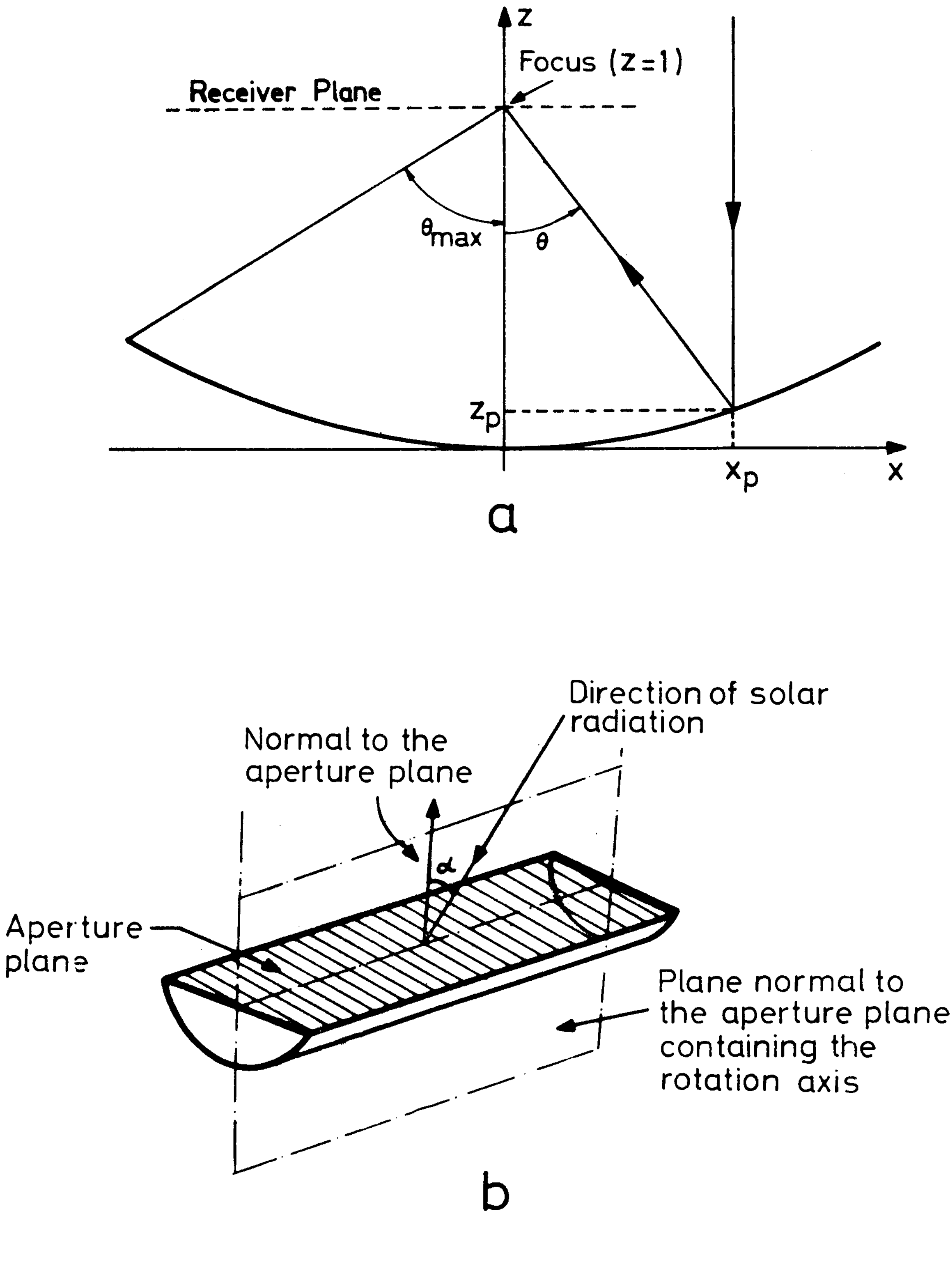


Fig. 11: Parabolic-cylindrical or parabolic trough concentrator.

