Integrated Function Nonimaging Concentrating Collector Tubes
for Solar Thermal Energy
Final Technical Report

Principal Investigator: Roland Winston

Co-Investigator: Joseph J. O'Gallagher

Research Assistant: Keith Snail

MASTER

The University of Chicago

The Enrico Fermi Institute

September, 1982

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ABSTRACT

A substantial improvement in optical efficiency over contemporary external reflector evacuated tube collectors has been achieved by integrating the reflector surface into the outer glass envelope. We describe the design fabrication and test results for a prototype collector based on this concept. A comprehensive test program to measure performance and operational characteristics of a 2 m² panel (45 tubes) has been completed. Efficiencies above 50% relative to beam at 200°C have been repeatedly demonstrated. Both the instantaneous and long term average performance of this totally stationary solar collector are comparable to those for tracking line focus parabolic troughs. The yield, reliability and stability of performance achieved have been excellent. Subcomponent assemblies and fabrication procedures have been used which are expected to be compatible with high volume production. The collector has a wide variety of applications in the 100°C-300°C range including industrial process heat, air conditioning and rankine engine operation.

I. INTRODUCTION

As the result of a two and one-half year effort, The University of Chicago Solar Energy Group has developed an advanced evacuated tube concentrating solar thermal collector which is competitive with tracking parabolic troughs while itself remaining completely fixed throughout the year. The design is unique in that it combines in a single integrated unit three significant advances in solar collector technology of modern times. These are a) nonimaging optical concentrators to allow non-tracking fully stationary operation, b) vacuum insulation to eliminate conductive and convective heat losses and c) spectrally selective coatings to suppress radiative losses. The project was conducted in collaboration with the staff of the GTE Research Laboratory in Waltham, Massachusetts, who assisted in the mechanical design and fabrication of both the pre-prototype and prototype tubes.

The optical, thermal and mechanical features were defined during a preliminary design phase in which several alternative approaches were evaluated. A total of 16 preprototype tubes incorporating a variety of modifications were fabricated and tested individually. After "freezing" the design, 80 prototype tubes were produced and a full panel of 45 tubes (2 m^2 net aperture area) was assembled and a comprehensive set of performance and operational tests were carried. This report is a summary of the complete project outlining the overall design approach, the technical obstacles encountered and overcome, the performance measurements on the prototype panel and projected results for future panels based on this design. Throughout this report and in subsequent work we will refer to this collector as the Integrated Stationary Evacuated Concentrator or ISEC collector.

II. DESIGN CONCEPT

Several versions of evacuated tube solar collectors which utilize nonimaging Compound Parabolic Concentrator (CPC) type reflectors¹ to couple the collecting aperture to a dewar type evacuated tubular absorber are now commercially available. The general features of such designs are illustrated in Fig. 1a. These collectors are characterized by very low heat losses permitting acceptable efficiencies (30%-45%) to be achieved in the range 100°C-150°C with a stationary design.²

A substantial improvement in optical efficiency over these external reflector designs both in initial value and its stability over a relatively long lifetime can be achieved by integrating the concentrating reflecting surface into the vacuum enclosure itself by shaping the outer glass envelope to the desired profile³ as illustrated in Fig. 1b. The performance gain is a consequence of two obvious advantages of the integrated design.

- 1) Since the reflector surfaces are in vacuum, high quality front surface mirrors (silver or aluminum with reflectances $\rho = 0.91-0.96$) can be used instead of anodized aluminum sheet metal or thin film reflectors ($\rho = 0.80-0.85$) typical of the external reflector designs.
- 2) The integrated design either eliminates the need for an external cover glass and the associated loss in transmission alternatively protects against the effects of exposure of the reflector surfaces to the elements as such a cover was let off.

Clearly the lifetime of such reflecting surfaces in vacuum can be expected to be essentially indefinite as long as the integrity of the enclosure is maintained.

The compatibility of the basic CPC profile with the cylindrical tubular enclosure is shown in Fig. 2a in which a stationary 1.5X CPC profile designed for a 2 inch aperture is superimposed on a 2" diameter glass tube. Figure 2b shows how a modest reshaping of the glass turns the outer glass enclosure into a wide angle concentrator. This report describes the design, fabrication and test results for a panel of prototype tubes based on this concept. Some preliminary discussions of this work have already been published.⁴⁻⁸ The final design profile selected for the concentrating tube is shown in Fig. 3 in cross section. The concentrator profile curve is an extended cusp type CPC⁹ matched to a circular absorber cross section of diameter 9.5 mm (0.375 in.). This design is a modification of the basic CPC which allows a gap of 1.9 mm (0.075 in.) for thermal isolation and mechanical clearance and permits a slightly larger geometrical concentration ratio. The design acceptance angle is $\pm 35^\circ$ to provide stationary operation with no tilt adjustments. The corresponding maximum geometric concentration for this design is 1.85X but has been truncated to yield an effective net concentration of 1.64X with a collecting aperture 4.91 cm (1.83 in.) in width. The outer glass envelope was formed from a standard 57 mm (2 in.) O.D. tube of borosilicate (Pyrex^(R)) glass which has an original I.D. of 52 mm. This has been shaped by vacuum drawing down to a cylindrical mandril of the desired profile. The reflector surface is a thin (2000 Å) layer of vacuum deposited silver with a reflectance $\rho > 0.95$.

The absorber tubes are 9.5 mm (3/8 in.) O.D. type 304 stainless steel with a wall thickness of 0.19 mm (0.0075 in.). The selective surface is similar to that used in typical commercial dewar tubes and consists of an evaporated multilayer coating which is stable to 400°C in high vacuum. The end to end absorber tube length is 119.4 cm (47 in.) which was the maximum compatible

with the equipment for deposition of the selective coating. This is the main constraint determining the length of the prototype tube shown schematically (not to scale) in the side view in Fig. 4. Special features of the mechanical design include:

- a. double-ended unidirectional flow-through configuration,
- b. copper glass-to-metal "Housekeeper" seals,
- c. metal bellows to allow for differential expansion between the absorber and glass tube
- d. a barium getter to preserve long lifetimes for hard vacuum ($<10^{-6}$ torr.).

