

PERFORMANCE OF EVACUATED SOLAR COLLECTORS WITH
COMPOUND PARABOLIC CONCENTRATORS

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By

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PERFORMANCE OF EVACUATED SOLAR COLLECTORS WITH COMPOUND PARABOLIC CONCENTRATORS* **

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ABSTRACT

Compound Parabolic Concentrators (CPC) achieve the highest possible concentration for a given acceptance angle, permitting geometric concentration ratios up to about 2 in fixed solar collectors and up to about 10 in collectors with day-to-day tilt adjustments. Design, construction and test results are reported for several CPC collectors with evacuated receivers supplied by Corning Glass, by General Electric and by Owens-Illinois. Efficiencies of 45% at $\Delta T = 150^\circ$ K above ambient have been reached with a fixed collector. This collector accepts more than half of the diffuse radiation in addition to all of the direct beam, for at least seven hours per day.

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Compound parabolic concentrators¹ (CPC) reach the thermodynamic limit of concentration², that is, they achieve the highest possible concentration

$$C = \begin{cases} 1/\sin \theta & \text{for 2-dimensional or trough-like concentrators} \\ 1/\sin^2 \theta & \text{for 3-dimensional or cone-like concentrators} \end{cases} \quad (1)$$

consistent with a given acceptance half angle θ . For nontracking solar collectors with maximal concentration, one will use CPC troughs aligned in the east-west direction. Demanding at least seven hours operating time³⁻⁵ at solstice, the time of the year with the largest apparent solar motion, one finds a concentration limit of 10 if tilt adjustments from one day to the next are permitted. A completely fixed collector can have a concentration ratio of 1.5 to 2.0. For some applications, collection of solar energy is required only during half of the year; in that case threefold concentration becomes practical with a fixed collector.

The first example¹ of a CPC shown in Fig. 1 was found independently in the U.S., Germany, and the U.S.S.R. about 1966. It consists of parabolic reflectors which funnel the radiation from aperture to absorber. The right and left half belong to different parabolas, as expressed by the name CPC. The axis of the right branch, for instance, makes an angle θ with the collector midplane, and its focus is at A. At the end points C and D, the slope is parallel to the collector midplane.

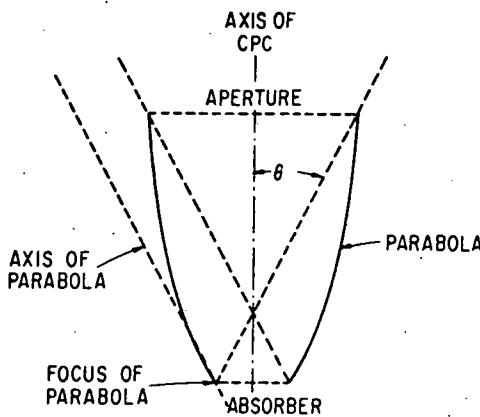
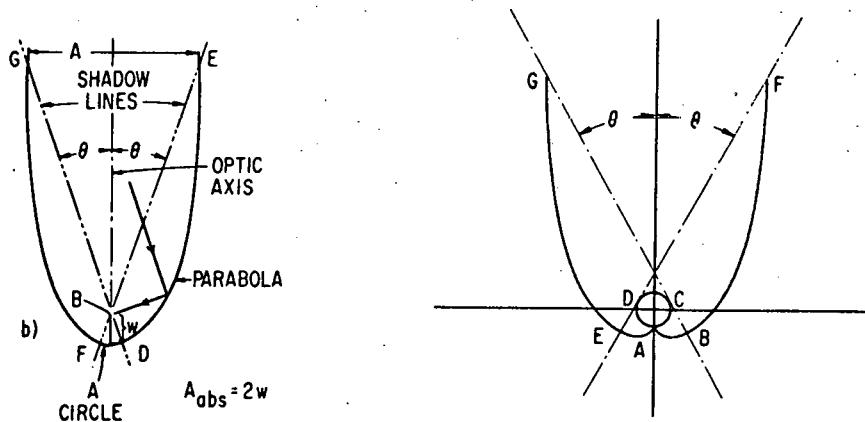


Fig. 1. Cross section of CPC with one-sided flat absorber.