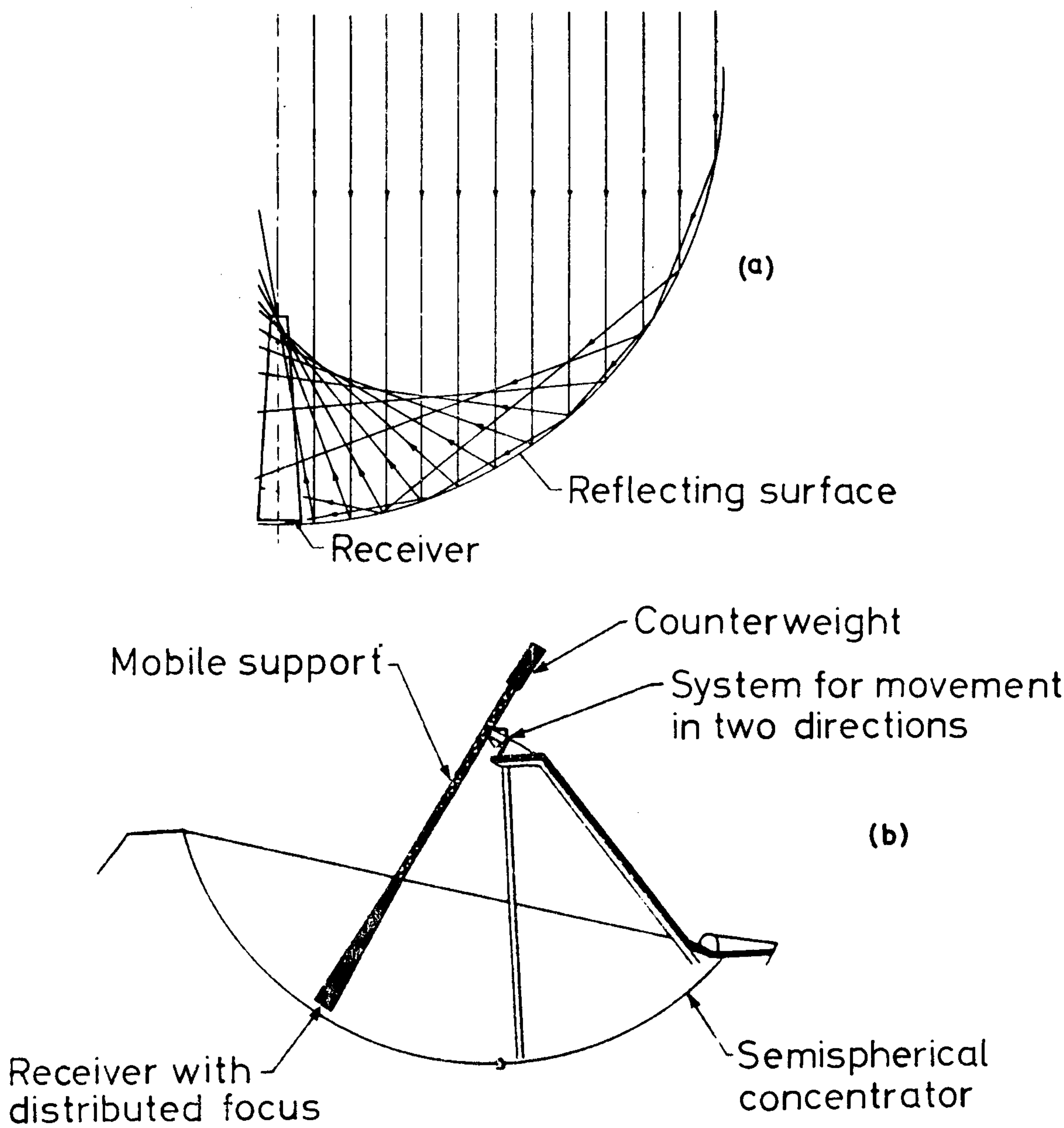


Fig. 12: Semispherical fixed concentrator (Spherical bowl).
(a) Focal distribution
(b) Schematic representation

