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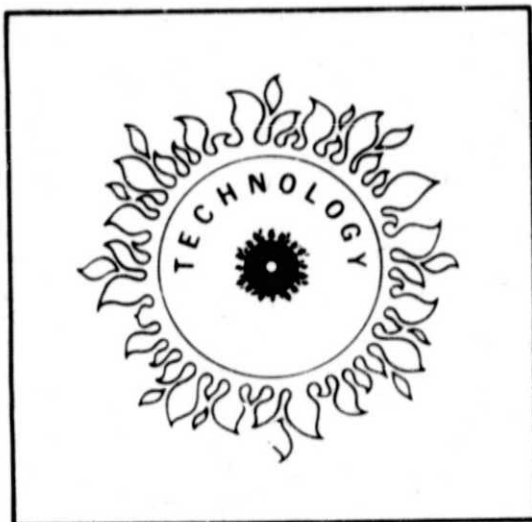
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The Parabolic Concentrating Collector

A Tutorial

V. C. Truscello



Prepared for

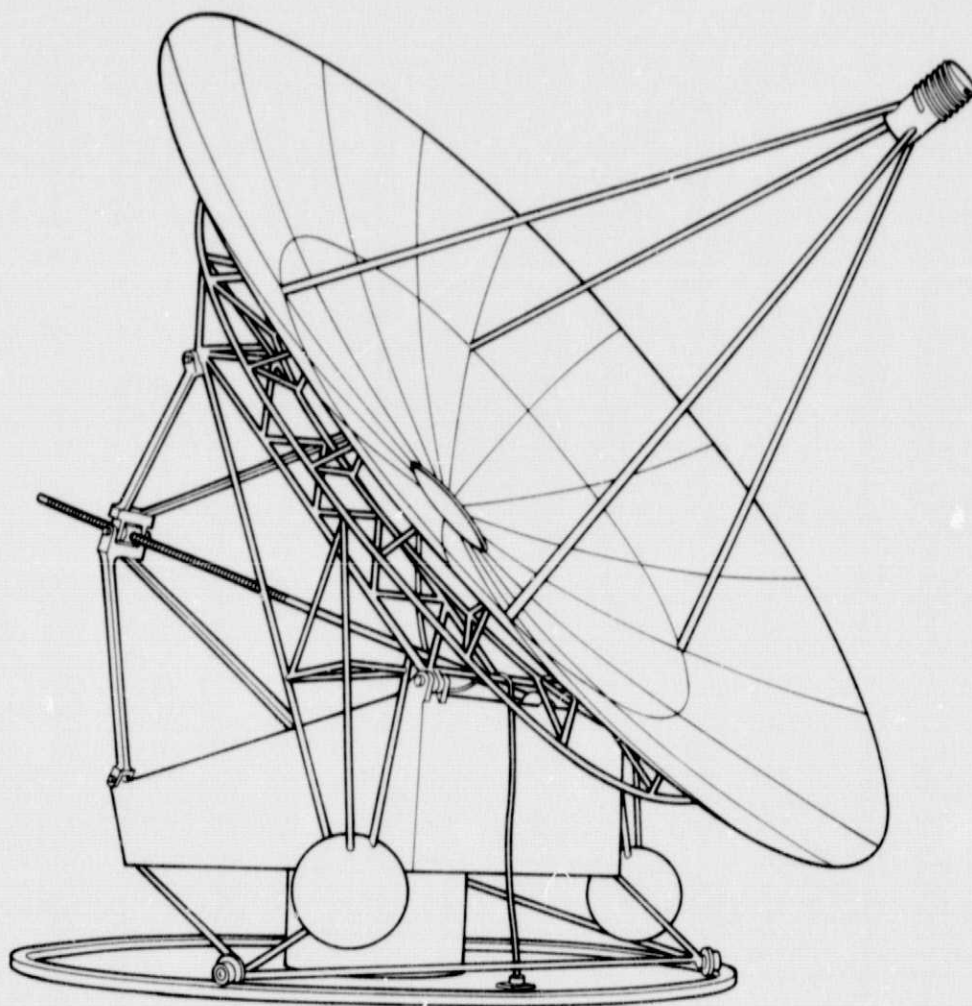
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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
(JPL PUBLICATION 79-7)



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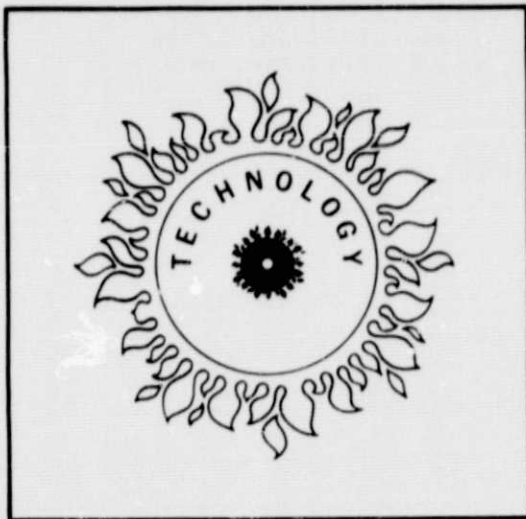


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Most of the technical information presented in this paper was compiled from papers and memos written by members of my staff over the past year or two.

The author's main contribution has been in reformatting the information in layman's language as a tutorial rather than a rigorous analytical presentation. Some liberties in interpretation were taken in order to accomplish this objective.

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ABSTRACT

This paper presents a tutorial overview of point-focusing parabolic collectors. Optical and thermal characteristics of such collectors are discussed. Data representing typical achievable collector efficiencies are presented and the importance of balancing collector cost with concentrator quality is argued through the development of a figure of merit for the collector. The impact of receiver temperature on performance is assessed and the general observation made that temperatures much in excess of 1500-2000°F can actually result in decreased performance. Various types of two-axis tracking collectors are described, including the standard parabolic deep dish, Cassegrainian and Fresnel, as well as two forms of fixed mirrors with articulating receivers. The present DOE program to develop these devices is briefly discussed, as are present and projected costs for these collectors. Pricing information is presented for the only known commercial design available on the open market.

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I. Introduction

The point-focusing parabolic concentrator is considered by many as the ultimate form of solar energy collector. It has such attractive features as modularity and high collection efficiency and can provide high-quality thermal energy for conversion into electricity by a variety of large and small heat engines operating over a wide range of temperatures. If desired, temperatures of 2000-3000°F are easily achieved, although most electric systems optimize at temperatures in the 1500-2000°F range. Because of their high temperature potential, it is possible to additionally use these devices as a source of heat for a variety of process heat and fuel and chemical applications.

An early version of a point-focusing parabolic collector was actually built in 1901 and was used for irrigation during the early years in California. However, the availability of cheap fuels curtailed subsequent utilization.

The purpose of this paper is to present a tutorial overview of point-focusing parabolic collectors. In the first section, the optical and thermal characteristics of such collectors are discussed in some detail. Data representing typical achievable collector efficiencies are presented, and the importance of balancing collector cost with concentrator quality is argued through the development of a figure of merit for the collector. The impact of receiver temperature on performance is assessed and the general observation made that temperatures much in excess of 1500-2000°F can actually result in decreased performance. In the second section, various types of two-axis tracking collectors are described, including the standard parabolic deep dish, Cassegrainian and Fresnel, as well as two forms of fixed mirror collectors with articulating receivers. In the third section, the present DOE program to develop these devices is briefly discussed. Finally, the last section discusses present and projected costs of these collectors. Pricing information is presented for the only known (to the author) commercial design available on the open market.

II. Analytical Considerations

A. Concentrator Optics

In its simplest form, the point-focusing parabolic concentrating collector intercepts solar energy and redirects it to a relatively small focal area as shown in Figure 1. With perfect optics and a point source of light, the focal area would, in fact, be a single point. The sun, however, has a finite diameter and, on a yearly average, subtends a half angle of about 4.6 milliradians (mrad), producing a somewhat enlarged focal point or image. Since a perfect parabolic concentrating surface does not exist, the image will be further enlarged due to misdirection of the light rays by misaligned surface elements caused by macroscopic surface waviness. The mirror quality (perfection of optics) can be statistically specified by both the circumferential and radial standard deviation of the surface normal. A surface error of $\sigma_s = 5$ mrad implies one standard deviation. Because of imperfect optics and the finiteness of the sun, additional enlargement of the sun's image occurs due to the relative location of the focal plane from the apex of the parabolic concentrator. This geometric effect is usually expressed in terms of the f/D ratio (i.e., the ratio of the focal length, f , and the diameter of the concentrator's aperture, D), or in terms of the rim angle (see Figure 1). The image becomes larger at large values of f/D (small rim angles) or at very small values of f/D (large rim angles). The optimum location, producing the smallest image size, occurs at an f/D value of about 0.6 (rim angles of about 45°) (Ref. 1). This optimum is not very sharp, and considerable departure from this value produces little enlargement of the solar image.

Another factor which is important in concentrator optics is the reflectivity of the surface. Not all of the energy that strikes the surface is reflected; some is absorbed. The fraction not absorbed is termed the total hemispherical reflectance. Unfortunately, not all of the energy reflected emerges at an angle demanded by perfect optics but, in fact, can

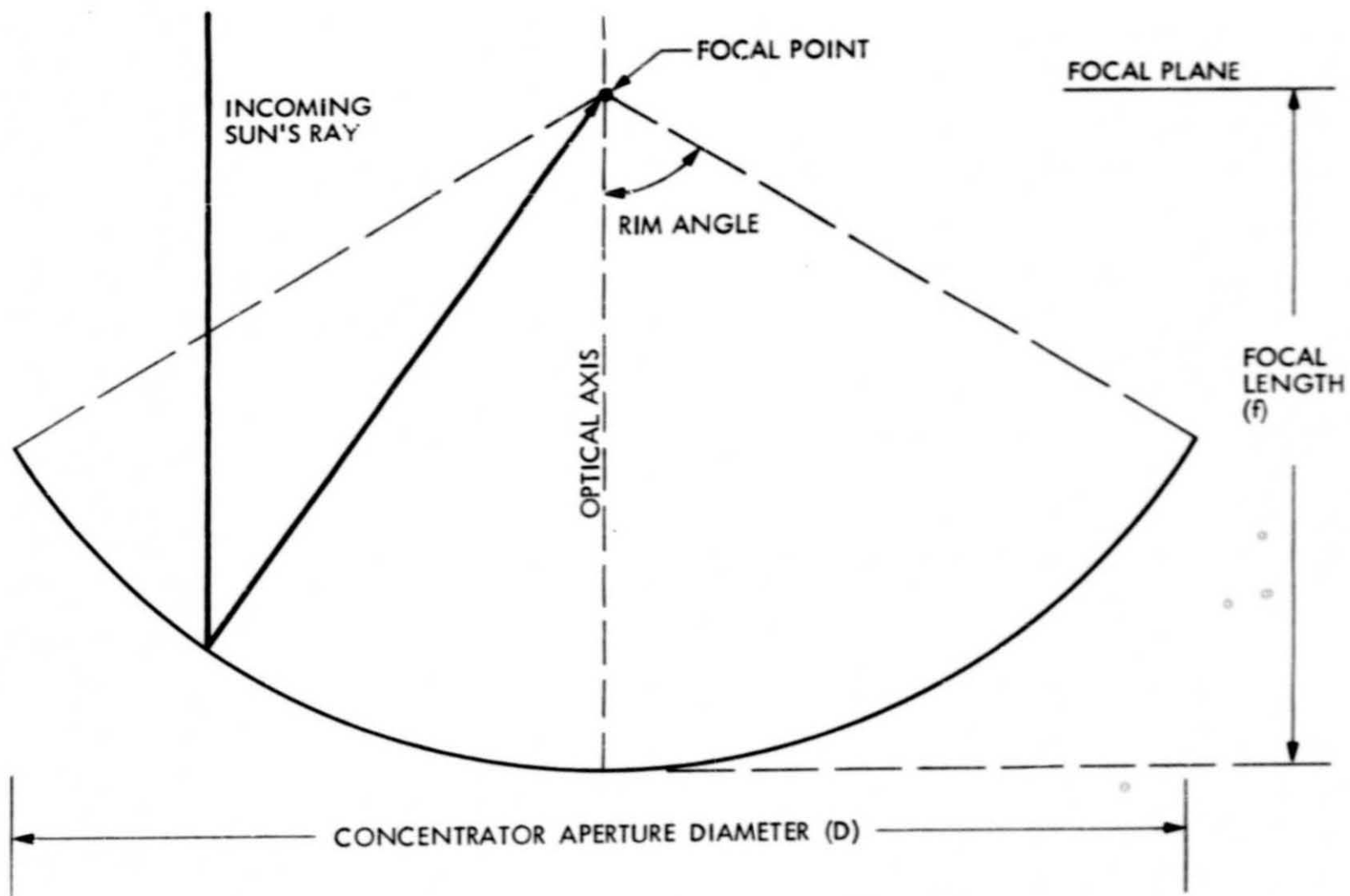
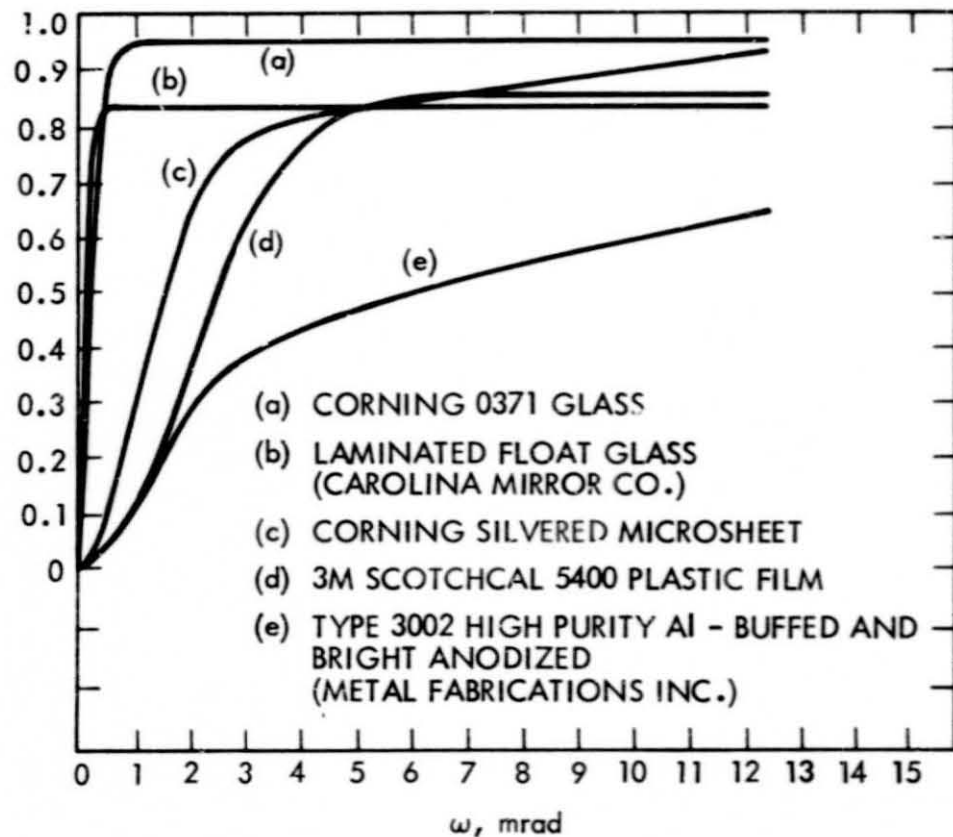
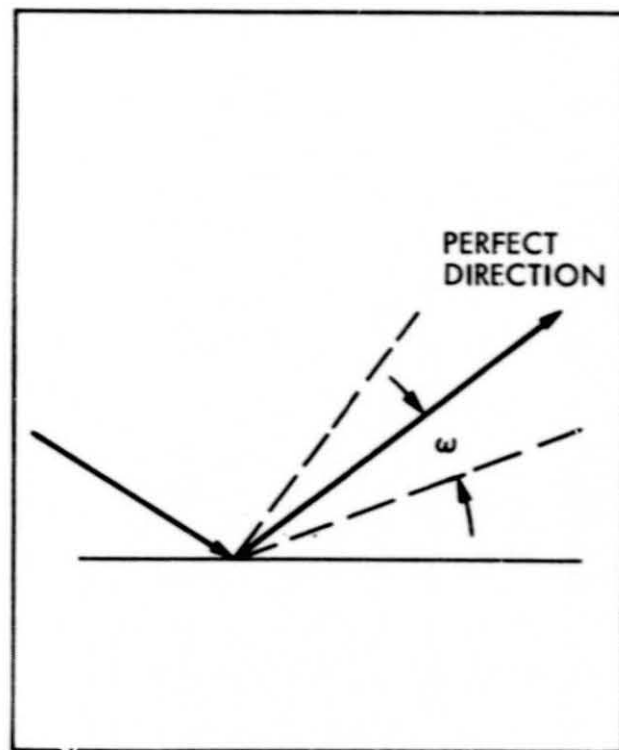