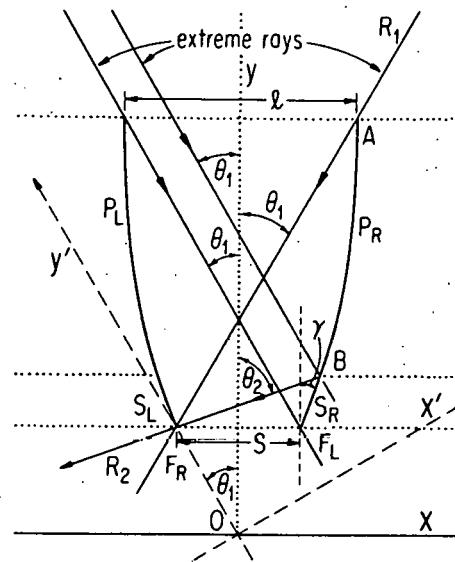
Subsequent to the discovery of the basic CPC, Fig. 1, several generalizations of the ideal concentrator have been described which are relevant for special applications. These generalizations concern

- (i) the use of arbitrary receiver shapes⁶, for example fins and tubes (the latter being important because of their ability to carry a heat transfer fluid), see Fig. 2.
- (ii) the restriction of exit angles θ_{out} at the receiver to values $|\theta_{\text{out}}| \leq \theta_2 < \pi/2$ (important because some receivers have poor absorptivity at large angles of incidence), see Fig. 3.
- (iii) asymmetric orientation of source and aperture (for the design of collectors with seasonally varying outputs)⁴, see Fig. 4.
- (iv) the matching of a CPC to a finite source of radiation⁷ (second stage concentrators have to collect radiation from a source, the first stage, which is a finite distance away).



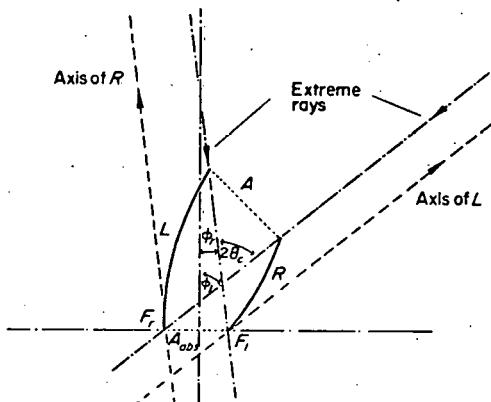
Ideal concentrator for tube. The example shown has concentration $= 1/(\sin \theta) = 2$ (ratio of aperture width to absorber diameter $= 2\pi$).

Fig. 2. Examples of non-imaging concentrators with fin absorber and with tube absorber.



$\theta_1 - \theta_2$ transformer, consisting of parabolic section P_R and P_L and of straight sections S_R and S_L .

Fig. 3. CPC with restricted exit angles $|\theta_{\text{out}}| < \theta_2$.



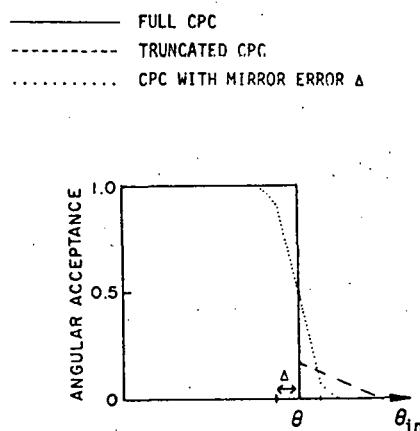
Asymmetric ideal concentrator with acceptance angle $2\theta_c = \phi_1 + \phi_2$. The effective concentration varies with angle of incidence. A = aperture, A_{abs} = absorber, R = right parabola, L = left parabola, F_R = focus of R , F_L = focus of L .

Fig. 4. Asymmetric CPC.