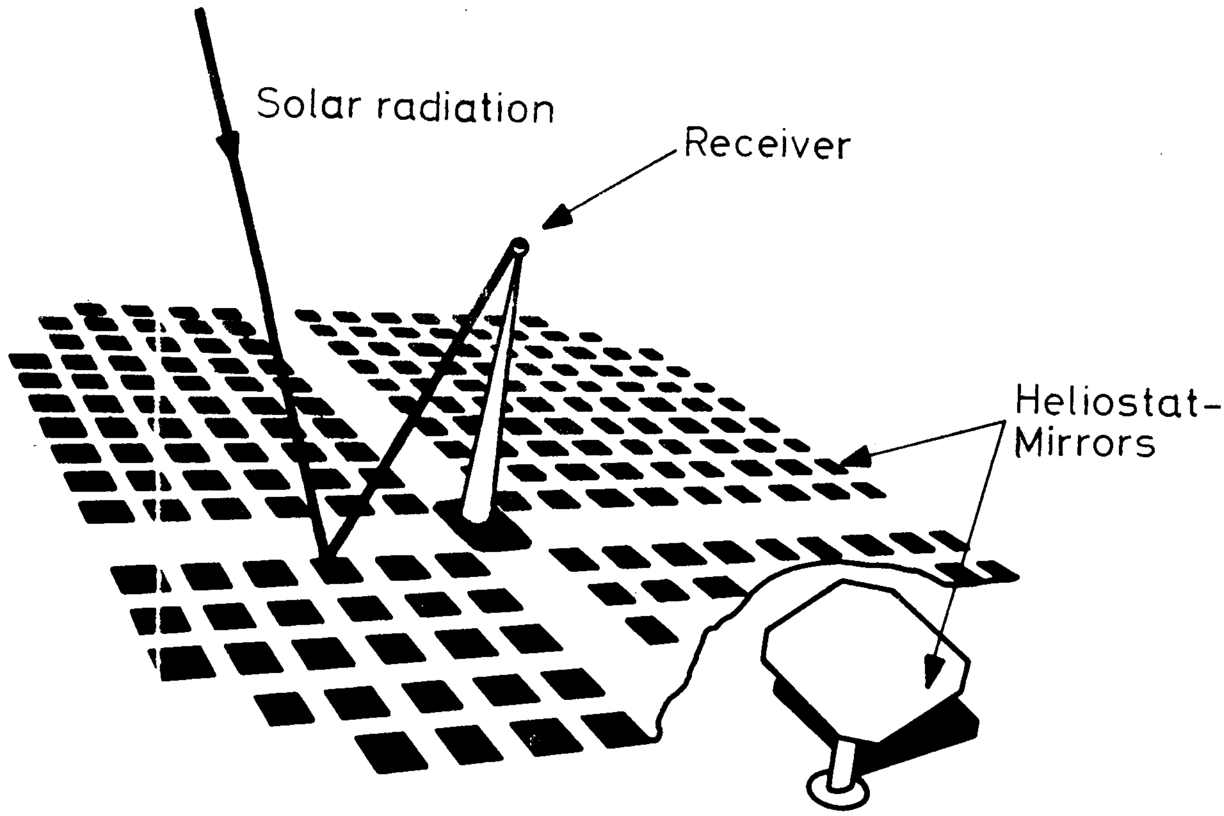


Fig. 13: Diagram of central tower.

