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NONIMAGING CONCENTRATORS FOR SOLAR THERMAL ENERGY

Final Report

By
Roland Winston
Joseph J. O'Gallagher

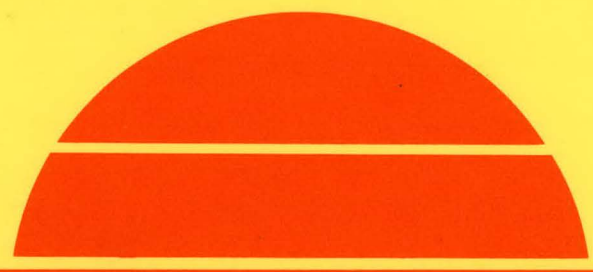
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The University of Chicago
Enrico Fermi Institute
Chicago, Illinois



U.S. Department of Energy



Solar Energy

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Final Report

Department of Energy

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Submitted by: The University of Chicago
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March 21, 1980

Abstract

A small experimental solar collector test facility has been established on the campus of the University of Chicago. This capability has been used to explore applications of nonimaging optics for solar thermal concentration in three substantially different configurations: 1) a single stage system with moderate concentration on an evacuated absorber (a 5.25X evacuated tube Compound Parabolic Concentrator or CPC), 2) a two stage system with high concentration and a non-evacuated absorber (a 16X Fresnel lens/CPC type mirror) and 3) moderate concentration single stage systems with non-evacuated absorbers for lower temperature (a 3X and a 6.5X CPC). Prototypes of each of these systems have been designed, built and tested. The most important performance characteristics are as follows:

- a) The 5.25X evacuated tube CPC achieved an operating efficiency (relative to beam insolation) of 58% measured at $\Delta T = 220^\circ\text{C}$ above ambient. The measured acceptance angle was $\pm 8^\circ$ in precise agreement with design, allowing year round energy collection with 12 to 14 tilt adjustments, collection of the circumsolar component and at least 20% of the diffuse, and the use of optically "sloppy" mirror surfaces.
- b) The 16X (non-evacuated) two stage lens mirror concentrator achieved an operating efficiency (also relative to beam) of 42% at $\Delta T = 240^\circ\text{C}$ above ambient. The measured acceptance angle was $\pm 3^\circ$ as designed and would allow sloppy tracking with only a constant speed clock device.
- c) The 3X CPC and a modified version of the 6.5X CPC with non-evacuated absorbers achieved efficiencies (relative to total insolation) referenced to operation at $\Delta T = 95^\circ\text{C}$ above ambient of 39% and 50% respectively. The acceptance angles were as designed and inexpensive materials and fabrication techniques could be used in large scale production.

In addition a 73 m² experimental array of 3X non-evacuated CPC's has been installed in a school heating system on the Navajo Indian Reservation in New Mexico. The full array has a peak noon time efficiency of $\sim 50\%$ at $\Delta T = 50^\circ\text{C}$ above ambient and has supplied about half the school's heat load for the past two heating seasons. Several theoretical features of nonimaging concentration have been investigated including their long term energy collecting behavior. Despite several unanticipated delays the results of this study have achieved the essential elements of the original objectives. The measured performance of the different systems shows clearly that non-tracking concentrators can provide solar thermal energy from moderately high "low temperature" regimes ($> 50^\circ\text{C}$ above ambient) up into the mid-temperature region (well above 200°C above ambient). The measured efficiency at 220°C for the 5.25X CPC was as high or higher than that for any of the commercial tracking systems tested at Sandia Laboratories. In addition nonimaging second stages can bring to focussing high concentration devices many of the advantages of thermodynamically maximal concentrating optics.

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I. The roof top test station on the University of Chicago campus

Nonimaging Concentrators for Solar Thermal Energy

I. Introduction

A. Background

Since early 1974 a new family of optical concentrators referred to as "ideal" light collectors^[1-2] has been under study at Argonne National Laboratory and the University of Chicago. These concentrators differ from those based on traditional focussing optics in that they are optimized for a wide angular field of view and attain the maximum possible concentration permitted by physical principles. Single stage reflecting troughs for solar energy collection designed according to these methods have come to be called Compound Parabolic Concentrators or CPC's and are by now well known for their ability to achieve moderate levels of concentration without active tracking of the sun^[3]. The profiles of commonly recommended CPC configurations^[4-6] are shown in Figure 1 and illustrate the wide angular acceptance possible. Reflecting troughs with these profiles achieve geometrical concentrations of $C = (\sin\theta_c)^{-2}$ directing all rays within $\pm\theta_c$ at the aperture to the absorber, be it a flat surface, fin, wedge or tube. Designs similar to that of Figure 1 coupled to an evacuated tubular absorber with a selective coating have been developed to a high degree at Argonne National Laboratory^[7] as totally stationary collectors. These serve as the basis for several collector models which are commercially available now or will be in the near term future.

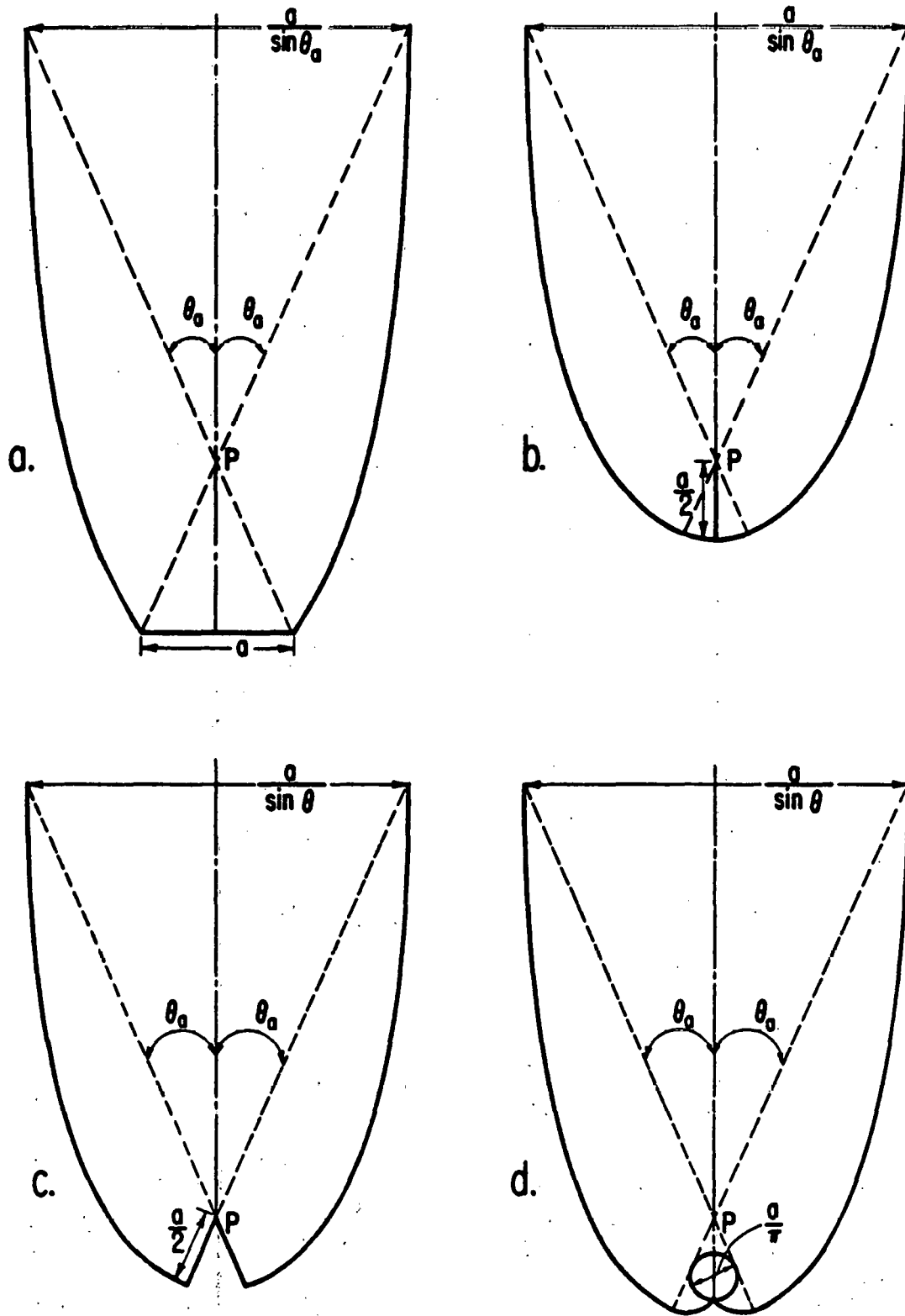


Fig. 1 Four basic CPC configurations.

After a period of close collaboration with the Argonne effort the Solar Energy Group at the University of Chicago established a small but separate experimental program to investigate selected advanced prototype designs and develop further the principles of nonimaging optics for solar applications. This report summarizes the work at the University supported during the Period July 1, 1977, to September 30, 1978, by Contract DE-AS02-76ER20236 under the auspices of the Advanced Technology Division of the Solar Thermal Branch of the U.S. Department of Energy with a total funding level of \$300,000.

B. Task Outline

The overall effort was divided into five separate hardware tasks in addition to some general topics in basic research. The five hardware tasks had to do with CPC prototype construction and test and supporting activities and are listed below.

1. Establishment of a Roof Top Test Station

A project to construct a small facility on the roof of the High Energy Physics Building on campus on Chicago's South Side was begun with the object of achieving the capability for testing small collector prototypes and monitoring insolation characteristics.

2. Construction and Test of a 5.25X CPC with an Evacuated Tubular Absorber

The object of this program was to examine experimentally, the performance of a high temperature CPC capable of efficient operation approaching 300°C.

3. Construction and Test of an Advanced Two Stage (Fresnel Lens/
CPC Type Mirror) Nonimaging Concentrator

This project involved the design and experimental evaluation of a high concentration (16X) nonimaging system with greatly relaxed tracking tolerances ($\pm 3^\circ$).

4. Construction and Test of Non-evacuated CPC's for Lower
Temperature ($\sim 100^\circ\text{C}$) Applications

A detailed program to evaluate design and construction methods for CPC's with nonevacuated absorbers was oriented around the development of two specific collector designs, one a 6.5X for a tubular absorber (Figure 1d) and the other a 3X concentrator for a vertical fin receiver (Figure 1b).

5. The Field Test of an Array of 3X Non-evacuated CPC's in New Mexico

This task represented the actual implementation of a project initiated in 1975 in collaboration with the Bureau of Indian Affairs. Its main objective has been to install an experimental array of non-evacuated CPC's as part of the space heating system at the Bread Springs Elementary School on the Navajo Indian Reservation near Gallup, New Mexico.

In addition, the following basic research areas were identified as being of immediate interest:

1. the development of a mathematical model and computer code capable of predicting the long term average performance of CPC's given climatological data for a particular location,
2. the investigation of the effect of non-specular features in the optical elements of nonimaging concentrators, and
3. the study of further applications of the basic formalism of nonimaging optics in the quest for possible new concentrator designs.

C. Program Highlights

During the spring and summer of 1977 a permanent test facility consisting of a low temperature water test loop and a small high temperature Therminol test loop was constructed on the proposed location. A comprehensive data acquisition system was installed and during the subsequent year a program of prototype collector testing was carried out. Some of the major accomplishments of these activities are listed below:

1. Two high temperature 5.25X CPC modules with acceptance angles of $\pm 8^\circ$ were constructed and tested. The second model had a measured optical efficiency of 63% and has been operated at a temperature of 220°C ($\sim 400^\circ\text{F}$) above ambient with a measured efficiency of $59 \pm 2\%$. This performance is comparable to that achieved by the best fully tracking parabolic trough concentrators and yet is achieved with a collector requiring only 12 tilt adjustments per year.

2. A high concentration 16X concentrator using a Fresnel lens combined with a nonimaging mirror to achieve a measured full angle of acceptance of 6° was built and tested. In a polar mount this wide acceptance would permit continuous tracking of the sun with only a constant speed clock drive.

3. It was shown that non-evacuated CPC's, although clearly not classified as high temperature collectors, have a measured performance which exceeds that for typical flat plate collectors at temperatures above roughly 60°C (140°F) and should have economic advantages as well if properly constructed. As part of this prototype development effort, a comprehensive

set of design methods and test procedures for non-evacuated CPC's was developed.

4. The full array of 73 m^2 (784 ft.^2) of 3X non-evacuated CPC modules was installed at the Bread Springs School in the spring of 1977. There has been a dramatic drop in the consumption of fuel oil by the school. The array has been supplying approximately half the building's heating load for two years and the full collector array noon time efficiency (including the effect of distribution losses) has typically been about 50% at $\Delta T = 50^\circ\text{C}$ (90°F) above ambient. The array is fully instrumented: a data acquisition system is in place and for the first time data on the long term optical performance of a CPC array is being systematically monitored.

Studies in basic research have contributed substantially to our understanding of nonimaging solar concentrators. A model for the prediction of long term annual energy collection by CPC's and other concentrating collectors has been developed and is now in wide use. The relationship between mirror slope errors and concentrator acceptance angle, optical throughput and intensity distribution on the absorber is now well understood. Finally, the basic family of concentrator designs has been expanded and new developments continue to occur.

All of the collector development efforts are reviewed in some detail in separate subsections of Part II of this report. Part III summarizes the basic research work and Part IV is an overall summary of the accomplishments and potential for future applications of nonimaging concentrators to solar thermal energy.

D. Explanatory Note

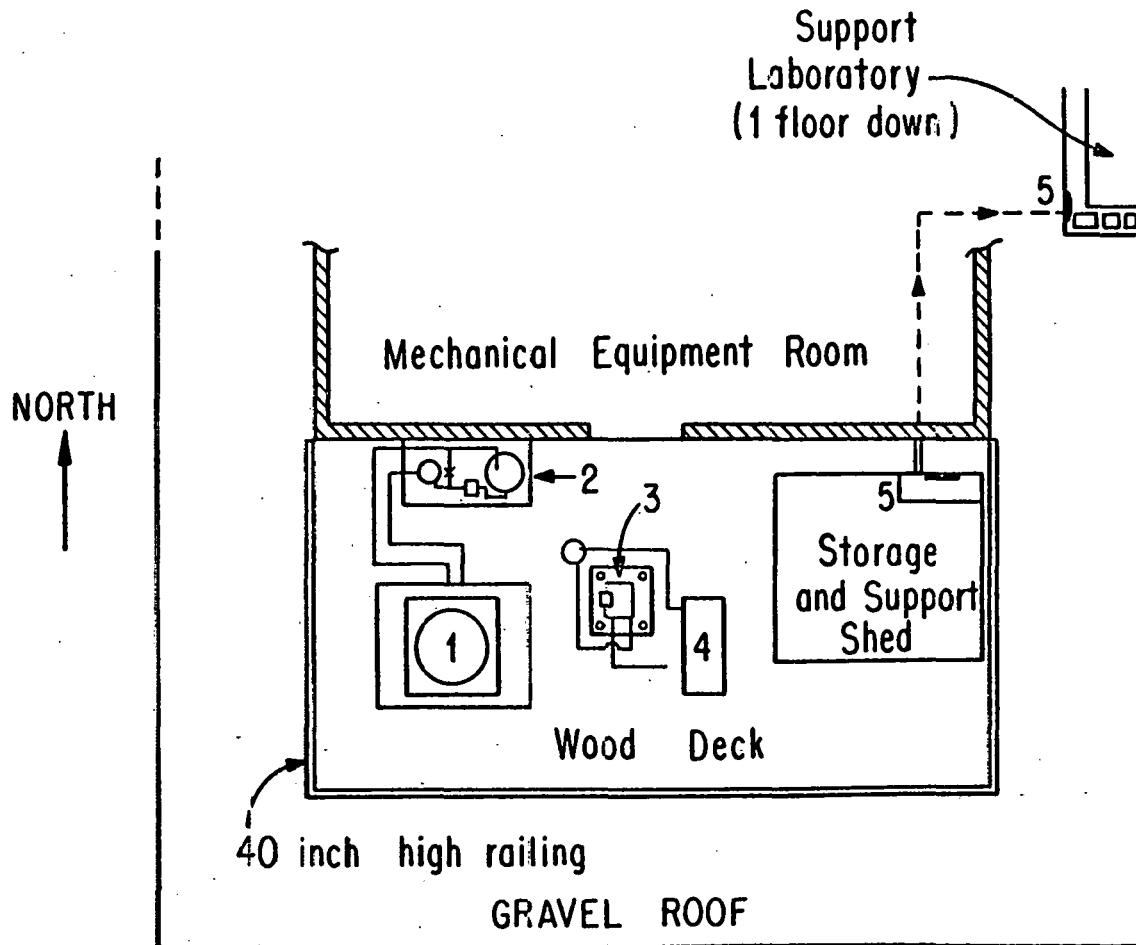
Some of the activities described in this report continued until the summer of 1979. It has been our desire to include the results of those efforts that account in part for the delay in issuance of this final report. In particular we wish to acknowledge additional support from Argonne National Laboratory under the auspices of the Department of Energy Office of Solar Applications, Market Analysis Division, which permitted the final field adjustments on the Bread Springs array to be completed.

II. Review of Prototype Development Tasks

A. The Roof Top Test Station

The test station was built on a 41' x 20' wooden deck surrounded by a 40 inch high railing constructed on the south portion of the roof of the High Energy Physics Building of the University of Chicago campus. This location was selected because it gives a completely unobstructed view of the southern sky and the sun's path throughout the year and because it is easily accessible by inside stairs through the mechanical equipment room of the building. The layout of the essential elements making up the facility is illustrated in Figure 2. There are two collector test stands (one permanent and one portable), two test loops (water and Therminol), a storage and support shed and finally a full support laboratory located one floor down inside the building.

The permanent collector test stand consists of a 4' x 8' aluminum frame mounted on a gymbals so as to be adjustable in elevation and set on



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 CAMPUS SOLAR TEST FACILITY
 Roof; High Energy Physics Building

1. Two-Axis Platform
2. Thermionol-Loop Protective Shed
3. Water-Loop
4. One-Axis Stand
5. Signal Terminal Boards

Figure 2 Layout of roof top test station at the University of Chicago.

a turntable which is bolted to the wood deck, permitting rotation about a vertical axis as well. The small portable stand is adjustable in elevation only, but is mounted on wheels so that it also can be positioned manually to any orientation desired. The permanent stand was used for the 5.25X evacuated CPC and the 6.5X non-evacuated CPC collectors. The portable stand has been used for the lens mirror concentrator and the 3X non-evacuated prototype module.

A schematic of the Therminol test loop system is shown in Figure 3. A reservoir of Therminol is maintained under a nitrogen atmosphere in an expansion tank. The fluid is drawn past three 1-kilowatt immersion heaters by a small capacity positive displacement metering pump (Bran and Lubbe Model N-P 31). The latter requires a pulsation dampener which works quite effectively to smooth the surges in flow caused by the strokes of the pump. The fluid is circulated through the external collector loop or partially diverted through an internal by-pass loop. Although a turbine flowmeter is used to measure the flow in the collector loop, an essential feature of the system operation is the calorimeter based on a technique developed by K. Reed at Argonne National Laboratory^[8]. This device allows direct measurement of the thermal characteristics of the circulating fluid as it passes around an insulated, calibrated heat source in series with the collector being tested. Thus direct calculation of the heat gain across the collector is possible from a simple comparison of the temperature increases in the collector and the calorimeter. Specifically the heat gain the collector Q_{coll} is given by

University of Chicago Hi Temperature Test Loop

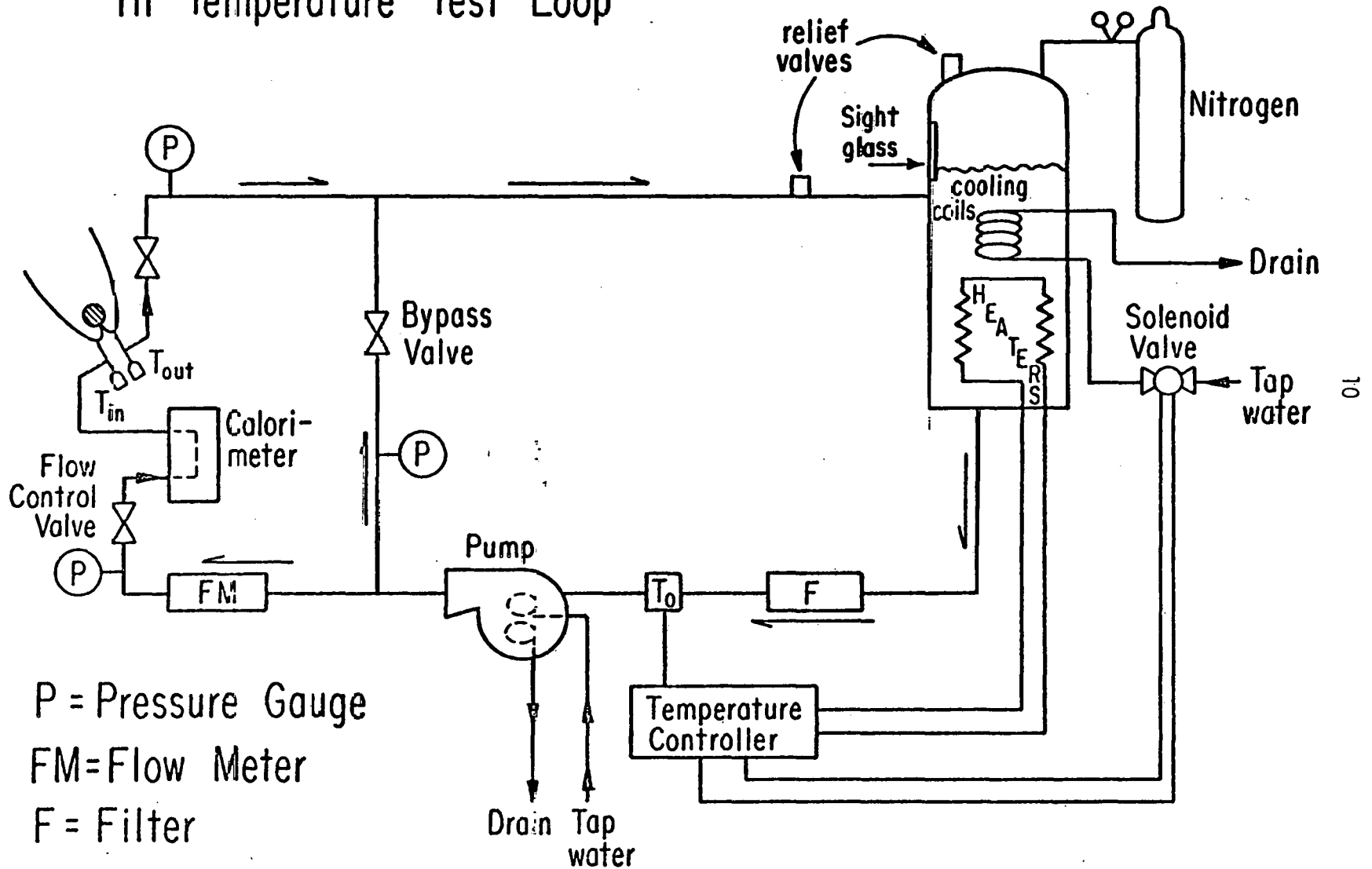


Fig. 3 Schematic of University of Chicago high temperature Therminol 66 test loop.

$$Q_{\text{coll}} = \frac{\delta T_{\text{coll}}}{\delta T_{\text{cal}}} \cdot \dot{Q}_{\text{cal}} \quad (1)$$

where Q_{cal} is the measured electric power dissipated in the calorimeter heater and δT_{cal} and δT_{coll} are the measured temperature increases across the calorimeter and collector, respectively. Note that Eq. (1) is independent of both the fluid flow rate and the fluid properties except for very small second order ($\sim 1\%$) corrections which are made in the data acquisition system described below to account for differences in the fluid properties due to the different temperatures at the calorimeter and collector.