Figure 1. Concentrator Optics

be scattered at an angle considerably different than the perfect direction. This effect also adds to the enlargement of the image at the focal plane. A measure of this effect is shown for a number of different materials in Figure 2(a) taken from Reference 1. The curves indicate a rapid increase of reflectance to the asymptotic value (hemispherical reflectance) with increased spreading angle (ω). The spreading angle is defined as the deviation from the perfect direction (Figure 2(b)). Some materials, such as plastic films, reflect most of the energy within a rather large spreading angle (7-15 mrad) while materials like glass have very little spreading of the beam (i.e., less than 1 mrad). Clearly, the less the spreading, the smaller will be the solar image.

REFLECTED ENERGY CONTAINED IN OPTICAL CONE
ENERGY INCIDENCE

2(a)



2(b)

Figure 2. Reflectivity

B. Collector Efficiency

The importance of the size of the image produced by the reflecting parabolic surface is appreciated when one attempts to determine the collector efficiency defined as the ratio of energy absorbed by the receiver to the energy impinging the concentrator surface (see Figure 3). The efficiency can be defined by the relationship:

$$\eta_c = \frac{\text{energy absorbed by receiver}}{\text{energy impinging concentrator}} = \frac{\rho I_o A_c \phi \alpha_{\text{eff}} - Q_L}{I_o A_c}$$

where

ρ = total hemispherical reflectivity of concentrator surface

ϕ = the interception factor defined as the fraction of the energy reaching the focal plane which enters the receiver aperture

α_{eff} = the effective solar absorptance

Q_L = the thermal losses from the receiver (primarily due to reradiation from the receiver aperture)

I_o = the solar insolation

A_c = the concentrator aperture area

To maximize η_c for a given insolation and concentrator size one can decrease the value of Q_L which is dominated by the reradiation of energy from the receiver aperture. This can be accomplished by decreasing the receiver aperture area. However, decreasing this area impacts the amount of energy which can enter the receiver because of the finiteness of the sun's image produced by the concentrator. Clearly, one wants to make this image size as small as possible to get as much of the image into the receiver aperture. It has been found that for most cases the optimum aperture size is not that which allows all of the energy to enter; rather, an intercept factor of 95-98% (i.e., a 2-5% spillover) is optimum. Typical intercept factors versus receiver aperture radius is shown in Figure 4 (from Ref. 2) for two

$$\eta_c = \frac{\rho I_o A_c \phi \alpha_{eff} - Q_L}{I_o A_c}$$

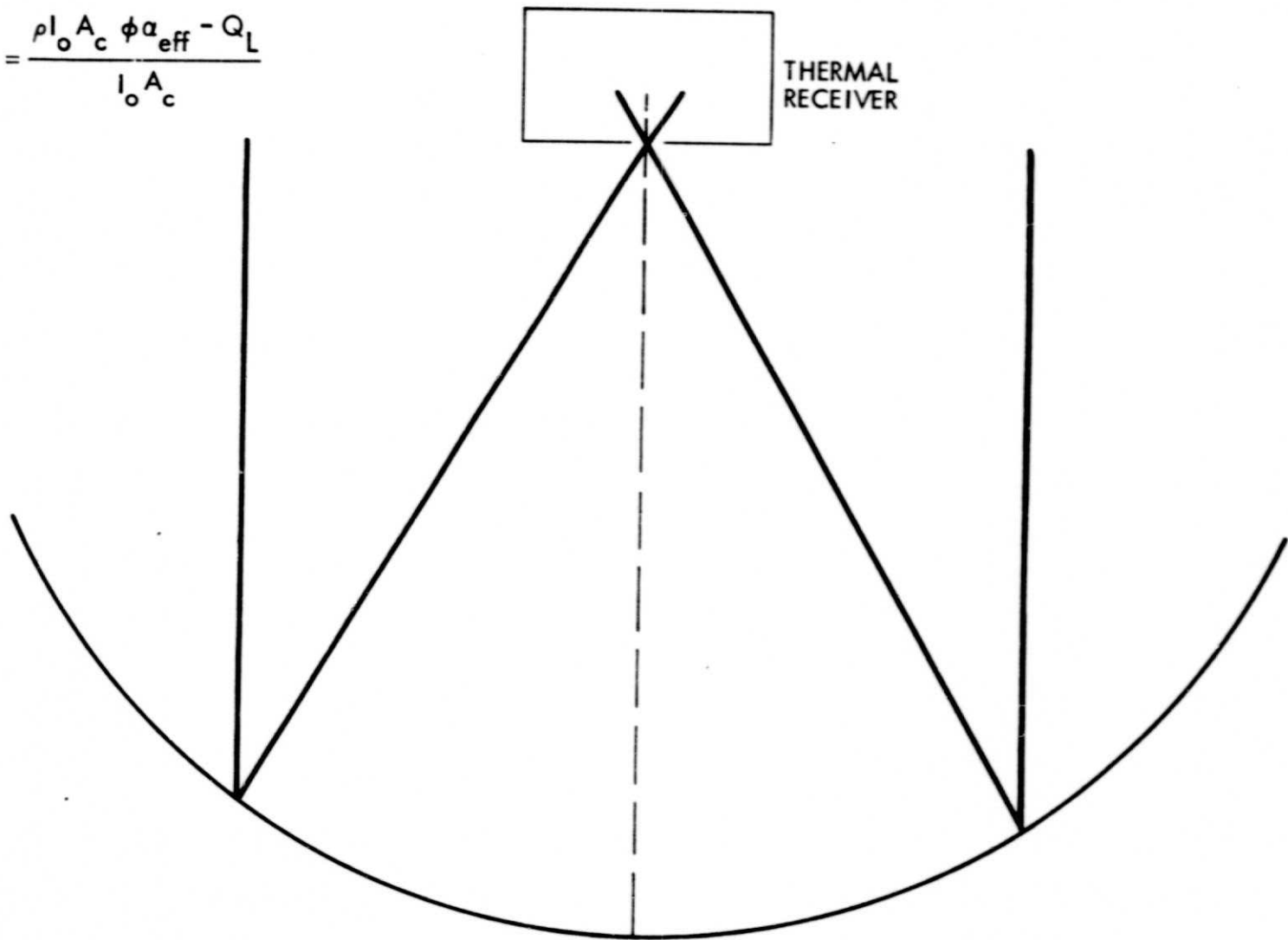


Figure 3. Collector Configuration

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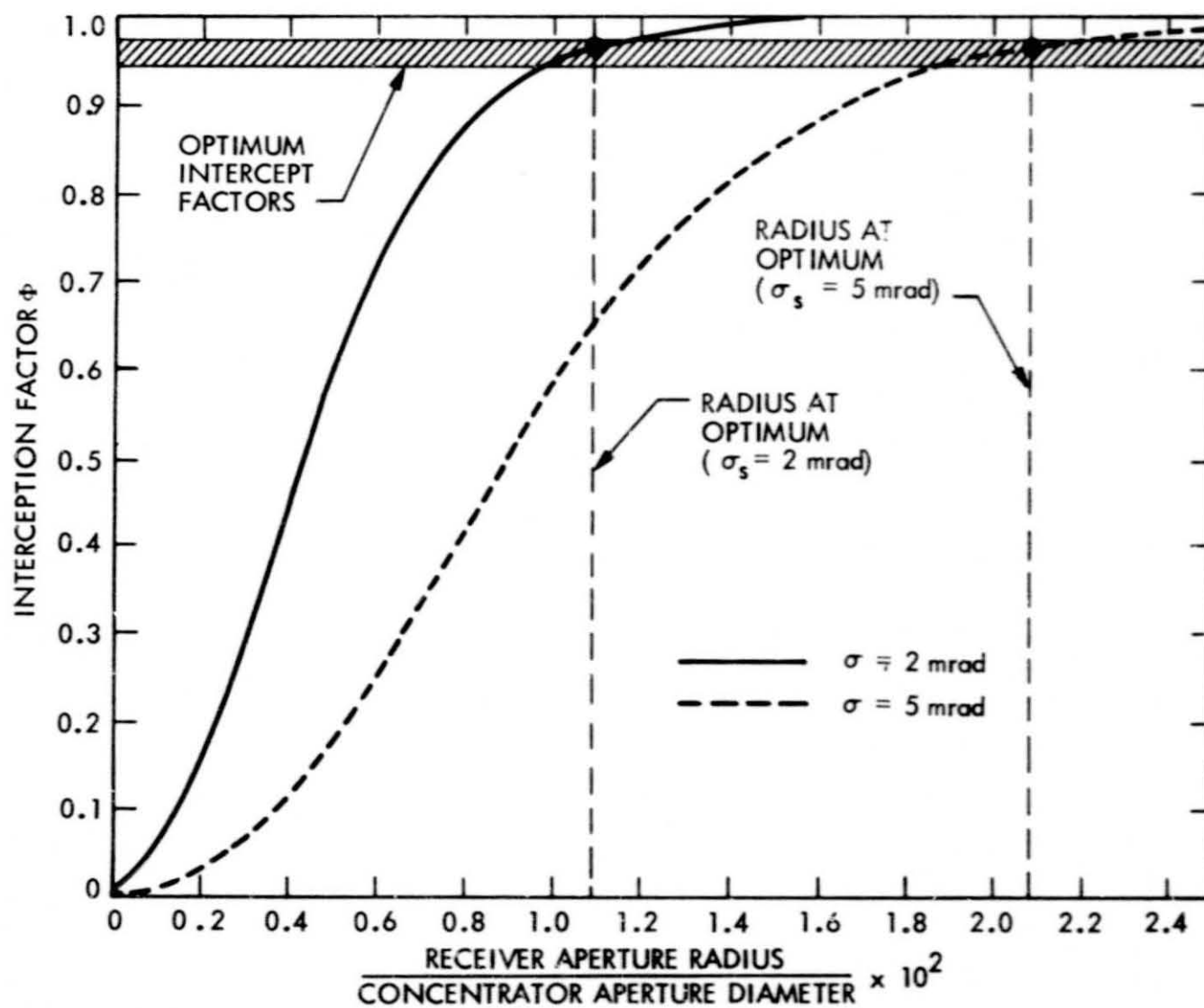


Figure 4. Interception Factor vs Receiver Aperture Radius

different values of concentrator quality. As is clearly shown, the larger the surface errors (i.e., $\sigma_s = 5$ mrad), the larger must be the radius of the receiver aperture to achieve the optimum beam intercept. Note also that most of the energy is found within the middle portion of the beam and little is at the edge. This is why the optimum aperture radius does not correspond to full acceptance of the beam (intercept factor of one).