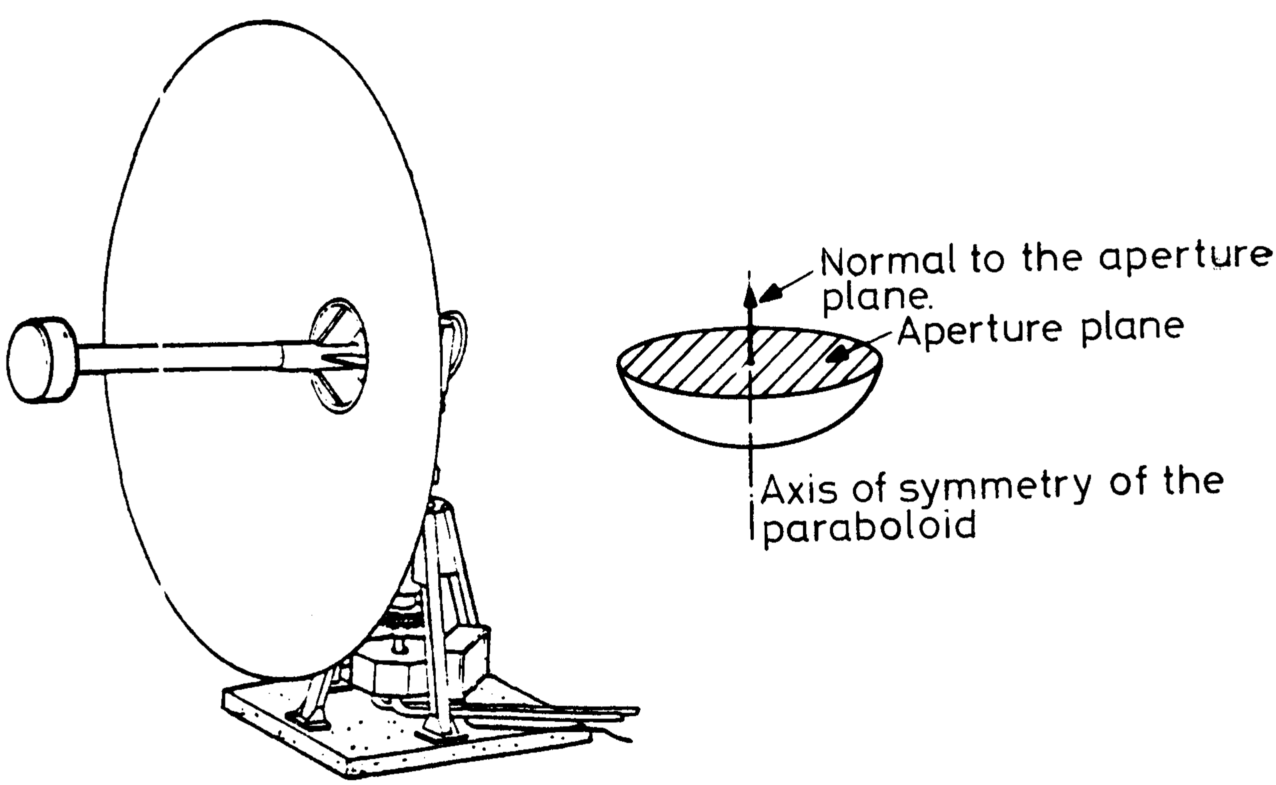


Fig. 14: Diagram of a parabolic dish concentrator.

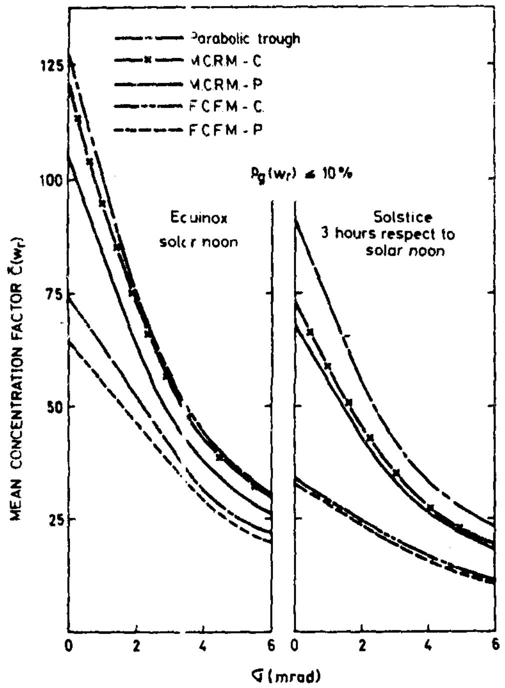


Fig. 15: Example of the mean value of the theoretical concentration factor $\bar{C}(w_r)$ as a function of the standard deviation of the error of the normal to each mirror surface element respect to the ideal position according to a Gaussian distribution.

M.C.R.M.-C: Concentrator with Multiple Concave Rotating Mirrors with rotation axes on a cylinder.

C.M.R.M.-P: Multiple Concave Rotating Mirrors with rotation axes on a plane.

F.C.F.M.-C: Fixed Concentrator with Faceted Mirror with cylindrical facets.

F.C.F.M.-P: Fixed Concentrator with Faceted Mirror with plane facets.

From Ref. 10.