All of these reflector geometries are loosely referred to as CPC, even though some of them are not even parabolic. More generally, they may be classified as non-imaging concentrators.

As for the choice between different absorber types, the configurations with fin or tube absorbers, Fig. 2, will be preferable for most solar applications. Not only is the absorber material used more efficiently than in other designs, but heat losses through the back are low. This will more than compensate⁸ for the slightly higher optical losses (the average number of reflections for the configurations of Fig. 2 is about 0.5 higher than for the CPC of Fig. 1).

In their optical properties, all CPC types are exactly or almost exactly alike. Above all, they have the same relation, Eq. 1, between concentration and acceptance angle. All rays incident on the aperture within the acceptance angle, i.e. with $|\theta_{in}| < \theta$ will reach the absorber, while all rays with $|\theta_{in}| > \theta$ will bounce back and forth between the reflector sides and reemerge through the aperture. This property is shown schematically by the solid line in Fig. 5.



Fraction of the radiation incident on aperture at angle θ_{in} , which reaches absorber, for ideal concentrator in two dimensions, with acceptance half angle θ , assuming reflectivity $\rho = 1$:
—, untruncated ideal concentrator with perfect reflectors;
- - -, truncated ideal concentrator with perfect reflectors;
....., untruncated ideal concentrator with surface errors Δ .

Fig. 5. Angular response of CPC (schematic).

As for the flux distribution at the absorber, it depends on angle of incidence and on absorber shape, and has to be determined by detailed ray tracing. However, the following important statement can be made about all CPC's, without any need for ray tracing: if the radiation incident on the aperture is uniformly spread over the entire acceptance angle, then it will be isotropic when it reaches the absorber - (unless the design was chosen to restrict the exit angles to values below $\theta_2 < \pi/2$, in which case the radiation at the absorber will uniformly fill the angular range from $-\theta_2$ to $+\theta_2$). This consideration of uniform illumination is very important because it gives a simple and reliable estimate of the average performance of a CPC solar collector. [For certain angles of incidence, hot spots of high flux concentration (of the order of 50) may appear on the absorber but they do not cause any problems in the collectors described in this paper].⁹

CPC's have a rather large reflector area. Fortunately this disadvantage can be alleviated by truncation¹⁰: the top portion of a CPC does not intercept much radiation and can therefore be cut off with little loss in concentration.

The number of reflections varies both with angle of incidence θ_{in} and with point of incidence on the aperture. To calculate the optical transmission coefficient τ for a CPC, the simple approximation¹¹

$$\tau = \rho^{<n>} \quad (2)$$

can be used where ρ is the reflectivity and $<n>$ is the average number of reflections. For the configurations of practical interest for solar energy $<n>$ is between 0.5 and 1.5. More detailed information on optical and thermal properties of CPC's can be found in Ref. 10.

In this paper, design, construction and test results are reported for solar collectors with evacuated receivers and non-imaging concentrators (CPC used for convenience). Concentration ratios of 1.5, 3.0 and 5.0 were chosen. (Fivefold concentration will necessitate about 12 tilt adjustments per year.) Concentration achieves two goals: it improves the high temperature performance, and it reduces collector cost because reflectors cost less than receivers.

The receivers are evacuated tubes, supplied by Corning Glass¹², by General Electric¹³ and by Owens-Illinois¹⁴. Several techniques for low-cost manufacture of the reflectors have been evaluated, in particular vacuum formed plastic, roll formed aluminum sheet, fiber-glass plus epoxy and aluminized mylar on urethane foam, and

aluminized mylar on paper honeycomb. With all these processes, the resulting mirror surface quality was quite satisfactory in view of the large acceptance angle of the CPC. This fact is illustrated by the angular scan shown in Fig. 6. It is the measured angular response of a 1.5x CPC with roll formed aluminum sheet reflector and Owens-Illinois receiver. The most durable reflector is obtained by roll forming anodized aluminum sheet. Even with this process which is the most expensive of the ones considered, the projected cost¹⁵ of the reflector assembly is only around \$25.-per m² of the collector aperture. With aluminized vacuum formed plastic, the reflector cost could be reduced to 5.-\$/m².