Values of collector efficiency have been calculated for a concentrator/receiver combination having an f/D of 0.6 under an irradiation of 0.8 kW/m^2 . Figure 5 shows collector efficiency versus concentrator quality expressed in mrad. Data adapted from Reference 2 are presented for four values of receiver temperature and two values of emissivity. The receiver absorption area to aperture area (A_w/A_o) was taken as 5. The concentrator was assumed to have a reflectivity versus spreading angle given by the curve corresponding to Corning 0317 glass shown in Figure 2(a), except that the hemispherical reflectivity was taken as 0.85 to account for potential degradation. At a receiver temperature of about 300°C the collector efficiency varies only from 75% to 83% over the range of 1 to 8 mrad in concentrator quality. At 900°C the collector efficiency is much more sensitive to concentrator quality and requires surface accuracies of 2 to 3 mrad to obtain reasonable efficiencies. Note the importance of surface emissivity (or absorptivity) as receiver temperature is increased. At low temperatures it is not much of a factor, but at receiver temperatures of 1300°C it appears important to have a low emissivity to maintain high collector efficiencies. Unfortunately, for cavity type receivers, it is extremely difficult to achieve a low value of effective emissivity. A plot of effective emissivity as a function of A_w/A_o for various values of surface absorptance or emittance (Ref. 2) is shown in Figure 6. Note that at $A_w/A_o = 5$ a surface emittance of 0.1 results in an effective emittance of nearly 0.4.

The optical parameters that correspond to the curves in Figure 5 are given in Figure 7. At a mirror quality of 8 mrad the optical concentration (ratio of concentrator aperture area to receiver aperture area) is from 250 to 280 at a 500°C receiver temperature. With a high quality concentrator (2 mrad) the concentration ratio is about 1500, meaning that

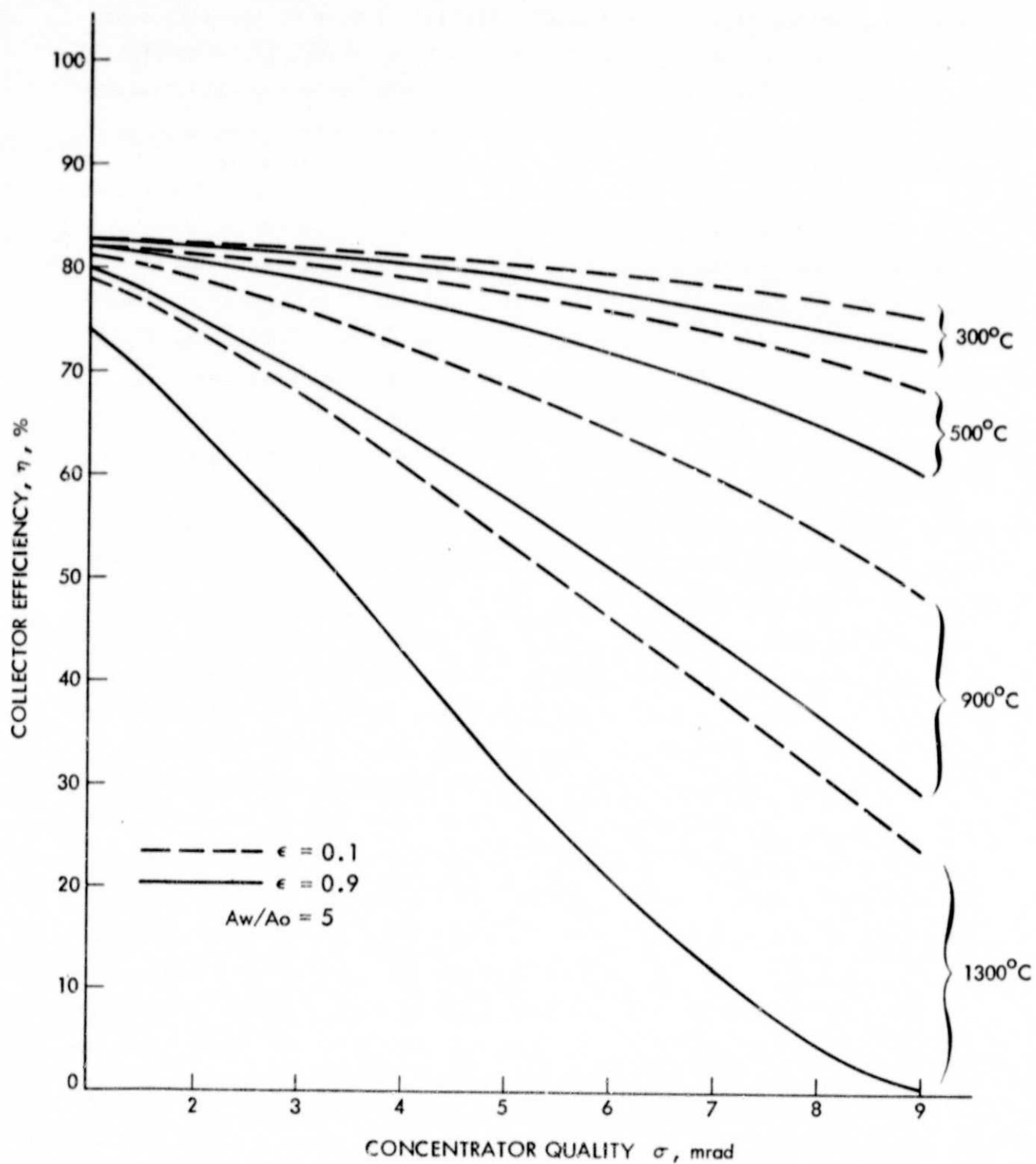


Figure 5. Collector Efficiency vs Concentrator Quality

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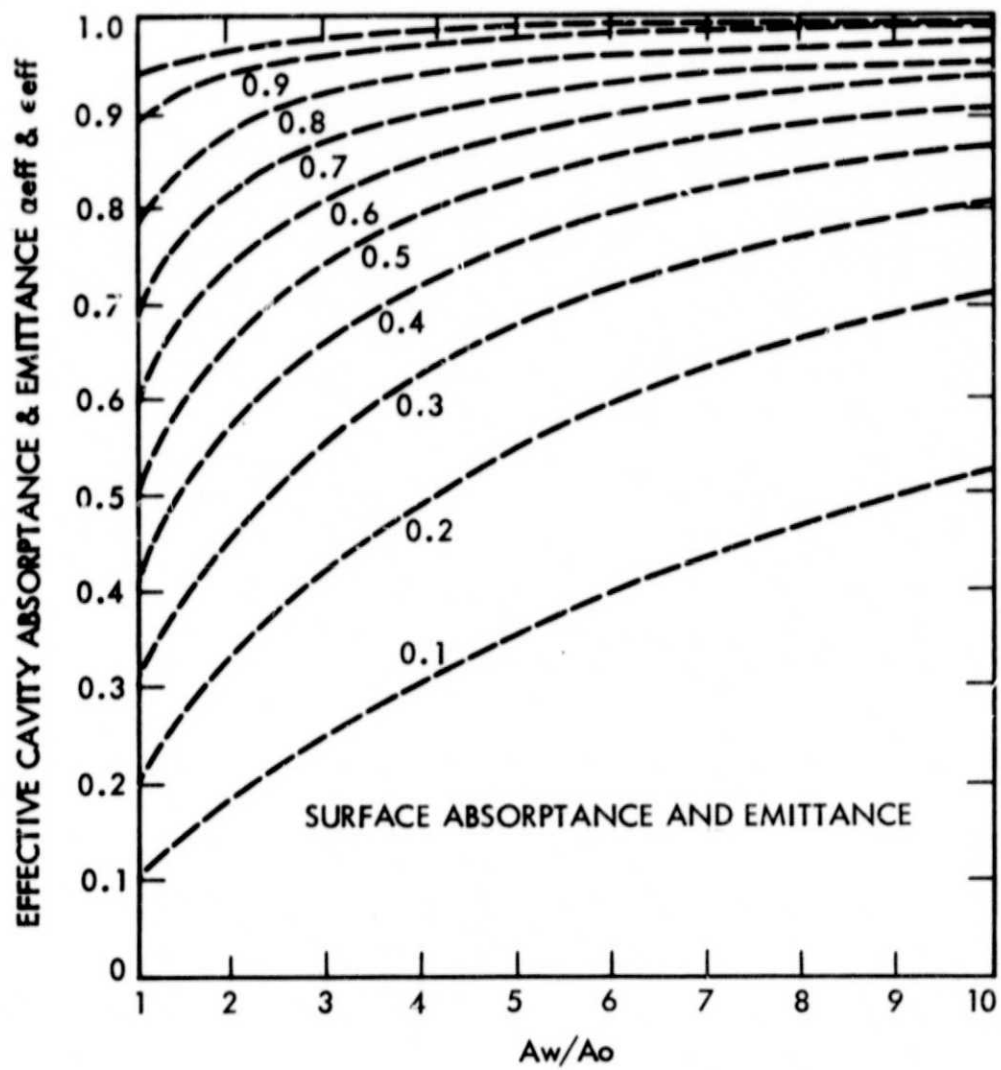


Figure 6. Effective Cavity Absorptance and Emittance vs A_w/A_o

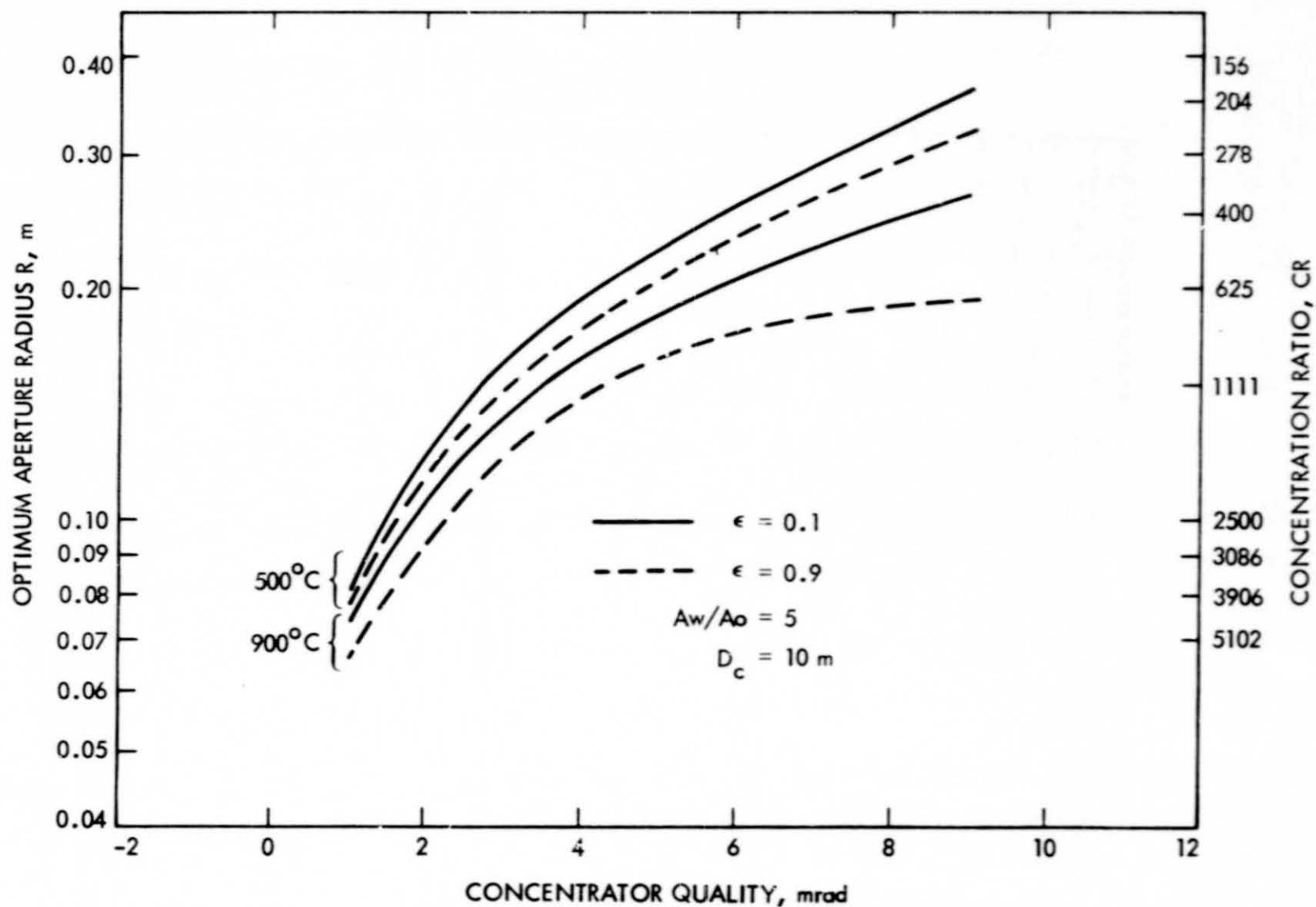


Figure 7. Aperture Radius and Concentration Ratio vs Concentrator Quality for Cavity Receiver

the allowable receiver aperture is much smaller with correspondingly lower reradiation losses and higher collection efficiency.

As was pointed out earlier, the collector efficiency shown in Figure 5 assumed a reflectivity versus spreading angle (ω) based on the top curve of Figure 2(a). This curve assumes very little spreading (< 1 mrad) of beam, i.e., a very specular surface. It is of interest to compare the performance of a collector having a very specular surface with one that is less specular, both having the same value of total hemispherical reflectivity. Referring to Figure 2(a), we note that the reflectivity curves for Corning 0317 glass and that of Corning silvered microsheet show a total hemispherical reflectivity of about 0.95; however, the microsheet is much less specular, i.e., has greater spreading of the beam. The resultant collector efficiencies are compared in Figure 8. Note that even though the specularities are significantly different, there is little difference in collector efficiency. The reason this occurs is that most of the energy is located near the center of the receiver aperture and not near the edge. Thus, the implication is that a modest amount of spreading does not significantly effect performance, and that a highly specular surface is really not required.