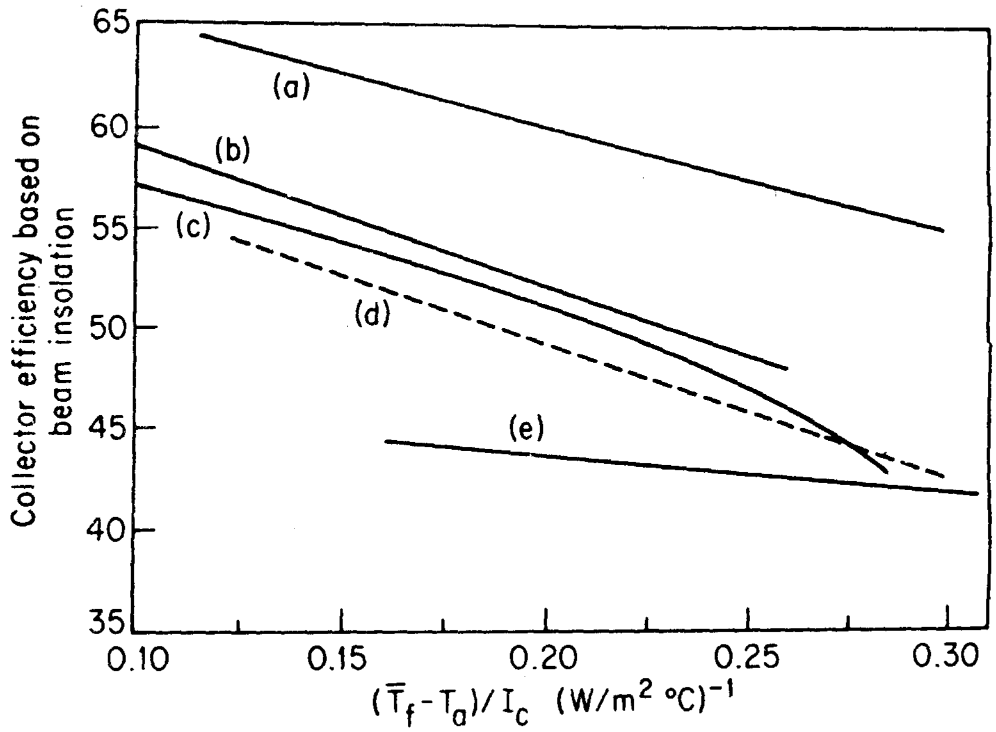
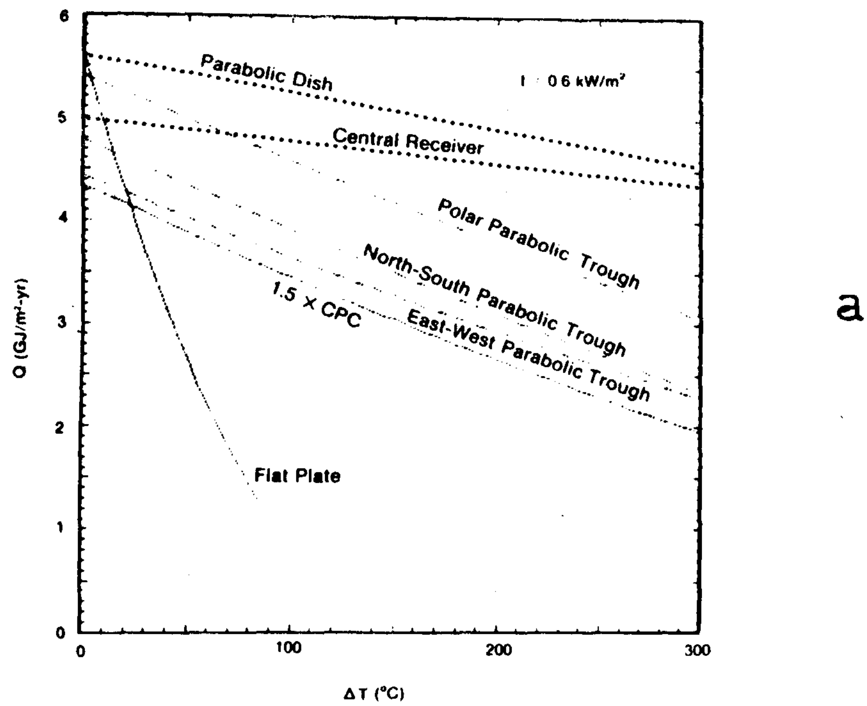