Despite the complications introduced by the flow through metal absorber tube this configuration was ultimately preferred because it provides the best heat transfer and the lowest pressure drops for a given size aperture. Because of the length taken up by bellows, seals and the getter, the active length in the prototype was limited to 91 cm (36.0 in.) and the relative effect of end losses was more important in the prototype panel than will be the case for a length optimized for production (probably ~6 feet).

III. TECHNICAL PROBLEMS AND SOLUTIONS

There were four significant problem areas encountered in the preprototype phase. Eventually satisfactory solutions were found for each but this did require more time to go through a "learning experience" than we had anticipated. The problems and their solutions are outlined below.

1. Obtaining and maintaining a sealed hard vacuum ($<10^{-5}$ torr.)

Electrical resistance heat loss measurements on the first few preprototype tubes revealed exceptionally high heat losses that were approximately 4 to 10 times expected radiation losses calculated from the absorber

coating properties. The source of the problem was traced to the presence of a soft vacuum inside the sealed tube caused by out-gassing of the glass and metal surfaces after the tube had been sealed off from the vacuum apparatus. The problem was eliminated by establishing a simple but thorough degassing procedure under high vacuum pumping including a high temperature bake-out and electrical resistance heating to degas the absorber. Pressures lower than 10^{-7} torr were then routinely achieved and have been maintained for almost 2 years in one tube which was fabricated with an ion gauge attached and which is monitored periodically. In addition, regular heat loss tests on selected spare production tubes for over one year indicates no change in vacuum quality.

2. Applying a uniform quality stable reflector surface.

Early attempts at GTE to vacuum deposit an aluminum surface on the shaped glass profile yielded disappointing results characterized by discolored patches that were caused by partial evaporation of the tungsten filament. Chemical spray silvering was then tried, but what appeared to be a highly reflecting coating was destroyed by the application of heat necessary to work the glass during assembly. Vacuum deposition of silver has proved to be quite satisfactory provided that care is taken to clean and prepare the glass surface beforehand.

3. Obtaining a reliable seal/bellows assembly.

The early preprototype tubes utilized a stainless steel glass-to-metal seal to attach the bellows section to the glass envelope. A few of these seals developed cracks or breaks during assembly, shipment and early testing leading to questions about their reliability. A design change was implemented which substituted a copper glass-to-metal Housekeeper seal for

the stainless steel seal. The stainless steel bellows are brazed to the copper section before the seal. None of these seals has failed or shown any sign of degradation in the more than 80 tubes produced. Furthermore one seal-bellows assembly was mechanically cycled more than 4000 times through a bellows extension corresponding to 300°C thermal expansion with no sign of incipient failure.

4. Maintaining proper tube position and alignment.

Early prototype tubes exhibited very large optical losses due to mis-positioning of the absorber tube. A spring type support to define the proper tube position and maintain it was designed to be located at two places along the tube length. Electropolished stainless steel wire was used because of its relatively low thermal conductivity and low emittance, thus minimizing the associated heat losses. Temperature profile measurements made with an electrical resistance calorimetric technique have determined that the associated heat loss at 200°C is a small fraction (~ 0.1) of a watt.

Although this project was concerned with the development of an experimental proof of concept prototype one of the major objectives was to develop a basic design which would ultimately be compatible with high volume production. Thus, although each of the 80 production tubes was literally hand made, the fabrication sequence was modeled after a continuous production line as illustrated schematically in Figure 5. There are really only two major components, the outer glass envelope and the absorber tube. The glass tubes must be shaped and silvered and the absorber tubes annealed and coated. The seal-bellows subcomponents were preassembled into glass end-caps and the wire center supports were pre-formed and positioned on the absorber tube. The assembly process then simply consisted of attaching one

glass end cap, inserting and aligning the absorber tube and attaching the other glass end cap. The metal portion of the glass-to-metal seals were then brazed to the absorber tube at each end. The completed assembly was connected through an evacuation tube to a high vacuum system. Then the tubes were baked out at 300°C to out-gas the glass and metal surfaces, with the absorbers heated to ~390°C with an electrical resistance heater. Finally a getter inside each tube was flashed and the tube tipped off from the vacuum manifold while maintaining the pressure at $\sim 10^{-7}$ mmHg. All of the steps in this procedure could be accomplished with automatic machinery. In the prototype fabrication the most labor consuming portion was the shaping of the glass which in high volume production would most likely be done when the glass tubes are drawn from the melt.

IV. PERFORMANCE GOALS AND PREDICTIONS

A test panel having a net collecting area of 2 m² was assembled using 45 of the 80 production tubes. A schematic illustration of this configuration is shown in Figure 6. The tubes are arranged in 15 rows of three each with the rows connected in serpentine fashion so that all 45 tubes are in series. The inter-row connections were made with flexible metal tubing and the two connections within each row of tubes were made with a rigid union. The total interconnected length was kept as short as possible and all tubing not inside the vacuum enclosures was insulated with 2 inches of ceramic fiber. The tubes are held by flexible rubber mounts which allow for longitudinal expansion within each row and are located on 3 inch centers to reduce wind loading, allow for cleaning and replacement if necessary and to hinder snow accumulation.