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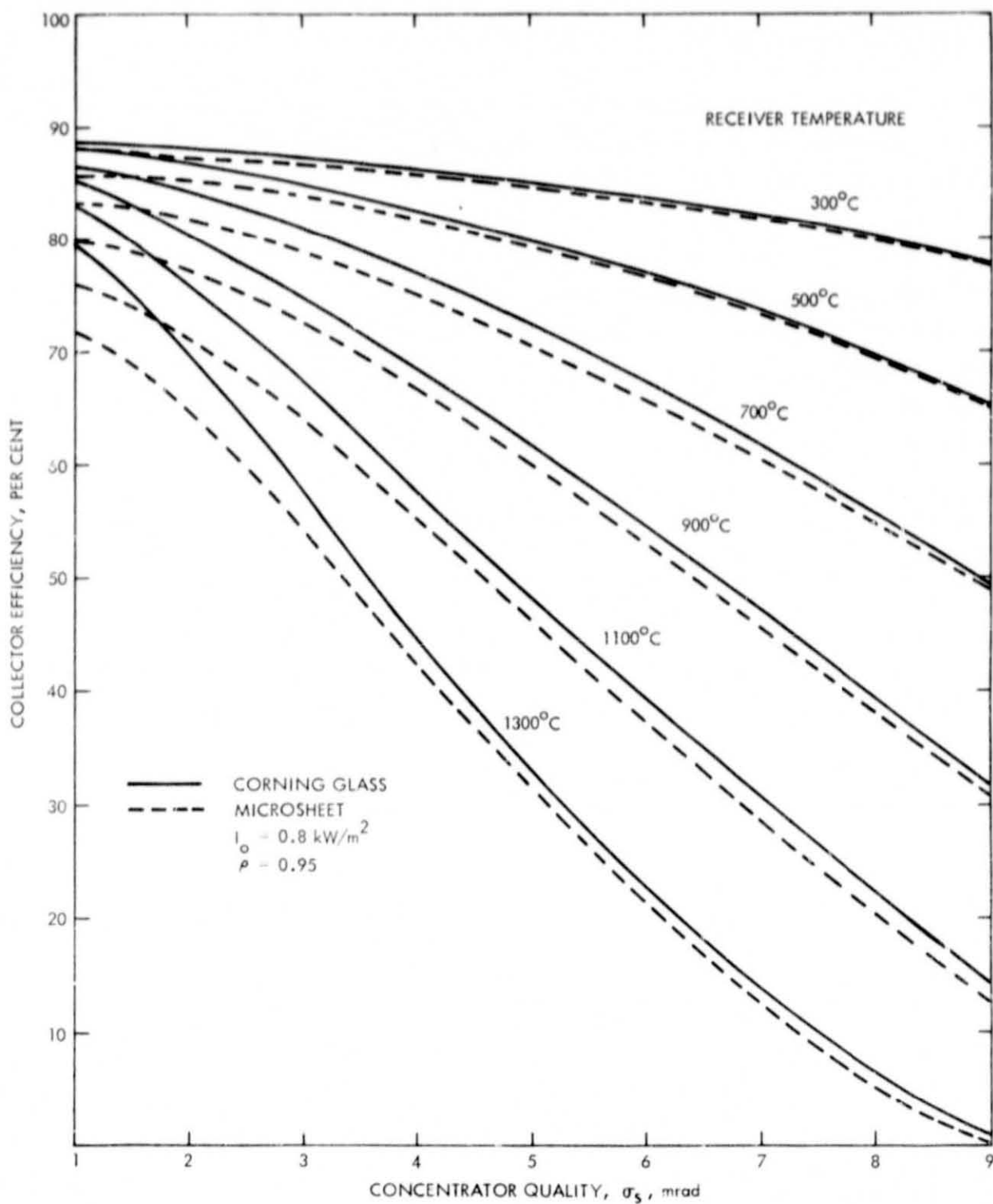


Figure 8. Collector Efficiency

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C. Pointing Error

In general, the geometrical center of the receiver does not coincide with the center of the solar image due to the concentrator pointing error. The pointing error includes inaccurate sun tracking, misalignment and receiver supporting structure deflections caused by gravity and wind loads. An expression for intercept factor ϕ has been derived at JPL (Ref. 3) as a function of pointing error (δ), receiver aperture (R), and the flux distribution $f(Z)$ at the focal plane. The geometry is shown in Figure 9. The final result is expressed below:

$$\phi(R, \delta) = \begin{cases} \int_{\delta-R}^{\delta+R} 2Z f(Z) \cos^{-1}(\gamma) dZ, & \delta > R \\ \int_0^{R-\delta} 2\pi Z f(Z) dZ + \int_{R-\delta}^{R+\delta} 2Z f(Z) \cos^{-1}(\gamma) dZ, & 0 \leq \delta \leq R \end{cases}$$

where $\gamma = \frac{Z^2 + \delta^2 - R^2}{2\delta Z}$

In the above equation obviously it is necessary to have a description of the flux distribution, $f(Z)$, at the focal plane. If the distribution were assumed Gaussian, it could be expressed analytically. However, in general, $f(Z)$ will not be so simple, and the use of a digital computer analysis is often found to be necessary to evaluate this expression. An example of the results of such an analysis is shown in Figure 10.

Another important aspect of the pointing error problem relates to recent information generated at JPL suggesting that certain pointing errors can be virtually eliminated from consideration through proper sensing and control. These errors would include those due to alignment, receiver sag, atmospheric refraction and steady winds. Transient pointing errors, due to wind gusts, must still be considered, but with a fast response control system such that the concentrator is quickly brought back to accurate pointing, little energy is lost.

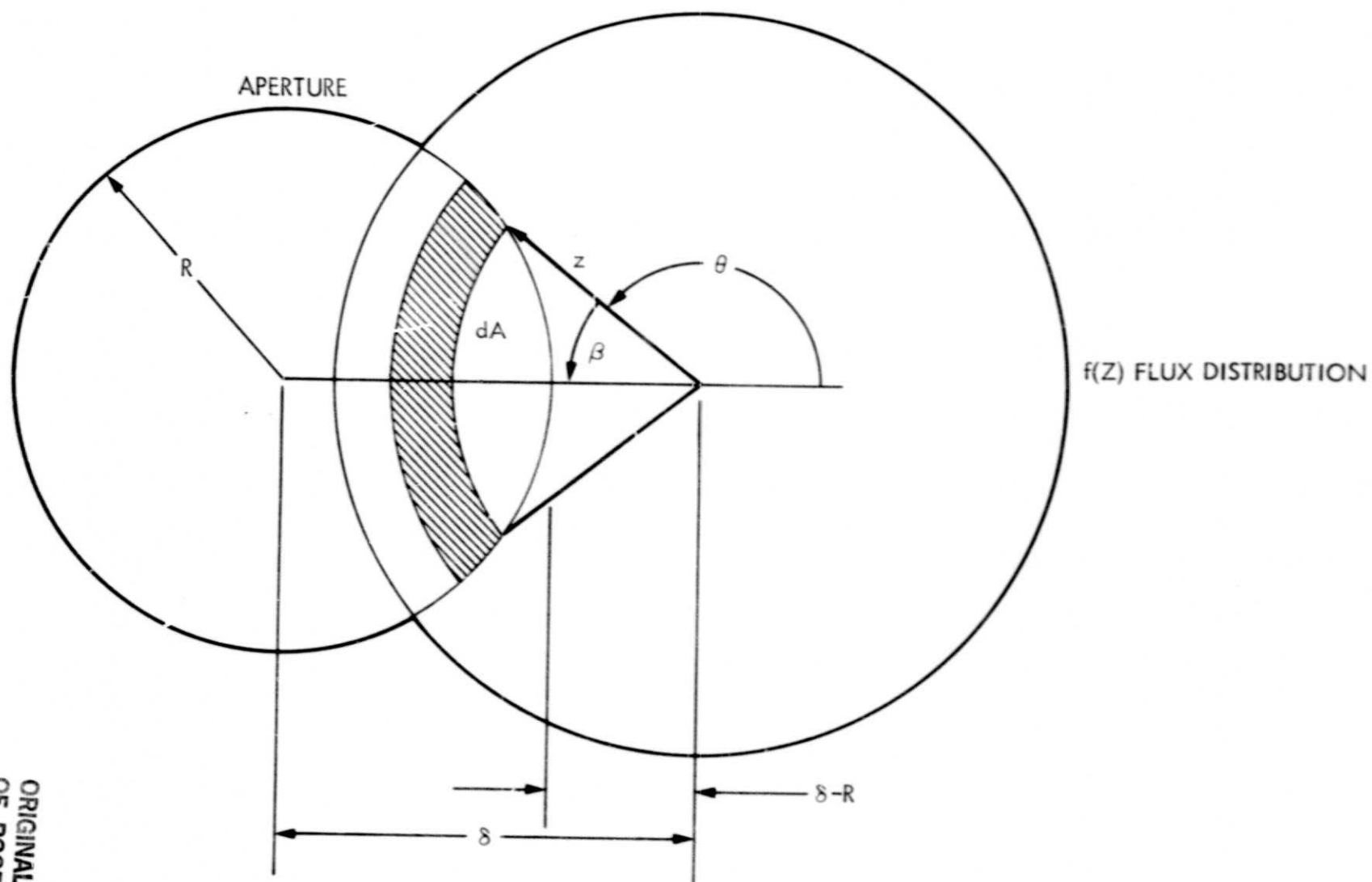
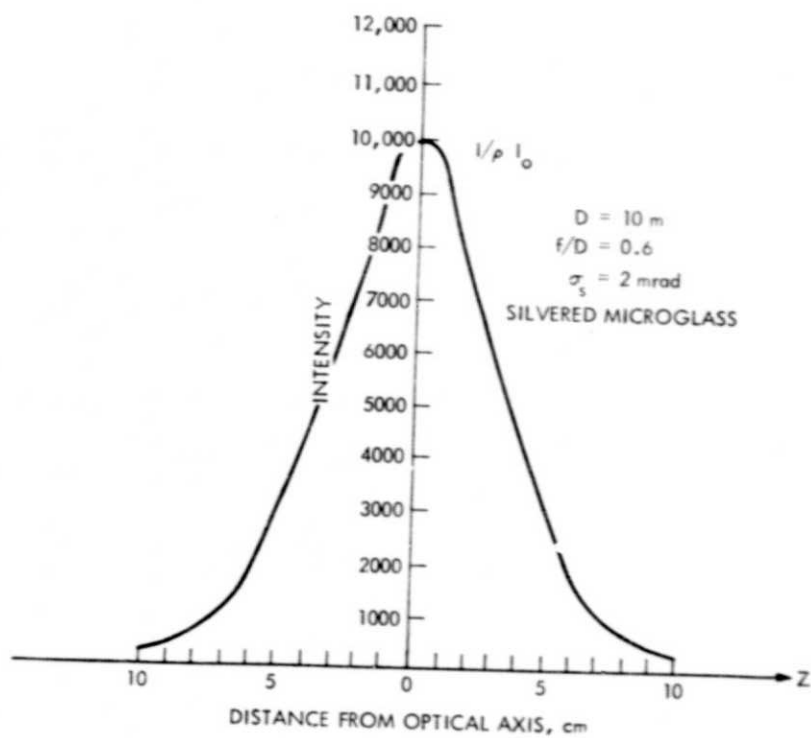
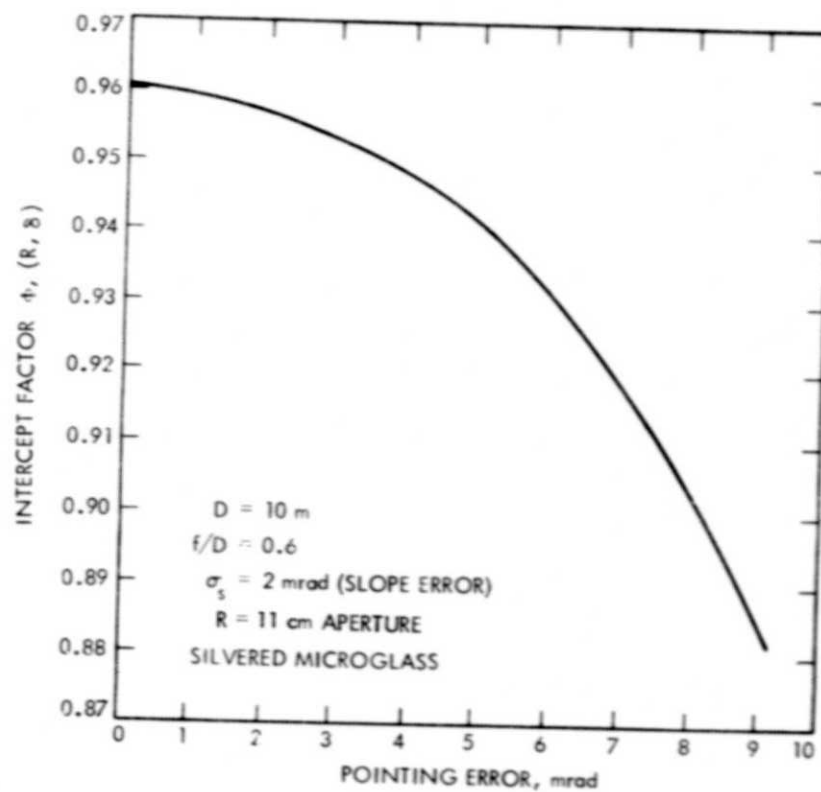


Figure 9. Radially Symmetric Flux Distribution



10a. PREDICTED FLUX DISTRIBUTION



10b. INTERCEPT FACTOR

Figure 10. Intercept Factor Evaluation

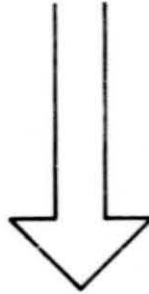
D. Collector Cost versus Quality

So far we have discussed the performance of concentrating collectors as a function of the quality of the surface. The conclusion one might reach is that the highest quality surface is the best because it gives you the smallest solar image and, thus, the highest collector efficiency. This argument totally disregards cost. In fact, it may well be that a poorer quality concentrator is preferred over one of higher quality if the cost were low enough. To obtain the optimum collector design, a figure of merit can be defined as shown in Table 1. The figure of merit is the ratio of the energy absorbed by the receiver at the specific temperature and the collector cost. The higher this ratio, the better the collector. As shown in Figure 11, as concentrator optical quality is increased, both collector cost and efficiency increase. The optimum quality is that point which maximizes the figure of merit. It is important to recognize that optical quality considers all factors that influence the size and location of the solar image such as surface inaccuracies, surface reflectivity and pointing errors. Moreover, the collector cost must consider all factors such as cost of surface, substrate, structure, tracking mechanisms and bearings as well as the cost of the receiver. Because of the complexity of these considerations, there is little present in the literature regarding the relationship between collector cost and optical quality. The problem becomes even more complex when the issues of receiver temperature and power conversion are introduced. A higher temperature may result in greater system performance because of the increased efficiency of the power conversion unit. However, to collect at higher temperatures, better quality optics are needed which increase collector costs. Clearly, an optimization study can and should be performed. Considerable work in this area needs yet be done before properly optimized systems are developed.