Fig. 16: Measured efficiency for five line-focus concentrators; $\bar{T}_f$ is the average fluid temperature, T_a the ambient temperature and I_c the component of beam radiation normal to the aperture area. a) Hexcel parabolic trough concentrator, $C_g = 67$; b) solar kinetic parabolic trough concentrator, $C_g = 41$; c) Mc Donnell-Douglas Fresnel lens, $C_g = 24$; d) Suntec multiple concave rotating mirrors, $C_g = 35$; e) General Atomic fixed concentrator with faceted mirror, $C_g = 43$, with C_g being the Geometrical Concentration Factor. All receivers use a black chrome selective surface. From Ref. 11.



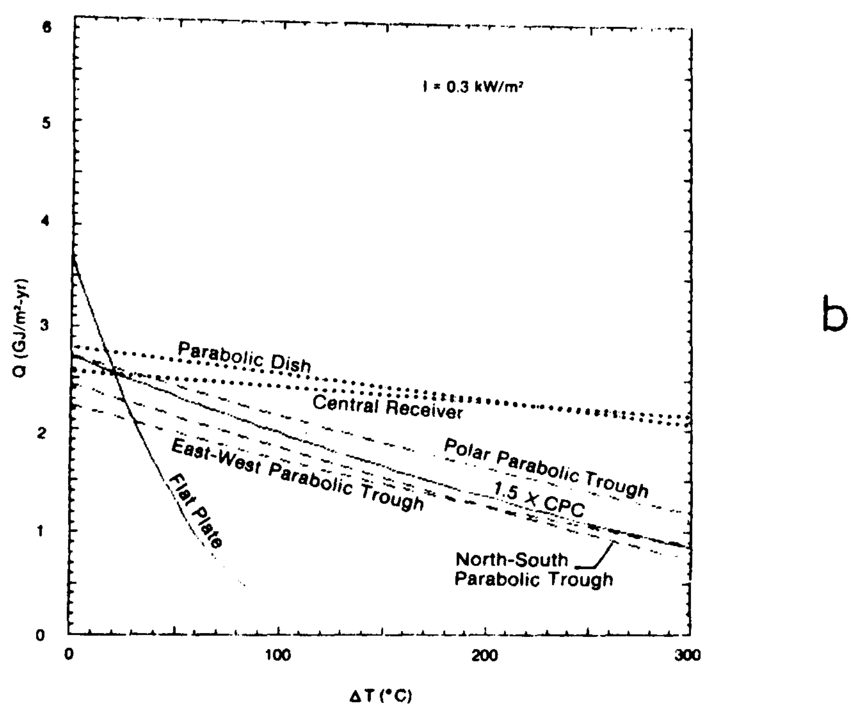


Fig. 17: Yearly collectible energy Q versus average difference between fluid temperature and ambient, for typical collectors: a) average daytime direct normal irradiance I = 0.6 kW/m^2; b) I = 0.3 kW/m^2. From Ref. 13.