A. Optical Model

To evaluate the performance of this panel its expected efficiency was parameterized in terms of three quantities characterizing the optical throughput, the radiative losses and the lumped conductive and convective losses. A quantitative expression for the optical efficiency η_0 in terms of the material and subcomponent properties is given by

$$\eta_{0,\pm\theta} = \tau \rho^{<n>} <\alpha> (1 - \bar{L}) \quad (1)$$

where τ = transmittance of the outer glass envelope

ρ = the reflectance of the mirror surface

$<n>$ = the average number of reflections $\cong 0.8$

$<\alpha>$ = the absorptance of the selective surface averaged over angles of incidence

$\bar{L}$ = the average value of L , the so called "gap loss" resulting from the necessity of maintaining some space between the absorber and the mirror

This expression is for the optical efficiency for all radiation within the acceptance angle. For experimental measurements and for comparison with performance of collectors of other designs it is also useful to define two other optical efficiencies. These are

$\eta_{0,\perp}$ = normal incidence optical efficiency which may be different than $\eta_{0,\pm\theta}$ since L is not uniform across the acceptance

and

$\eta_{0,b}$ = the optical efficiency calculated relative to beam radiation only.

The latter parameter is always higher than $\eta_{0,\pm\theta}$ due to the contribution of a fraction of the diffuse insolation within the acceptance angle for which the collector is not "charged". The diffuse fraction accepted by a CPC is well approximated by $1/C$ so that one can relate the two efficiencies by

$$\eta_{0,b} = \eta_{0,\pm\theta} \left(1 + \frac{1}{C} \cdot \frac{f}{(1-f)} \right) \quad (2)$$

where f is the diffuse to total fraction. It should be noted that for radiation incident on a circular metal absorber tube with fluid flowing inside the heat transfer is excellent so that the so-called heat removal factor sometimes designated by F' is essentially unity and experimentally should be regarded as being incorporated into the definition in equation (1).

B. Thermal Model

The heat loss from the test panel was parameterized in terms of U_m , the effective linear heat loss coefficient per unit net aperture and ϵ^* the effective total emittance of the absorber surface normalized to the net active absorber length as follows.

$$Q_L (T_c, T_a) = U_m (T_c - T_a) + \frac{\epsilon^*}{C} (T_c^4 - T_a^4) \quad (3)$$

where T_c - average collector temperature in $^{\circ}\text{K}$

T_a = average ambient temperature in $^{\circ}\text{K}$

σ = the Stefan-Boltzman constant = $5.67 \times 10^{-8} \text{ w/m}^2 \cdot ^{\circ}\text{K}^4$

C = geometric concentration ratio = 1.64X

To avoid variations in measured performance for CPC's arising from changes in the distribution of the insolation (e.g., the diffuse to total fraction) we have found it most convenient to use a pyronometer masked so as to accept radiation from within the same field of view as the CPC.

This measured insolation $I_{\pm\theta}$ is then used as the reference base for

defining efficiencies. Thus based on equations (1) and (3) we can express the expected operating efficiency at an elevated temperature for the full panel to be described by

$$\eta_{\pm\theta}(T_c, T_a, I_{\pm\theta}) = \eta_{0,\pm\theta} - \frac{U_m(T_c - T_a)}{I_{\pm\theta}} - \frac{\epsilon^* \sigma}{C} \frac{(T_c^4 - T_a^4)}{I_{\pm\theta}} \quad (4)$$

C. Materials and Component Parameters

The material property values which determine the optical and thermal performance parameters are listed in Table 1. The first column lists the design goal values for each property adopted early in the project as being achievable with then current technologies based on specifications quoted by suppliers. The second column gives the values actually measured on samples prepared early in the preprototype phase. As can be seen the design goals were met or closely approached for all parameters but one. In particular the absorptance of the selective coating used fell somewhat short of expectations and as will be seen this was the major factor responsible for a slight (~ 5%) shortfall in the efficiencies actually achieved relative to those projected in the original proposal. However, this was a relatively minor disappointment since the performance was as expected in all other areas and the yield and reliability of the produced collector tubes far exceeded expectations. Table 2 summarizes the collector model parameters derived from the subcomponent and material properties in Table 1 which are used to predict the performance of the prototype panel as built. These will be discussed in greater detail and compared with the measurements below in section VI.

V. TEST AND MEASUREMENT PROCEDURES

The efficiency and heat loss have been measured repeatedly throughout a time period spanning more than one year under a variety of ambient temperature conditions on both our low temperature water loop and our high temperature oil (Therminol-66^(R)) test loop. A schematic diagram of the high temperature loop is shown in Figure 7. The water loop is similar but considerably simpler, consisting of an open reservoir, a gear pump, filters and in-line heaters. Measurements with the water loop were usually conducted with the inlet temperature determined by that available directly from the mains so that the average temperature was very near ambient although 2 kilowatts of in-line electric heaters were used on occasion to raise the collector inlet to 60°C-80°C. For the Therminol loop 3-6 kw of electric power in the fluid reservoir and in-line are available to provide collector inlet temperatures from ~80°C to nearly 300°C. In the case of water measurements the heat gained by the collector ΔQ is determined from the following relation.

$$\Delta Q = \rho(T_F) \cdot \dot{V} \cdot c (T_o - T_i) \quad (5)$$

where T_o, T_i are the outlet and inlet temperatures of the collector tube array

c is the specific heat of water assumed constant = 4.19 joules/gm

$\rho(T_F)$ is the (temperature dependent) density of water in gms/ml

$\dot{V}$ is the volumetric flow rate of fluid through the collector

T_F is the average fluid temperature = $(T_o + T_i)/2$

Here T_o and T_i are measured by matched platinum resistance thermometers

(RTD's) and V is measured with a beaker and a stop watch at regular intervals and monitored with a visual flow meter.

In the case of the high temperature oil loop the heat gain or loss is measured simultaneously by two different methods. The first is the conventional method similar to that used for water where

$$\Delta Q = \rho_{th}(T_F') \cdot c_{th}(T_F) \cdot \dot{V} (T_o - T_i) \quad (6)$$

with $c_{th}(T_F)$ the specific heat of Therminol evaluated at the average fluid temperature in the collector

$\rho_{th}(T_F')$ the density of Therminol evaluated at T_F' , the temperature of the fluid where $\dot{V}$ is measured.