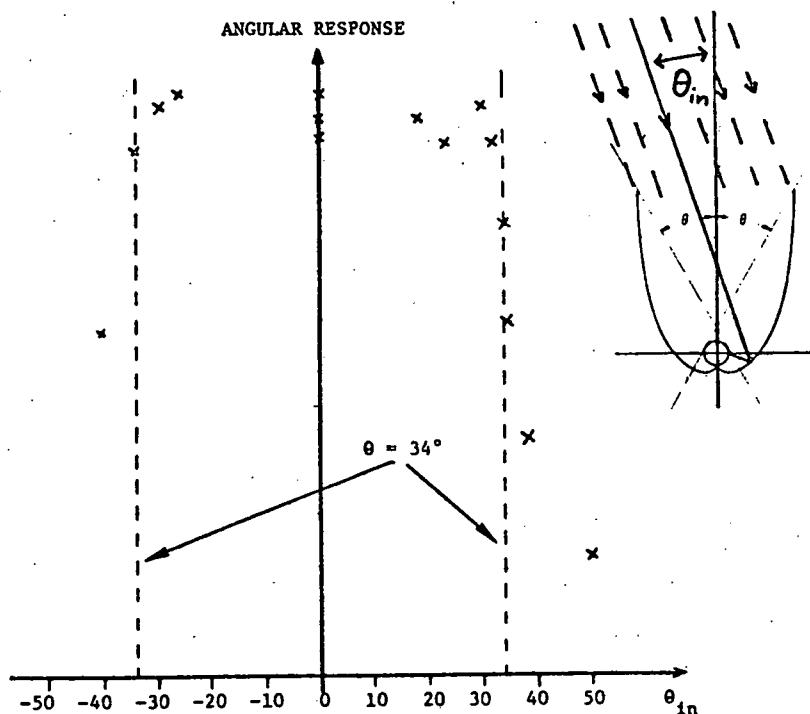


Fig. 6. Measured angular response (relative units on y-axis) of 1.5x non-imaging concentrator.

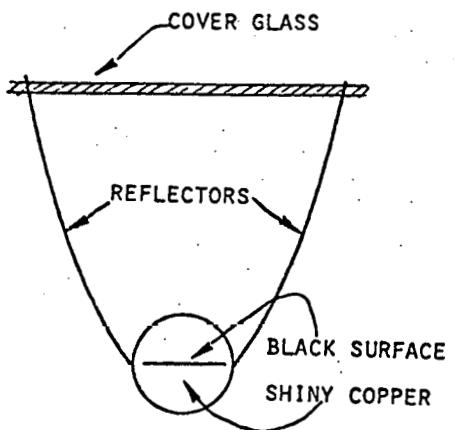


FIGURE 7. CROSS SECTION OF 3x CPC
WITH CORNING RECEIVER

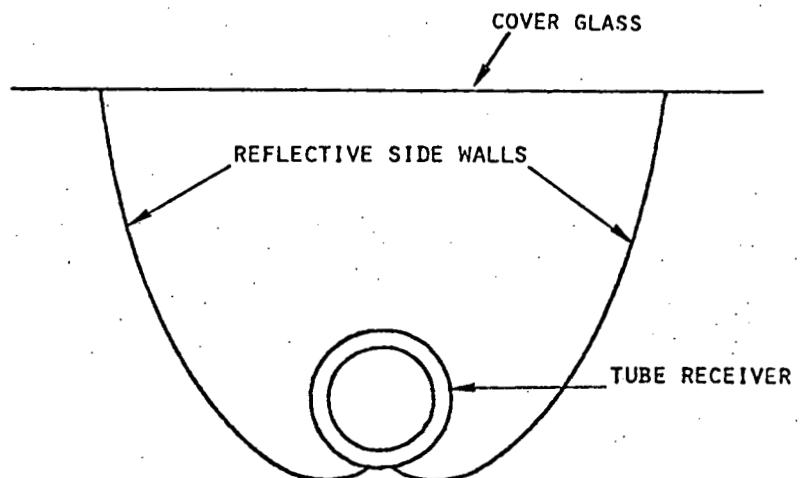


FIGURE 8. NONIMAGING 1.5X CONCENTRATOR COUPLED
TO TUBULAR EVACUATED RECEIVER (GENERAL
ELECTRIC OR OWENS-ILLINOIS)