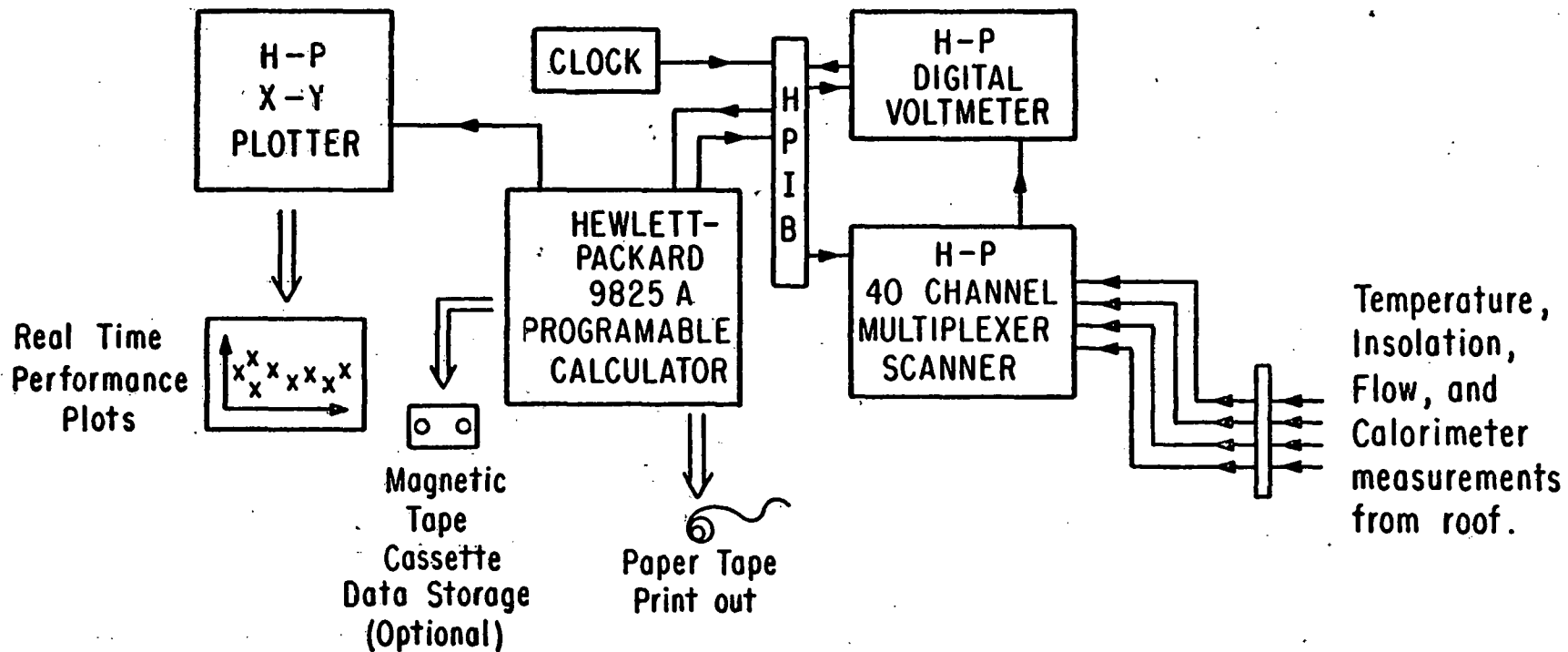
The low temperature loop is a simple unpressurized water or ethylene glycol system consisting of a small reservoir, variable speed motor driven gear pump, 2-kilowatt heater, and visual flow meter. During tests the flow is measured at regular intervals (\sim every 10 minutes) with a beaker and stop watch and monitored visually in the interim. This loop is used mostly in an "open loop" or "once through" configuration in which the water is drawn directly from the mains, heated to the desired temperature and then returned to the drains. This allows continued stable operation at very low temperatures near or at ambient so that very accurate measurements of the optical efficiency can be made.

Insolation measurements are based on a variety of instrumentation. An Eppley Black and White Pyronometer (Model 8-48) is used for monitoring of the total insolation on a horizontal plane. This instrument is not used as a reference for collector efficiency tests. The data is continuously recorded on a strip chart recorder for reference purposes, but no effort

as yet is being made to provide a reliable quantitative data base over long term periods. During active collector testing the beam component is routinely monitored with a Normal Incidence Pyroheliometer (Eppley Model N.I.P.) and total insolation is measured with a precision spectral pyroheliometer (Eppley Model PSP). Measurements of the diffuse component are made directly at regular intervals during tests by using an occulting disk 9 cm in diameter held 90 cm in front of the PSP. In addition to these instruments we also use an Active Cavity Radiometer (Radiometrics Model 10, ACR: California Measurements) for measurements of the beam component.

Temperature measurements are made using either Platinum Resistance Thermometers (PRT's) or thermocouples. The most critical temperatures, for instance at the collector and calorimeter inlet and outlet, are made using matched four-terminal PRT's. Other less critical fluid temperatures are monitored with three terminal PRT's. Collector component temperatures and ambient temperatures are monitored with type E (chromel or nickel-chromium versus Constantan or copper-nickel) thermocouples.

All critical parameters which are to be routinely monitored are measured by the data acquisition system illustrated schematically in Figure 4. The heart of this system consists of a Hewlett-Packard 9125A programmable calculator with peripheral equipment including a 40 channel multiplexer-scanner, a controllable digital voltmeter and a X-Y plotter. All of this equipment is located in the support laboratory one floor down inside the building. Signal leads from the test facility are brought



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 Data Acquisition System

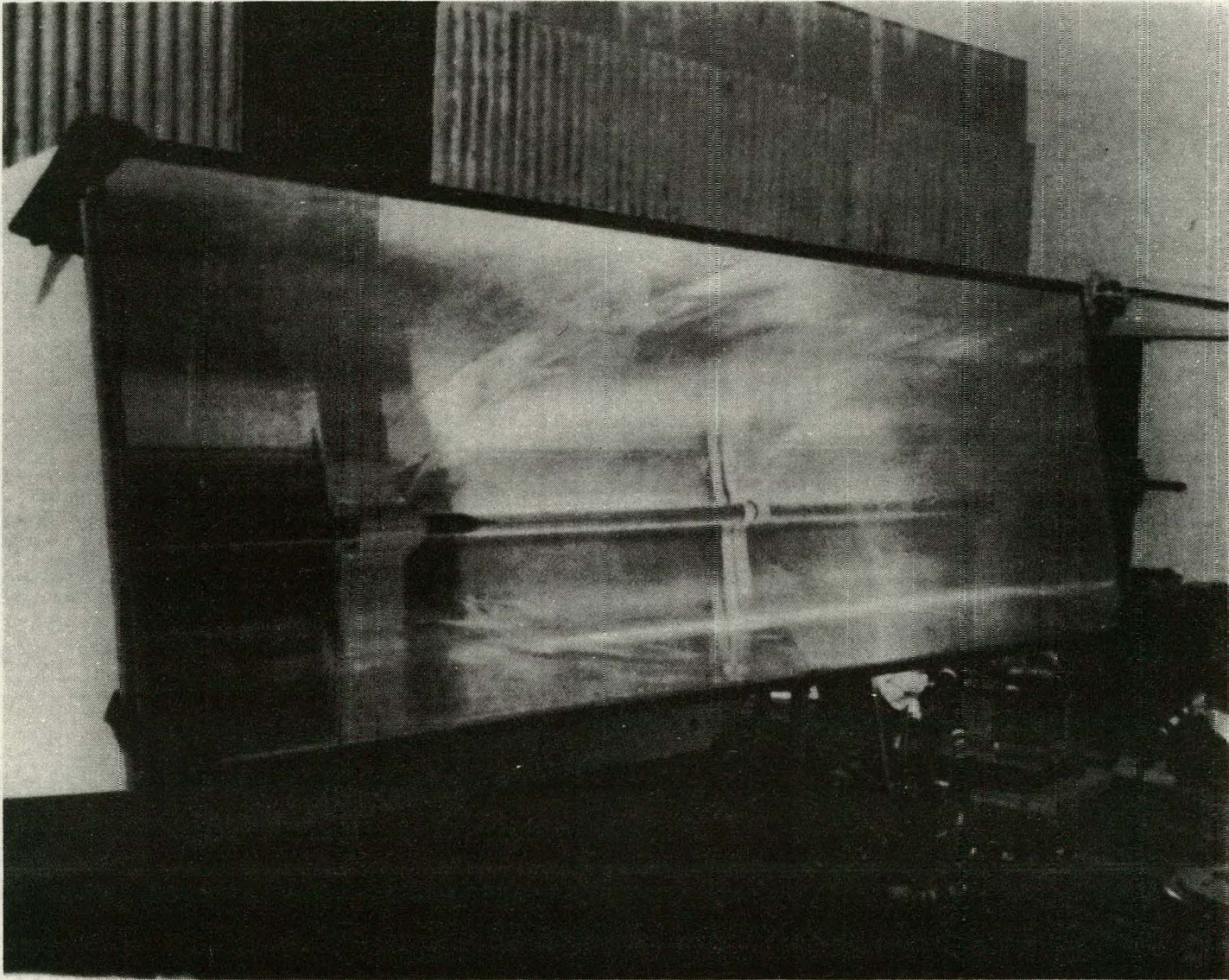
Fig. 4 Schematic of data acquisition system at University of Chicago test facility.

to a 40 channel terminal board in the support shed, from which the signals are routed downstairs to the indoor laboratory and connected to the 40 channel scanner.

During collector testing all relevant sensors are interrogated every 2-4 seconds. The calculator is programmed to make all necessary conversions and corrections. The resulting data is accumulated over a pre-set time interval, usually 1 to 3 minutes, and then the average efficiency, insolation, collector inlet temperature and other data are printed out on paper tape and plotted in real time. An example of the output of this system is shown in Figure 5 which is an all day performance test of the 5.25X evacuated tube CPC discussed in the next section.

B. The 5.25X Evacuated Tube CPC

Because nonimaging concentrators of the Compound Parabolic Concentrator (CPC) type are limited to concentration factors ≤ 10 in non-tracking applications, it is sometimes not recognized that they are capable of competitive performance at the high temperature ($\sim 300^{\circ}\text{C}$) required for power generation. In particular, when an intermediate concentration is combined with other recent high technology improvements in absorber design, i.e., selectively coated vacuum enclosed receivers, collector heat losses can be reduced to values per unit aperture area usually associated with much higher concentration ($\approx 15\text{X}$). Based on calculated performance projections^[9,10] a 5.25X CPC coupled to commercially available evacuated tubular receivers of the Owens-Illinois or General Electric type, was selected as a baseline design for two prototype modules for experimental study.



II. 5.25X evacuated CPC

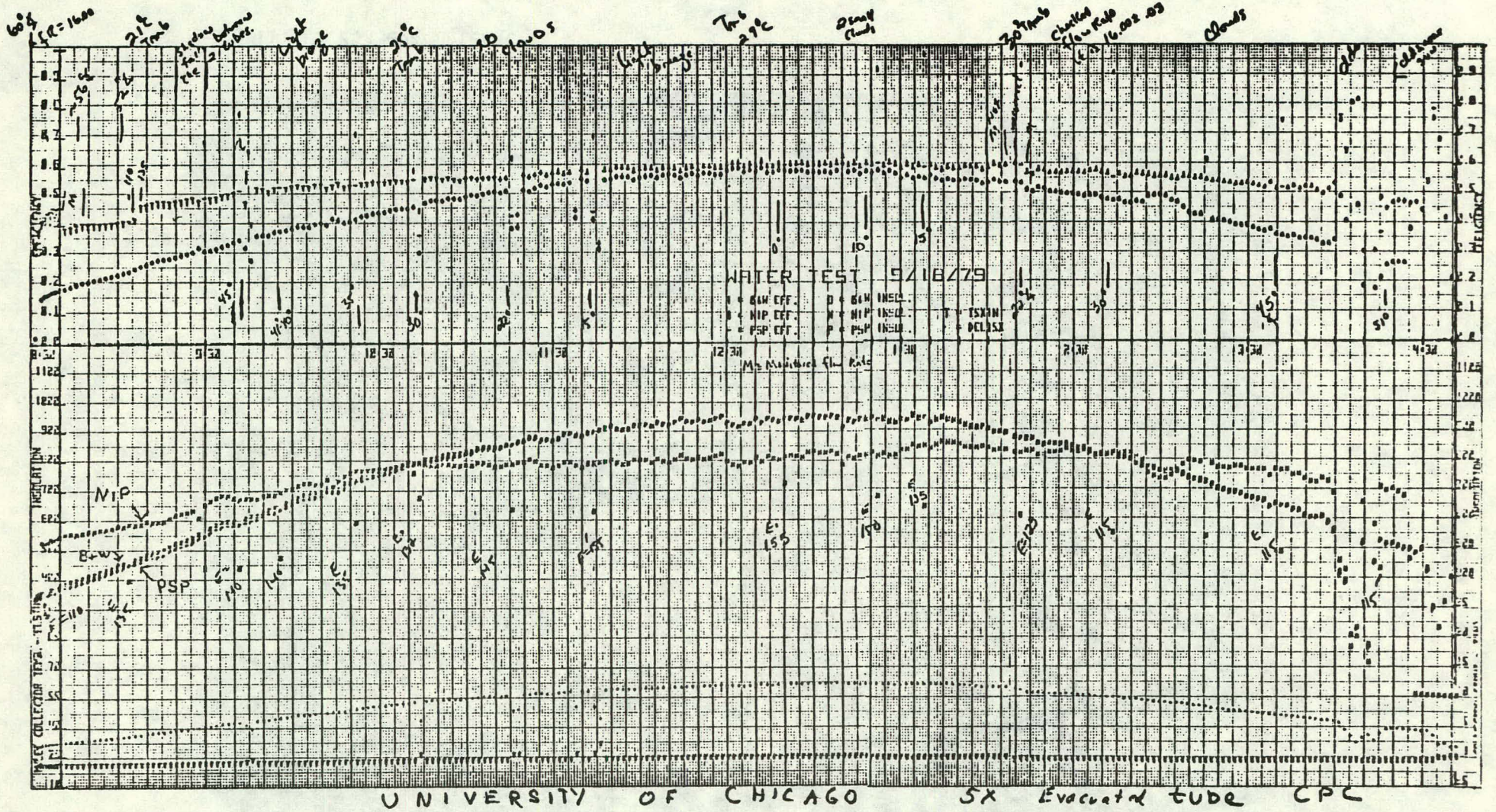


Fig. 5 Real time computer plot of all day efficiency data for 5.25X evacuated CPC.

The basic CPC trough module design selected for this experiment is illustrated in two views in Figure 6. The CPC reflector shape is the solution for the tubular absorber with a design acceptance half angle of $\pm 8^\circ$. This angle allows an ideal concentration of 7.2X but the profile has been truncated to yield the desired effective net concentration of 5.25X and a more practical aspect ratio, while still requiring only 12-14 annual tilt adjustments (depending on the particular minimum daily collection time desired). The solution was scaled so as to match either of the two commercially available evacuated tubular absorbers cited above, both of which have an absorber diameter $d = 4.3$ cm (1.7 in). If an absorber of say, 1 cm diameter were available the aperture and height of each trough would be correspondingly reduced by more than a factor of four.

Note that the effective concentration of 5.25X is applied to the entire circumference of these absorbers so that the corresponding collecting aperture is $(5.25) \times \pi \times d$ or 71 cm. for the absorbers used here. This results in a concentrator module of rather large overall dimensions but at the same time serves to emphasize that, in terms of the precise thermodynamic definition of concentration ratio ($C \equiv \frac{\text{aperture area}}{\text{total absorber area}}$), a 5X concentrator represents a large collecting power. There remain throughout the general solar concentrator literature considerable discrepancies in the definitions of C which require that one must be careful not to use quoted values as a relative figure of merit unless they are all defined consistently. For example, the definition of $C \equiv \frac{\text{aperture}}{\text{illuminated area}}$

University of Chicago

5.25 X High Temperature
CPC

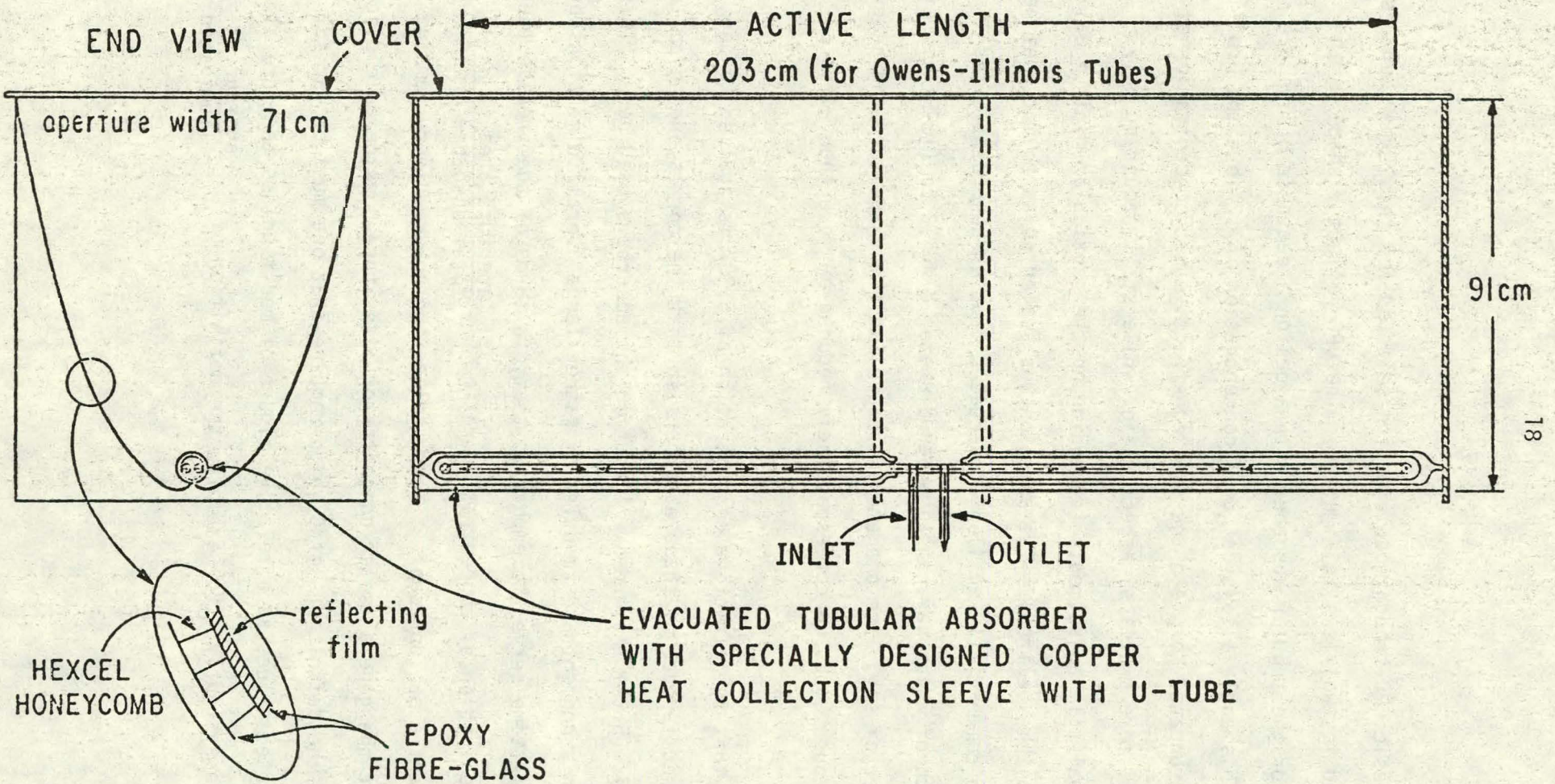


Fig. 6 Diagram of construction of 5.25X evacuated CPC.

can lead to large numerical values of C which are misleading in terms of thermal performance since heat losses may occur from some areas of the absorber which are not illuminated.

Two different prototype reflecting trough modules (A and B) were built. Both used generally the same fabrication techniques but in the second trough (module B) a reflecting foil with a higher reflectance ($\rho = 0.94$) was used to improve the optical efficiency. In both modules the reflector was formed from the same mold, machined to the desired CPC shape. Each side of a half-trough was then built up of a laminate, formed of (1) the reflecting foil, (2) epoxy fiberglass cloth, (3) Hexcel honeycomb, and (4) another layer of epoxy fiberglass. The laminate thus formed yields a rigid substrate carrying the reflector. Two symmetric halves were then mounted in a frame consisting of four wooden ribs along the length of the trough and end pieces covered on the inside with reflecting foil. Of course, since the outer glass envelope containing the vacuum enclosed glass absorber tubes must have a larger outer diameter of $\sim 5.1 - 5.3$ cm (2.0 - 2.1 in), the reflector was terminated somewhat short of the theoretical solution. This gap between the mirrors and the physical absorber allows some rays to miss the absorbers and escape back out through the aperture. The resulting "gap loss" in this case is quite small; about 1 - 2% as can be shown from application of the thermodynamically derived formula in Ref. [6] or by detailed ray trace (W. McIntire, private communication).

Two receiver tubes are mounted along the length of the trough with the open ends facing one another in the trough center. The heat transfer

fluid is carried down and back each absorber through a U-Tube which is welded to a copper heat collecting sleeve of circular cross section. The whole trough is then covered with a glazing to protect the reflecting surfaces and prevent accumulation of dust or dirt in the deep troughs. The active length of the trough modules is different for the two types of absorber and yields net aperture areas of 1.5 m^2 and 1.7 m^2 for A and B respectively. The optical properties are summarized in Table 1. The only differences between the two modules are that Module B used Sheldahl silvered foil reflectors and G.E. tubes whereas Module A used aluminized mylar foil receivers and O-I tubes. All of the differences in performance to be discussed below can be attributed to the higher reflectance of Module B.

The optical efficiencies of each collector are calculated from the formula

$$\eta_0 = \tau_1 \rho^{<n>} \tau_2 \alpha (1 - L) \quad (2)$$

(where τ_1 and τ_2 are the transmissivities of the cover glazing and absorber tube envelope respectively, ρ is the reflectivity of the foil surface, $<n>$ is the average number of reflections and α is the absorptivity of the selective coating on the receiver tube and L is the fractional "gap loss"). Note that the values of 0.52 and 0.63 for Modules A and B respectively do not include a correction of "loss of diffuse" and so should be interpreted as being with respect to direct beam radiation, not total insolation as had been conventional for lower concentration CPC's ($\approx 3X$) and flat plates. A small "bonus" due to the collection of $\sim \frac{1}{C}$ of the diffuse

Table 1

Optical Parameters of Prototype 5.25X Evacuated Tube CPC's

Cover transmissivity (τ_1)	0.90
Reflectance (ρ)	
Module A	0.85
Module B	0.95
Average number of reflections $\langle n \rangle$	1.4
Glass envelope transmissivity (τ_2)	0.90
"Gap loss" correction (1 - L)	0.98
Absorptance (α)	0.85
Net optical efficiency (η_0)	
Module A	0.529
Module B	0.625

component might be expected to add 1 to 2 percentage points to these efficiencies with respect to beam and is not quantitatively accounted for by Eq. (2).

Both collector modules, particularly Module B, have been tested extensively, both with our water test loop and our Therminol 66 loop. The operating efficiencies were determined following what we have now developed as standard operating procedure which is very similar to the methods employed at Sandia Laboratory's Mid-Temperature Test Facility^[12]. In particular, we require that the flow rate, collector inlet temperature and insolation all be stable during the measurement. To attain this stability at high temperatures sometimes requires several hours and in many cases only one efficiency point is determined from an entire day's testing - although sometimes two or more points can be obtained. The actual measurement represents an average over 15-30 minutes of stable operation at the desired temperatures. The efficiency is determined from the following relationship

$$\eta(T_{\text{coll}}) = \frac{\dot{Q}_{\text{out}}(T_{\text{coll}})}{A I_{\text{DN}}} \quad (3)$$

where A is the collector area and I_{DN} is the direct normal component of the insolation measured by either a NIP (when the collector is normal to the sun) or by a PSP in the plane of the collector after subtracting the diffuse component measured by occulting the sun's image with a 9 cm disk, held 90 cm from the PSP. The numerator of Eq. (3) is determined by the calorimetric ratio technique. In particular

$$Q_{\text{out}}(T_{\text{coll}}) = h(T_{\text{coll}}, T_{\text{cal}}) \cdot \frac{\delta T_{\text{coll}}}{\delta T_{\text{cal}}} \cdot \dot{Q}_{\text{cal}} \quad (4)$$

which is the same as equation (1) except for the factor $h(T_{\text{coll}}, T_{\text{cal}})$ which is the ratio of the specific heat per unit mass at the collector temperature to that at the calorimeter temperature. Typically $h \sim 0.99 - 1.01$. As a check we often also use the metering capability of the pump, adjustable with a micrometer dial, to determine \dot{Q}_{out} from

$$Q_{\text{out}} = \rho(T_{\text{pump}}) \cdot C(T_{\text{coll}}) \cdot F \cdot \delta T_{\text{coll}} \quad (5)$$

where F is the volumetric flow rate from the metering pump, ρ is the fluid density evaluated at the pump and C is the specific heat per unit mass evaluated at the collector.

