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IMAGE COLLAPSING CONCENTRATORS

Final Technical Report, October 1, 1977—October 1, 1980

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FINAL TECHNICAL REPORT
IMAGE COLLAPSING CONCENTRATORS
1 October 1977 - 1 October 1980

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IMAGE COLLAPSING CONCENTRATORS

ABSTRACT AND SUMMARY

Wide-angle focusing Fresnel Lenses with specially curved image collapsing mirrors are developed for nontracking solar concentrators. A new type of stepped prism lens is designed with prism facets on either the inside or outer lens surface which concentrates solar radiation incident in a 60° elevation by 100° azimuth angle sectors.

Thermal tests on a small model collector with a dielectric lens aperture $30\frac{1}{2} \times 30\frac{1}{2}$ cms were conducted using a single subreflector which concentrated all acceptance zone radiation onto a fixed absorber shelf 8 cms wide. With absorbing copper tubes coated with black chrome carrying water as circulant thermal efficiencies of approximately 50% on large East West deployed solar panels are estimated. Vacuum absorbers were also installed with improved efficiencies and operating temperatures. Segmented subreflectors were designed to increase concentration ratios from 3 to approximately 12.

An economic study of the comparative cost vs performance advantages of this new technology was made. Production cost (1980) for the stepped lens - single subreflector concentrator were estimated at about \$113. per meter² (\$10.50 per ft²). Because of the wider angular coverages, thinner structures, and sharp focusing available for larger concentration ratios, the new technology offers important advantages at lower costs over other concentrating nontracking solar collectors.

A thin collector panel was studied which uses a novel internal absorber rod lens and the high thermal conductivity of copper strips for heat extraction. Thermal efficiencies and concentration ratios of about 3 are projected with important savings in collector materials.

This research and development effort contributed several new analytic design techniques for wide-angle lenses and shaped subreflector synthesis and ray tracing. These scientific results are summarized in the next section.

SYNTHESIS OF LENS AND SUBREFLECTOR CONTOURS FOR WIDE-ANGLE SOLAR COLLECTORS

Part I - Design Theory and Summary of Results

Introduction

These investigations of wide-angle dielectric lenses with image collapsing subreflectors resulted from favorable consideration by ERDA (later by the Department of Energy) of a SET, Inc. proposal submitted in April 1977 in response to PRDA EG-77-D29-0002, Category MLC-3, "Develop 3X Lens Concentrators." The research results obtained and reported in three scientific reports have met or surpassed the original DoE objectives. The concentrator work has been enlarged to include collector experimentation and inventions unforeseen at the beginning of the project. Interim Scientific Report #1 has been published in slightly abridged form in APPLIED OPTICS, Vol. 19, No. 9, May 1980. Interim Scientific Report #2 with additional technology contained in this Final Report will also be submitted to a journal for publication.

This Final Report summarizes the significance of results published earlier and includes new data on recent investigations on economic studies and vacuum absorbers not reported before. Some analytical details not available earlier on lens synthesis are included here also.

The principal advantages of 3X Lens Concentrators over 3X Reflector Concentrators for solar heat collection appear to be in the wider (non-tracking) coverage angles, available with two point corrected lenses and the shaped subreflectors and in the generation of sharp focal lines which can be used for higher concentration applications with segmented subreflectors for example. This concentrator technology can be used to advantage also with flat photovoltaic devices installed on the flat shelf such that both surfaces of the cells are illuminated by the sun. The reduction in photo active area in the 3X concentrator over flat plate designs is an important advantage and because the reflected rays tend to be normal to the shelf surface the concentrator is well suited for generating electricity. These same advantages obtain for the internal absorber design also.

Summary of Principal Project Achievements

1. Design of wide-angle Stepped Prism Lenses focusing to lines over a $\pm 30^\circ$ elevation angle sector and a $\pm 50^\circ$ azimuth angle sector with prism facets on either the inner or outer lens surfaces.
2. Design of Image Collapsing Subreflector surfaces to contract the broad images of lenses used in non-tracking collectors onto a narrow shelf in both elevation and azimuth angle acceptance zones.
3. Design of segmented Image Collapsing Subreflectors for increasing non-tracking collector concentration ratios beyond 3 which are suitable for automatic switching using heat pipes, temperature dependent viscous oils or for photo voltaic applications.
4. Design of Internal Absorber Collectors for construction of miniature collectors in thin solar panels in which heat is removed by thermal conductivity in solid metal absorbers.
5. Conducted an experimental test program to verify the performance of lens and subreflectors using laser ray tracing and thermal testing of a 30 cm by 30 cm collector model equipped with selective coated and vacuum absorbers.
6. Made an economic study of the comparative cost of manufacture for technology developed under this Grant in relation to costs for trough type collectors.

A Resumé of Significant Results Reported in Interim Scientific Report #1 and in Applied Optics, May 1980

The Two-Point Corrected Lens and Subreflectors:

The Fresnel-type lens which we have designated the Stepped Prism Lens is of a new design which produces sharp line focusing over a 60° elevation angle sector. These cylindrical lenses also focus well over an azimuth acceptance interval of $\pm 50^\circ$ from lens normal with the line focus moving closer to the lens with increasing azimuth angles. The lens profile is nearly flat with prism facets on the outer surface of the lens (facing the sun). The inner lens contour can be a flat portion of a large circular arc. On the

30½ by 30½ cms square aperture of the lens model constructed, the inner circular arc had a radius of about 145 cms. Forty prism steps of equal height, but with different angles, were milled into the outer surface of the acrylic lens according to the two point correcting method developed by F. S. Holt of SET, Inc. Analytic details of this lens synthesis method are given in both Interim Reports and in Appendix I of this report.