Table 1. Collector Figure of Merit

$$FM = \frac{Btu}{\$/ft^2} :$$

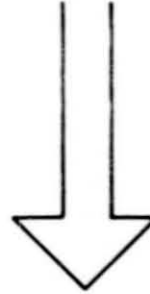
$\rho(w)$
(REFLECTIVITY)



REFLECTIVE SURFACE

- FILM
- GLASS
- POLISHED SURFACE
- CHEMICALLY BRIGHTENED

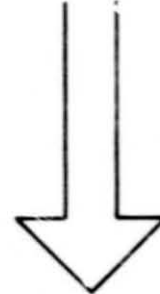
ϵ_s
(SURFACE QUALITY)



SUBSTRATE FABRICATION

- STRETCH FORMING
- CASTING
- GRINDING
- SPINNING

ϵ_p
(POINTING ERROR)



CONTROL AND STIFFNESS

- CONTROL COST
- STRUCTURE COST

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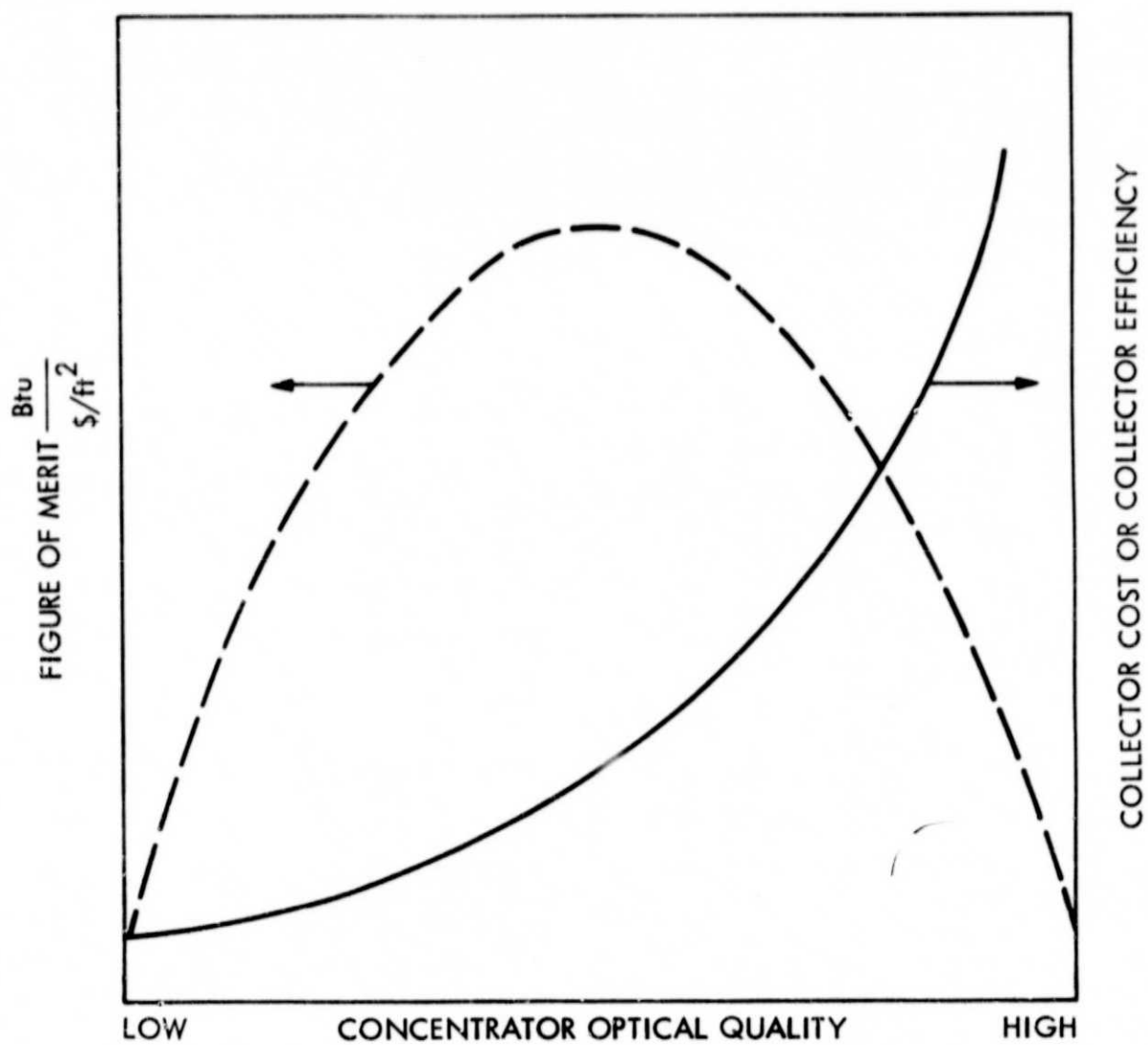


Figure 11. Collector Figure of Merit vs Concentrator Optical Quality

E. System Performance

In the previous section it was implied that increasing receiver temperature can lead to improved system performance, but that cost might also be significantly increased. It can also be shown that, above certain temperatures, little is gained with respect to performance by further increases in temperature. Figure 12 is a plot of system efficiency (product of collector and engine) versus receiver temperature parametric with percent of Carnot efficiency. These curves, based on perfect optics (i.e., the receiver aperture corresponds to the solar image), indicate that, above about 1000-1200°C, little is gained in system efficiency. The reason is that the solar image size is fixed, and going to higher temperatures increases the reradiation from the receiver aperture more rapidly than it increases conversion efficiency. When real optics are considered, the situation is even worse and temperature of about 800-1000°C probably should not be exceeded.

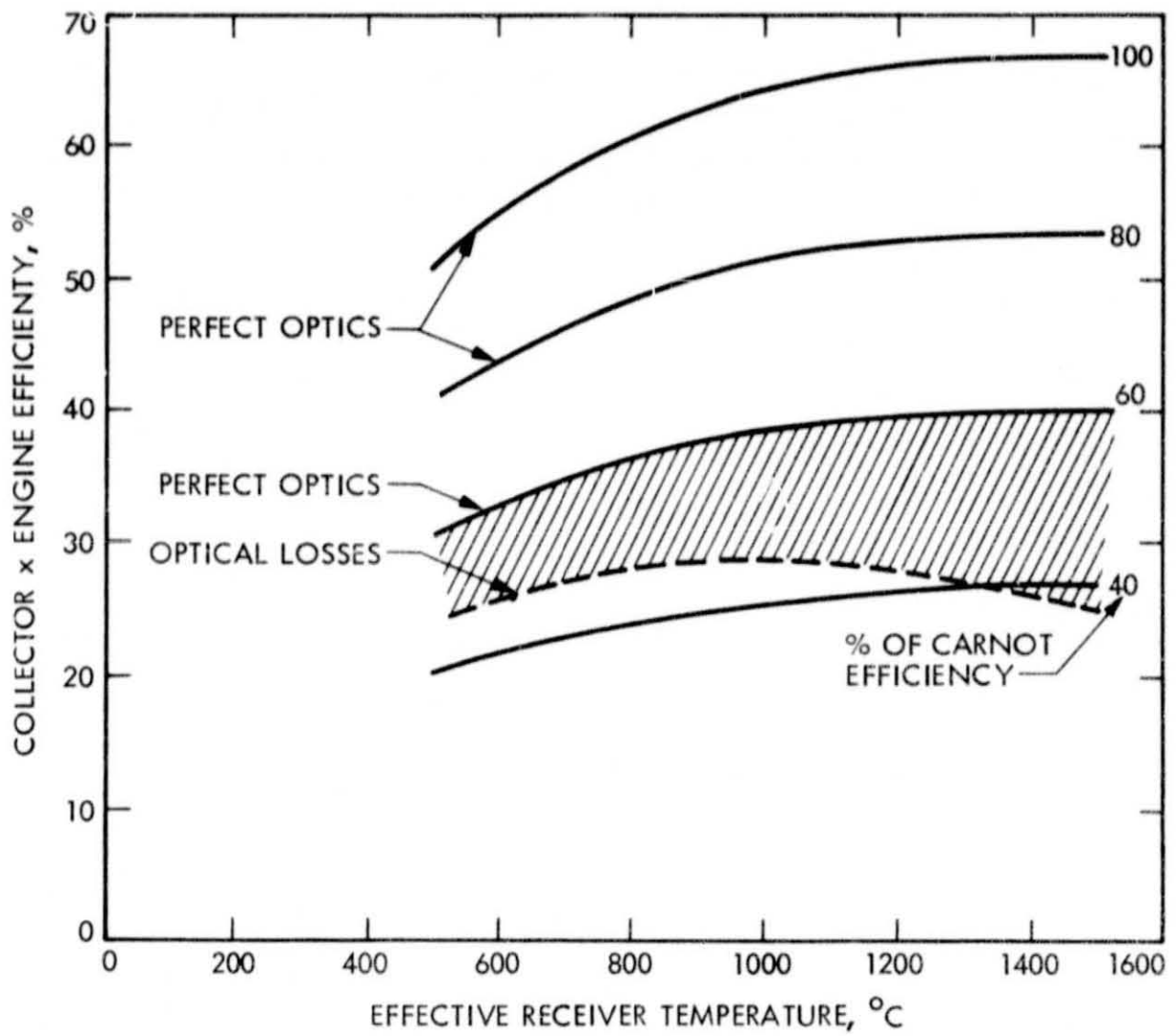


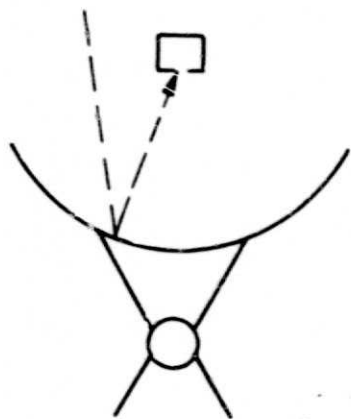
Figure 12. System Performance

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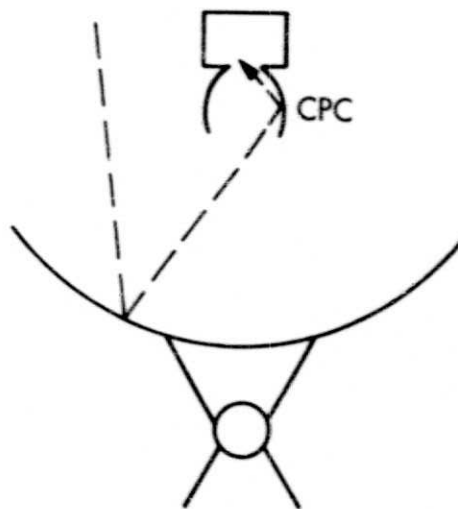
III. Collector Types

There are a number of variations of the point-focusing parabolic concentrating collector. The conventional type is termed a deep dish (Figure 13a) in which the receiver is located at the focal point and accepts energy from single reflections. A variation of this is shown in Figure 13b in which a secondary reflector (CPC) is placed at the receiver to redirect and better focus the energy into the cavity. Such a design enables the use of a poorer quality concentrator with a high concentration receiver. Another version has a secondary reflecting surface (Figure 13c) so that the receiver can be located at or near the tracking axis. This configuration, known as a Cassegrainian, has certain design advantages, but has the basic disadvantage of additional reflections. It is also possible to replace the parabolic reflecting surface with a flat-plate reflecting Fresnel lens (Figure 13d). Finally, a curved refracting Fresnel lens is possible and has many inherent advantages (Figure 13e), the most important being a lightweight structure.

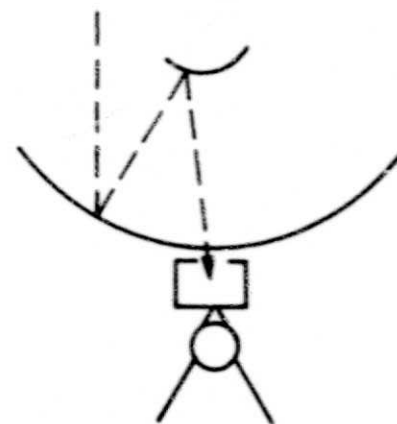
Up to this point the collector types discussed have been two-axis tracking collectors for which the concentrator is continually pointed at the sun, redirecting and concentrating the sun's energy into a receiver which remains at the focal point of the collector. Another class of essentially a point-focusing collector is the fixed mirror concept in which the receiver is the only element of the collector which articulates and maintains itself roughly in the focal region of the rays reflecting from the fixed concentrator surface. At least two versions have been proposed. One version, under development by E-Systems, is known as the Fixed Mirror Distributed Focus Concept (Figure 14), and has an aperture diameter of from 200-300 feet. The collector can produce about 1000°F heat with a concentration ratio of about 1000. A more modest version has recently been suggested by Meinel of the University of Arizona, having an aperture diameter of 5 to 10 feet. It produces temperatures of 300°C at a concentration ratio of only about 10-20. Both of these concepts use a spherical mirror surface and are fashioned after the early work of Steward and Kreith (Ref. 4) on small diameter fixed mirror concepts.