The performances for both Modules A and B measured in this manner are shown in Figure 7. Also shown is the predicted performance based on the calculated optical efficiencies in Table 1 and theoretical heat losses based on thermal properties of the tubes. In both cases, the data insofar as it extends is in good agreement with the calculated performance^[11]. To dramatize how good this performance is, we show for reference a dashed straight line characterizing the performance of the Hexcel parabolic focussing concentrator as measured by Sandia Laboratory^[12]. This prototype CPC, the first of its kind ever built, has essentially the same performance around 200°C as the Hexcel trough, which in turn, was the best among all of the commercial focussing concentrating collectors tested to date at Sandia. An operating efficiency of $58 \pm 2\%$ at a temperature 220°C above ambient has been measured for the

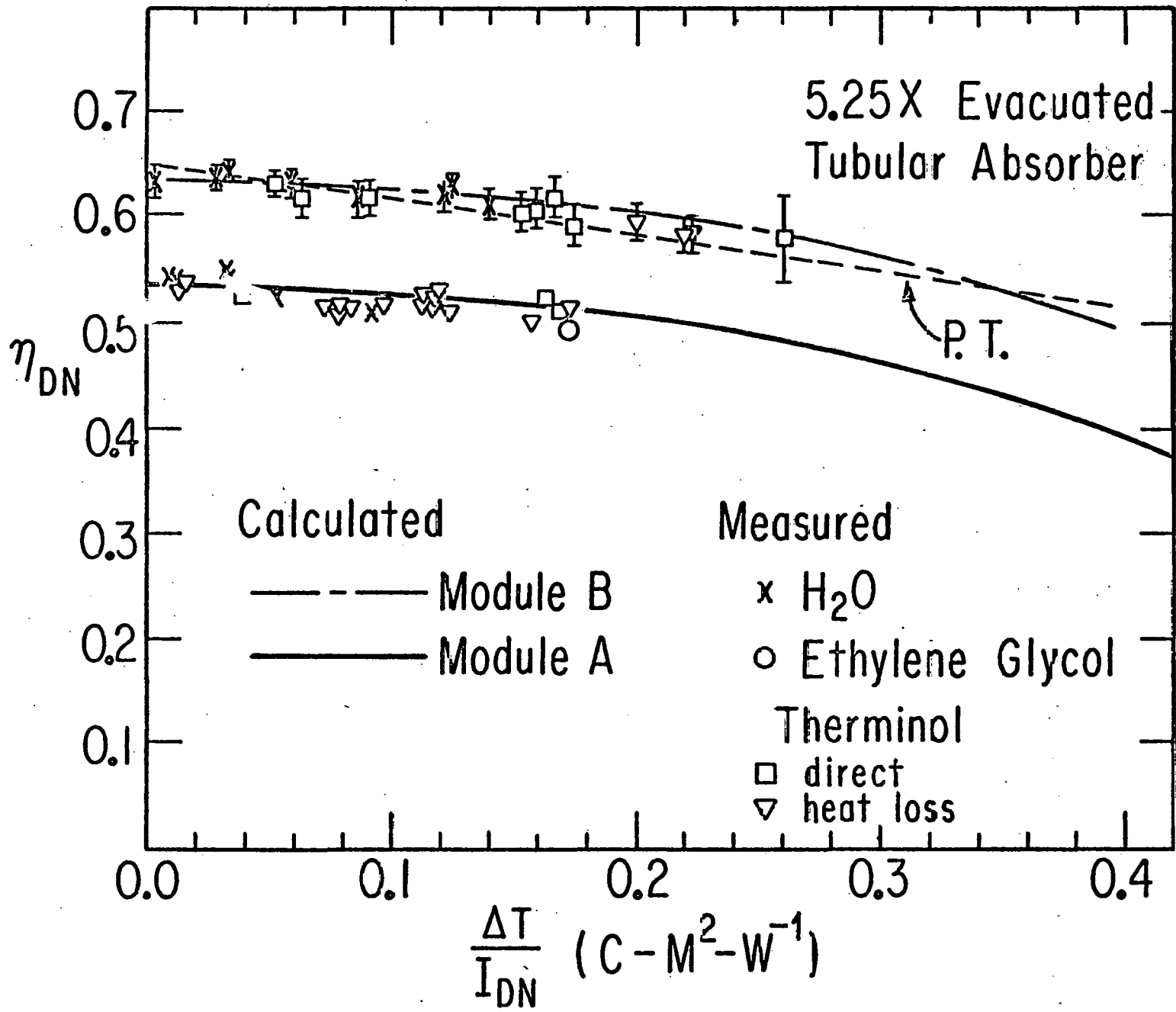


Fig. 7 Measured and predicted thermal performance curve for 5.25X evacuated tube CPC.

CPC. Extrapolation to 300°C based on the calculated performance curve yields an anticipated efficiency well above 50%, quite suitable for electric power generation applications. Clearly lower temperature industrial process heat uses are also of great potential. This has been achieved with a collector whose angular acceptance properties are broad enough so that it requires only 12 adjustments a year.

The measured angular response is illustrated in Figure 8 and is precisely as designed. The relative output remains flat (within 1%) over a full angle of 16° ($\pm 8^\circ$ with respect to the optic axis). In the top portion of the figure the response is plotted in polar coordinates with respect to an optic axis oriented as it would be in actual operation for the ten week period centered on summer solstice if it were located at a latitude of 35° (e.g., Albuquerque, N.M.). This "wedge" of acceptance in elevation would then be adjusted 12 times a year to one of the 7 tilt positions between summer and winter solstice and back as indicated in the bottom portion of Figure 8. The time interval between adjustments is not constant being shortest near equinox and longest near solstice.

The goal of operation at 300°C has not yet been achieved. No fundamental difficulties have been encountered, but certain technical difficulties have been encountered, which have prevented the extension of testing to 300°C. In particular the following two problems are of concern.

1. The Therminol test loop apparently occasionally allows a small seepage of Therminol vapor out of some of the connections inside the collector, thus depositing a thin oil film on most of the reflector surfaces, and resulting in degraded performance while operating above $\sim 200^\circ\text{C}$.

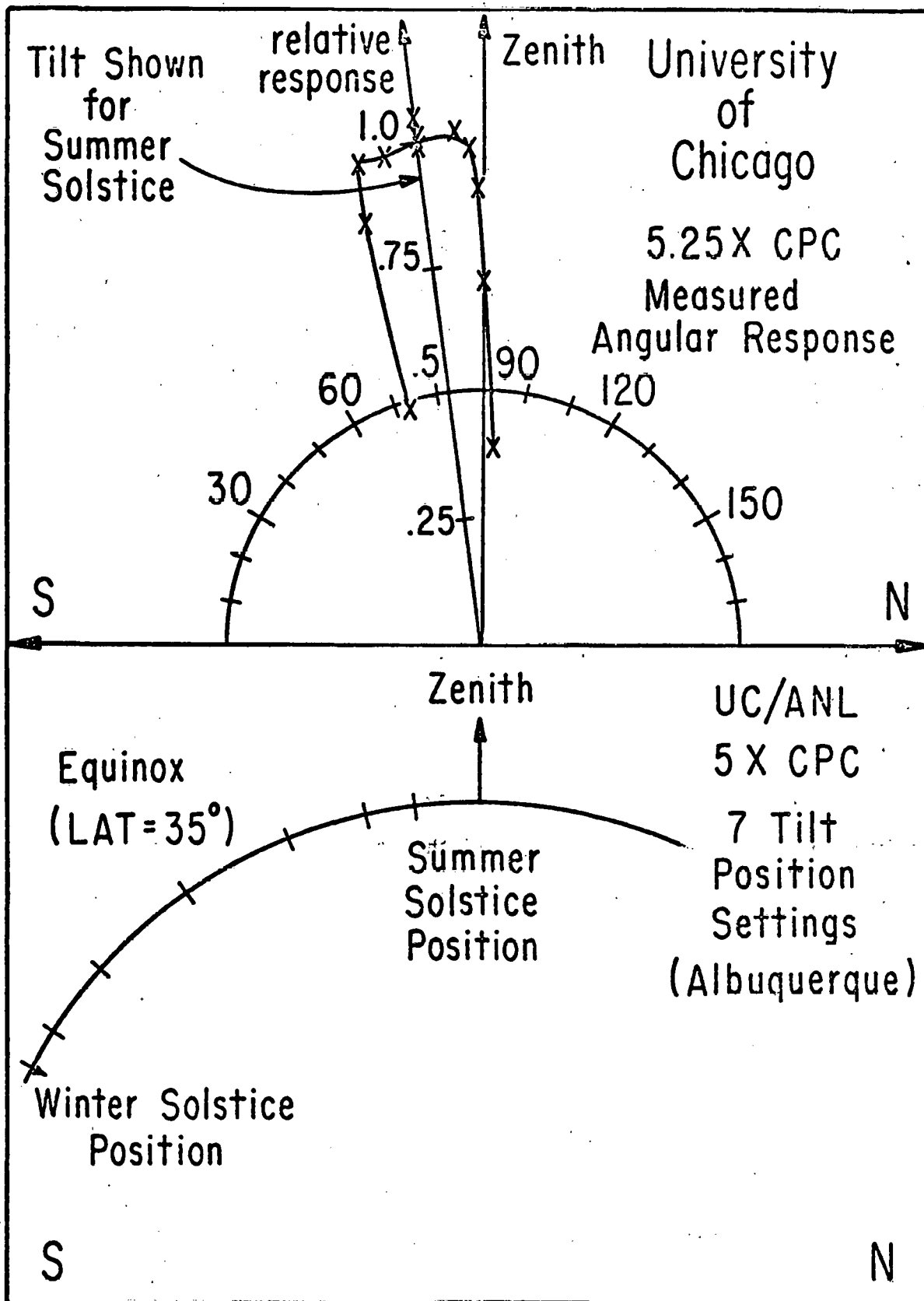


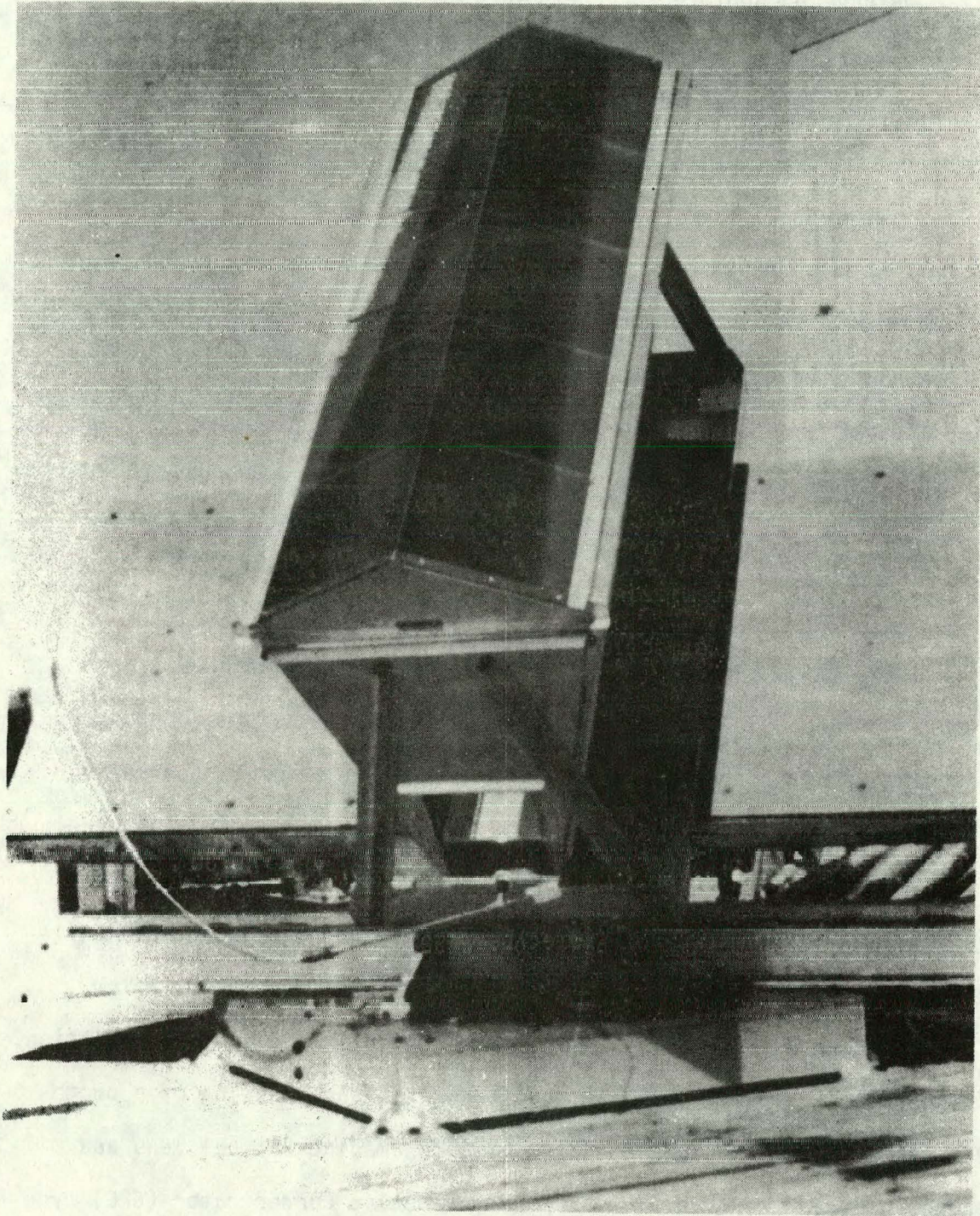
Fig. 8 Angular acceptance function for 5.25X evacuated CPC and 7 tilt orientations for annual energy collection.

2. We have encountered overheating of the tube-and-fin heat extraction sleeve, which is situated inside the evacuated tubular absorber. These tube-and-fin assemblies are essentially as designed for low concentration 1.2X CPC's with only slight modifications to improve their heat transfer capabilities. Our tests now indicate that these modifications have been adequate only for operation up to about 225°C. We are now working on a solution to improve the thermal contact between the tubes and the sleeves and increase the thickness of the heat carrying fins inside the sleeve. Calculations show that this should improve the heat transfer so that the full operating range can be extended to 300°C as planned.

C. Advanced Two Stage Lens/CPC Type Nonimaging Concentrator

To attain high temperatures in solar thermal application without the use of evacuated receivers it is necessary to use selective absorber surfaces under high concentration. If this concentration is accomplished through traditional focussing optical systems, the relationship between the concentration and acceptance angle falls short of the limit established by the 2nd law of thermodynamics. Practical consequences of this are the requirement for a precise tracking mechanism (typically a few tenths of a degree) and the loss of some circumsolar and diffuse radiation.

The present project involved the fabrication and testing of a prototype ideal type collector, consisting of a nonimaging Fresnel lens and a secondary concentrator of the Compound Parabolic Concentrator (CPC) type with a tubular receiver^[13,14,15]. The overall concentration is 16X, the



III. The lens mirror concentrator

acceptance angle is $\pm 3^\circ$ (6° full angle) and the tracking is done with a polar axis orientation. This system has the following advantages over conventional tracking systems: (i) it allows tracking of the sun with a tolerance of $\pm 3^\circ$, which would permit a simple clock mechanism (constant tracking speed) to perform the tracking, rather than a sun sensor (or micro-processor) and a variable speed tracking mechanism, (ii) it allows the collection of circumsolar radiation which is typically a few percent of the beam^[16], (iii) it matches optically in an optimum way a plane entrance aperture to a cylindrical receiver, which implies no "back losses", i.e., conductive heat losses through a nonilluminated back of the absorber, (iv) the system makes very little use of reflecting materials and since it is enclosed, use can be made of first surface glass/aluminum reflectors of high reflectivity, (v) the system has all the inherent advantages of polar and N.S. tracking systems which typically collect in all year performance 25% more than E.W. oriented tracking systems^[17], (vi) because it maintains a wide acceptance angle for rays inclined to the tracking axis, it does not require seasonal tilt adjustments of the tracking axis, as other Fresnel lens collectors do. Furthermore the lens acts as a cover and makes the whole system as immune to dust and dirt as possible.

A comprehensive description of the collector construction is contained in Ref. [18]. The overall configuration of the optical elements is shown in Figure 9 and schematically in perspective in Figure 10.

The lens was made out of acrylic and was produced by Optical Sciences Group in San Rafael, California, according to our design. It consists of

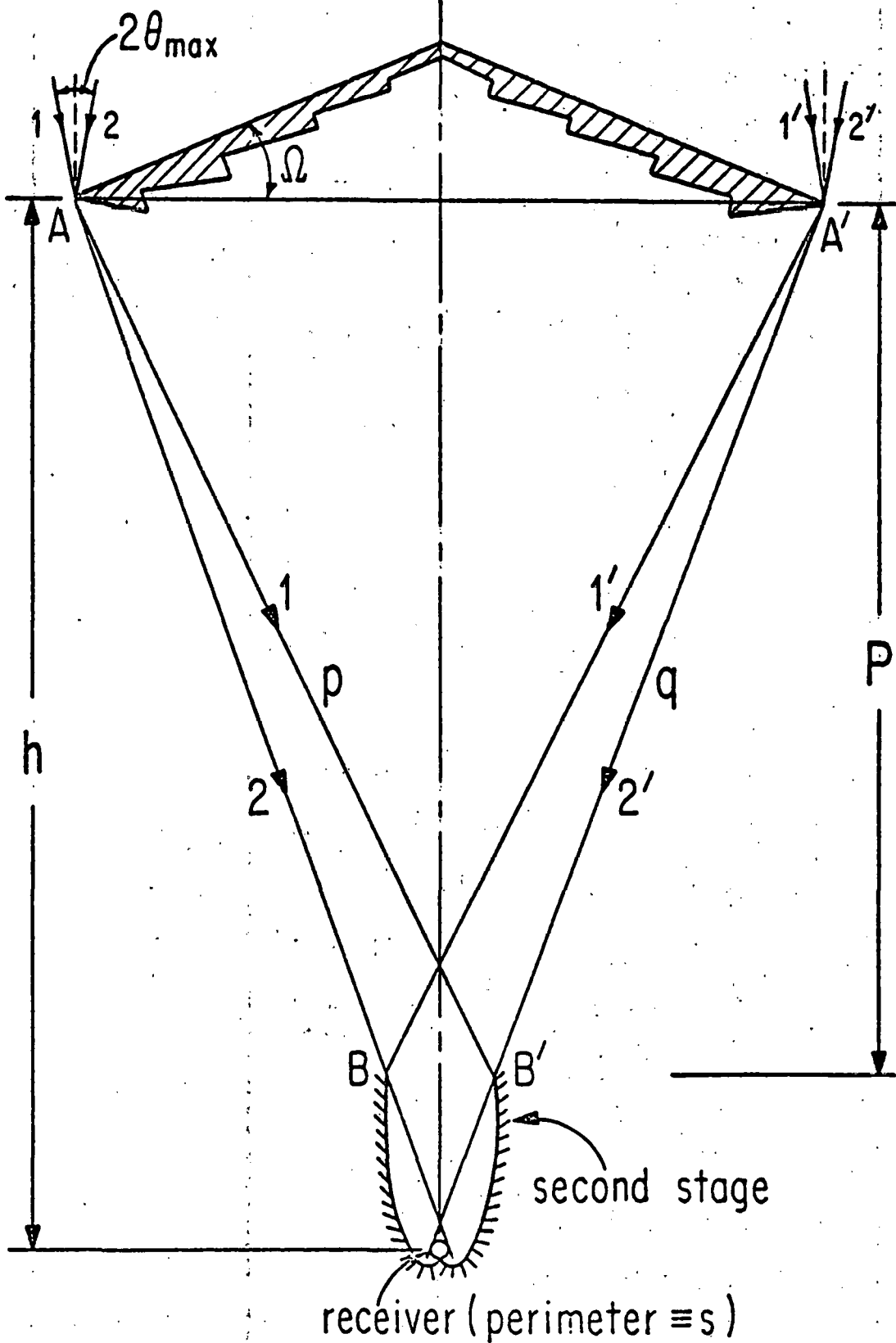


Fig. 9 Transverse cross section profile of 16X lens/CPC mirror two stage concentrator.

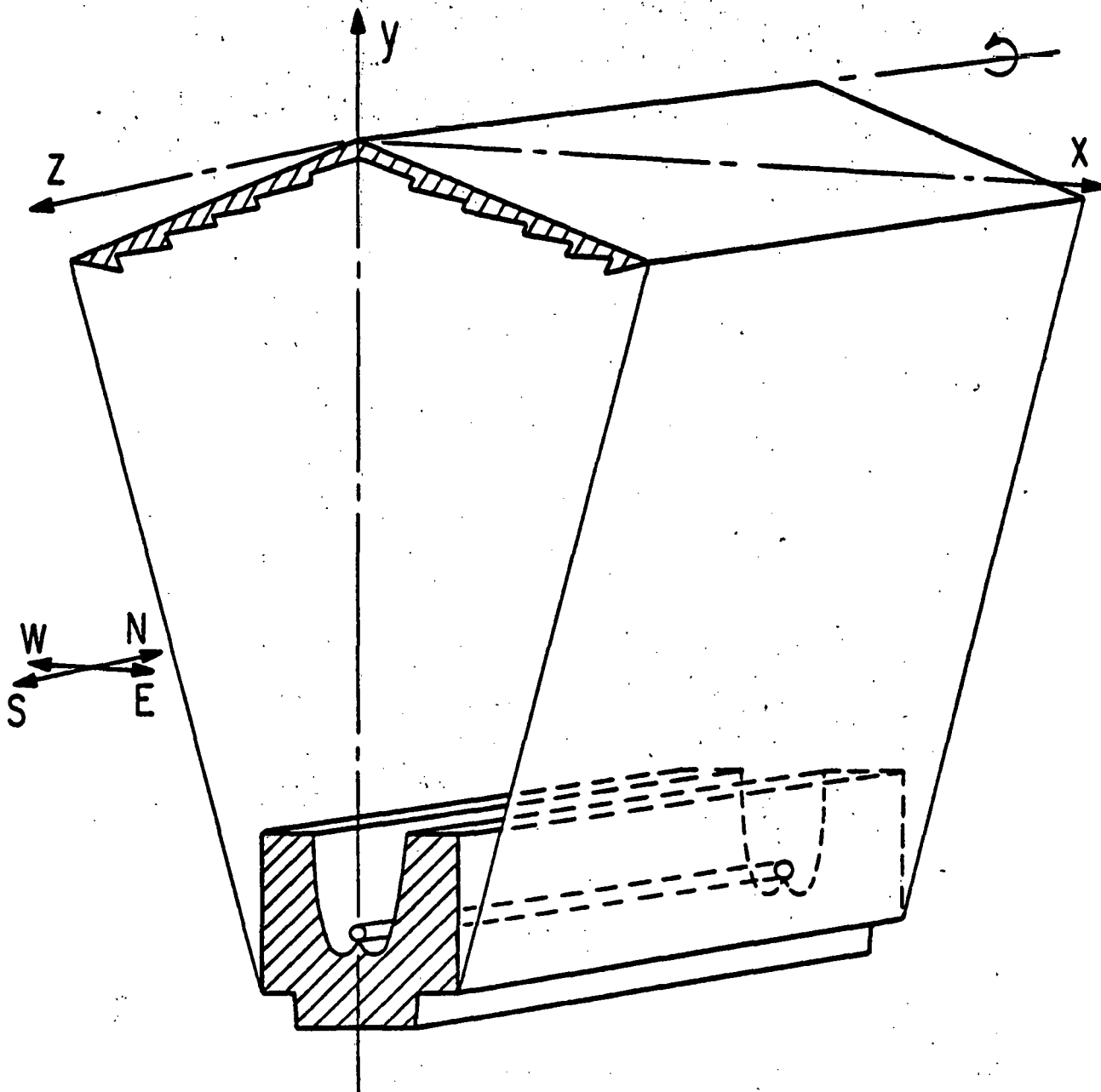


Fig. 10 Perspective schematic of overall lens/CPC mirror concentrator.

two symmetric flat halves tilted at an angle Ω with respect to the aperture plane. This has an effect similar to that obtainable by curving the lens. Radiation incident within angles $\pm 3^\circ$ of the normal to $\overline{AA'}$ is refracted to the plane BB' in such a way as to produce the minimum spread possible. It is further concentrated by a second stage concentrator of the CPC type which makes the best possible match between a flat effective entrance aperture and a tube. The second stage was made out of sagged glass with evaporated aluminum as the reflecting surface. The tube is stainless steel pipe, selectively coated with black chrome.