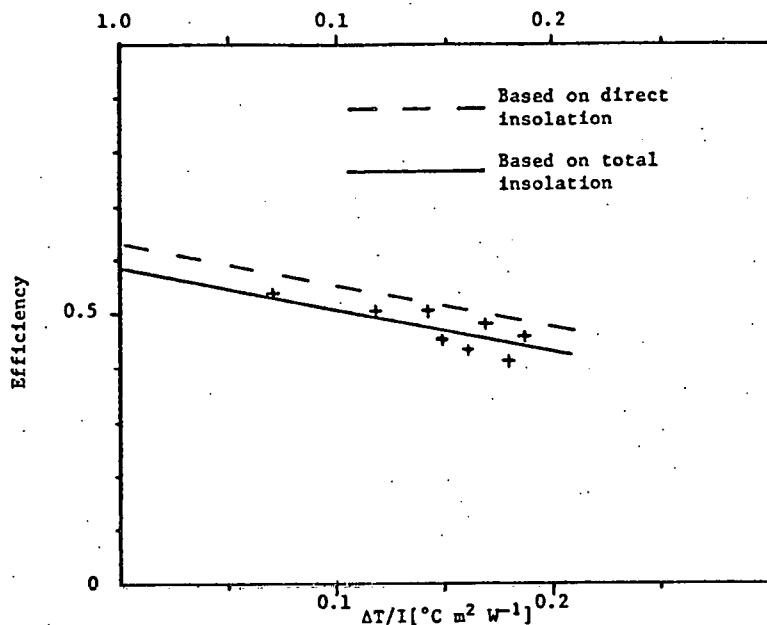


Fig. 9. Measured performance of fixed 1.5x nonimaging concentrator with General Electric receivers.

The cross section of the Corning receiver (one-sided flat absorber) with its matching CPC reflector is shown in Fig. 7. The CPC configuration appropriate for the Owens-Illinois and for the General Electric receivers (tubular absorbers) is shown in Fig. 8. In order to prevent the accumulation of dirt and snow in the reflector troughs, we choose to cover the aperture of all collectors with a flat sheet of glass or acrylic. Even though such a cover causes reflection and absorption losses, it enhances the long term performance by keeping the reflector clean. Furthermore, it allows the use of low-cost light-weight reflector structures which need not be protected against wind loading.

The following collectors have been built or are under construction:

- (i) a 1.5x with General Electric receiver (i.e. geometric concentration ratio $C = 1.5$).
- (ii) a 1.5x with Owens-Illinois receiver.
- (iii) a 3x with Corning receiver.

- (iv) a 5x with Corning receiver (etched glass¹⁶ used for cover and for receiver, silvered plastic film used for reflector.)
- (v) a 5x with Owens-Illinois tubes (but with heat transfer fluid loop modified to be like that of the General Electric receiver).

Several optical and thermal tests were carried out in order to measure optical efficiency and heat loss of the collectors. The most important of these are the measurement of angular acceptance characteristic (see Fig. 6), the measurement of optical efficiency η_0 , and the measurement of the heat loss coefficient U . For collectors with General Electric and Owens-Illinois receivers, the optical efficiency can best be determined by the following method. One fills the inside of the receiver tube of a single CPC module with cold water and then exposes the receiver plus reflector module to steady sunshine for about half an hour. The resulting temperature rise multiplied by the heat capacity of the water (with small corrections for heat losses and for heat capacity of the inner glass tube) gives a direct measure of the energy absorbed and thus of the optical efficiency. The heat loss coefficient U can be measured in the laboratory or outside at night by flowing water through the collector and measuring temperature drop and flow rate. The efficiency η of a collector operating at a plate temperature T_p which is $\Delta T = T_p - T_a$ above ambient, is then given by

$$\eta = \eta_0 - U \Delta T / I \quad (3)$$

where I is the insolation. (In most collectors, U will increase somewhat with ΔT).