Here ρ_{th} and c_{th} are determined from tabulated fluid properties supplied by the manufacturer and $\dot{V}$ is measured by an in-line turbine flow meter. The second method is based on the calorimetric ratio technique first developed at Argonne National Laboratory by K. Reed¹⁰ and later adopted by ourselves and others.¹¹ The purpose of the method is to circumvent sources of error inherent in Eq. (6) due to uncertainties in the fluid parameters and the difficulties in obtaining an accurate flow rate measurement. The essential element is the use of an accurately calibrated reference heat source Q_{ref} in the test loop in series with the collector whose heat gain one is trying to determine. In this case the temperature rise across the reference heat source, ΔT_{ref} will be related to Q_{ref} by an equation similar to (6) above. That is,

$$Q_{ref} = \rho_{th}(T_F') \cdot c_{th}(T_F'') \cdot \dot{V} \Delta T_{ref} \quad (7)$$

where T_F'' is the fluid temperature at the reference source. Solving for the product $\rho_{th}(T_F') \cdot \dot{V}$ and substituting in (6) yields

$$\Delta Q = Q_{ref} \cdot \frac{(T_o - T_i)}{\Delta T_{ref}} \cdot \frac{c(T_F)}{c(T_F'')} \quad (8)$$

which is independent of fluid density and volumetric flow rate and only very weakly dependent on fluid properties since $c(T_F) \approx c(T_F'')$ under most circumstances. In our system ΔT_{ref} is measured by a matched pair of RTD's and Q_{ref} is determined by an electrical power meter across a resistance heater. This heater is immersed inside a section of pipe (the "calorimeter" proper) which is placed inside a vacuum dewar and very thoroughly insulated. The residual heat losses although small have been accurately measured as a function of T_F'' with $Q_{\text{ref}} = 0$ and a correction is made for this effect in the data analysis.

During operation data taking is under the control of a Hewlett-Packard 9825A programmable calculator which controls a 40 channel multiplexer and a high precision digital voltmeter. The data acquisition and analysis system is outlined in Figure 8. All relevant sensors e.g., RTD's, flow meters, thermocouples for T_a and pyranometers (here an Eppley model PSP masked as described earlier) are scanned every 2 seconds and the data accumulated for a preset interval (usually one or two minutes) after which the average values of measured and calculated quantities are printed out and plotted in real time. In determining $T_o - T_i$ allowance is made for the transit time of a fluid element through the collector. For a measurement to be considered valid we require a) that the collector inlet temperature be constant to within $\pm 0.05^\circ\text{C}/\text{minute}$, b) that the heat gains or losses from Eq. (6) and (8) agree to within 2.5% of one another and c) for efficiency measurements that the masked insolation $I_{\pm\theta}$ be stable within 15 watts/meter^2 . The data reported in the next section consists of longer term time averages over periods meeting these criteria ranging from a minimum of 10 minutes to order of one hour.

VI. TEST RESULTS

A. Optical Performance

The angular response function, that is, the optical efficiency as a function of solar incidence angle θ in the plane perpendicular to the longitudinal axis of the tubes in the panels is plotted in Figure 9. The individual tubes were aligned so that their optic axes (and aperture planes) were as close as possible to being parallel to one another (within $\sim \pm 1^\circ$) during panel assembly so that the panel response should be representative of a "typical" tube. The values plotted (solid triangles) were measured on the water loop by determining the efficiencies at an average collector temperature very close to ambient so that thermal losses are completely negligible. For comparison the results of a detailed ray trace calculation of the net optical throughput based on the prototype materials and configurations are also shown (open circles). Three features revealed by the measurements are of particular importance:

1. The average value of the efficiency across the roughly flat top of the response curve is $\eta_0 = 0.65 \pm 0.01$. This is taken to be a representative value of $\eta_{0,\pm\theta}$ as defined above in section IV. It is listed in the third column of Table 2 and is in perfect agreement with the value predicted from measured component parameters (Table 2, second column). It is approximately 5 percentage points lower than the original design goal but this can be completely attributed to the lower than expected absorptance as is confirmed by the good agreement with the ray trace results which were based on the measured prototype parameters and configuration.

2. Both the measurements and ray trace show "shoulders" in the response curve near the edge of the acceptance region separated by a valley in the middle near normal incidence. This is due to the effects of the "gap losses", illustrated by the sample ray trace in Figure 10, which are most pronounced near normal incidence. Ray traces predict the effect to be more pronounced than is observed probably due to variations of tube alignment within tolerances which average out the effect and fill in the valley somewhat. However, the effect is still measurable as noted in the table and the difference between $\eta_{0\pm\theta}$ and $\eta_{0,\perp}$ must be born in mind.
3. The acceptance angle is slightly smaller than the design value. Defined between values corresponding to 80% of the "plateau" response one finds that $\theta_{c, meas} = \pm 32^\circ$ versus $\theta_{c, des} = \pm 35^\circ$. This narrowing is attributed to two deviations in the actual prototype tube CPC configuration from the theoretical design profile as illustrated in Figure 11. First of all, the inside glass surface resulting from the shaping procedure was slightly distorted from design due to warping of the hot mandril relative to its cold (machined) shape. Secondly, rounding the cusp portion of the glass profile increased the size of the physical gap so that the nominal tube position was deliberately lowered as indicated to keep the normal incidence gap losses near the original design values. This results in some losses near $\pm\theta_c$ and the good agreement between the measurements and ray trace calculations confirm the importance

of this effect. Long term energy delivery calculations indicate that the loss in annual performance due to the narrow acceptance angle is small ($\lesssim 3\%$) and in any case in future design iterations the loss in acceptance can be recovered.