The detailed dimensions of the overall system are summarized in Table 2. A 1 mm gap was left between the tube and the reflecting surface to prevent direct thermal contact. This results in a calculated optical "gap loss" of 2 percent. The second stage was enclosed in a box, surrounded by insulation. The whole system, lens and second stage, was framed in an aluminum box, with the lens acting as the cover (see Figure 10).

The collector was mounted on our portable test stand and its performance was measured with both the water and Therminol 66 test loops using the same methods as for the 5.25X evacuated CPC described in the preceding section, except that the incident direct beam was measured with an Active Cavity Radiometer rather than a NIP or PSP and occulting disk. All required tracking was done manually by repositioning the portable test stand from time to time. An adjustment was required about every 20 minutes.

The instantaneous optical efficiency was measured using water in an "open loop" configuration and found to be

Table 2

Dimensions of Fresnel Lens/CPC Type Nonimaging Concentrator

Half acceptance angle	θ	$\pm 3^\circ$
Concentration ($= \overline{AA'}/\pi d$)	C	15.6
Slope angle	Ω	25°
Effective entrance width	$\overline{AA'}$	62.15 cm
Distance between lens and second stage entrance	P	73.5 cm
Height of second stage	h	12.93 cm
Entrance of second stage	$\overline{BB'}$	10.04 cm
Tubular absorber diameter	d	1.27 cm
Second stage length	L	1.82 m
Entrance aperture area	A	1.13 m^2

$$n_0(\text{meas}) = 0.66 \pm 0.01$$

This value is in good agreement with the calculated value based in Eq. (1) with $\tau_1 = 0.81$ (lens transmittance), $\tau_2 = 1.0$ (no glass envelope), $\rho = 0.91$ (front surface aluminum), $\langle n \rangle = 1.2$ (from Reference 19) and $\alpha = 0.94$ (black chrome) and "gap loss" correction $(1 - L) = 0.98$ which yields

$$n_0(\text{calc}) = 0.666.$$

The acceptance angle of the collector was measured by monitoring the change in the optical efficiency as the sun moved across the field of view of the collector. It is also important to determine the acceptance angle for off-meridian rays, i.e., rays that are not in the plane of the paper of Fig. 9. This because the collector is intended to function with a fixed tilt position (polar mount) for the tracking axis throughout the year. The angle $\theta_{||}$ that the sun makes with the y-axis of Fig. 10 will vary from $\sim -23^\circ$ at winter solstice to $\sim +23^\circ$ at summer solstice. A complete description of this effect and of the measurements made is given in Reference [18]. A full summary of the results is shown in Fig. 11 and it can be seen that the full acceptance angle is indeed 6° for meridian rays ($\theta_{||} = 0^\circ$) and becomes smaller for increasing $\theta_{||}$ in agreement with predictions. The definition of efficiency in Fig. 12 includes a correction for cosine effects of oblique incidence with respect to the longitudinal axis of the trough according to the equation

$$\dot{Q}_{\text{inc}} = A \cdot I_{\text{ACR}} \cdot \cos\theta_{||} \quad (6)$$

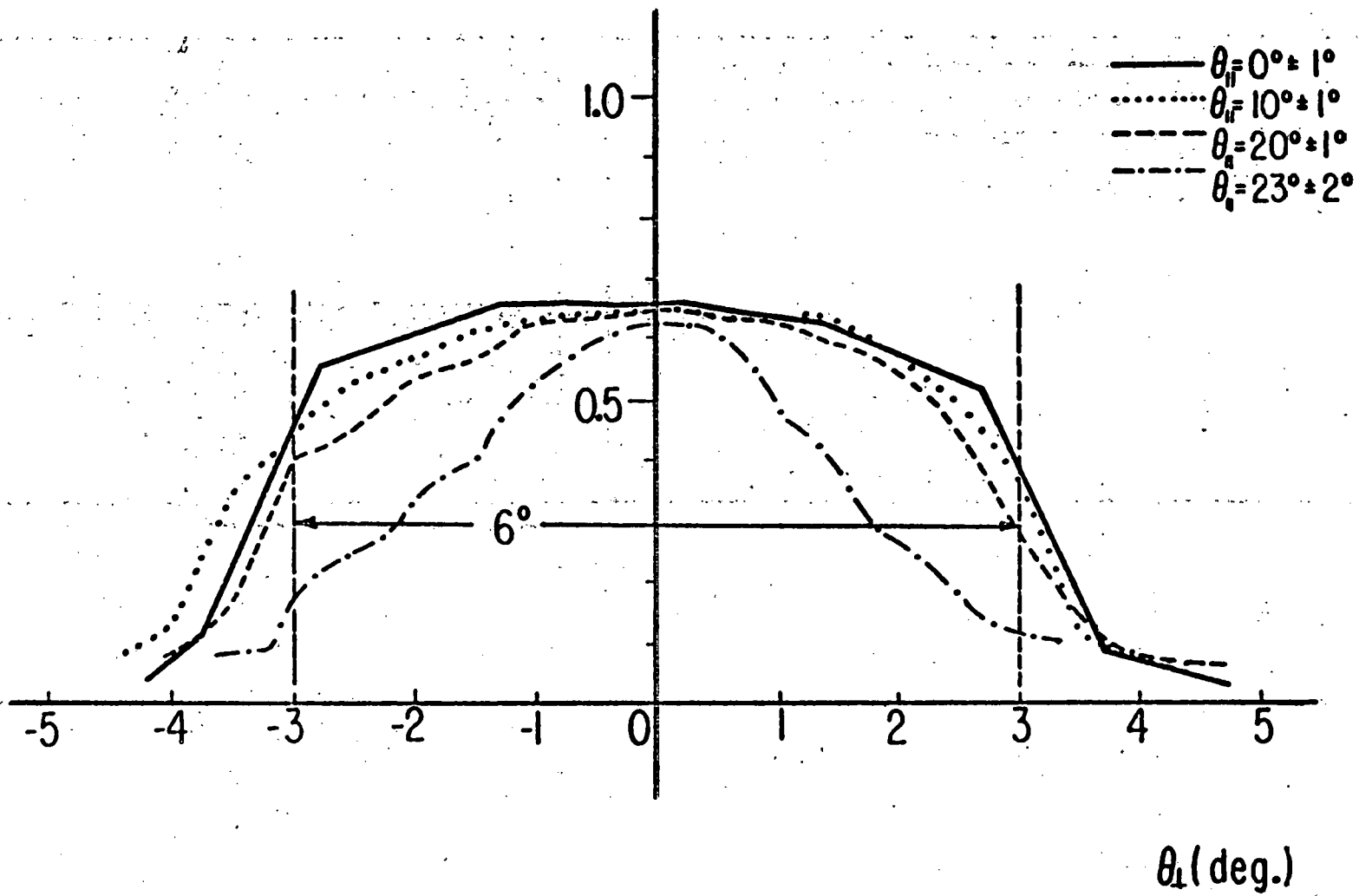


Fig. 11 Measured angular acceptance for lens/mirror.

where A is the net aperture area = 1.13 m^2 and I_{ACR} is the ACR reading (in Watt/m^2).

The results of thermal performance measurements are shown in Fig. 12. The testing was done with two different absorber tubes with slightly different black chrome coatings as shown by the solid and open data points. Data were taken extending to values of as high as 240°C above ambient before encountering small Therminol leaks in the fluid loop similar to these mentioned in the description of the 5.25X CPC tested. This corresponded to a $\Delta T/I$ of 0.28°C-m^2 for $I_{\text{ACR}} = 850 \text{ Watt/m}^2$ and yielded an efficiency of 0.42. At a ΔT of 200°C ($T/I = 0.235^\circ\text{C-m}^2$) the measured efficiency of 0.48 was in good agreement with the predictions [12]. The solid line is a quadratic least square fit to all the data points; the fit is

$$\eta = 0.656 = 0.435 (\Delta T/I) - 1.462 (\Delta T/I)^2$$

with $\Delta T/I$ in $^\circ\text{C-m}^2/\text{Watt}$.

The triangles in Fig. 12 are heat-loss measurements converted to an operating efficiency by normalizing to an optical efficiency of 66% and an insolation of $I_{\text{DN}} = 1000 \text{ W/m}^2$. They were conducted at temperatures as high as 200°C and are seen to be in very good agreement with the operating efficiency measurements.

The calculated behavior of the collector in a "double glazed" configuration (i.e. with a second tubular glazing as a convection barrier around the tubular absorber) is also shown in Fig. 4. The measurements were of

the heat loss only since high transmissivity etched glass ($\tau \sim 0.96$) of the proper size was not available at the time of the study. The dashed line in the figure shows the results of these heat loss measurements referred to an optical efficiency of 0.63 (obtained by multiplying η_o by $\tau_{\text{etched glass}} = 0.96$) and $I = 1000 \text{ W/m}^2$. It can be seen that extrapolation to $\Delta T/I = 0.3^\circ\text{C}\text{-m}^2/\text{Watt}$ would yield an efficiency of 0.48.

D. Non-evacuated CPC's (6.5X and 3X) for Applications near 100°C

Two different non-evacuated CPC designs were assembled and evaluated as part of a development program with two basic objectives. First we wanted to examine the optical tolerances, angular acceptances, and collection properties of basic CPC designs including a high concentration, narrow angular acceptance design. Second, we wanted to study the thermal problems which are unique to low concentration, non-tracking non-evacuated collectors. The results of these studies have appeared in preliminary form in a number of short reports^[20,21] and in greater detail in a full technical report^[22] to be published in Solar Energy. The major features of these efforts are summarized here.

The design problems for non-evacuated CPC collectors are entirely different from those for CPC's with evacuated absorbers. The former are particularly vulnerable to high heat losses if one uses an improper design. The recommended design constraints based on more than two years of non-evacuated collector development are summarized below: 1) use of one of the "backless" or "wrap-around" designs such as the cusp for a tubular absorber or vertical fin design of Fig. 1a or 1b respectively, 2) use of selective

coating on the absorber, 3) avoidance of the use of cavity absorbers since they are characterized by high heat losses, 4) minimization or elimination of heat loss via conduction through the reflectors. This can be accomplished by using reflectors whose thickness is negligible compared to the overall dimension (e.g., height, aperture) of the trough such as metalized plastics or films or by thermally decoupling the absorber from the reflectors by a small gap maintained by insulating stand-offs, 5) use of a CPC profile calculated for an imaginary absorber surface which is inside the actual absorber surface. A resulting oversize of the actual absorber size of 5% - 20% is recommended.

The two prototype non-evacuated CPC designs built in the laboratory at the University of Chicago had different objectives in mind. An experimental 6.5X for a tubular absorber and with a very narrow acceptance angle ($\pm 6.4^\circ$) was built to examine the behavior of a high concentration, small acceptance angle CPC. The absorber was a 6.4 mm diameter (1/4") copper tube coated with black chrome. The profile of a cross section of the reflecting trough is shown in Fig. 13. The design acceptance angle was 6.4° , corresponding to an ideal concentration of 9.0X, but the profile was truncated to $\sim 1/3$ of its full height resulting in a net concentration of 6.5X. The full collector consisted of 7 troughs each 6 ft. long with a total area of 1.67 m^2 (18 ft.²).

A prototype of a 3X for a vertical fin absorber was built to verify the production design for the experimental array of low temperature CPC collectors at the Bread Springs School. Since this collector was designed for heating applications only, the design acceptance angle was chosen to

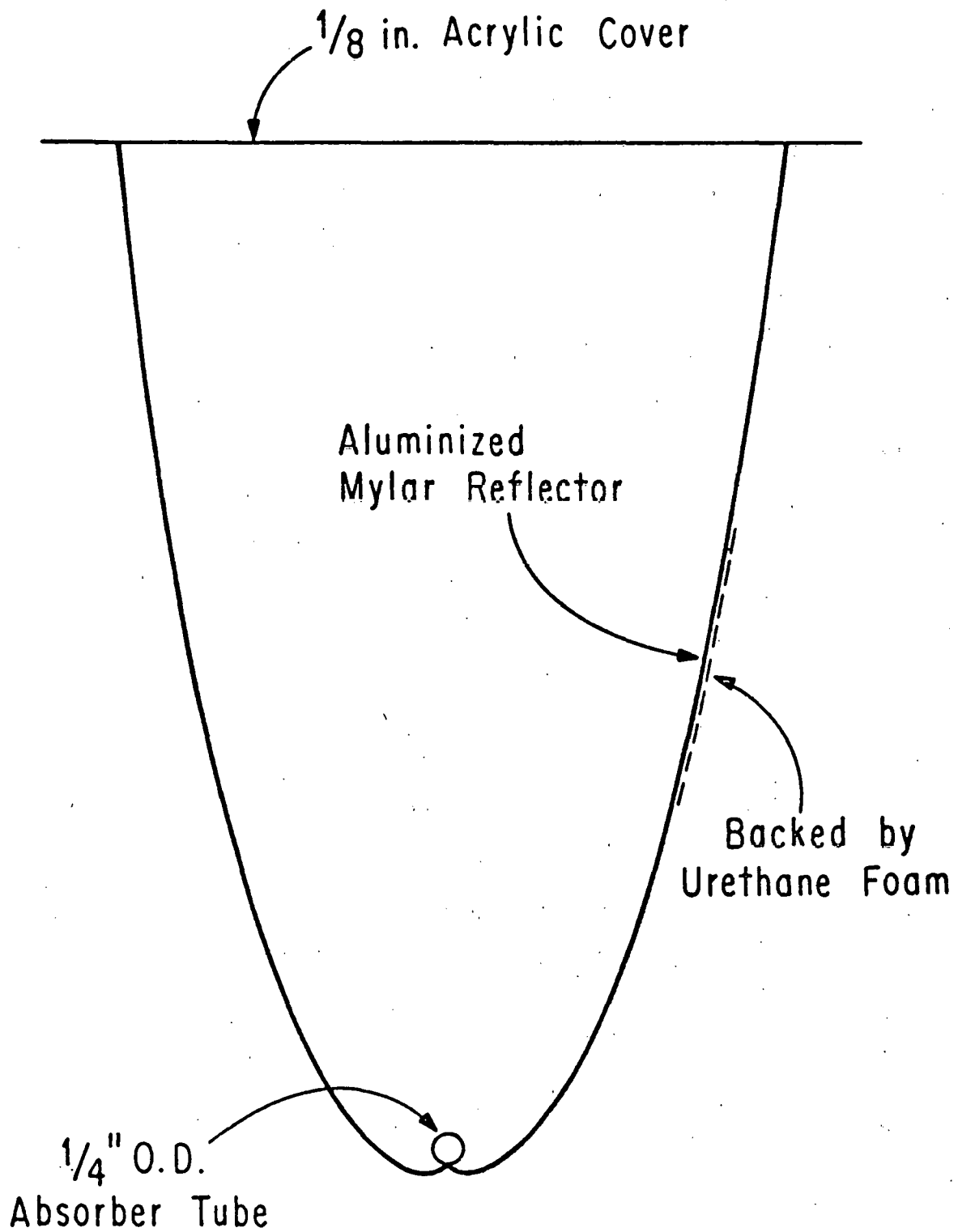


Fig. 13 Profile curve for non-evacuated 6.5X CPC.

be $\pm 18^\circ$ to insure collection for at least 7 hours a day for the six month period between the fall and spring equinoxes with no tilt adjustments. The absorber is a fin (configuration of Fig. 1b) with a center tube and each collector consists of a two-trough module with a cross section as shown in Fig. 14. Each module is 1.3m^2 (14ft.^2) in net area and the troughs were 46 cm (18 in.) deep. Kinglux aluminum sheet 0.5 mm (.020 in.) thick was used as the reflector ($\rho = 0.84$). The outer enclosure was a fiberglass epoxy tub with ASG water white glass as a cover.

We summarize below the performance parameters of these two collectors as determined from a series of measurements conducted over the past two years.

The performance is characterized in the usual two parameter form as

$$\eta_h (\Delta T/I) = \eta_{0,h} - U \Delta T/I_h \quad (7)$$

where η_0 is the "optical efficiency" (including heat removal factor) and U the best fit linear heat-loss coefficient, ΔT is the difference between average fluid temperature and ambient temperature and I_h is the total hemispherical insolation on the collector aperture and the subscript h refers to the efficiency relative to this quantity.

The measured instantaneous performance for the 6.5X collector is shown in Fig. 15. The solid line is a least squares fit to the data assuming the form of Eq. 7 and corresponds to collector parameter values of

$$\eta_{0,h} = 0.65 \pm 0.02$$

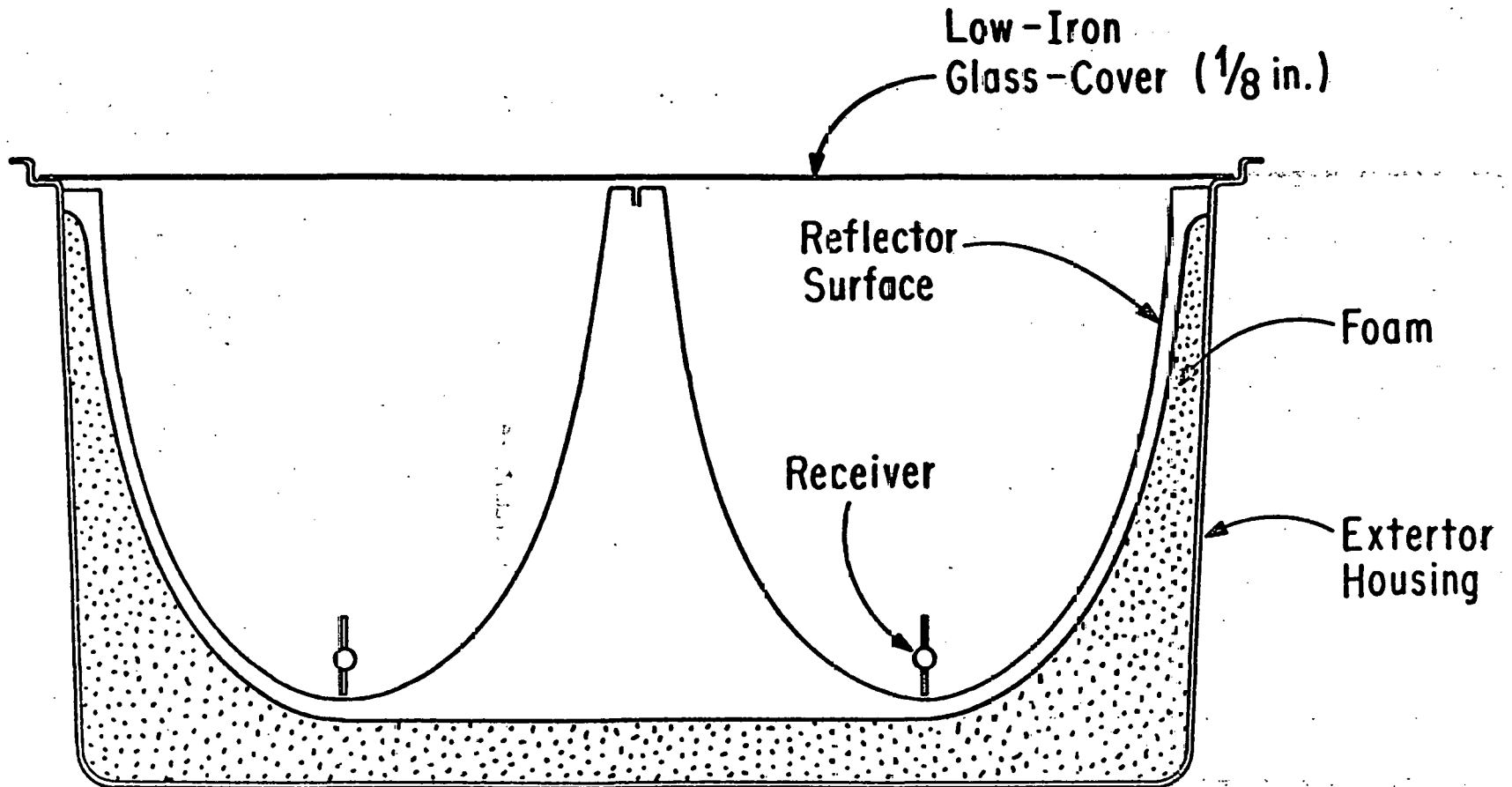


Fig. 14 Cross section of non-evacuated 3X fin CPC (prototype for Bread Springs project).

and

$$U = 2.2 \pm 6/2 \text{ W/m}^2\text{-}^\circ\text{C}.$$

The shaded region in the figure defines the range of expected performance based on preliminary diagnostic tests. The agreement between overall observed performance and predicted behavior is quite good. However, the heat loss coefficient was somewhat higher than expected, possibly due to uncertain corrections for variations in the level of diffuse on different days during the measurement but also possibly due to some loss in effective optical efficiency due to warping of the absorber tubes. The collector was rebuilt with oversize absorber tubes, 7.9 mm (5/16") in diameter and made of steel in an effort to reduce optical losses. This also, of course, reduced its net concentration from 6.5X to 5.2X. The rebuilt collector was retested using careful correction for variations in the diffuse component yielding the revised performance shown in Fig. 16. This performance is felt to be representative of what a high concentration non-evacuated CPC can achieve using aluminized mylar reflectors ($\rho = 0.90$) and a black chrome absorber under a single glazing. Note that it is characterized by an efficiency of 50% at temperatures around 100°C and thus could be a relatively simple low technology collector for industrial process heat applications. A straight line fit in the data in Fig. 16 yields parameter values of $\eta_{o,h} = 0.68 \pm 0.01$ and $U = 1.85 \pm 0.1 \text{ W/m}^2\text{-}^\circ\text{C}$.

The thermal performance of the 3X fin receiver CPC is shown in Fig. 17. The solid line is a least squares fit to the efficiencies measured under clear day conditions and as in the case of the 6.5X collector in Fig. 15

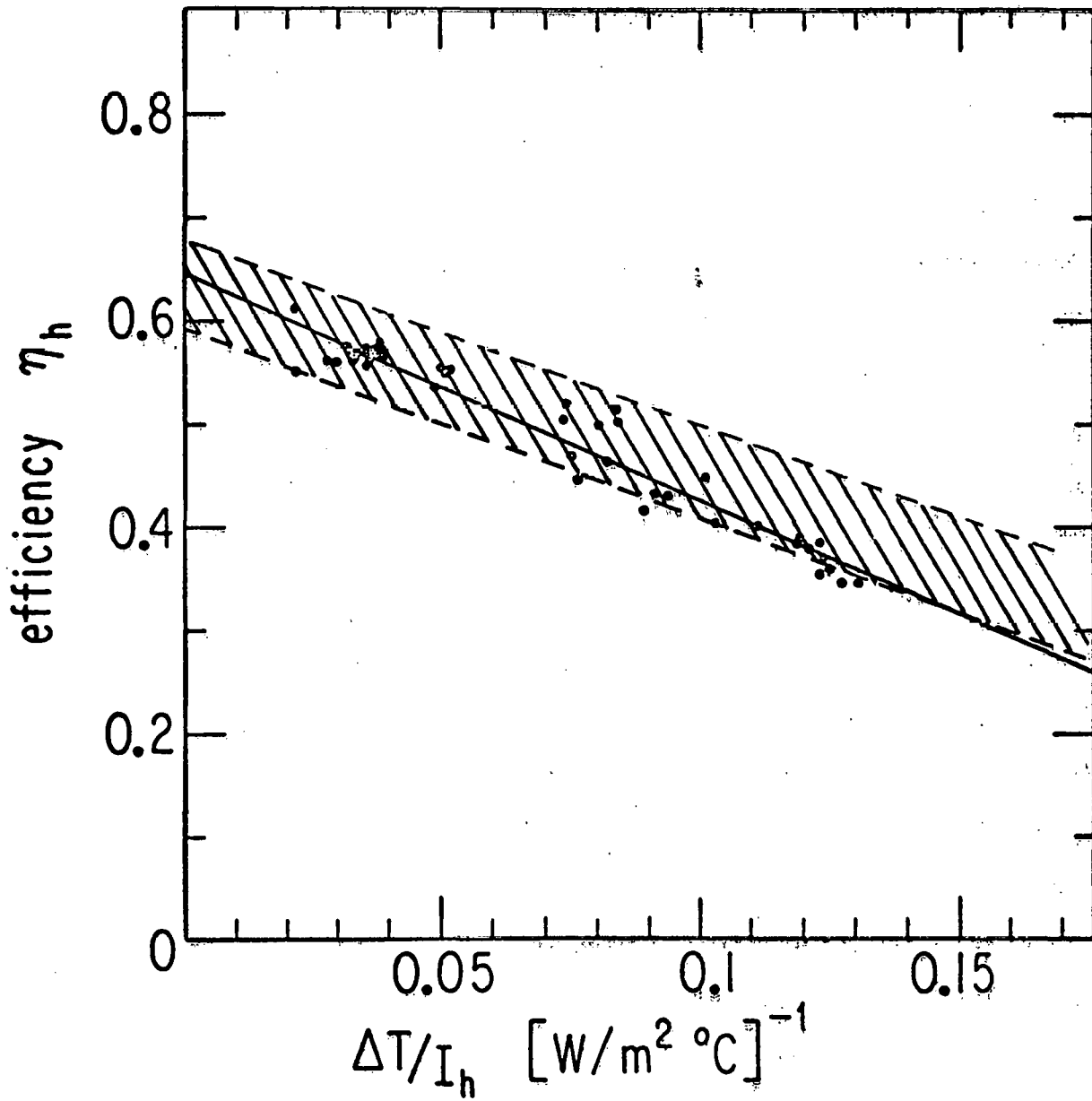


Fig. 15 Measured performance curve for 6.5X non-evacuated CPC.