In addition, one can perform the so called masked stagnation test. This test simply involves running a collector under stagnation condition, i.e. at zero efficiency. To control the stagnation temperature, one reduces the incident sunshine by means of a mask, for example a perforated sheet (which should be painted black on the side facing the collector). This method measures the ratio of U value (at temperature $T_p = T_a + \Delta T$) and optical efficiency as

$$\frac{U(\Delta T)}{\eta_0} = \frac{fI}{\Delta T} \quad (4)$$

where f is the fraction of insolation I transmitted through the mask.

All of these tests are valuable because they permit determination of collector performance from a single small collector module consisting of just a single receiver in one reflector trough. Only when these tests prove satisfactory will one proceed with the construction of a complete collector panel. These tests correlate well with the performance of the collectors under actual operating conditions. Test data for collector i) are given in Fig. 9 implying operating efficiencies above 40% at $\Delta T = 150^\circ\text{C}$ above ambient with a fixed

collector. Note that the efficiency is stated in terms of total insolation on clear days. The quoted efficiency would be about 15% higher (dashed line in Fig. 9) if it were referred to direct insolation as is customary for most concentrators.

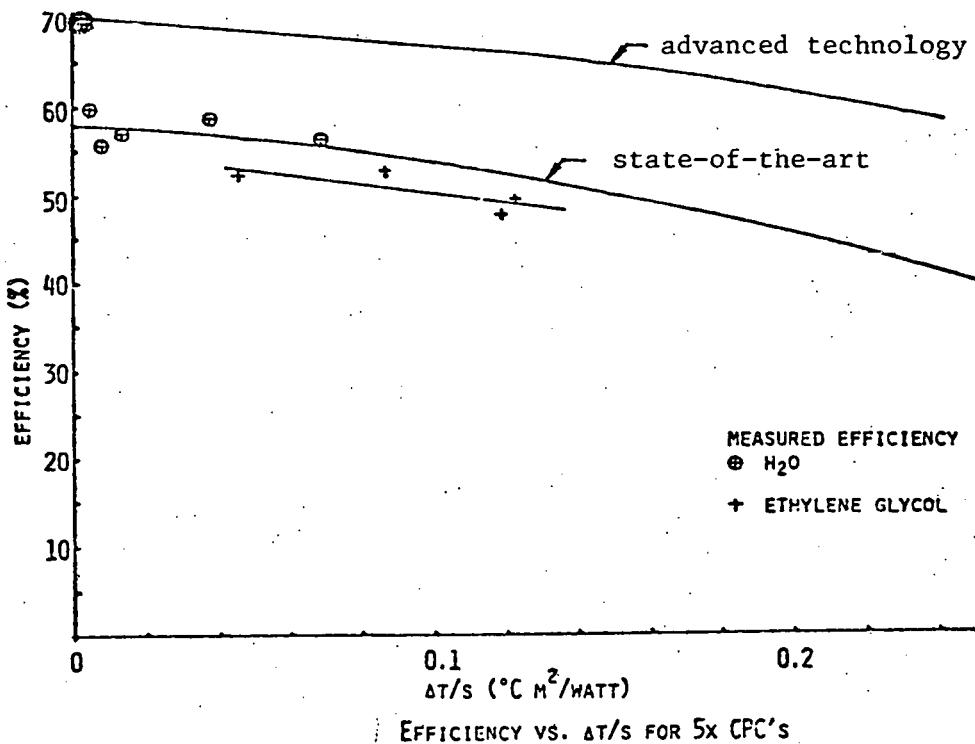


Fig. 10 Performance data of 5x CPC.

Data for a 5x CPC with Corning receiver are shown in Fig. 10. Two versions were tested, a state-of-the-art collector with untreated glass and aluminum reflectors, and on advanced technology version with etched glass and silvered reflectors. For the latter, only the optical efficiency has been measured so far; the heat losses should be the same as for the state-of-the-art version. The corresponding efficiency curve indicates operating efficiencies above 50% at 250°C making this nontracking collector a suitable candidate for electric power generation.