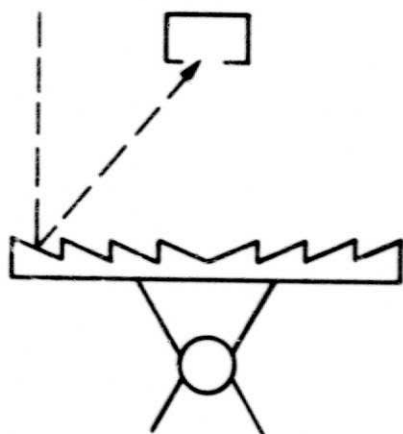
(a) DEEP DISH PARABOLA



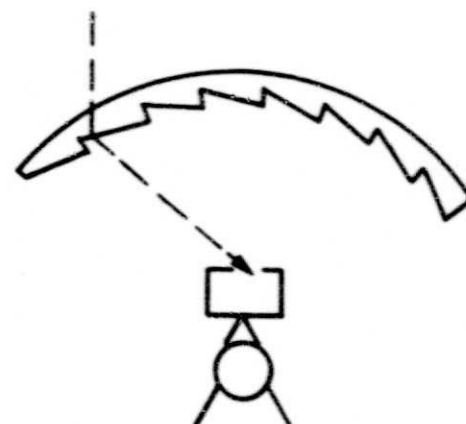
(b) PARABOLIC WITH CPC



(c) CASSEGRAINIAN



(d) FLAT PLATE REFLECTING FRESNEL



(e) CURVED REFRACTING FRESNEL

Figure 13. Collector Types

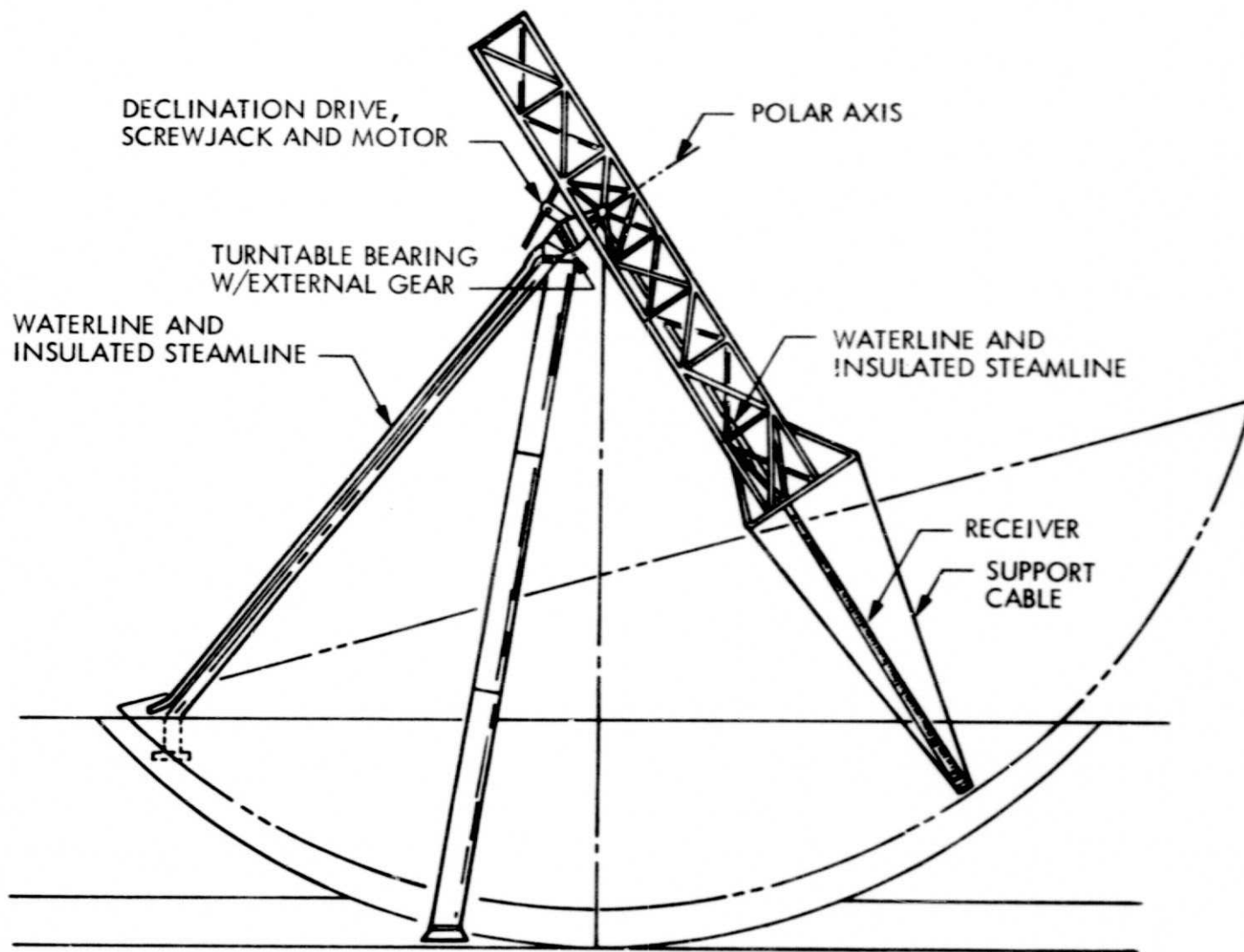
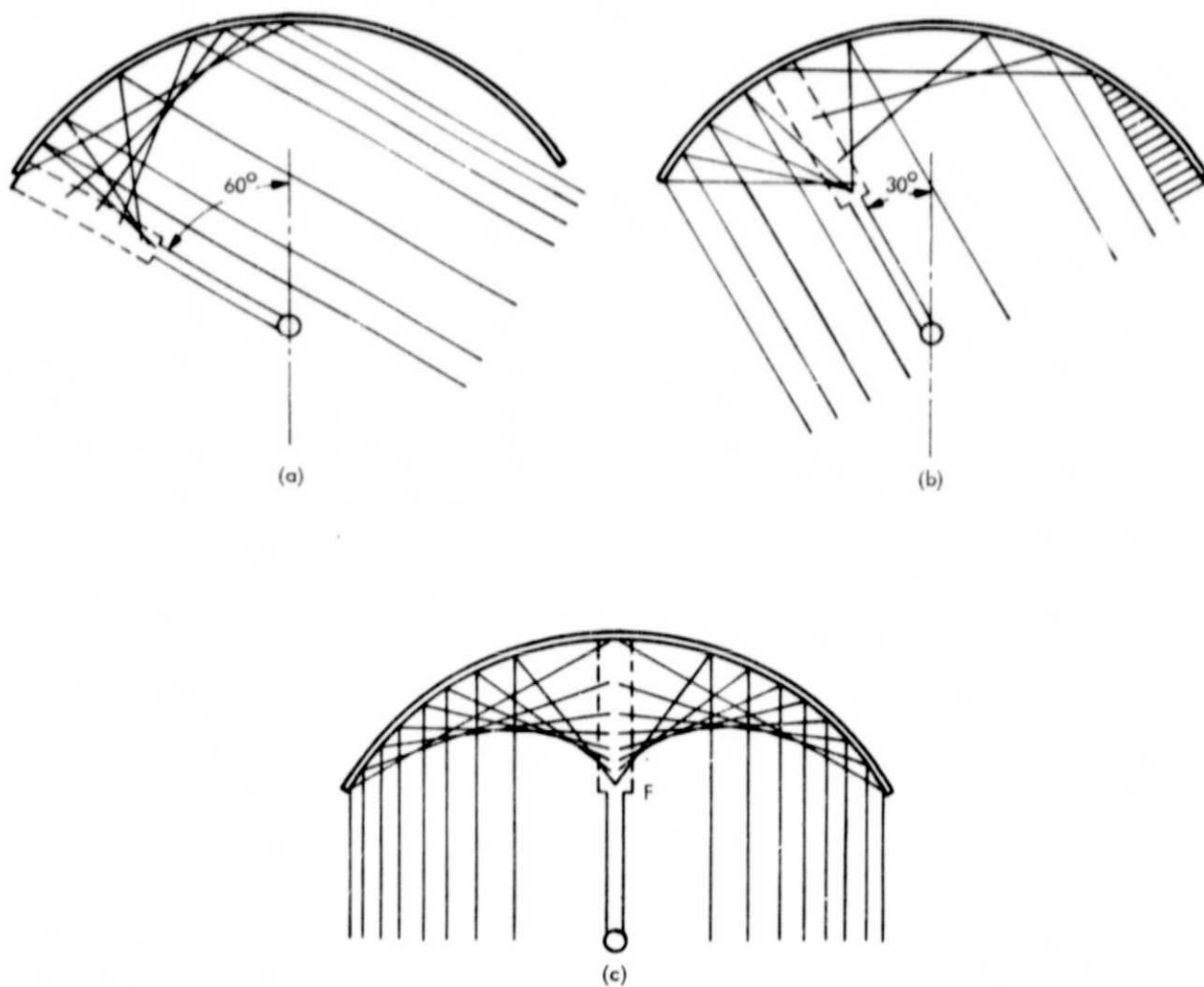


Figure 14. Fixed Mirror Distributed Focus Concept

The fixed mirror distributed focus (FMDF) concept does not focus energy at a single point, but rather along a line, either cylindrical or conical surface (see Figure 15). Because of this feature and unavoidable cosine losses, the FMDF system has a lower collection efficiency than those concepts in which the concentrator articulates. Its main advantage is the potential lower cost associated with a concentrator structure that does not need to articulate.



- (a) POSITION OF THE ABSORBER AT 8:00 A.M. OR 4:00 P.M.
- (b) POSITION OF THE ABSORBER AT 10:00 A.M. OR 2:00 P.M.
- (c) POSITION OF THE ABSORBER AT 12:00 NOON

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OF POOR QUALITY

Figure 15. Optical Principles of FMDR System

IV. Present Development Programs

As indicated in the last section, until recently very little work was done in the development of point-focusing distributed receiver (PFDR) systems. The Government now has a very active program to develop this concept. JPL has been selected by DOE to manage an industrial program that will lead to evolving low-cost, high-performance options of the PFDR. This program recognizes that parabolic concentrators can be coupled with a number of energy transport and power conversion techniques. The energy transport options are

- 1) thermal
- 2) chemical
- 3) electrical

Thermal transport systems, in which a group of collectors are interconnected and thermal energy transported to a central heat engine, are limited to about 1000°F operation because of the difficulty of transporting high temperature heat by piping. Chemical transport avoids this high temperature transport problem by converting the thermal energy at the receiver into potential energy in a chemical. By removing any sensible heat, relatively low temperature gases or liquids are transported to a central heat engine where reconversion to heat, and then electricity, can occur. In electrical transport, the heat absorbed by the receiver is immediately converted to electricity by a small heat engine located at or near the focal area. Electricity is then transported from each collector. These three concepts are schematically represented in Figure 16.

The power conversion systems that may be coupled with these types of collectors can be based on Rankine, Brayton or Stirling cycles. With our present level of understanding, any of these three conversion systems are felt to be capable of leading to attractive, cost-competitive power plants. The Government's program is presently structured to develop and mature various collector, receiver and heat engine options. A program to develop a low-cost, high-performance point-focusing concentrator has been initiated. Proposals are presently being evaluated in order to

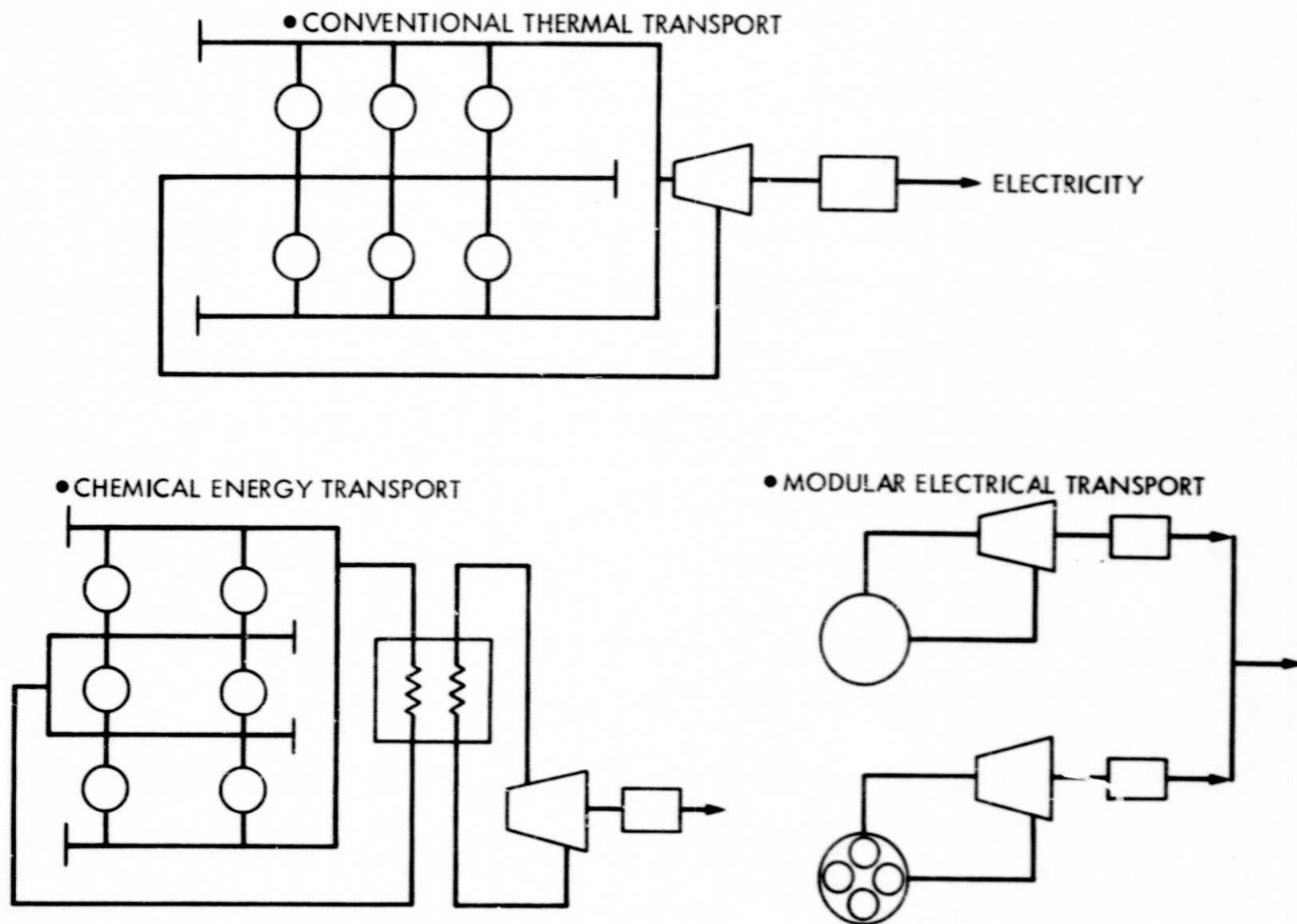


Figure 16. Transportation Concepts for Distributed Dish Concentrators

select three contractors for concept definition and mass production cost estimating. By the end of June 1978, contracts will have been negotiated with a number of industrial firms for the development of gas and steam receivers and the development of small Stirling, Rankine and Brayton heat engines.