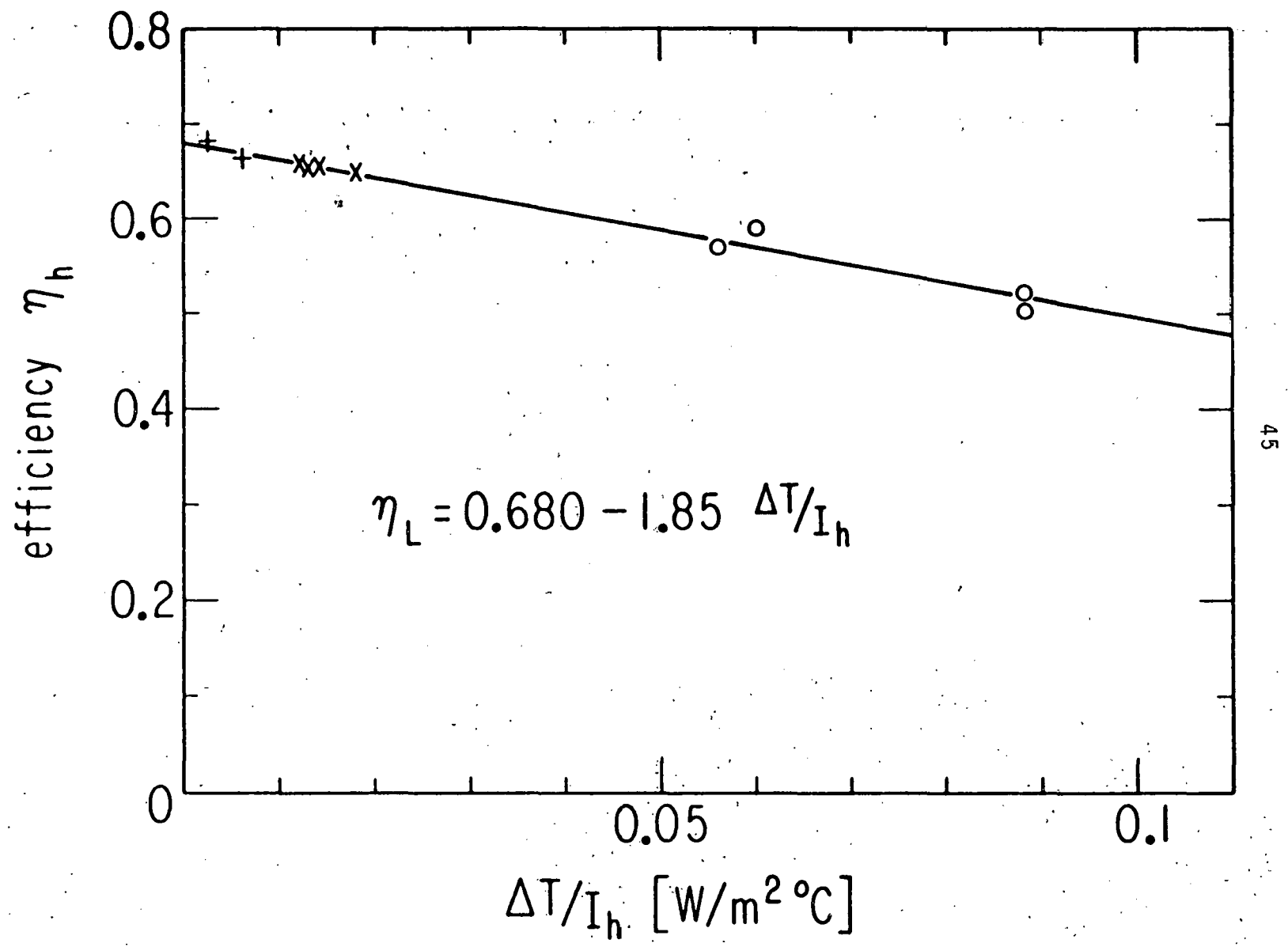


Fig. 16 Measured performance curve for 5.2X CPC (modified 6.5X).

the shaded region bounded by dashed lines represents the expected performance based on preliminary diagnostic testing. Again the agreement is quite good. Here the corresponding performance are

$$\eta_{o,h} = 0.58 \pm 0.02$$

and

$$U = 2.7 \pm 0.2 \text{ W/m}^2\text{-}^\circ\text{C}.$$

When corrected to the same relative sky conditions as the data in Fig. 16 (very clear day; diffuse fraction = 0.11) this corresponds to

$$\eta_{o,h} = 0.63 \pm 0.02.$$

The angular acceptances of both collectors were well within expectations of the design values. For example, the measured response for the 3X is shown in Fig. 18 and shows what can be attained with simple aluminum sheet reflectors held in place by ribs spaced several feet apart.

Finally we show for comparison in Fig. 19, the 6.5X and 3X performance curves along with those for typical double glazed and single glazed flat plates^[23]. (These latter represent an average over the best collectors of each type tested by the Florida Solar Energy Center in a nine month period during 1978.) Also shown is the calculated performance for a non-evacuated 1.5X CPC with a second glazing (around the absorber tube) in addition to the cover. This would be a totally stationary collector with the same thermal performance of the modified 6.5X which required over 20 tilt adjustments per year.

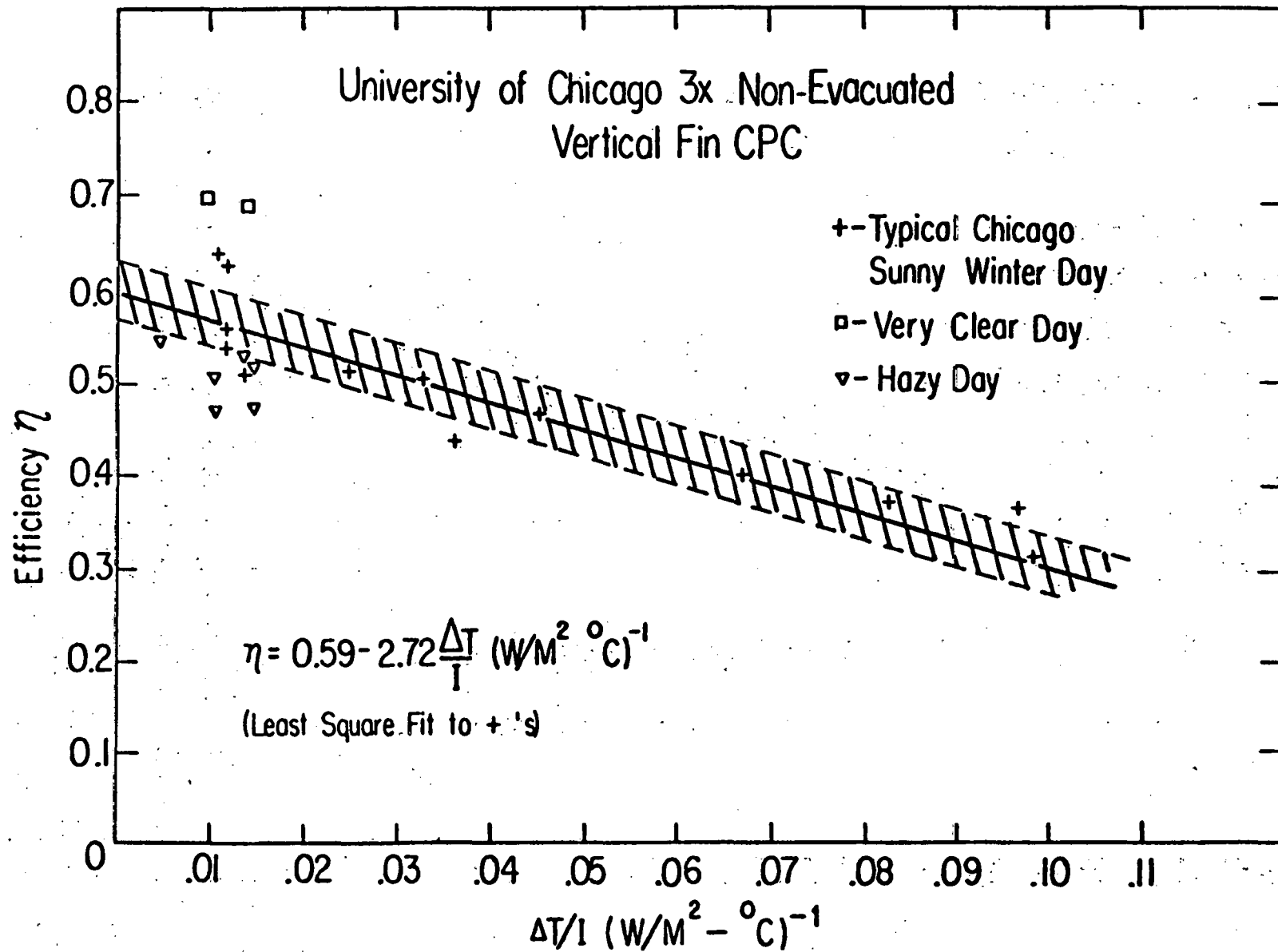


Fig. 17 Measured performance curve for 3X vertical fin non-evacuated CPC.

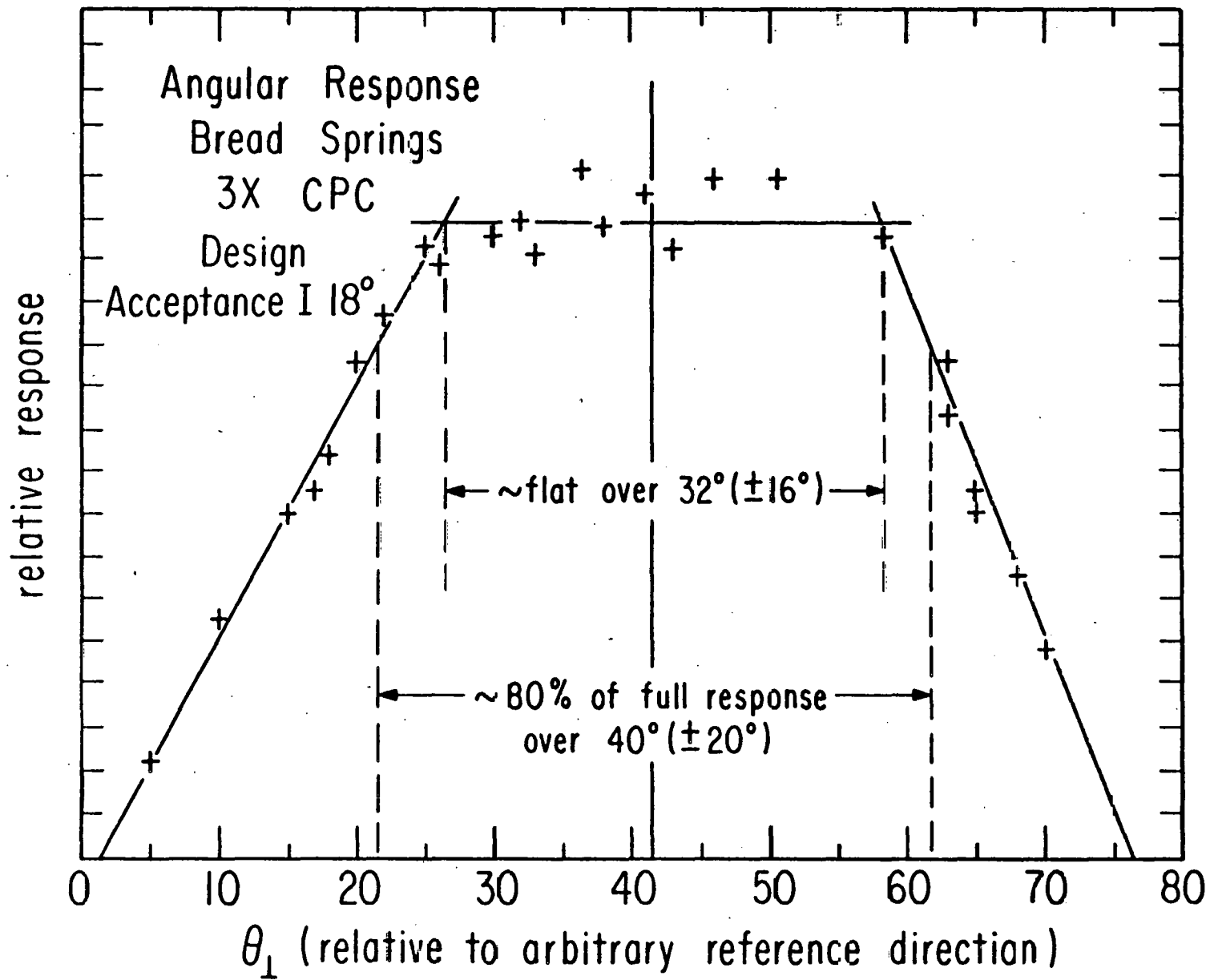


Fig. 18 Angular acceptance of 3X non-evacuated CPC.

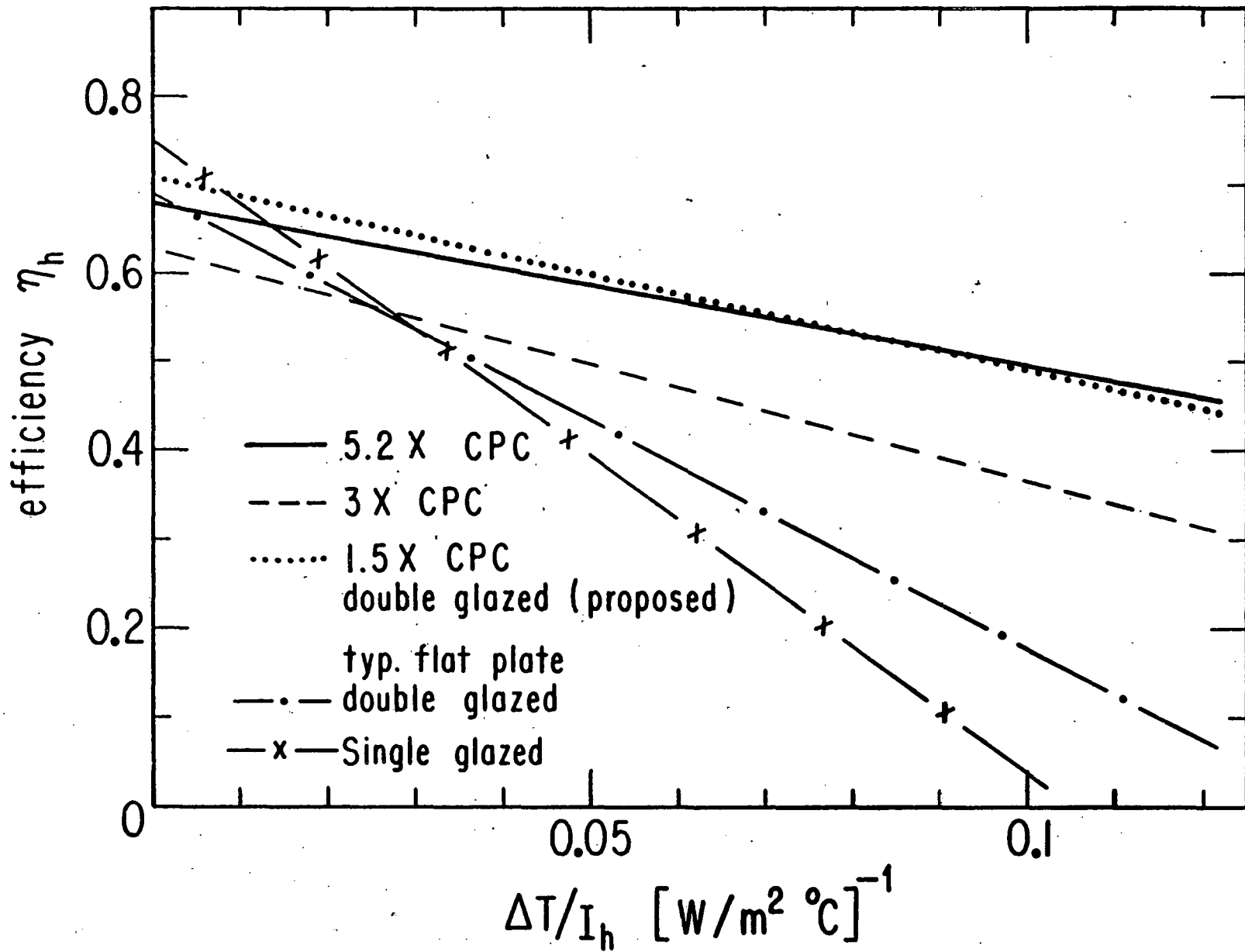


Fig. 19. Comparison of performance curves for non-evacuated CPC's and flat plate collectors.

The performance of each CPC collector described above has been shown to agree quite well with calculations and with predictions derived from preliminary optical and thermal diagnostic procedures. This means that with proper care one can design practical non-evacuated CPC collectors with confidence that their performance will meet expectations.

In particular we found that the angular acceptance properties, on which the seasonal tilt schedule depends, agreed very well with nominal design values. With conventional reflectors the optical efficiencies are somewhat lower than for flat plate collectors but at the same time the heat loss coefficients are also substantially lower, yielding a comparatively better performance at higher temperatures.

Despite lower optical efficiencies, the CPC's outperform typical flat plates above temperatures of as low as 10°C above ambient (for the 5.2X) to about 35°C above ambient (for the 3X). This is particularly important when it is recognized that the 3X should represent a relatively inexpensive collector design. While a detailed economic analysis cannot be based on the prototype construction methods used here and is beyond the scope of the present work there are several unique features listed below which contribute to its low cost potential.

1. The metal absorber fin of only 6.4 cm (2.5 in) height effectively covers 30 cm (15 in) of collector aperture. Thus the cost per unit aperture area of absorber plate is reduced by a factor of 6. (Both sides of the fin surface are utilized.)

2. No insulation (other than dead air space behind the reflectors) was used inside the actual production modules deployed in the field with no noticeable change in thermal loss coefficient. Thus what is a significant cost component of most non-concentrating collector designs could be eliminated.

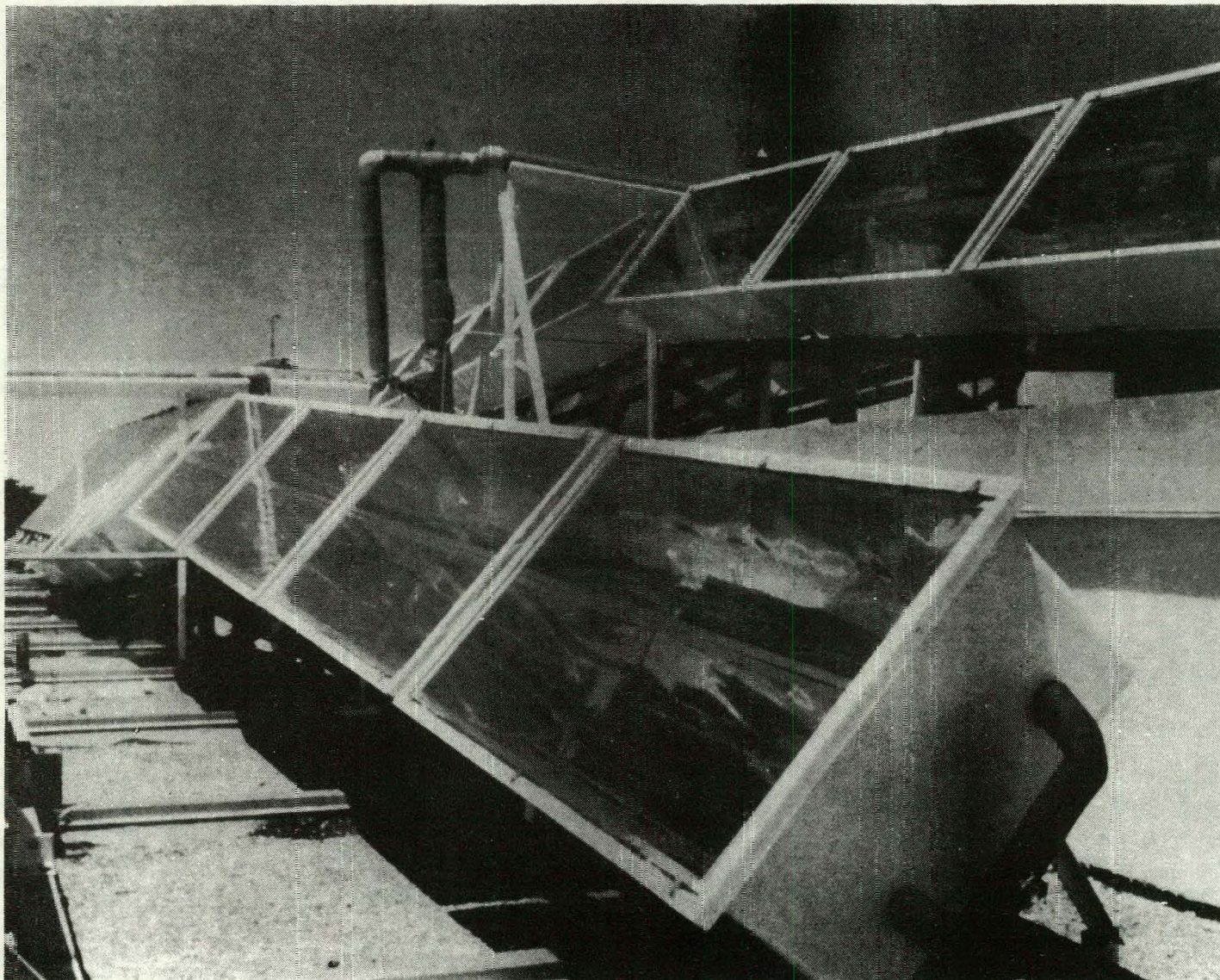
3. Inexpensive reflector materials (i.e. aluminized plastic reflectors or aluminized films on a thin substrate) could be used.

We reiterate our caution that care must be taken in the design of any non-evacuated CPC to avoid large parasitic losses through the reflector. Furthermore, to avoid sensitivity to misalignment and thermal deformation, particularly in the cases where high concentration ($\gtrsim 4X$) is combined with absorbers of small absolute dimensions ($\lesssim 1.25$ cm), we strongly recommend a) the use of absorbers oversized by about 20% with respect to the "theoretical" mathematical absorber surface for which the reflector profile surface is generated and b) the use of steel or other relatively strong material for the absorber tubes.

E. Field Test of 3X Non-evacuated CPC's at the Bread Springs School

1. Project Background

On June 22, 1978, a dedication ceremony was held for the new solar array at the Bread Springs School near Gallup, New Mexico. This event marked the transition between the first and second phases of an unusual experiment involving the first deployment of CPC collectors. Although the principle for CPC solar collector design was first developed in 1973^[3], all the experimental work to date had been concerned with fabrication and



IV. Close-up view of 3X CPC's at Bread Springs School

testing of individual prototype units under selected environmental conditions. In early 1976, in an effort to establish a basis for obtaining performance data relevant to the long term average optical response of such non-tracking concentrators, a cooperative project was initiated. This effort involved the collaboration of the Navajo Area Office of the Bureau of Indian Affairs and the Solar Energy Group at the University of Chicago. At a higher level it involved interagency cooperation between the Department of the Interior supporting the BIA activities and the Department of Energy (then ERDA) which provided support for the University and some support for the BIA as well.

The basic project was to retrofit a small elementary school (three classrooms and a multipurpose-gym/cafeteria room) with a space heating and domestic hot water heating solar system including nominally $\sim 1000 \text{ ft.}^2$ of non-evacuated CPC collectors. The division of responsibility was as follows. The University was responsible for the CPC collector design, procurement, instrumentation and data collection and analysis. The BIA Office of Facilities Management was responsible for overall solar system design, required building modifications (i.e. new insulation, new roof and support structures for the collector array); as well as the installation and operation of the full system.