B. Heat Losses

Heat loss measurements were conducted either late in the same day on which efficiency measurements had been taken or on cloudy days. In both cases the collector tubes were covered by diffusely reflecting panels. The measurements taken through May 15, 1982, are plotted in Figure 12 along with two curves calculated from Eq. (3) for different ambient temperatures typical of the range of test conditions. Both U_m and ϵ^* depend on the relative importance of end and manifold losses compared to active collecting area and so will depend on tube length. The values are listed in Table 2 for both 3 ft. and 6 ft. tube lengths derived from the parameters in Table 1. The ratio of total length to active (illuminated) length of absorber tubes is 1.26 for the prototype tubes so $\epsilon^* = 1.26\epsilon$. Similarly, the total length of insulated interconnect tubings in the panel is 4.0 m yielding a value of $U_m = 0.2 \text{ W/m}^2\text{-}^\circ\text{C}$ for our 2 m^2 panel. In general the agreement between measurement and calculation is excellent in the range 150°C to 200°C which is the range for which ϵ and U_m were experimentally determined. Between 100°C and 150°C the lower than calculated heat losses observed and the higher values above 200°C are probably due to a slight temperature dependence of either ϵ or U_m which is not taken into account in our simple two parameter heat loss model. Note that the model indicates that the relative importance of the two components of the loss is $\sim 20\%$ conductive and $\sim 80\%$ radiative near 200°C , which is borne out by the good agreement between the model and the observations for the total heat loss as indicated by the values listed in Table 2.

C. Thermal Efficiency

Values of the solar thermal conversion efficiency measured at normal incidence

$$\eta_{\pm\theta\perp}(T_c, T_a, I_{\pm\theta}) = \frac{\Delta Q(T_c, T_a)}{I_{\pm\theta} A} \quad (9)$$

where ΔQ is the average of the measured values determined from Eqs. (6) and (8) are plotted in Figure 13. Here A is the net collecting area of the panel defined as the total transparent tube length in the panel time the tube aperture width. Shown for reference are calculated curves for two sets of parameters representing the typical range of test conditions. The cluster of points near $(T_c - T_a)/I_{\pm\theta} = 0$ represents the value of $\eta_{0\perp}(\pm\theta)$ as determined from water measurements while those points at elevated temperature are Therminol ^(R) measurements taken between September and May. In general, the agreement is quite good. There is no evidence for a temperature dependent deterioration of performance which would be indicated by a gradually increasing discrepancy relative to the calculations at high values of $(T_c - T_a)/I_{\pm\theta}$. It should be noted that these data have been obtained with the prototype panel of 91 cm (3 foot) long tubes for which the relative importance of manifold and end losses is somewhat higher than will be the case for a practical production version of 180 cm to 240 cm (6 to 8 ft.) tubes.

D. Absence of Deterioration with Time

In order to search for effects of two potential degradation modes a) a gradual deterioration in optical performance with time or b) a temperature dependent loss of optical efficiency (which might have been expected if thermally induced distortions produced misalignment of the

absorber tubes) a systematic procedure was adopted. Immediately following every operating efficiency measurement (time and weather permitting) a careful heat loss measurement was carried out at essentially the same average collector temperature. Using this measured heat loss, the operating efficiency was corrected to determine the corresponding gross heat gain (in the absence of thermal losses) which then together with the measured value of $I_{\pm\theta}$ in turn was used to derive the effective optical efficiency $\eta_{o\perp}(\pm\theta)$ for the temperature and date. The results of these determinations are plotted in Figure 14 versus time using different symbols for each of 4 elevated temperature regimes. An examination of these results shows conclusively that there is no significant deterioration in optical performance to the highest temperatures measured. The gross behavior with time also shows no significant long term deterioration although there is a suggestion of a very slight seasonally dependent variation in the derived optical efficiency. That is, the points taken near winter solstice are about 2 ± 1 percentage points below the values observed near equinox, which in turn are lightly lower than (although within experimental error of) the water measurements taken in mid-summer. This effect is still under investigation and may be due to a tilt dependence of the PSP response since all measurements are taken with the panel tilted to be at normal incidence to the beam radiation.

E. Longitudinal Angular Effects

The efficiency values plotted in Figure 13 were all measured at normal incidence utilizing a movable two axis test mount. However, since the collectors are designed to be fully fixed, tilted at the latitude angle with the tube axis aligned east-west the efficiency for off-normal

incidence in the longitudinal plane is of great importance. The optical throughput is expected to fall off slowly with increasing angle due to increased reflection losses at the glass and absorber surfaces, shading losses and other similar effects. The measured longitudinal response as a function of $\theta_{||}$, the angle relative to the normal in the longitudinal plane ($\theta_{\perp}$ projected in the transverse plane was maintained equal to 0) is shown in Figure 15. There is very little measurable effect (less than 2 percentage points) out to $\theta_{||} \approx 40^\circ$ and then a gradual drop off at larger angles. Shown for comparison is a nominal response function described by a 4th order polynomial suggested by Rabl¹² from a fit to data for flat plate and line focus troughs. The CPC results seem to be well described by the same function with the drop off at the highest measured point including some effects due to shading by part of the panel structure.

To illustrate the expected day long response behavior an all day performance test with Therminol was carried out on June 22, 1982. The values of incident insolation, temperature rise across the collector, net heat gain in watts and efficiency are plotted at 10 minute intervals throughout the day in Figure 16. The average collector temperature was maintained near 150°C during the test. Note that the efficiency is very flat for nearly 6 hours with a gradual drop for $\sim 1/2$ an hour on either side of this plateau due to the effects discussed in the previous paragraph. For periods beyond $\pm 3 1/2$ hours from solar noon the sun was outside the normal acceptance angle.