The state-of-the-art collectors, using aluminum reflectors and glass without antireflection surface treatment, have optical efficiencies in the range of 55 to 60%. Their U-values are on the order of $U \sim \frac{C}{\bar{W}/m^2 \cdot K}$ where C is the concentration ratio; the quoted U-value includes heat losses from the collector manifold. The collector efficiency factor F' (in the notation of Duffie and Beckman¹⁸) is better than 0.95; in other words, the difference between fluid and plate temperature does not significantly reduce the efficiency. This is due to the combination of vacuum and selective coating in collectors of this type.

New technologies are becoming available which will significantly improve the performance of nonimaging concentrating collectors. For example, etching of glass is a low-cost process which can reduce reflection losses from 4% to 1% per surface. By using etched glass and silvered reflectors, the optical efficiency can be raised above 70%.

REFERENCES

1. H. Hinterberger and R. Winston, *Rev. Sci. Instr.* 37, 1094 (1966).
V. K. Baranov and G. K. Melnikov, *Soviet Journal of Optical Technology* 33, 408 (1966).
M. Ploke, "Lichtfuehrungseinrichtungen mit starker Konzentrationswirkung", *Optik* 25, 31 (1967).
2. R. Winston, "Light Collection with the Framework of Geometrical Optics", *J. Optic Soc. Am.*, 60, 245 (1970).
3. R. Winston, 'Solar Concentrators of a Novel Design", *Solar Energy*, 16, 89 (1974).
4. A. Rabl, "Comparison of Solar Concentrators", *Solar Energy*, 18, 93 (1976).
5. H. Tabor, "Stationary Mirror Systems for Solar Collectors". *Solar Energy* 2, 27 (1958). H. Tabor, "Mirror Boosters for Solar Collectors", *Solar Energy* 10, 111 (1966).
6. R. Winston and H. Hinterberger, "Principles of Cylindrical Concentrators for Solar Energy", *Solar Energy* 17, 255 (1975).
A. Rabl, "Solar Concentrators with Maximal Concentration for Cylindrical Absorbers", *Applied Optics* 15, 1871 (1976).
7. A. Rabl and R. Winston, "Ideal Concentration for Finite Sources and Restricted Exit Angles", *Applied Optics* 15, 2880 (1976).

REFERENCES (Cont.)

8. A. Rabl, N. B. Goodman, and R. Winston, "Practical Design Considerations for CPC Solar Collectors", (Jan. 1977), to be published in Solar Energy.
9. W. McIntire, Argonne National Laboratory
10. A Rabl, "Optical and Thermal Properties of Compound Parabolic Concentrators", Solar Energy 18, 497 (1976).
11. A Rabl, "Radiation Transfer Through Specular Passages", Int. J. Heat Mass Transfer, 20, 323 (1977).
12. R. Bingman, Final Report for Contract 31-109-38-3805, General Electric Space Division, (1977).
13. U. Ortabasi and W. M. Buehl, "Analysis and Performance of an Evacuated Tubular Collector", presented at ISES Conference in Los Angeles, California (July 1975).
14. D. C. Beekley and G. R. Mather, Jr., "Analysis and Experimental Tests of High Performance Tubular Solar Collectors", presented at ISES Conference in Los Angeles, California (July 1975).
15. Estimate of Reflector Cost by Chamberlain Manufacturing Corporation, Waterloo, Iowa 50705, U.S.A.
16. R. E. Peterson and J. W. Ramsey, "Thin Film Coatings in Solar-Thermal Power Systems", J. Vac. Sci. Technol., 12, 174 (1975).
An etching process for borosilicate glass (pyrex) has been developed by Corning Glass, Corning, New York.
17. Supplied by Sheldahl, Inc., Northfield, Minnesota.
18. J. A. Duffie and W. A. Beckman, "Solar Energy Thermal Processes", John Wiley & Sons, New York, 1974.