The project has had its share of delays and unanticipated difficulties, but on the whole, judged in terms of the original objectives it must be regarded as quite successful. Operation of the array is nearing the end of its second heating season. During the rather severe winter of 1978/79 the consumption of fuel oil at the school was reduced to about half of what it

had been the preceeding year. During the 1979/80 winter, while the solar system was operating there has been little or no furnace activity at all. During 1978/79, data on the array performance was obtained only at intermittent intervals due to our need to accumulate experience with the problems associated with maintaining routine automatic data acquisition at a remote site. In this regard we note that there are no phone lines to the school, no technically trained personnel regularly present, frequent power outages (several times a week) and no financial support for the maintenance of this activity. With the cooperation of BIA personnel in Gallup and at the school we have been somewhat more successful during 1979/80 and have data taken covering operation of the system nearly continuously from mid-December to mid-March.

In the next section the technical features of the collector array and overall system are described and some preliminary results of the array performance are presented. A more comprehensive analysis of the array's long term average performance will be carried out after sufficient data has been accumulated.

2. System Technical Description

The CPC collector array at the Bread Springs School consists of 56 of the two-trough 3X vertical fin modules whose prototype was described in Section D above. The layout of the individual modules on the building roof and a simplified schematic of the distribution network and performance monitoring sensors is shown in the two different perspectives in Fig. 20 and Fig. 21. There are 7 rows of 8 collectors each, 5 on the

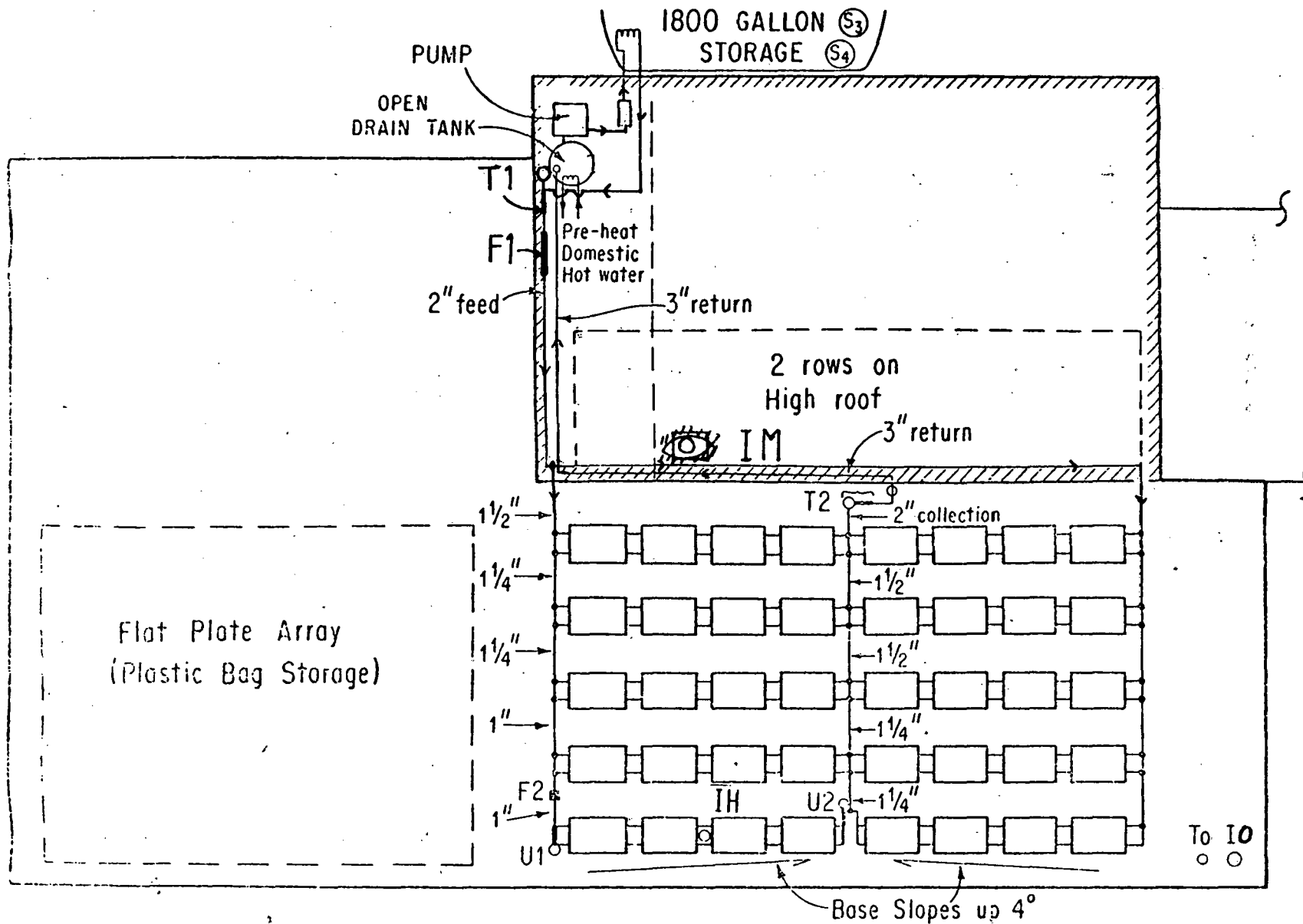
main portion of the roof and 2 more on the raised portion over the gym which is about 3 feet higher than the rest of the roof. A long closet at the west end of the gym inside the building contains the main system control elements, the data acquisition system and a 450 gallon open-drain tank. A large 1800 gallon insulated tank (housed in a small protective shed outside the north wall of the building) comprises the main system storage.

In operation water is pumped from the drain tank through a heat exchanger in the large storage tank and from there directly to and through the collectors on the roof. The feed is split between the two halves (east and west) of the array. The two troughs in each module are fed in parallel with the four troughs in each half row connected in series. Each array half is mounted so that it slopes up towards the center at a 4° angle and the collection pipe also slopes gradually up as it rises to the high point of the system where it spills back down through the 3" diameter open pipe to the drain tank. Upon pump shut-off the entire fluid capacity drains back down under gravity to the tank in the storage closet, so that ordinary water with antifreeze is used as the heat transfer fluid.

Each trough has a net active length of 67 inches (1.70 meters) and a width of 15 inches (0.38 meters) yielding a net collecting area for each trough of 7 ft.^2 (0.65 m^2) of 14 ft.^2 (1.3 m^2) per module. Thus the entire collecting area of the 56 module is 784 ft.^2 (72.8 m^2). This is slightly less than the nominal array size of $\sim 1000 \text{ ft.}^2$ because the BIA decided not to install an eighth row originally planned. Since the gross area of each module is $\sim 16 \text{ ft.}^2$, this would have yielded almost exactly 1000 ft.^2 ,

but the actual installed array size is more than adequate to meet all the project objectives, both technical and operational. In fact the 1000 ft.² flat plate array installed on the west portion of the roof which is connected to a separate pump and storage loop has not been in operation for the last two heating seasons, due to small leaks in the plastic bag storage which was slightly damaged in installation. Presently the BIA is considering removing this array and deploying it elsewhere since the building heating needs are being met by the CPC array alone.

The basic test points in the system instrumentation are also indicated in Fig. 20 and Fig. 21. Type T (copper vs. Constantan) thermocouples from Omega Engineering are used to measure all temperatures. Four array temperatures corresponding to the full array inlet (T_1) and output (T_2) as well as the inlet and outlet of the west half of the front row (U_1 and U_2 , respectively) are measured. The temperature T_1 is measured down inside the storage closet immediately after the fluid returns from charging the storage tank and T_2 is measured just after the heated water spills into the open drain return. Thus the temperature difference, $T_2 - T_1$, includes the effect of distribution and collection losses. The four collector sub-array in the front row is measured separately to provide a data base closer to individual module performance for comparison with the known prototype performance measured in Chicago. Additional temperature measurements are those for the water temperature as it leaves the drain tank T_s and the ambient temperature T_a of the outside air. Flow rates for



Bread Springs School Project
 University of Chicago CPC Array Layout

Fig. 20 Layout of 56 module non-evacuated CPC collector array on Bread Springs roof.

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BREAD SPRINGS
SCHOOL PROJECT
University of Chicago
CPC Array
Simplified System Schematic
and Test Points

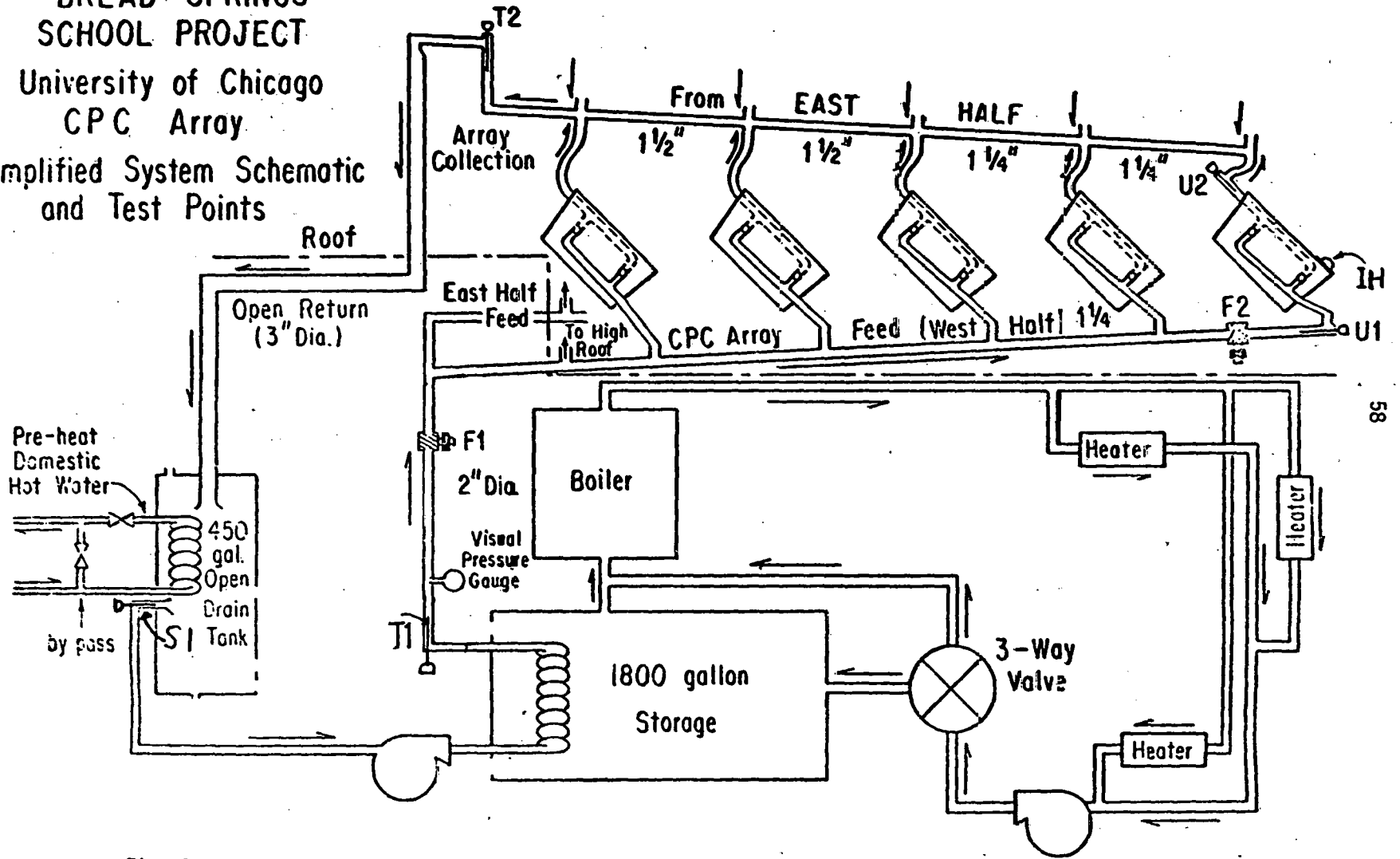
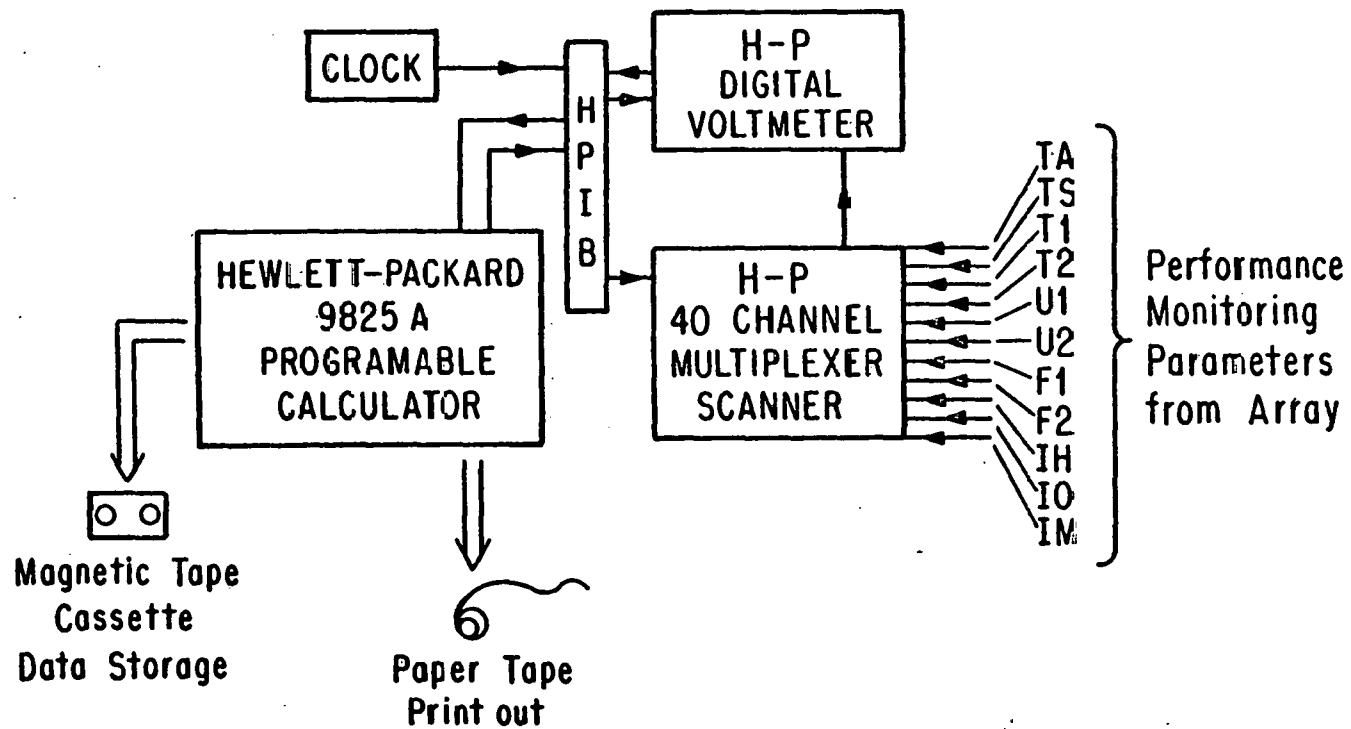


Fig. 21 Schematic of Bread Springs system.

the full array (F1) and front half row (F2) are measured separately using a paddle wheel flowmeter and a magnetic sensor flowmeter respectively, both from Signet Engineering. Finally three Eppley Model 8-48 black and white pyrometers are used to measure a) global insolation on a horizontal plane (I_0), b) hemispherical insolation in the plane of the tilted collector aperture (I_H) and c) insolation masked to be within $\pm 18^\circ$ in elevation of the normal to the collector aperture (the collector acceptance angle) (I_M).

A simplified schematic of the data acquisition system is shown in Fig. 22. The heart of the system is a Hewlett-Packard 9825A programmable calculator. It is augmented by two peripheral devices: a) a 40 channel multiplexer-scanner and b) a Hewlett-Packard high resolution digital voltmeter (DVM). Both the scanner and the DVM are controllable by the programmable calculator. Signals are selected by command for connection through the scanner to the DVM. The digitized measurement is then interrogated by the calculator and can be converted to appropriate scales and dimensions by preprogrammed calibrations. Zero-point compensation for all the thermocouple readings is made by the calculator using a thermistor reference in the scanner.

During routine data collection all six temperatures, both flow rates and the three pyrometers are each read every 20 seconds. These values are accumulated for 10 minute intervals after which the cumulative average is determined and stored in the computer. Data is recorded on a magnetic cassette with a capacity for storing approximately 50 days worth of



UNIVERSITY of CHICAGO
 BREAD SPRINGS SCHOOL
 Data Acquisition System

Fig. 22 Schematic of data acquisition system at the Bread Springs array.

operating data. At regular intervals (normally every 4 to 6 weeks) these cassettes are replaced and mailed to Chicago for analysis.

As is clear from the above description, the emphasis of the University's effort is devoted to an evaluation of the array rather than the full system performance. No automated system for recording building functions (i.e. furnace on and off times, fuel consumption, building temperatures, thermostat settings, etc.) has been incorporated. A semi-quantitative analysis of these functions may be possible from written records but it is not a major objective of our continuing analysis.

3. Summary of Operating Experience to Date

During the nearly two full heating seasons of operation to date the array has successfully provided substantial heat to the building and we have gathered but not yet systematically analyzed a net total of several months worth of performance data. However, it is only at this writing in the late winter of 1980 that the full system has really reached the point where the data and experience accumulated henceforth can be expected to meet the original objective in full. By overcoming several problems and difficulties we have learned a great deal in three specific areas: a) the collectors themselves, b) the system operation and c) operation of the data system.

As was described in some detail in the monthly reports filed in the active term of support under this contract, we were very disappointed in the actual physical condition of the collectors as they were delivered to the site. A total of seventy-two collector modules was fabricated for

the University of Chicago by the Ceilheat Division of ITE Gould. A prototype was fabricated to specification by Ceilheat, tested by the University and approved for production. However, in implementing the final production run the fabricators made several changes from the approved design and failed to incorporate several recommended changes from the prototype with the result that the final units were unsatisfactory for several reasons. The most important problems were the following.

1. The 72 mass produced units were made without reflectors at each end of the trough. The purpose of such reflectors is to make the troughs appear infinitely long when viewed obliquely from the aperture (the "barber shop mirror" effect) which is necessary to eliminate shading and end losses. Although both prototypes approved by the University had been made with end reflectors, the production units were all made without them.

2. Recommended strengthening of the end fixtures and supports to control the orientation of the vertical fin absorbers which had been agreed to was not carried out in the production units. In fact, if anything, these were weaker than in the prototype units.

3. A recommended method for sealing the glass covers on the units in such a way that they could be easily removed was not incorporated. In fact, the final seals were not tight in most units, however, the sealing compound was inaccessible to tools so that the covers were very difficult to remove for maintenance.

An attempt was made to have Ceilheat remedy the situation by restoring the modules to the approved design, however, they refused to do this without

additional cost and shortly thereafter this division was liquidated by the parent company (ITE Gould).

The difficulties with the collectors led to problems. During installation many of the fins were torn from their fixtures and improperly positioned. The all day performance of the collector array was degraded due to shading losses with no end reflectors and after one season of operation sand and/or dirt had penetrated the collectors through the bad seals and affected the operation. Despite these problems the front row efficiency near midday was 60% at low temperature as reported earlier^[24] and the whole collector array performance was surprisingly good, typically about 45% at noon.

One additional difficulty with the collector design worth noting was our use of ASG "Sunadex" water-white very low iron glass. Although this glass has a transmittance of ~93%, better by about 3 percentage points than the next best low iron glass available, it has a surface texturing which distorts the view of the inside of the collector. While this has no significant effect on the angular acceptance properties of the CPC it is a great disadvantage for visual inspection and diagnosis of a new collector design. It is very frustrating and unsatisfying psychologically not to be able to see inside to verify absorber placement and orientation, mirror condition etc.

The operation of the system as a whole with which the University has no connection or responsibility has had a few minor problems. The three way valve has not functioned properly. As a result the control system has been simplified so that it is always wide open such that feed water to the boiler always passes through the storage tank. In addition, a simple differential thermostat turns

the array pump on when the temperature of the absorber fin in a control collector reaches a preset temperature with respect to storage.

The open drain system has operated routinely without major problems but there was one small "freeze-up" when a small amount of water was trapped in between two collectors in a flexible coupling that was improperly positioned. These couplings have been replaced with straight through hoses (no valleys to trap water) and the problem has not recurred.

We have had numerous problems with the data system as described above. When first installed the system would not operate properly due to regular, nearly continuous line voltage variations. The nominal 115V AC power at the school varies typically over a range from 130V down to 90V or even less. To overcome this problem we installed a line voltage regulator for the supply to the Hewlett-Packard equipment which solved that problem. Regular power failures have also been a problem since the time base reference is lost and must be reset by personnel at the school. We now feel that we have established a good relationship with the on-site people and recently the data taking reliability has improved.

To remedy the defects in the collector modules we carried out an extensive overhaul of the entire array in August, 1979. Since support for all this activity terminated in September, 1978, this was accomplished with the partial support of DOE through programmatic funds allocated through the Solar Group at Argonne National Laboratory, and some private funds from the University's Solar Fund. The major steps undertaken in this work were:

1. removal of the old cover glazing on all the modules,
2. installation of end reflectors of aluminum sheet,
3. installation of new stainless steel support fixtures for the absorber fins,
4. cleaning of sand and water from many of the reflector surfaces, and
5. installation of new clear glass cover glazings with a hermetic seal which is readily removable.

Inspection of the refurbished collectors in March, 1980, indicated no evidence of sand penetration, fin warping or other degradations in six months of exposure.

4. Summary of Collector Array Performance

As noted above we have just recently (since November-December, 1979) begun to accumulate on a regular and reliable basis, comprehensive data on the array with collectors which meet design specifications. A detailed analysis of this data is being deferred until a later date. However, for completeness we show in Figure 23 instantaneous efficiency data for the entire array as a function of temperature for typical times during clear day operation. The data are compared with a line showing measured performance from the prototype module. Note that even though the array is not in thermal equilibrium and the efficiency is that for the entire array including distributive and collector losses, the agreement is quite good. This data is shown in another form in Figure 24, which is an all day performance curve for very clear sky conditions.

In general we conclude that the array performance is meeting predicted expectations (this was true even before the array overhaul last summer) and

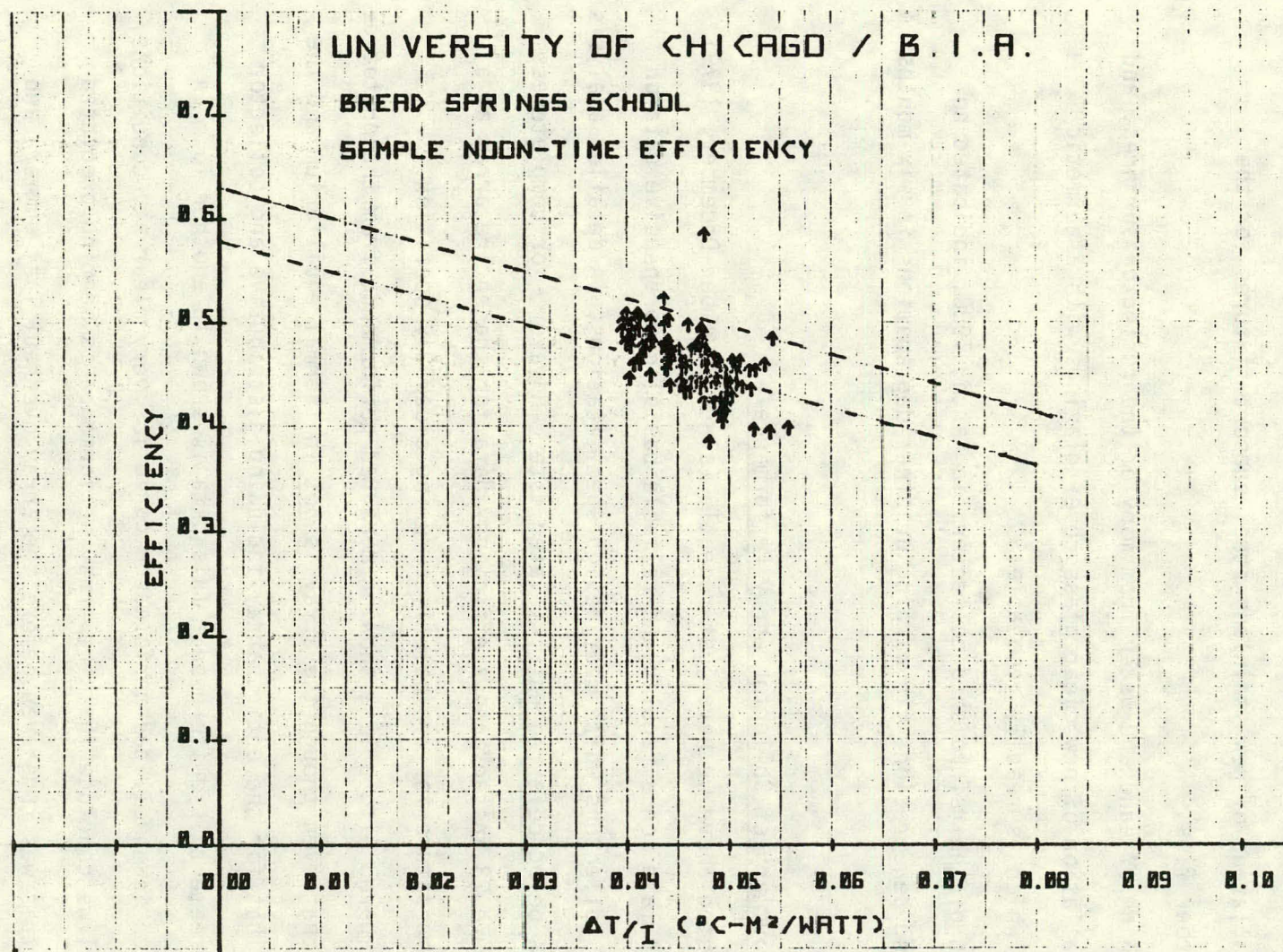


Fig. 23 Full array efficiencies (including effects of distribution losses) for a large number of 10 minute intervals within ± 1 hour of noon for several clear days in Dec. 1978 and Jan. 1980. The lower dashed line corresponds to the prototype performance as measured in Chicago and the upper line is the projected "very clear day" ($I_{\text{dif}}/I_{\text{dir}} = 0.11$) performance.