F. Stagnation Behavior

One of the serious operational questions having to do with any high performance stationary collector is the problem of stagnation survival and it remains a potential problem for this collector. The calculated stagnation temperature under worst case conditions is about 450°C which is above the system's damage threshold for both the heat transfer fluid and selective coating. For obvious reasons we have not tried a stagnation test on the full existing prototype panel, however, to gather data on the relative seriousness of the problem we have carried out a number of single tube stagnation tests one of which is shown in Fig. 17. The insolation levels were quite high but highly variable. The maximum absorber temperature just reached 400°C which is acceptable although marginally so. Tests have shown that the coating is safe for many hundreds of hours at 390°C. This test was carried out with the absorber tube full of Therminol and the resulting relatively long response time is thought to be of some value in ensuring that locally very high temperatures are not generated on portions of the absorber. The problem of fail safe stagnation survival remains unsolved at this time although we will investigate several methods as part of a follow-on project. The most promising alternative is the use of a selective surface which is stable to ~500°C such as the coating developed in Australia by the University of Sydney solar energy group.¹³

VII. DISCUSSION AND CONCLUSIONS

A. Accomplishments

Over one year of operating experience with a 2 m^2 panel of prototype integrated CPC collector tubes has confirmed that the optical and thermal performance is as predicted from preliminary measurements on the actual components and materials carried out before fabrication and that no serious technical problems exist in the design.

The entire panel operated perfectly without any failure for over six months. In late winter the vacuum in one tube suddenly deteriorated and it was replaced. The heat losses of all the other tubes remained nominal and there have been no further failures in the ensuing six months up to the time of this report. Thus we have experienced a spontaneous tube failure rate of only 1 per year out of a population of 80 produced tubes. Two other tubes were broken in laboratory accidents. The cause of the spontaneous failure is as yet undetermined but does not appear to be due to a leak but more likely a sudden outgassing of some component inside the tube. Neither the spontaneous failure nor any of the tube breaks involved the glass-to-metal seals, no single one of which has failed. This level of reliability in a newly developed design was unexpected and is a favorable indication regarding the ultimate widespread use of similar designs.

As noted in earlier sections, the optical efficiency actually achieved is about 5% points below the original design goal due to a somewhat lower than predicted value of absorptance α of the selective coating (the actual $\langle\alpha\rangle \cong 0.8$ instead of the design value of 0.85). Several other materials and techniques which produce coatings with the same low values of ϵ but high $\alpha > 0.90$ are currently available commercially and a new coating with

these properties which is also stable to temperatures above 500°C has recently been developed.¹³ Use of such a coating would improve the optical performance of future versions of this concept and at the same time would provide a practical solution for any potential stagnation problems.

It should be emphasized that, however, even with this less than optimum coating, our prototype fully stationary collector panel has exhibited performance comparable to that of a tracking parabolic trough. This is illustrated in Fig. 18 in which some of the most recent panel efficiency measurements are plotted relative to beam insolation I_b , rather than I , along with the calculated prototype performance curve. For comparison the dashed line in the figure shows the performance for an average of the two most widely used commercial tracking line-focus parabolic troughs (Accurex and Solar Kinetics).¹⁴ Even with the shortfall in optical efficiency relative to the design goal it can be seen that the ISEC panel efficiency is directly comparable to the trough to values of $\Delta T/I \approx 0.2$ and remains respectable throughout the plotted range. There are two changes which will be incorporated into subsequent versions of this collector which will improve the achieved performance somewhat further above the plotted performance already demonstrated with our initial prototype: 1) longer tubes (6 ft. to 8 ft.) with a lower ratio of end and manifold losses to active collecting area, and 2) use of the more recently developed coating¹³ referred to above.

The present prototype is currently being reviewed in order to identify other improvements in design and materials which can be incorporated in future versions of the basic design. To illustrate in detail how the performance of the present and future versions of our ISEC collector compares with that for tracking parabolic troughs of both commercial and experimental

designs we have plotted in Figure 19 the peak performance relative to direct normal insolation I_{DN} for the integrated CPC and the measured performance for four line focus troughs. The two integrated CPC curves are for a) panels comprised of 6 ft. long tubes otherwise identical to the prototype panel and b) panels comprised of 6 ft. long tubes with improved optical design and materials including a selective coating with a higher absorptance, anti-reflection coatings on the inside of the tubes and smaller gap losses. The troughs fall into two groups 1) currently available commercial troughs using FEK 244 reflectors and 2) second generation parabolic troughs of limited availability using back silvered glass reflectors and other optical improvements. We emphasize that the currently achieved prototype technology for the integrated tube concept which has only been under development for slightly under 3 years produces results comparable to commercial troughs. Furthermore with readily attainable materials, performance comparable to the best experimental troughs is expected to be achieved. No technical barriers remain and the obvious advantages of attaining this level of solar collection efficiency from a simple totally stationary evacuated tube collector should justify the additional development necessary for large scale production and deployment of these collectors.

B. Preliminary Energy Delivery Studies

The performance curves discussed in previous sections are all represented as instantaneous solar thermal conversion efficiencies and are not adequate to serve as the basis for economic analysis or even comparative collector rankings. For this purpose one requires an estimate of how a given collector responds to the solar input integrated over a full yearly cycle.

The following discussion and associated tables and graphs summarize the results of computer runs to calculate the annual projected performance of the ISEC collector tube at five selected locations. These are:

Phoenix, AZ	Latitude 33.4N
Albuquerque, NM	Latitude 35.1N
Miami, FL	Latitude 25.8N
Cape Hatteras, NC	Latitude 35.3N
Boston, MA	Latitude 42.4N

The input weather data (beam and diffuse solar components plus ambient air temperature) were taken from SOLMET tapes obtained from the National Climatic Center operated by the U. S. Department of Commerce. At each location data are available at hourly intervals throughout an entire so-called "Typical Meteorological Year" (TMY) comprised of 12 real individual monthly data sets taken from many years of observations and chosen such that the average behavior over the TMY is the same as the real long term (10 - 20 years) average at that location. This allows our program to simulate solar collector gains and losses for each hour of operation in a "typical year" and by accumulating these hourly increments to determine the expected long term average energy delivery as a function of operating temperature at each location. The simulations have been carried out for a variety of collector

types and operating configurations as well as our Integrated Stationary Evacuated Concentrator or ISEC collector. The five locations considered cover a range typical of the continental United States ranging over two very good solar climates (Phoenix and Albuquerque), two intermediate climates (Miami and Cape Hatteras) and one relatively poor location (Boston).