An overview of the schedule for hardware development and test program is shown in Figure 17.

In addition to this effort by JPL in developing PFDR concepts for electric power applications, work is underway by Sandia (Albuquerque) to develop the parabolic point-focusing concentrator collector for lower temperature applications (about 600-750°F) for use in irrigation or total energy systems.

Sandia is developing two concepts of the parabolic collector. One is being developed for them by Raytheon and the other by General Electric. The Raytheon collector (Ref. 5) is about 6.7 m in diameter with an f/D of 0.45. It consists of spherical mirror segments hard mounted on an aluminum substructure. The mirrors are sagged, water white crystal glass and back-silvered to provide a specular reflectance of about 0.9. The collector is driven in azimuth and elevation by dc stepping motors. The drives are computer controlled in an open-loop incremental manner. The elevation drive system consists of a ball screw driven by a worm gear reducer from the stepping motor. A double-reduction chain drive and worm gear comprise the azimuth drive system. An artist's conception of the collector is shown in Figure 18. One of these units is presently under test at Sandia.

The GE concentrator is a modified scientific-Atlanta antenna with a diameter of about 7 m. It uses aluminized acrylic, FEK-244 (made by the 3M Company) bonded to a solid aluminum substrate. The support structure is a tripod type pedestal. The energy is focused onto a cavity-type receiver with a concentration ratio of about 250. An artist's conception of a field of these collectors is shown in Figure 19. The collector field will power a total energy system for a knitware factory in Shenandoah, Georgia. A five-foot prototype of the collector unit has

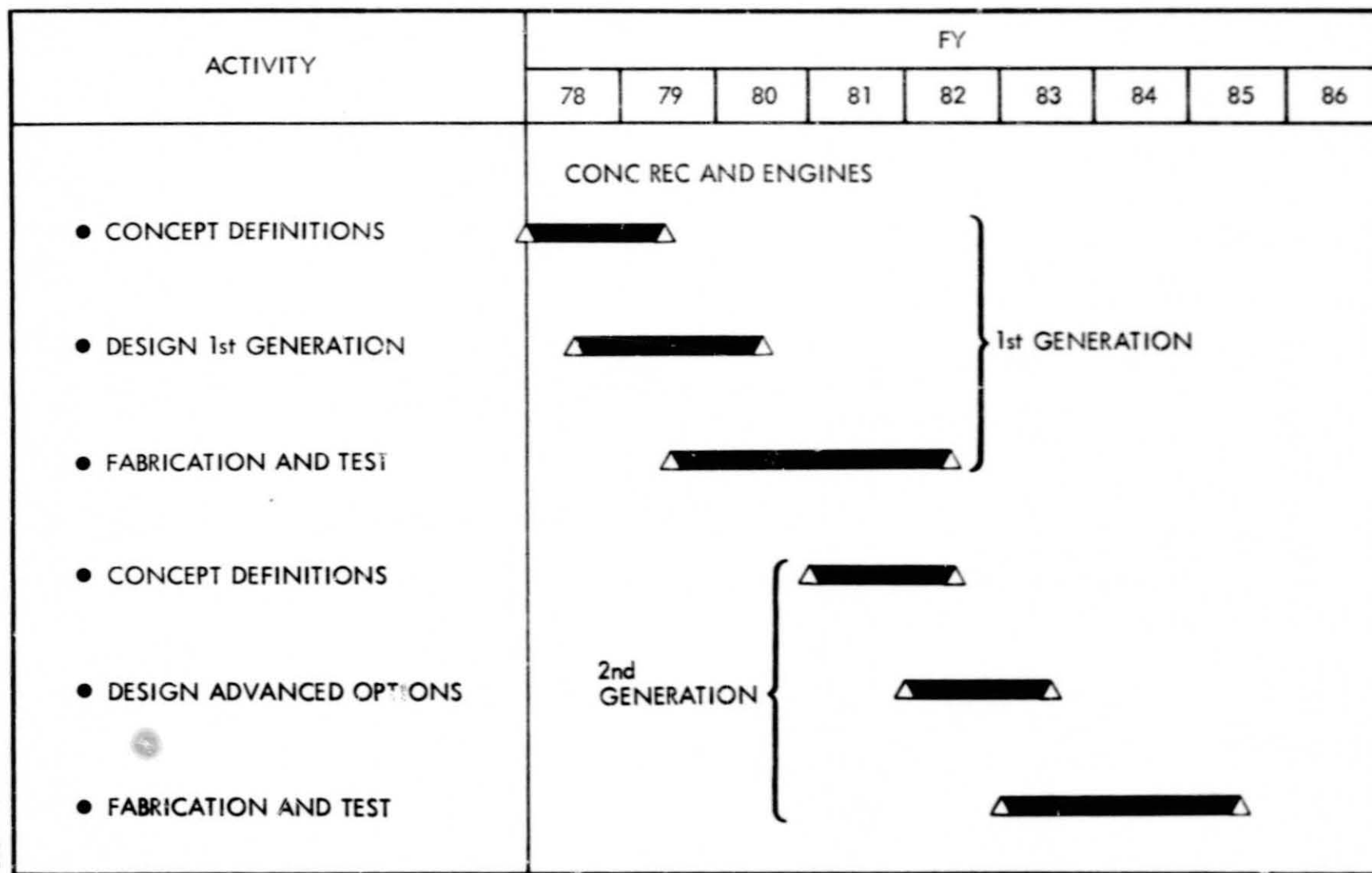


Figure 17. PFDRT Schedule

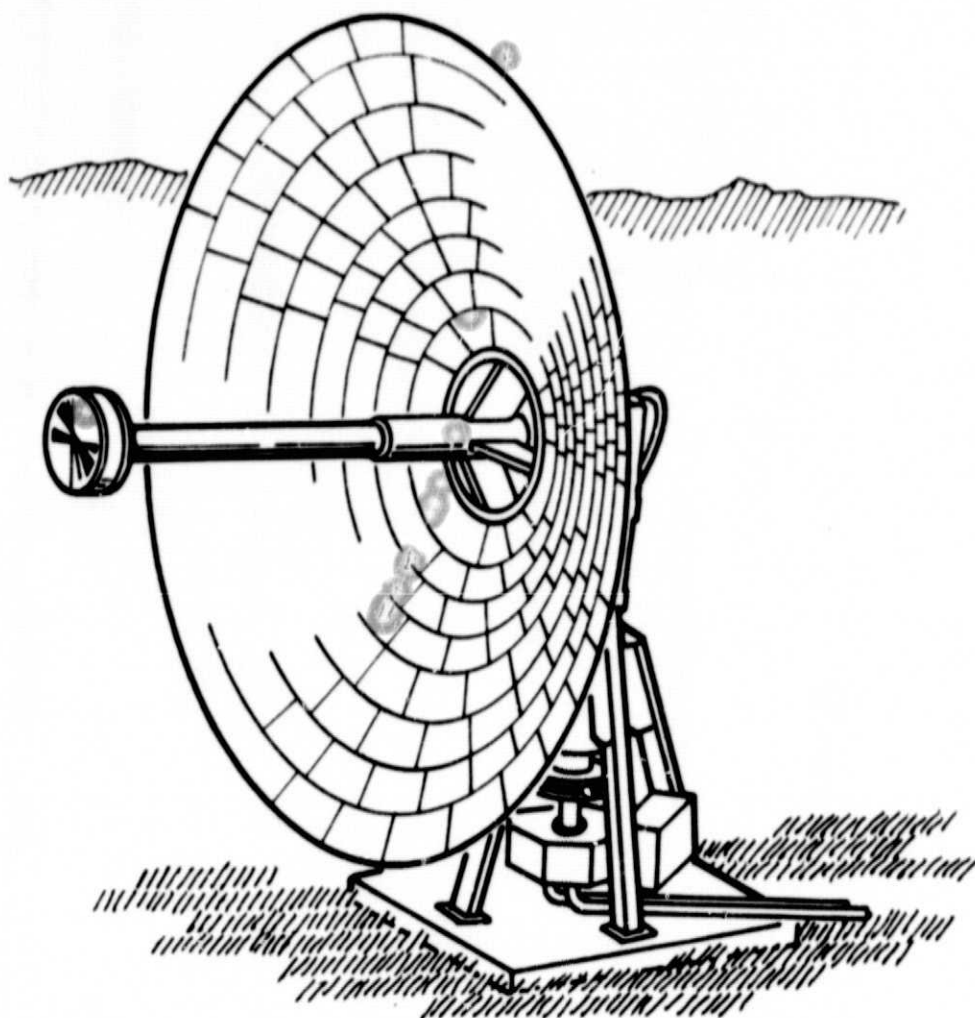


Figure 18. Raytheon Point-Focusing
Concentrator Collector

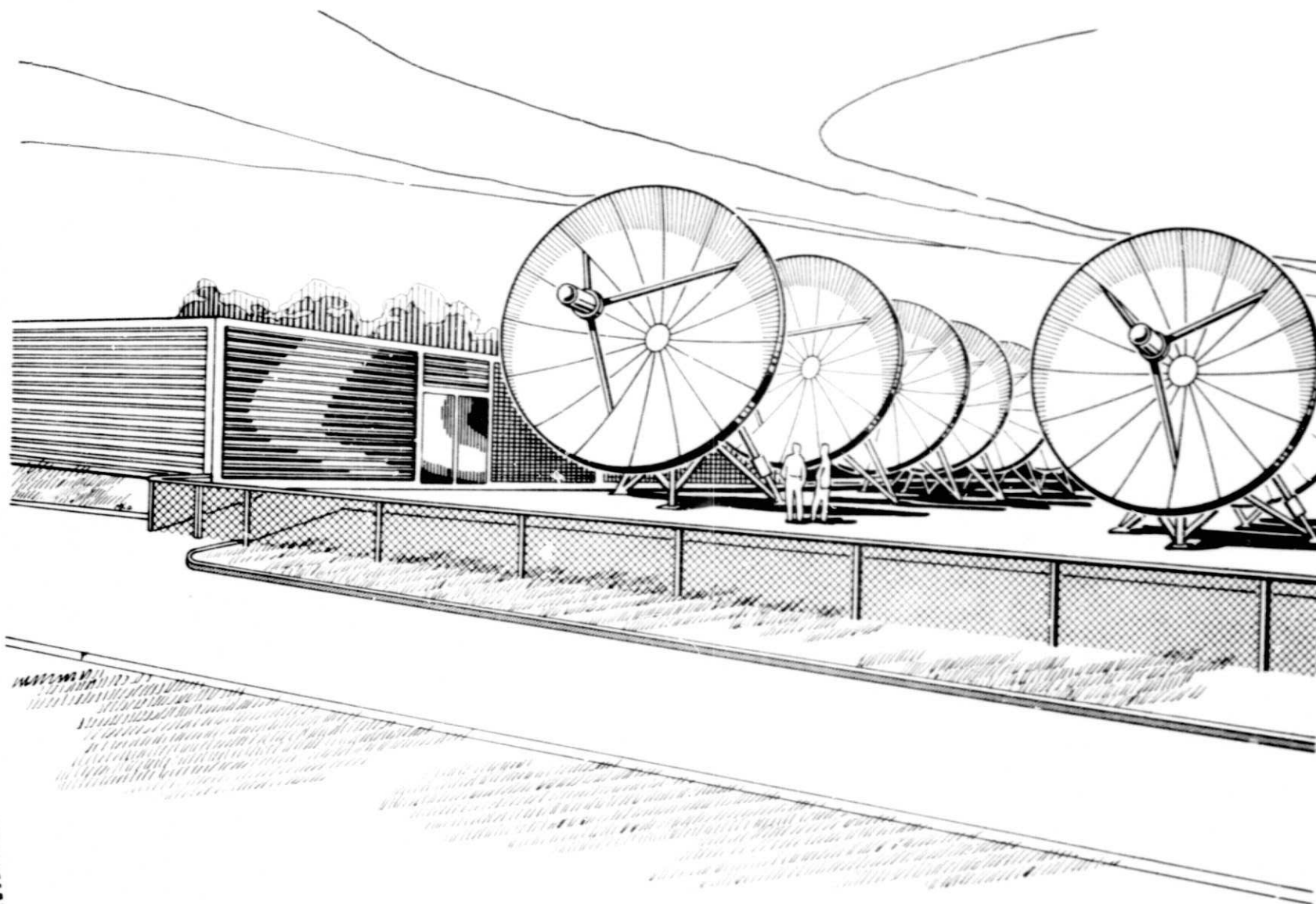


Figure 19. General Electric Parabolic Collectors (Shenandoah)

been sent to Sandia for tests (Figure 20).