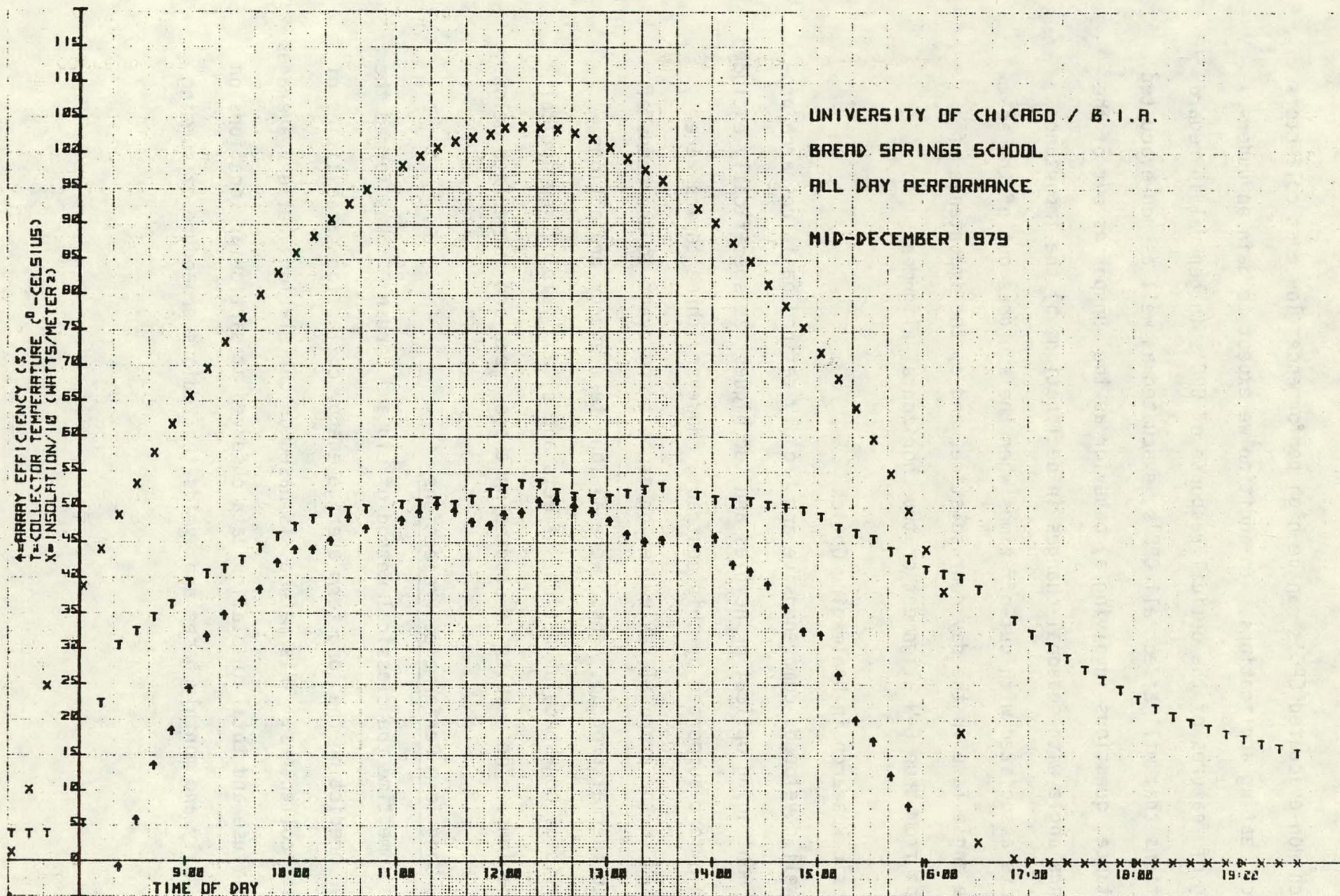


Fig. 24 All day performance curve near winter solstice showing available hemispherical insolation, average collector array temperature and array efficiency as functions of time. The fluctuations in temperature and efficiency near mid-day show the effect of load variations correlated with lunch time activities, e.g., dish washing, clean up, etc. The all day efficiency (8:30 to 16:30) is 39%.

that such non-evacuated CPC's can be high performance, low cost collectors for space heating applications. In addition we expect to gain an understanding of features of the optical response of CPC's in general in regard to questions that will affect all CPC's, evacuated as well as non-evacuated. For instance, questions involving a) behavior as the sun passes out of the acceptance angle with seasonal changes in declination, b) the importance of effects associated with cut-off times when the sun goes out of the acceptance angle late in the day near solstice, and c) the importance of deviation from true E-W alignment or true horizontal alignment.

III. Basic Research in Nonimaging Optics

A well developed, comprehensive and broadly defined basic research program in nonimaging optical principles and techniques was specifically excluded from the effort supported by this contract. However, three topics were identified in the proposal review period as being relevant to the needs of the solar thermal program. These were a) long term energy projections, b) analysis of non-specular optical effects and c) analysis of new optical configurations. The results of studies on these areas are summarized below.

A. Long Term Performance Projections

For some time the classical method of Liu and Jordan^[25] has formed the basis for predicting the long term average energy collection capabilities of flat plate collectors. This method is based on correlations between averages of the diffuse and total insolation data observed at particular locations on hourly, daily and monthly bases and avoids the tedious procedure of summing

for an entire year the hour by hour contributions calculated from weather tapes and the instantaneous thermal behavior of the particular collector being studied. Until recently, however, the latter procedure has been the only method applicable to CPC's and other concentrating collectors because no model existed for incorporating quantitatively the relative effects of the diffuse components at differing concentration. The recent works of Collares-Pereira and Rabl in our group^[26,27,17] have now extended and updated the Liu and Jordan approach and generalized it to include all types of concentrating collectors. A detailed explanation of the method is inappropriate here, but their major conclusions are listed below.

- a) The validity of the Liu and Jordan approach has been confirmed but numerical inaccuracies in their correlations were found due in part to their reliance on uncorrected measurements using a pyronometer plus shade ring for the diffuse component.
- b) New parameters characterizing the correlations have been established.
- c) These new correlations imply that the diffuse component is significantly larger than predicted by Liu and Jordan.
- d) The new model gives a complete description of the long-term average solar radiation on any surface. It has been found to predict radiation availability for solar concentrating collectors to better than 3%.
- e) The model provides a framework for optimal matching between solar radiation and ideal concentrators, in particular CPC's.

As an example of the utility of this model we show in Fig. 25 the predicted annual energy delivery (per m^2 of collector aperture) as a function of operating temperature for an East-West aligned tracking parabolic trough and a 5.25X evacuated tube CPC. The instantaneous performance curves used for these model calculations are that for the Hexcel parabolic trough^[12] and the 5.25X collector built and measured here at Chicago (Fig. 7 of this report). The predicted output has been found to agree within 3 percent with calculations made on an hour by hour basis. Thus as a result of this work a simple procedure now exists for making the kind of tradeoff studies necessary for optimizing a particular collector design or comparing different generic collector types.

B. Non-specular Optical Effects

Since their discovery, it has been known that near-ideal nonimaging concentrators would be more forgiving in terms of mirror slope and contour errors and small angle scattering associated with dust and scratches on the optical elements than focussing concentrators. However, a quantitative understanding of the tradeoffs between the tolerance limits and optical losses has been lacking. Furthermore there are applications where perfect mirrors lead to effects which are undesirable, in particular severe non-uniformities in the energy flux distribution on the absorber.

To understand the relationship between many of these features a ray trace procedure was developed which incorporated a parameter σ , characterizing the degree of non-specularity of a reflector surface. The definition of this parameter is illustrated in Fig. 26. Effectively σ is a measure

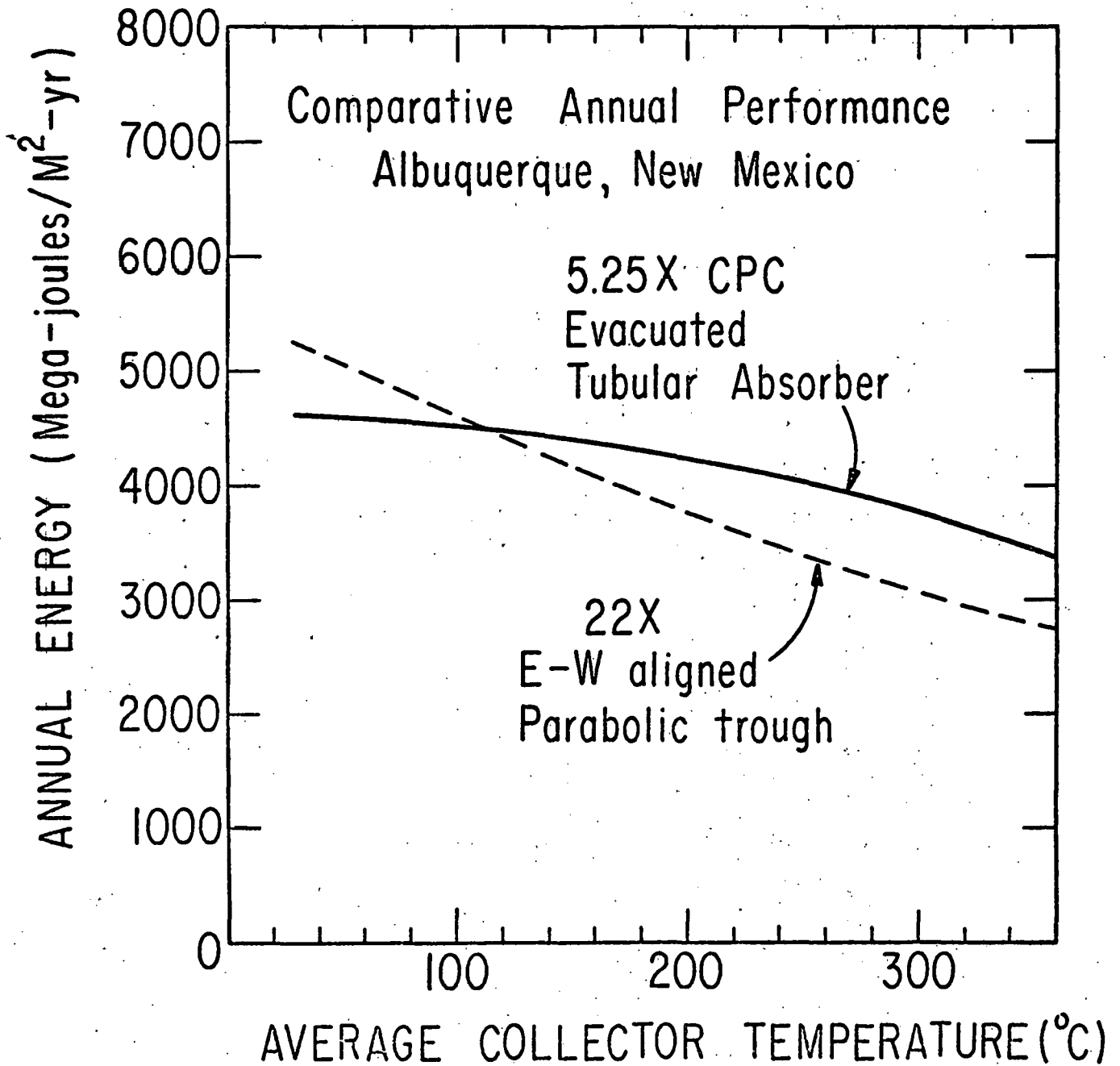
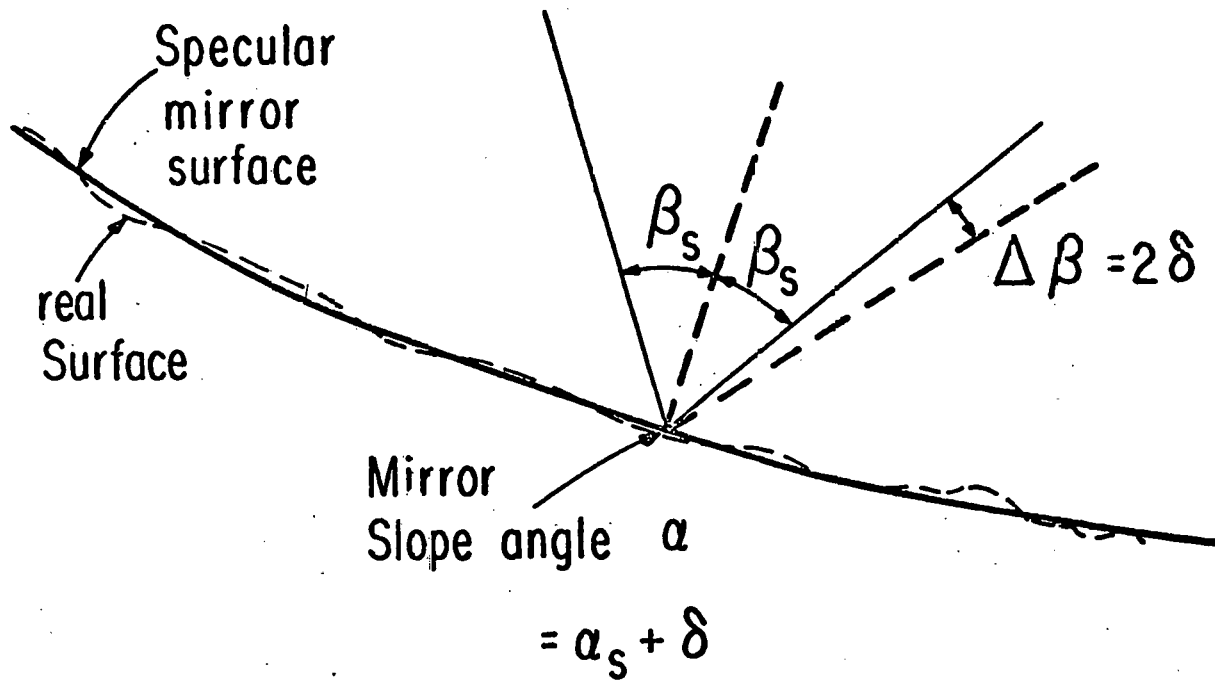


Fig. 25 Long term annual energy projections; comparison between 5.25X evacuated tube CPC and a good tracking East West aligned parabolic trough.



Gaussian Model

std. dev σ

$$P(\delta) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\delta^2/2\sigma^2}$$

or

Sinusoidal $\delta = \sqrt{2}\sigma \sin(\phi) \quad \phi \leq \phi \leq 2\pi$

Fig. 26 Illustrative definition of mirror slope error parameter σ .

of the amplitude of the optical error characterized by the deviation from a mathematically perfect mirror shape. A great variety of optical configurations were then ray traced while varying σ from zero (perfect mirrors) to values comparable with the acceptance angle itself. The main results of this analysis can be summarized as follows:

1. the major effect of non-specularity is a rounding of the corners of the angular response function of the collectors relative to the "ideal" rectangular response function (which has a sharp cut off at the design acceptance angle $\pm\theta_c$),
2. the width of the sloping region (from $\sim 10\%$ to 90% of full response) is approximately 2σ centered on the original sharp cut off,
3. there is no appreciable loss near the center of the response curve as long as $\sigma \lesssim 0.5 \theta_c$, and
4. non-uniformities can be dramatically reduced by values of $\sigma \sim 0.25 \theta_c$ without prohibitive optical loss.

C. Properties of Other Non-imaging Optical Configurations

1. Asymmetric Concentrator Designs

One sub-class of ideal concentrators whose existence has been known since the initial symmetric CPC design principles were under study, but which has not been studied in great detail as yet, consists of shapes optimized for collection between two extreme rays which are not symmetrically oriented with respect to an optic axis (normal to an aperture plane). These have been discussed briefly by Rabl^[19] and in somewhat more detail

by Mills and Guitronich^[28]. The latter authors have pointed out that such devices may be advantageous in certain applications where variable concentration is desired. We have carried out a comparative study of these designs relative to CPC's. The limiting case of asymmetric concentrators (referred to as Extreme Asymmetric Concentrators) consisting of only one curved mirror designed for a tubular absorber is illustrated in Fig. 27. The major advantages of these designs is that they have an effective concentration which varies with incidence angle and at the same time conserves phase space over well defined limits so that for the same peak concentration they have a broader angular range of partial acceptance than a CPC (although their average concentration is only 1/2 that of the CPC with the same limits of acceptance). This triangular shaped response can be oriented such that the solar angle of incidence is near the peak concentration value for a long time near noon and yet the absence of a sharp cut off allows practical non-tracking operating (tilt adjusting perhaps every few days) at higher peak concentration ratios ($\approx 10X$) than are considered practical with CPC's. Our analysis shows that it is in this high concentration region that the main potential for this family of concentrators lies. A savings in mirror area coupled with the non-tracking option combine to suggest attractive possibilities. At peak concentrations $< 5X$ where seasonal load matching has been suggested^[29] the asymmetric concentrator has comparable or larger mirror area than the corresponding CPC (and half the average concentration). Thus it appears from this study to be limited to applications where the load matching capability is of significant economic benefit.

Extreme
Asymmetric
Ideal Concentrator
for tubular
Absorber
(Mills and Guitronich)

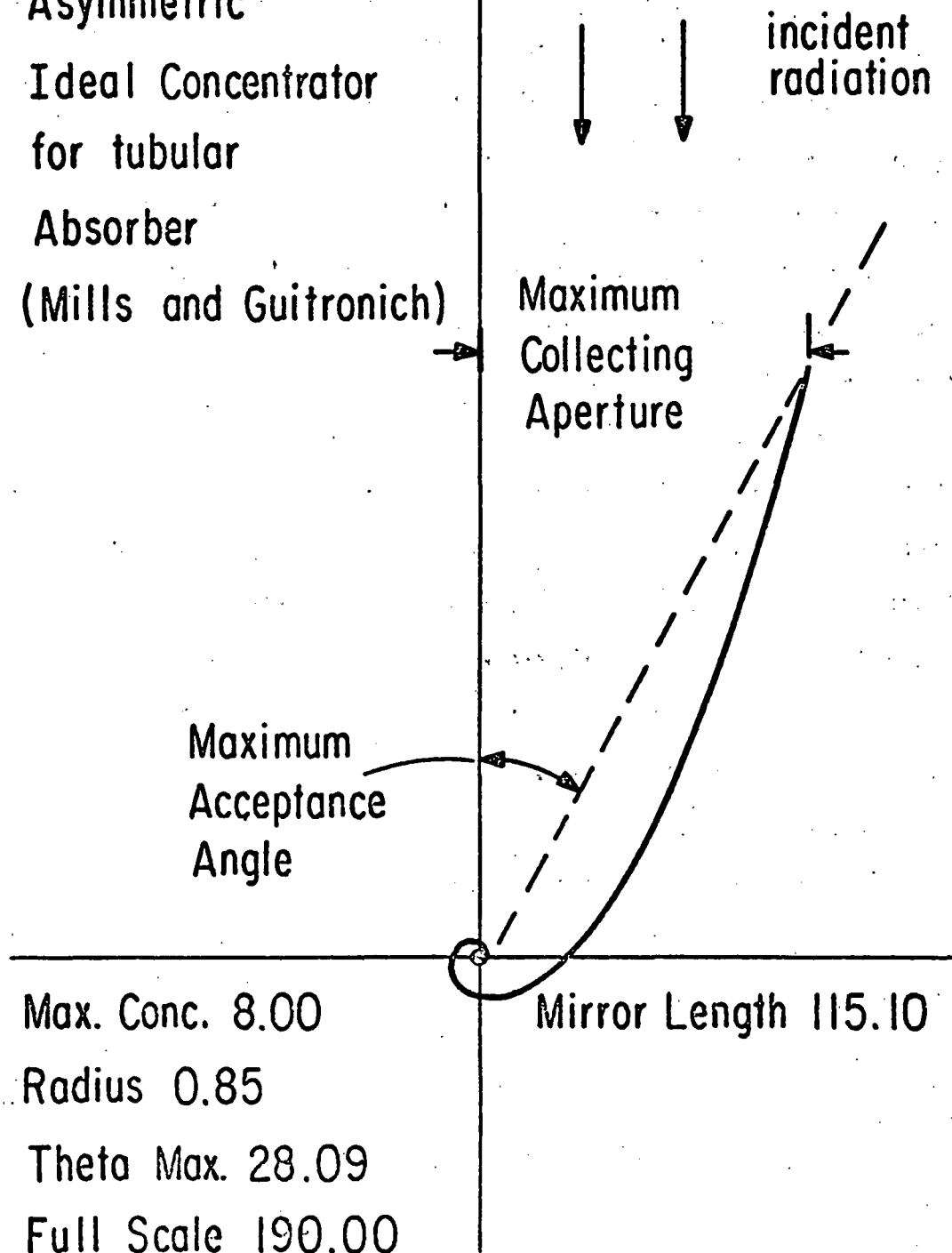


Fig. 27 Profile of "ideal" extreme asymmetric concentrator based on non-imaging design principles.

2. Solution for Ideal Solar Concentrators with Reflector Gaps

In designing a thermally efficient solar absorber one is often led to the requirement that it be enclosed by a glass shield for vacuum containment or as a convection barrier. On the other hand Welford and Winston^[30] have shown that reflectors which extend from the entrance aperture to contact the absorber are a necessary condition for coupling any absorber to an ideal concentrator. Therefore one cannot design a truly "ideal" concentrator for such an absorber where there must be a "gap" between the end of the reflector and the absorber^[6]. One approach to a practical collector design has been simply to calculate the reflector profile for the given absorber but to terminate the reflectors at the point at which they intersect the obstruction. However, in this case the optical losses become quite large if the gap size is comparable to the absorber dimensions. Winston has analyzed this problem in work partially supported by this project and developed a new solution which attains the thermodynamic maximum in flux concentration on the absorber for a given design acceptance angle. (Although it is not an ideal concentrator since the geometrical concentration ratio, C , of entrance aperture A_1 , to absorber area A_2 actually exceeds the thermodynamic limit.)