In carrying out the simulations a number of simplifying assumptions have been made.

1. The performance of the collector array alone is analyzed independent of the rest of the system. That is, any losses due to interaction with storage and load are neglected.

2. The calculations are carried out under steady state conditions at each temperature (transient effects are assumed small).

3. Thermal losses are calculated as if the entire array were at one average temperature throughout the year (the design temperature).

The most important results of the detailed computer calculations have been extracted and summarized and certain typical behavior illustrated in the Tables 3 and 4 and Figures 20 - 23. A brief explanation of each of these items is given below.

Table 3: The average annual total solar thermal energy in gigajoules per meter squared of collector area (1 gigajoule = 1 billion joules is approximately 1 million BTU's) expected to be delivered by the ISEC collector is listed as a function of temperature for each of the five locations. The results listed here are for both improved high absorptance coating¹³ and those for the present multilayer coating. The latter are typically $0.5 \text{ GJ/m}^2\text{-year}$ less. To indicate the relative character of the solar climate

in each location the annual total insolation on a horizontal plane is listed in parenthesis. Clearly the amount of collectible energy and its relative value depend strongly on both collector temperature and location. As a rule of thumb the variation from a good to a poor location at a given operating temperature is about a factor of two and at a given location the variation is also about a factor of 2 over the range of temperature given. It should be noted that the cost of the fuel being displaced by the solar energy also varies with location, in some cases partially compensating for the poorer solar climate. Also it should be mentioned that the average collector temperature is not the same as "end use temperature". Depending on the particular system parameters the latter is usually somewhat (5°C to 25°C) higher although setting the two equal is usually a good first order approximation to the effects of parasitic losses.

Table 4: The collectible solar energy per meter squared (in the same units as in Table 3) at an average temperature of 115°C (239°F) for each of five collector types is given for the five locations. In addition to the ISEC collector the others given are (1) a good double-glazed-selective surface flat plate collector, (2) a contemporary commercial evacuated tube collector as represented by the Sunmaster performance parameters, (3) a commercial tracking parabolic trough with the axis aligned east-west based on performance parameters for the Solar Kinetics and Accurex collector designs, and (4) a point focus 2 axis tracking dish using parameters approximating the GE/Solar Kinetics Shenandoah project design. The flat plate is clearly not practical at these temperatures. The ISEC collector performance is superior to both the simple evacuated tube and the E-W trough at all locations with some variation in the relative performance due to differences in the

diffuse insolation. The point focus dish results are listed for comparison only since the systems are presently very expensive and the performance parameters and operational behavior in the field are still highly uncertain.

Representative performance versus temperature behavior for four collector types is shown in Figure 20. The broadband labeled ISEC represents the range of performance for 6 foot tubes with the present coating to the high absorptance coating (no other improvements have been assumed in the latter case). Note that as in the instantaneous performance curves the annual output of the ISEC collector is competitive with tracking troughs and dramatically improved over contemporary evacuated tubes and flat plates. The temperature for a candidate absorption air conditioning system is 240°F or 115°C and is indicated. This serves as a reference temperature for some of the other figures as well. For instance, in Figure 21 we show the seasonal variation in the energy delivered at 115°C for the same four collector types in Phoenix, Arizona. Figure 22 depicts the relative annual average energy delivery for 5 collector types (including the 2-axis dish) at 115°C at the 5 different locations and finally in Figure 23 we show the annual energy delivery for the ISEC collector as a function of collector temperature for the five locations.

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Table 1 Performance Parameters for ISEC Subcomponent Materials

	Design Goal	Measured on Subcomponent
<u>Optical</u>		
Glass transmittance (τ)	0.91	0.92
Mirror (silver) reflectance (ρ)	0.96	0.95 $\pm$ 0.02
Selective surface absorptance (α)		
normal incidence $\alpha_{\perp}$	0.88-0.90	0.80-0.85
averaged over incidence angles $\langle\alpha\rangle$	0.85	0.79 $\pm$ 0.02
Gap loss (L) averaged over $\pm\theta$	0.06*	0.05-0.10
<u>Thermal</u>		
Selective surface emittance (ϵ)	0.06	0.07 $\pm$ 0.005
Thermal loss coefficient per unit length of insulated interconnect tubing (W/ $^{\circ}$ C-m)	0.08	0.1 $\pm$ 0.02

*Increased from 0.03 in original proposal to allow for realistic mechanical tolerances.

Table 2 Performance Parameters for Panel
of ISEC Tubes

	Design Goal (from col. 1 Table 1)	Predicted for Proto- type Panel (from col. 2 Table 1)	Measured on 2 m ² Panel
$\eta_{(\pm\theta)}$	0.70	0.65	0.65±0.01
η_b	0.76	0.71	0.71±0.01
$\eta_{o\perp}$	0.655	0.61	0.64±0.01
ϵ^* 3 ft. tubes	0.076	0.088	
6 ft. tubes	0.068	0.078	
U_m 3 ft. tubes	0.16	.2 w/m ²	
6 ft. tubes	0.10	.13 w/m ²	
Thermal loss at 200°C ($T_a=25^\circ\text{C}$)(w/m ²)			
radiative	110	128	
conductive	28	35	
total	138	163	170±15
Operating efficiency (200°C, $T_a=25^\circ\text{C}$)			
$\eta_{\pm\theta}$	0.55	0.48	0.49±0.02 [†]
η_b	0.60	0.52	0.53±0.02
$I_{\pm\theta} = 950 \text{ w/m}^2$			
$I_b/I_b + I_{dif} = 0.87$			

$$^{\dagger} \eta_{\pm\theta \text{ obs}} = \frac{.65}{.64} \times \eta_{\perp}$$