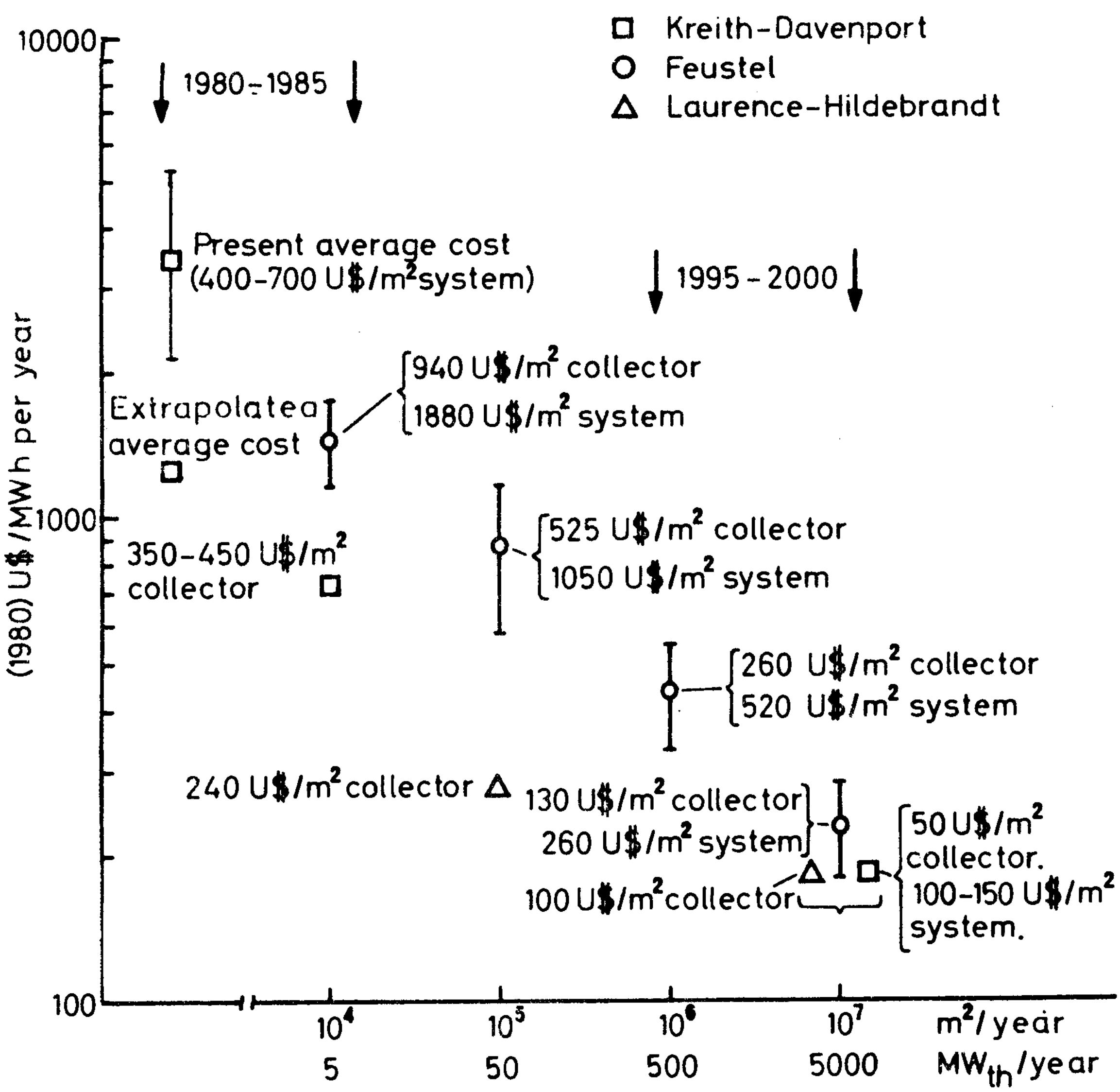


Fig. 18: Energy capacity cost, in 1980 dollars per MWh-year versus the annual production rate of collectors (m^2 per year) and the nominal power in MWh installed per year. From Refs. 16, 22 and 23.