The new solution is illustrated by the mirror profile curve shown in Fig. 28 for a case with a gap $g = r_2 - r_1$ equal to the absorber radius itself. The conventional approach requires the mirror simply to be terminated leaving a gap $g = r_2 - r_1$, which results in a "gap loss" of $\sim 22\%$, and thus the actual energy reaching the absorber even for otherwise perfect optics

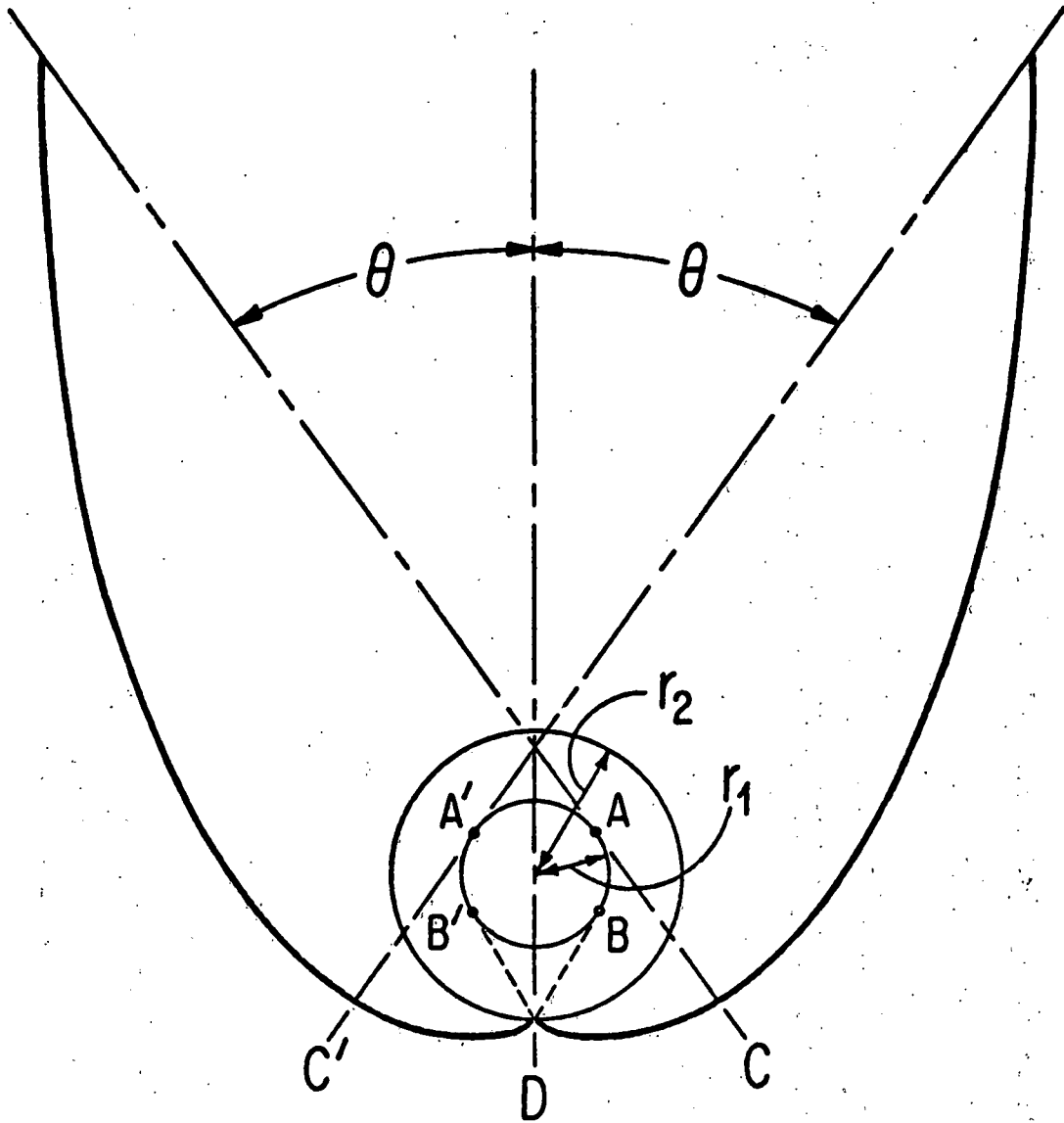
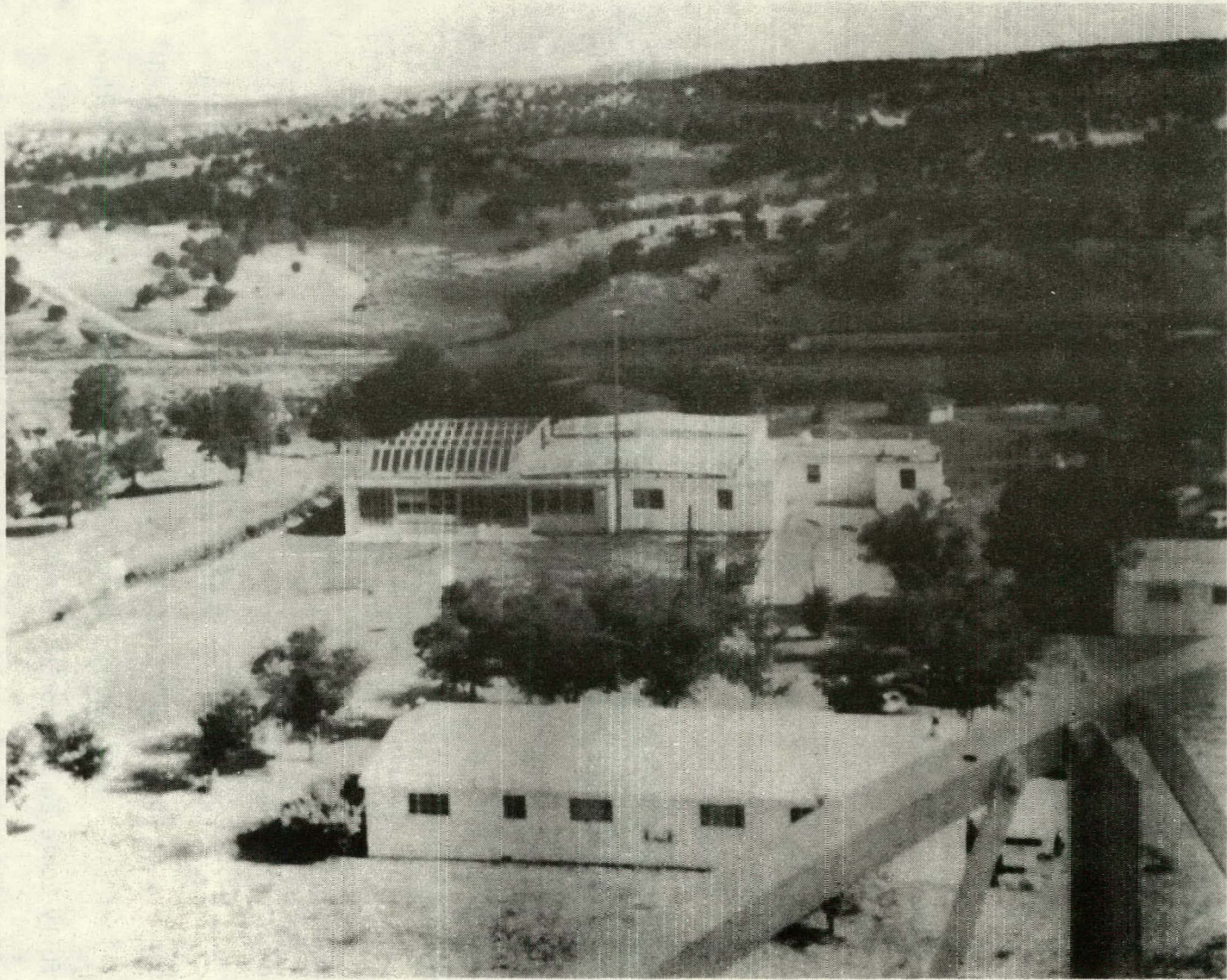


Fig. 28 Cross section profile of new "extended cusp" solution for nonimaging concentrator for a tubular absorber with reflector gaps.

will be only 78% of what it could be for the design acceptance angle θ_c . For the new solution in Fig. 28, the profile curve is generated by constructing a "virtual absorber" by laying out tangent lines to the absorber from the point D (the point along the extension of the desired optic axis where it meets the obstruction). The reflector curves then begin at D and are the ideal solution obtained by applying the fundamental design principle^[4] to the virtual absorber (D B A A' B' D). This new solution will accept no radiation outside $\pm\theta_c$, but it is not an ideal concentrator in the usual sense since it will still reject some rays entering the aperture within $\pm\theta_c$ due to the gap. Although these gap losses as a fraction of aperture area are not reduced dramatically below that of the old solution, the new design has an aperture $A_1 > \pi r_1 / \sin\theta_c$ such that the net flux concentration seen by the absorber is $1/\sin\theta_c$ and is therefore the maximum permitted for this acceptance angle by the Second Law of Thermodynamics.

The above modification in design is not simply a subtle improvement. It should be emphasized that both of the fundamental motivations behind concentration, thermal and economic, have to do with the receiver (heat loss/unit area and cost/unit area). This new design increases the total amount of energy within a given acceptance angle which is directed onto a given receiver from roughly 4/5 of the thermodynamic maximum to the maximum allowed; a relative increase of about 25%.



V. Overview of Bread Springs School

IV. Summary and Conclusions

The field of nonimaging optics represents a new technology. Its first application to solar energy concentration dates back only a little more than six years. The first years of its development were marked by a close collaboration between the University of Chicago and Argonne National Laboratory. This effort led to the evolution of a variety of optical designs and eventually to the Argonne prototype of a stationary 1.5X concentrator for evacuated tubular absorbers which has been the model for several non-tracking evacuated collector designs now emerging into the commercial market place.

This report has been concerned with a subsequent advanced hardware development phase at the University of Chicago beginning in 1976 and continuing until the present. Specifically we have described those activities supported by DOE Contract DE-AS02-76ET20236 (formerly EY-76-S-02-2446) which was in effect from July 1, 1977 to September 30, 1978 with a total funding of \$300,000. During this phase a small but well equipped test station was established on the roof of the four story High Energy Physics Building on campus in the heart of Chicago's South Side. This facility is described in the recent SERI survey of existing solar thermal collector test facilities^[31] and recommended there for continued low level support to maintain its capabilities. Furthermore the fundamental goals associated with all of the objectives outlined in the May, 1977 proposal have either been fully achieved or brought close enough to realization to identify a few remaining minor technical obstacles. In addition to the construction of the roof top test station, three quite different thermal applications of these new techniques were explored, an operating system using

CPC's has been installed and instrumented to provide the basis for a long term field test and selected topics in basic nonimaging optical problems were studied.

The specific thermal applications involved a medium concentration ($\sim 5X$) evacuated tube CPC, a two-stage high concentration (16X) nonimaging concentrator designed for sloppy tracking and non-evacuated CPC's for low to mid-temperature applications.

a) The large evacuated tube CPC has been operated with an efficiency of nearly 60% at a temperature of 200°C above ambient. This performance meets or exceeds the efficiency prediction in the preliminary analysis, is comparable to that attained by the best tracking systems and clearly demonstrates the viability of the non-tracking option for solar thermal applications in this temperature regime.

b) The 16X two stage lens-mirror system has a measured efficiency of 48% at 240°C and a measured full angle of acceptance of 6° which was the design goal. This clearly demonstrates the potential of nonimaging techniques for increasing angular tolerances of tracking concentrators.

c) Two non-evacuated CPC's have shown performance significantly better than that for double glazed flat plate collectors at temperatures above $\sim 50^{\circ}\text{C}$ and have been demonstrated to have a good efficiency (noon time efficiencies of 50% in the temperature range near 100°C above ambient) in the temperature regime from 80°C to 150°C without the requirement for high technology systems.

The Bread Springs Elementary School on the Navajo Reservation near Gallup, New Mexico, now has an array of nearly 800 ft.^2 (net area) of 3X CPC collectors which have operated for two heating seasons. The array supplies

nearly 50% of the building's heating requirement which exceeds the design load fraction by about a factor of 2. After a variety of operational problems the instrumentation and automated data system is functioning properly and about 6 months of nearly continuous (2 years of intermittent) data has been acquired. The noon time efficiency of the entire array (including distribution losses) is typically just under 50% at a $\Delta T = 50^{\circ}\text{C}$ (90°F) above ambient.

A comprehensive method for predicting long term energy collection capability of CPC's and all types of concentrating collectors has been developed. A quantitative ray trace program to analyze non-specular effects in the reflector surfaces has been developed and a variety of both old and new nonimaging ideal concentrator configurations have been and continue to be studied.

In conclusion we emphasize that this work and the work at Argonne National Laboratory must be regarded as just the beginning of the exploration of applications of nonimaging concentrators for solar thermal collectors. It must be recognized that the best developed focussing systems existing today, for instance, the parabolic trough and dishes have been under development for many decades or even centuries. The potential for the field of nonimaging optics is open ended. The most obvious immediate applications are characterized by the three widely different prototypes studied in this effort. In particular

1. Low technology (non-evacuated) low cost (inexpensive reflectors) CPC's suitable for temperatures around 100°C are particularly well suited for application in rural areas or in less developed countries.

2. Second stage nonimaging elements in both line focus and point focus geometries can combine in one system the advantages of focussing systems and near ideal optics to result in truly optimized optical concentrating systems.

3. The use of moderate nonimaging concentrators (2X - 6X) combined with good materials (high reflectivity, good selectivity in the absorber surface, evacuated absorber surface) has the greatest potential for a high performance but operationally simple mid-temperature (around 250°C) solar collector. The marginal gain in increasing concentration is most dramatic at low concentration ratios as is illustrated in Fig. 29. It is not generally recognized that at 250°C , for instance, the gain in performance in going from 1.5 to 5X is many times greater than in going from 5X to 25X. It is this fact together with the operational simplicity of these systems which makes the non-tracking option a really viable approach to mid-temperature solar energy collection.

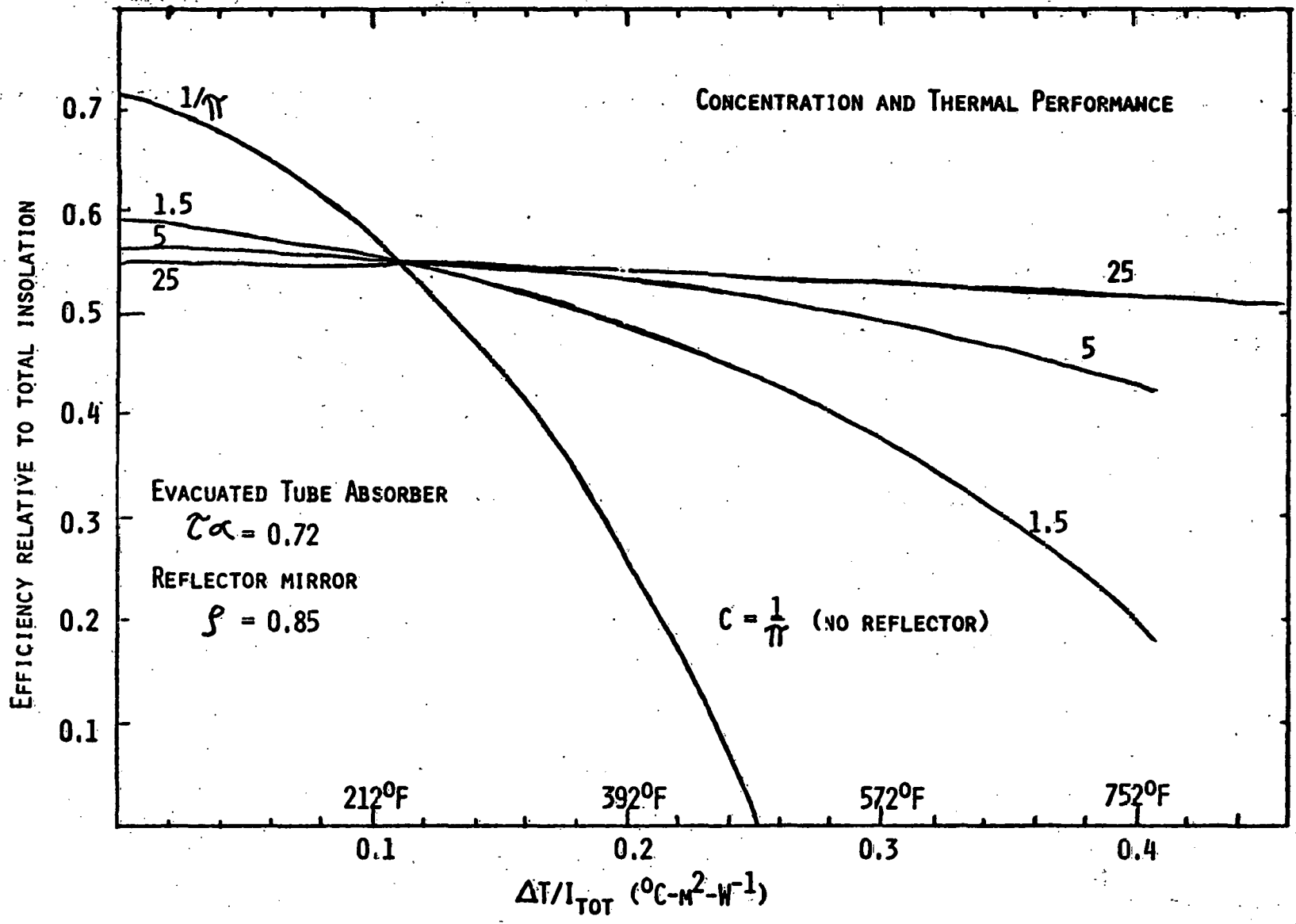


Fig. 29 Illustration of the non-linear dependence of thermal performance on concentration ratio.

Acknowledgements

In a long term multifaceted program such as this there are a great many people we would like to thank. First of all the students and technical staff of our own solar energy group deserve special mention, in particular Bill Zitek, Mike Hilgart, Peter Roothaan, Ari Rabi, Manuel Collares-Pereira, Nancy Goodman and Peretz Greenman. The work of personnel of the Research Institute Central Shop Bob Byrnes, John Sabo, Tony Kittler and Pat Abbeduto in fabricating the collector prototypes was absolutely essential to the project. In addition we would like to thank the members of the Argonne National Laboratory Solar Energy Group, Bill Schertz, Kent Reed, Bill McIntire, Roger Cole, John Allen and Tony Gorski for their helpful advice and suggestions on the many aspects of this work.

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List of References

1. H. Hinterberger and R. Winston, "Efficient Light Coupler for Threshold Cerenkov Counters", Rev. Sci. Inst. 37, 1094 (1966).
2. R. Winston, "Light Collection within the Framework of Geometrical Optics", J. Opt. Soc. Am. 60, 245 (1970).
3. R. Winston, "Principles of Solar Concentrators of a Novel Design", Solar Energy 16, 89 (1974).
4. R. Winston and H. Hinterberger, "Principles of Cylindrical Concentrators for Solar Energy", Solar Energy 17, 255 (1975).
5. R. Giugler, A. Rabi, K. Reed, V. Sevcik, and R. Winston, "Compound Parabolic Concentrators for Solar Thermal Power", Progress Report January-June 1975, Argonne National Laboratory Report ANL-75-52.
J. W. Allen, N. M. Levitz, A. Rabi, K. A. Reed, W. W. Schertz, G. Thodos and R. Winston, "Development and Demonstration of Compound Parabolic Concentrators for Solar Thermal Power Generation, Progress Report July-December 1975, Argonne National Laboratory Report ANL-76-71.
6. A. Rabi, N. B. Goodman and R. Winston, "Practical Design Considerations for CPC Solar Collectors", Solar Energy 22, 373 (1979).
7. R. L. Cole, J. W. Allen, N. M. Levitz, W. R. McIntire and W. W. Schertz, "Performance and Testing of a Stationary Concentrating Collector", Proc. of the ERDA Conference on Concentrating Collectors, Atlanta, CA, pp. 3-31, (1977).

8. Kent A. Reed and John W. Allen, "Solar Thermal Collector Testing: Calorimetric Ratio Technique", Proc. of the 1979 Annual Meeting, American Section, International Solar Energy Society, Denver, CO (1979).
9. M. Collares-Pereira, J. O'Gallagher, A. Rabl and R. Winston, "A Compound Parabolic Concentrator for High Temperature Solar Collection Requiring Only Twelve Tilt Adjustments per Year", Proc. of the International Solar Energy Congress, New Delhi Meeting, (1978).
10. J. J. O'Gallagher, M. Collares-Pereira, A. Rabl and R. Winston, "A Compound Parabolic Concentrator for Operation at 300°C", Proc. of the 1978 Annual Meeting, American Section of ISES, Denver, 1, 885 (1978).
11. M. Collares-Pereira, J. O'Gallagher, A. Rabl, R. Winston, R. Cole, W. W. McIntire, K. Reed and W. Schertz, "Design and Performance Characteristics of Compound Parabolic Concentrators with Evacuated and with Non-evacuated Receivers", Sun II. The Proc. of the International Solar Energy Society Congress, Atlanta, 2, 1295 (1979).
12. Vernon E. Dudley and Robert M. Workhoven, "Summary Report: Concentrating Solar Collector Test Results at the Collector Module Test Facility (CMTF) January-December 1978, Technical Report SAND78-0977 (1979).
13. M. Collares-Pereira, A. Rabl, R. Winston, "Lens Mirror Combinations with Maximal Concentration," Appl. Opt. 16, 2677 (1977).
14. M. Collares-Pereira, J. O'Gallagher, A. Rabl, R. Winston, J. K. Williams, J. R. Egger, "High Temperature Solar Collector of Optimal Concentration", Proc. of the ISES New Delhi Meeting (1978).

15. M. Collares-Pereira, J. O'Gallagher, A. Rabl and R. Winston, "Non-evacuated High Temperature Linear Fresnel Lens and Second Stage CPC Type Collector with Large Tolerance for Tracking Errors", Sun II, Proc. of the ISES, Atlanta 1, 501 (1979).
16. D. F. Grether, A. Hunt, M. Wahlig, "Circumsolar Radiation: Correlations with Solar Radiation", Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720.
D. F. Grether, A. Hunt, M. Wahlig, "Circumsolar Radiation: Monthly Summaries of Effect on Focussing Solar Energy Collection Systems:", Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720.
17. M. Collares-Pereira and A. Rabl, "Simple Procedure for Predicting Long Term Average Performance of Non-concentrating and of Concentrating Solar Collectors", Solar Energy 23, 235 (1979).
18. M. Collares-Pereira, "High Temperature Solar Collector with Optimal Concentration: Non-focussing Fresnel Lens with Secondary Concentrators", Solar Energy 23, 409 (1979).
19. A. Rabl, "Comparison of Solar Concentrators", Solar Energy 18, 93 (1976).
A. Rabl, "Optical and Thermal Properties of Compound Parabolic Concentrators", Solar Energy 18, 497 (1976).
20. M. Collares-Pereira, N. B. Goodman, P. Greenman, J. O'Gallagher, A. Rabl, L. Wharton and R. Winston, "Nonevacuated Solar Collectors with Compound Parabolic Concentrators", Proc. of 1977 Annual Meeting, American Section, ISES, Orlando, FL, 1, 36 (1977).

21. M. Collares-Pereira, N. B. Goodman, P. Greenman, J. O'Gallagher, A. Rabl, H. Simmons, L. Wharton and R. Winston, "Compound Parabolic Concentrators with Non-evacuated Receivers: Prototype Performance and a Larger Scale Demonstration in a School Heating System, Proc. of the ISES Congress, New Delhi, India (January, 1978).
22. A. Rabl, J. O'Gallagher and R. Winston, "Design and Test of Non-evacuated Solar Collectors with Compound Parabolic Concentrators", University of Chicago Preprint EFI-79-42, to be published in Solar Energy (1980).
23. Florida Solar Energy Center Summary Test Package issued Feb. 15, 1978 and Supplements 1 and 2 issued April and July, 1978, respectively.
24. M. Collares-Pereira, J. O'Gallagher, A. Rabl, H. Simmons, C. Stein, L. Wharton, R. Winston and W. Zitek, "Preliminary Results from a Test Array of 3X CPC Collectors in a School Heating Application", Proc. 1978 Annual Meeting, American Section ISES, Denver, Vol. 2.1, 347 (1978).
25. B. Y. H. Liu and R. C. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation", Solar Energy 4, 1 (1960).
26. M. Collares-Pereira and A. Rabl, "The Average Distribution of Solar Radiation, Correlations between Diffuse and Hemispherical and between Daily and Hourly Insolation Values", Solar Energy 22, 155 (1979).
27. M. Collares-Pereira and A. Rabl, "Derivation of Method for Predicting Long Term Average Energy Delivery of Solar Collectors", Solar Energy 23, 223 (1979).
28. D. R. Mills and J. E. Guitronich, "Asymmetrical Nonimaging Cylindrical Concentrators for Solar Energy", Solar Energy 20, 45 (1978).

29. D. R. Mills and J. E. Guirionich, "New Ideal Concentrators for Distant Radiation Sources", *Solar Energy* 23, 85 (1979).
30. R. Winston and W. T. Welford, "Two-dimensional Concentrators for Inhomogeneous Media", *J. Opt. Soc. Am.* 68, 289 (1978).
31. Keith Masterson, "Survey of Solar Thermal Test Facilities", Tech. Report SERI/TR-34-083, August, 1979.