TABLE 3
UC/GTE ISEC COLLECTOR*

Average Annual Energy Delivery (GJ/m^2)⁺

Location (Yearly insolation [#])	Phoenix (7.7)	Albuquerque (7.3)	Miami (6.4)	Cape Hatteras (5.9)	Boston (4.7)
Average collector temperature					
115°C (239°F)	4.0-4.5	4.0-4.5	2.6-3.0	2.6-3.0	2.0-2.2
165°C (329°F)	3.5-4.0	3.5-4.0	2.2-2.5	2.2-2.6	1.6-1.9
215°C (419°F)	2.0-3.4	2.9-3.3	1.6-2.0	1.7-2.1	1.2-1.5
265°C (509°F)	2.1-2.6	2.1-2.6	1.1-1.3	1.2-1.5	0.8-1.0

*The lower number is for the present coating while the higher number is for the recommended high absorptance coating.

⁺1 GJ = 10^9 joules $\approx 10^6$ BTU's (1 BTU = 1054 joules).

[#]Total (beam plus diffuse) on horizontal surface.

TABLE 4

Average Annual Energy Delivery ($\text{GJ}^+/\text{m}^2\text{-yr}$)
 Average Collector Temperature - 115°C (239°F)

Location	Phoenix	Albuquerque	Miami	Cape Hatteras	Boston
Collector Type					
Flat Plate	1.1	0.8	0.5	0.4	0.2
Cont. Evac. Tube (e.g. Sunmaster)	2.9	2.7	1.9	1.8	1.3
UC/GTE ISEC*	4.0-4.5	4.0-4.5	2.6-3.0	2.6-3.0	2.0-2.2
E-W aligned tracking parabolic trough [#]	4.1	4.2	2.3	2.4	1.8
2-axis tracking paraboloidal dish	5.9	6.1	3.2	3.5	2.6

⁺1 GJ = 10^9 joules $\approx 10^6$ BTU's (1 BTU = 1054 joules).

*The lower number is for the present coating and the higher for the recommended high absorptance coating.

[#]Corrected for shading loss when spaced with a ground cover factor $\phi = 0.5$.

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(A)

(B)

Fig. 1 Evacuated CPC collector designs: (A) Contemporary external reflector configuration and (B) integrated design as originally suggested by Garrison³.

Advanced Integrated Stationary CPC

a)

b)

Fig. 2 Illustration of how the stationary CPC profile conforms readily with a cylindrical tubular design.

Fig. 3 Details of the actual profile shape and collector design implemented in the ISEC tube.

Fig. 4 Schematic (not to scale) illustration of the longitudinal construction of an ISEC tube.

FABRICATION SEQUENCE

Fig. 5 Simplified representation of the fabrication and assembly sequence utilized in producing the 80 prototype tubes.

PROTOTYPE TEST PANEL (45 TUBES; 2.1 m^2 NET AREA)

Fig. 6 Diagram of the tube layout and panel design for the 2 m^2 test panel of ISEC tubes.

UNIVERSITY OF CHICAGO HIGH TEMPERATURE TEST LOOP

Fig. 7. Schematic diagram of the University of Chicago high temperature oil test loop on which the ISEC panel was tested.

UNIVERSITY of CHICAGO
CAMPUS SOLAR TEST FACILITY
Data Acquisition System

Fig. 8 Diagram of the test and data acquisition system for the panel performance measurements.

Fig. 9 The angular response function (optical efficiency as a function of transverse incidence angle) as measured for the integrated tube panel and as calculated from a ray trace.

Fig. 10 Sample illustration of a ray trace diagram for normal incidence light showing a variety of geometric effects.

CONCENTRATOR PROFILE FOR
INTEGRATED CPC TUBE

Fig. 11 Comparison of the theoretical concentrator design profile with that actually resulting in the final fabricated tubes illustrating the deviations resulting from mechanical constraints.

Fig. 12 Measured and predicted heat losses as a function of temperature.

Fig. 13 Measured peak thermal efficiency values compared with model calculations.

Fig. 14 Variation of effective "optical efficiency" with time and temperature over more than seven months of testing.

Fig. 15 Measured variation of optical efficiency in the longitudinal plane (parallel the tube axis) compared with a prediction based on a fit to other collector types.

Fig. 16 Results of an all day performance test conducted near summer solstice showing efficiency (top curve), heat gain, incident insolation ($I_{\perp}$) and panel temperature rise (bottom curve) from 9:00 a.m. (local time) to 5:00 p.m. $\pm \theta$

Fig. 17 Single tube stagnation test conducted on a bright but variable day. The maximum absorber temperature on this day did not exceed 400°C.

Fig. 18 High temperature efficiency data measured on a 9 month old prototype panel and plotted relative to beam insolation. The calculated curve for the 3 ft. long tube is shown as the solid line and average performance for commercial line focus troughs is shown as the dashed line. The arrow marked D.G. indicates the design goal optical efficiency which will be achieved with a high absorptance ($\alpha > 0.90$) selective surface.

Fig. 19 Comparison of predicted performance for two versions of the integrated CPC tube collector with that for four line focus parabolic troughs.

Fig. 20 Representative performance vs. temperature behavior for four collector types in Phoenix.

Fig. 21 Representative seasonal variations in the output at 115°C for each of the four collector types in Phoenix.

Fig. 22 A comparison of the output of five collector types at a fixed temperature (115°C or 239°C) at each location.

Fig. 23 The energy output of the ISEC collector as a function of collector temperature for five locations (see Table 1).