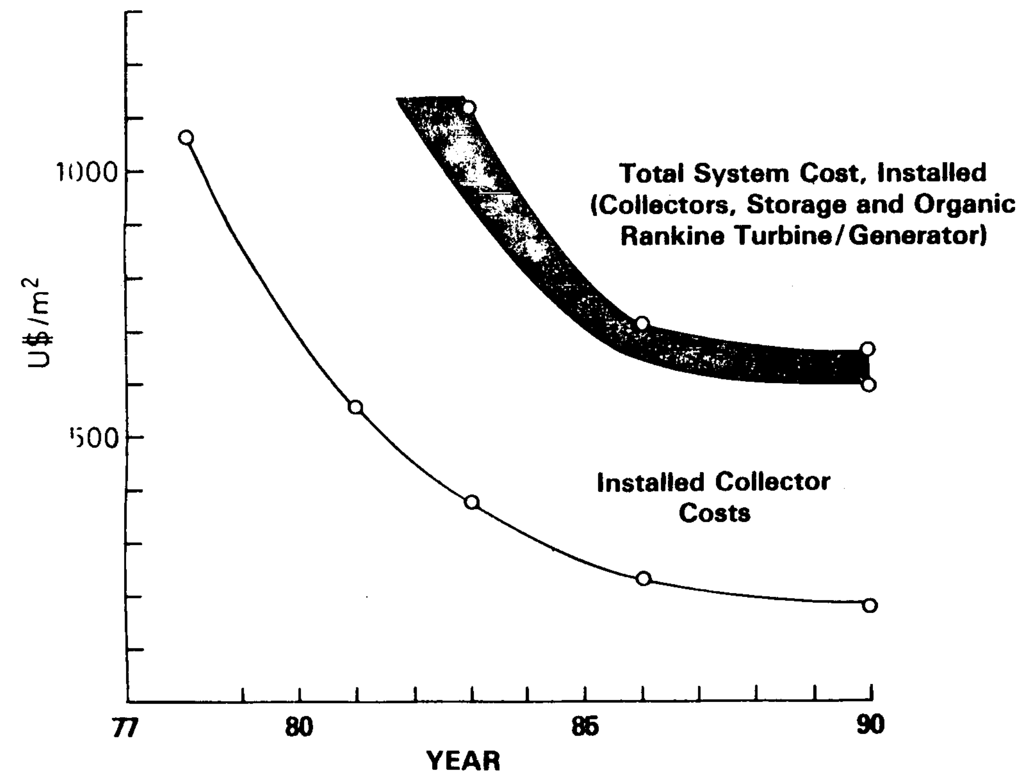


Fig. 19: Installed Collector and Total System Costs Projections for Solar Thermal Irrigation. From Ref. 24.

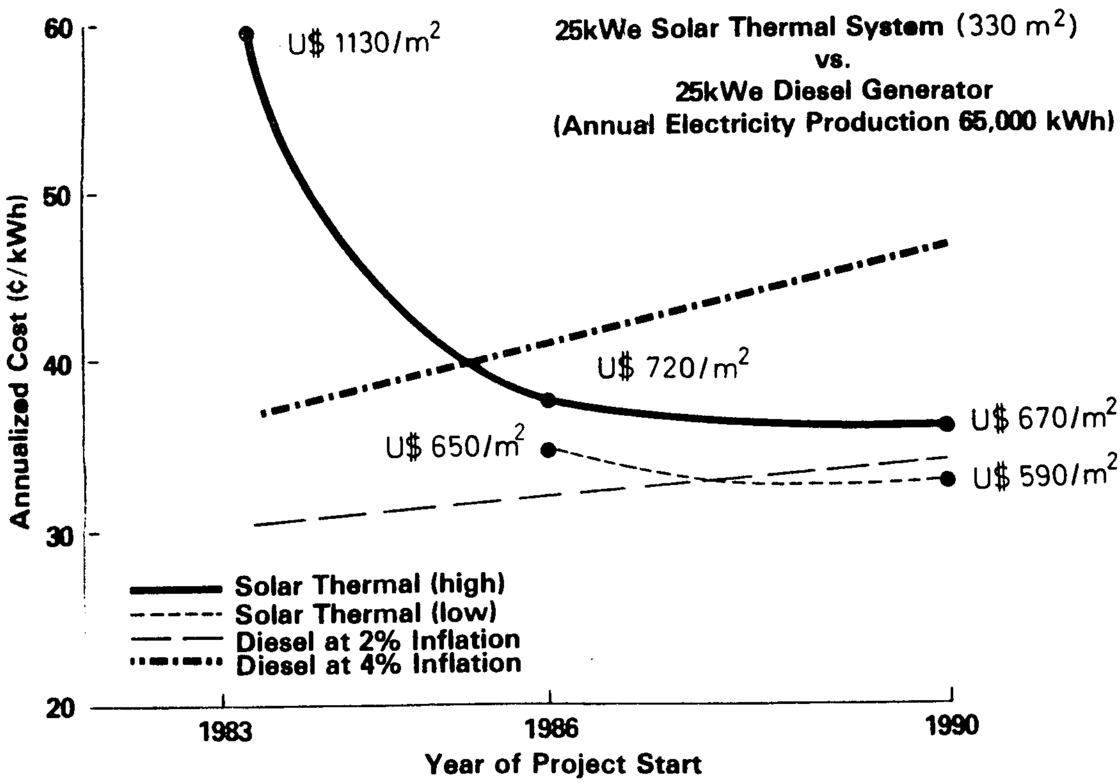


Fig. 20: Anualized Costs of Solar Thermal and Diesel Generator. From Ref. 24.

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