Both the Raytheon and GE collectors are designed to collect thermal energy within a cavity receiver. In application, the energy would be transported to a central point for conversion to electricity.

In addition to the efforts in developing PFDR concepts, some additional work is being performed in testing and evaluating the fixed-mirror distributed focus collector concept. This work is being done both by E-Systems and the University of Arizona. A photograph of a prototype version of the E-System collector is shown in Figure 21.

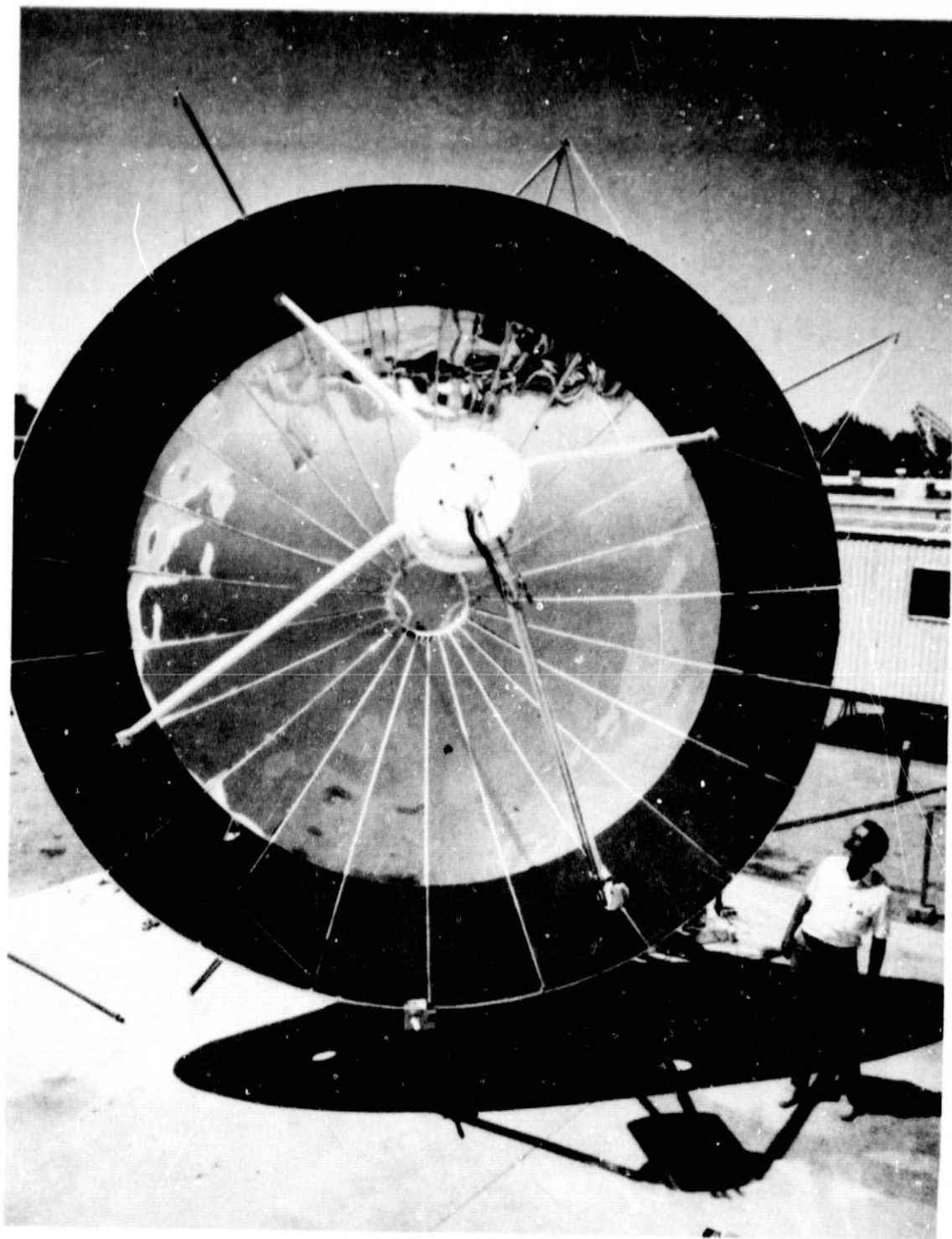


Figure 20. Engineering Prototype Collector

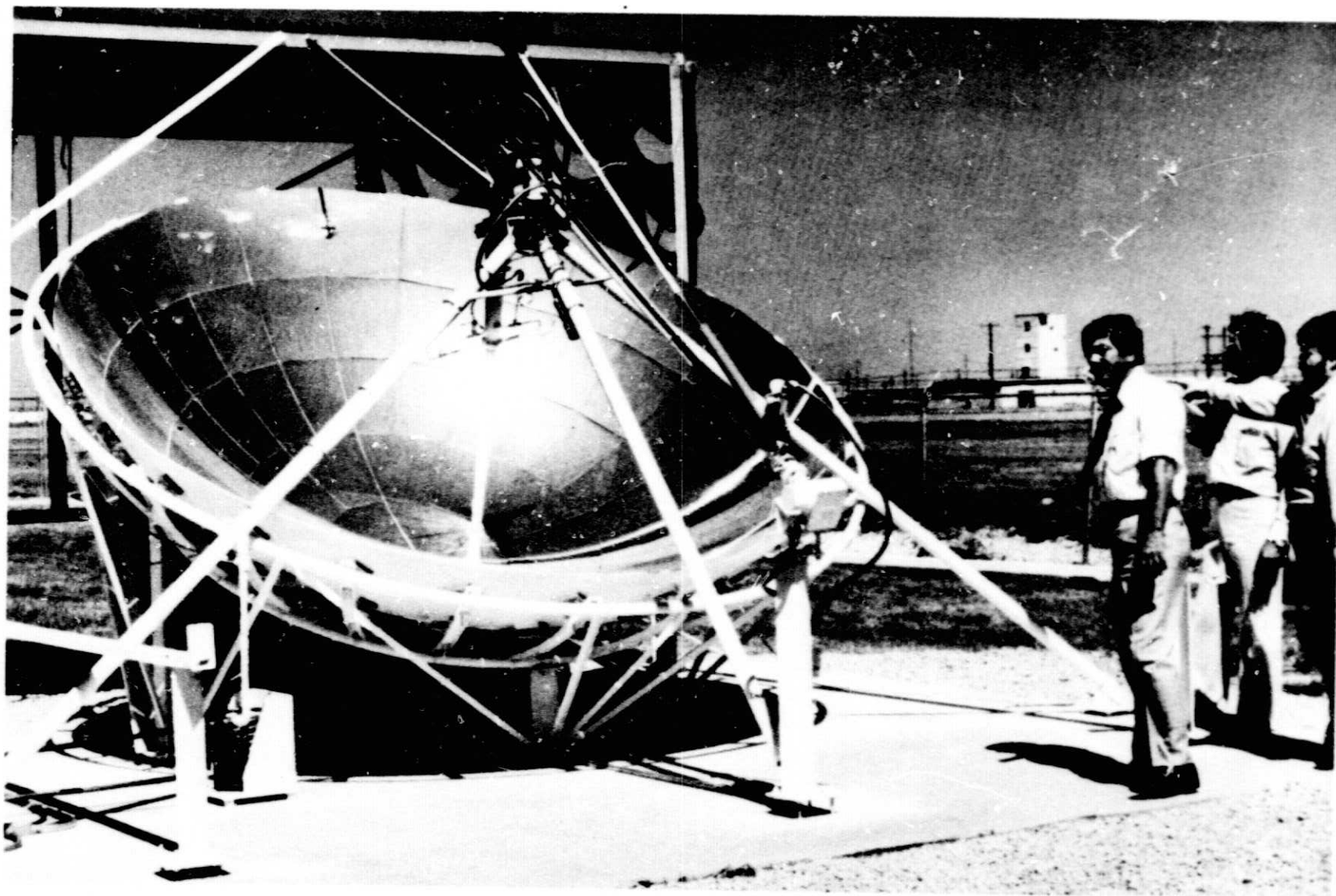


Figure 21. Prototype of Fixed-Mirror Distributed Focus Collector

V. Cost Estimates

No firm cost data are yet available for the parabolic point-focusing collector in production quantities. In fact, only several of these units have been built to date. The only commercially available parabolic collector is one produced by Omnium-G, located in Anaheim, California (Figure 22). This company is producing a 6m collector in small quantities at a sale price of around 1000 $\$/\text{m}^2$. The collector has an f/D of 0.67 and an electro-polished aluminum surface. The only other units available are the prototype versions of the Raytheon and GE collectors discussed previously. Cost estimates for these units in prototype versions are in the 1000-2000 $\$/\text{m}^2$ range.

Microwave antennas that are similar in construction are being built for 500-750 $\$/\text{m}^2$ in very modest quantities (< 100 per year).

Considerable cost reduction in parabolic collectors is both necessary and probable with mass production and proper structure design.

The Department of Energy's goals for PFDR technology, including the parabolic concentrator, are shown in Table 2. The long-range goal for concentrators in mass production is 70-100 $\$/\text{m}^2$. Present estimates indicate that most of the cost of a parabolic concentrator (~80%) is associated with those parts of the concentrator other than the surface (re the bearings, tracking mechanisms, structure, and foundations). However, the weight and structural stiffness of the concentrator surface can markedly affect the design (thus cost) of the other components. With the use of advanced concentrator surface structural materials, such as cellular glass and high quality reflective surfaces, such as microsheet glass, a total low cost concentrator design is felt possible, one that can meet the cost goals in mass production.

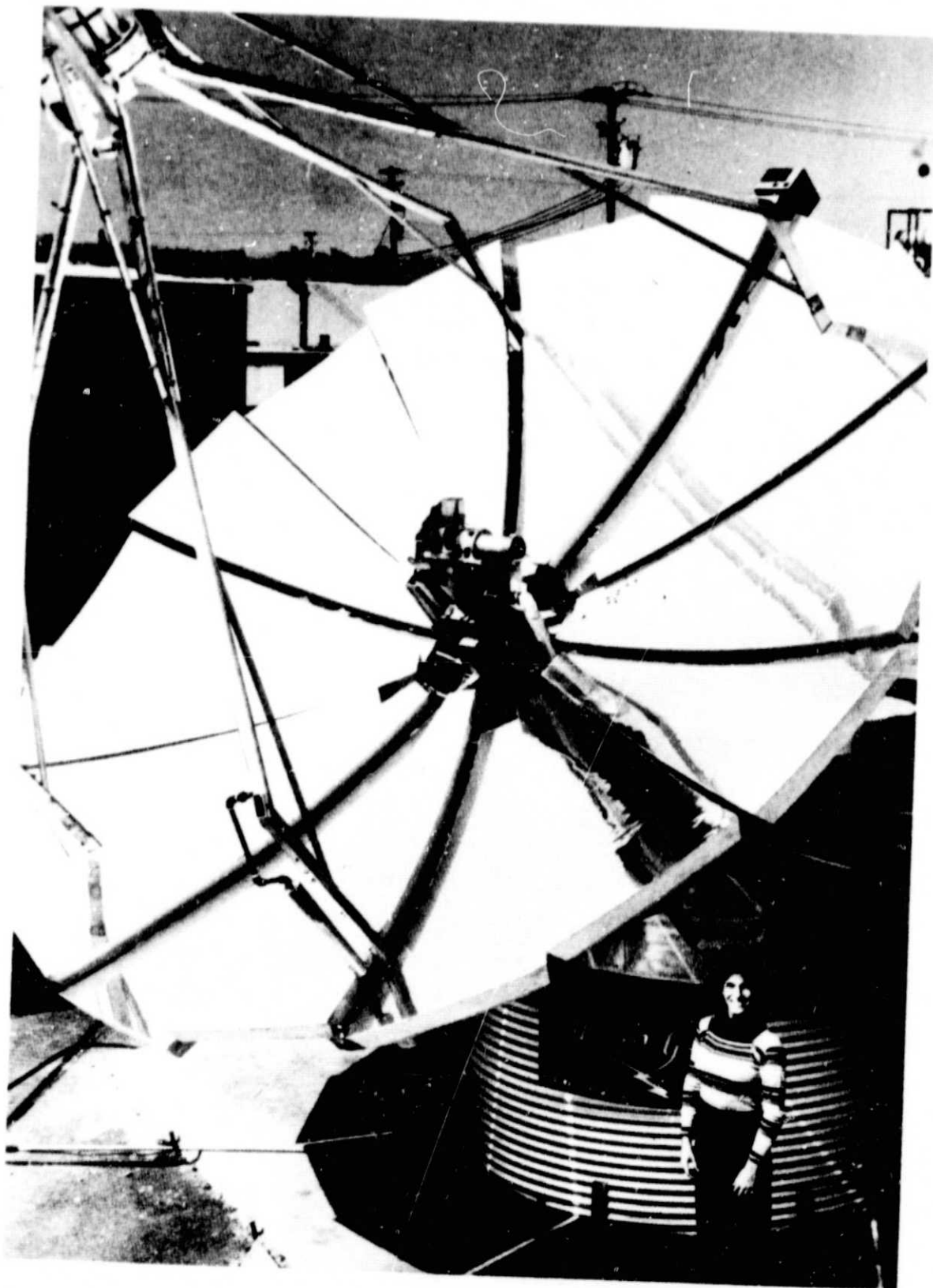


Figure 22. Omnim-G Collector

Table 2. Cost and Performance Targets

TEST AND EVALUATE	TARGETS FOR FY	1982	1985
CONCENTRATORS	COST IN MASS PRODUCTION	\$100-150/m ²	\$70-100/m ²
	REFLECTOR EFFICIENCY	90%	92%
RECEIVERS AND ENERGY TRANSPORT	COST IN MASS PRODUCTION	\$30/kWe	\$20/kWe
	EFFICIENCY	80%	85%
POWER CONVERSION	COST IN MASS PRODUCTION	\$75/kWe	\$60/kWe
	EFFICIENCY	25-35%	35-45%

VI. References

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