The inner and outer prism angles are calculated beginning at the edges of the lens such that each prism focuses perfectly to lines for incident solar ray angles of $\pm 25^\circ$ in the elevation plane (and zero azimuth angle incidence). Although equations are given for the prism angles, considerable design experience and additional computer algorithms are needed to optimize the lens configuration regarding F/D step shadowing and allow a smooth circular arc to approximate the inner prism surfaces. FIG. 1 shows a photograph of the lens as constructed and FIG. 2 gives dimensions and details.

Another important objective was the synthesis of subreflecting mirrors which concentrate the image fields of lenses onto the smallest absorbing surfaces possible for the acceptance interval of the collector. Several techniques were developed. Working with wide angle but aberrated lens like the dielectric rod cylindrical mirror shapes were calculated for bringing all incident rays from a given direction to a true line focus. When the lens profiles are known (for a homogenous dielectric lens) then a geodesic method was derived for shaping the mirror contour. A second shaping synthesis requires the ray fields transmitted through the lens to be known. Then by an iterative numerical procedure the subreflector surface can be shaped that again focuses rays passing through a cylindrical lens from a single direction to be focused to a line. This second subreflector synthesis method has been the most useful and we have extended the technique to shaping image collapsing subreflectors for wide angle solar collectors and for wide angle segmented solar collectors. The

basic concept of incremental shaping of mirrors employing a step-by-step interpolation among a given ray population is very general and powerful. The author has extended this concept to doubly curved surfaces.

Image collapsing of images requires the wide angle contraction of the lens focal fields. To accomplish this contraction two mathematical methods were developed. The first concept applies the theory of mathematical envelopes to the lens focal fields. One example described in the Applied Optics article generates subreflector surfaces by using the envelop method to contract the fields of dielectric rod lenses. The paraxial focal lines for the rod form a simple circular arc when the elevation plane incidence only is varied. The theory is then extended to other cylindrical focusing lenses with focal arcs of different shapes. When the lens focal surface can be represented by mathematical expressions which can be differentiated (gradients found) then subreflector contours to concentrate the wide angle fields of the lens. In Interim Scientific Report #2, the theory of envelop synthesis is further extended by allowing the envelop of elliptical surfaces to have a slowly varying parameter C_z which parameter is normally a fixed constant. With this extension to the theory more versatility in the location of the collector absorber can be achieved.

Most of the subreflector shapes described and constructed in this project were computed however using the Δx or numerical synthesis method. Image collapsing subreflectors were calculated for the Stepped Prism Lens with facets on the outside surface (the Straight Lens actually constructed) and for the second Stepped Prism Lens with facets on the inside lens surface (the Curved Lens). The objective of the subreflector design was nearly always to reflect all the rays passing through the lens over the full elevation-azimuth acceptance zones onto a narrow fixed shelf, located near the vertex of the subreflector.

To apply the Δx synthesis method, the rays passing through the lens in the $\pm 30^\circ$ elevation sector must be given. These rays

were found by ray tracing through the lens. To guarantee that all rays transmitted by the lens prisms intercept a strip between a given point and the subreflector vertex only the edge rays for regular intervals in elevation angle over the acceptance zone are needed. As all these rays pass through the lens focal arc, we can define the lens focal arc by an equation and obtain equations of lines representing the edge rays passing through the focal line at each elevation angle. Note that these edge rays for different elevation angles of the sun usually do not occur simultaneously but that these rays are the ones used in the interpolation routine to synthesize the subreflector surface. The subreflecting shape obtained has the interesting and desirable property that all rays (not just the edge rays) strike the shelf which area extends from a subreflector focal point F_0 , where all the edge rays focus, to the vertex of the subreflector. Rays incident on the lens $\pm 20^\circ$ from the lens normal in the elevation angle plane may require two or more reflections from the subreflector surface before they strike the shelf. It is a fortunate and remarkable characteristic of the lens-subreflector optics too that skew rays incident from different azimuth and elevation directions in the acceptance zones also intercept the shelf. The details of the Leading Ray Subreflector Synthesis method are described in the section of Reference 3 in the Section with that title.

In order to trace rays reflected from the sack-like shaped image collapsing mirrors a new ray tracing method was developed to operate on cylindrical point-defined reflecting surfaces. This procedure is explained in Reference 1 and its generalization to doubly curved surfaces is reported in Reference 4 for applications to reflector antennas.

In addition to mathematical ray tracing a neon laser technique was developed to experimentally verify the characteristics of the straight Stepped Prism Lens and several image collapsing subreflectors constructed. The laser technique also gave reflection and transmission loss data on these optical components. Theoretical and experimental results check to within measurement accuracies and the technique details are reported in Reference 1.

Problems in Collector Construction and Testing:

References 1 and 2 and the eight Quarterly Technical Reports submitted to the DoE report some of the experimental difficulties encountered in this project. The straight profile Stepped Prism Lens was machined from a solid slab of acrylic. We were fortunate to find a capable machine shop that performed the milling at a reasonable cost. The lens surfaces had to be optically polished by a company specializing in lens polishing.

The construction of the shaped mirrors required for image collapsing was done in-house. Aluminum templates were laid out and constructed by hand based on the subreflector contour coordinates. Usually 3 or 4 identical templates were cut and then spaced about 15 cms apart. Then a subsurface of flexible plastic was bent and formed to lie on the template curves. Finally, a surface of highly reflecting aluminum foil was bonded by adhesive to the plastic substrate. Difficulties occurred in finding the best thickness and flexibility of plastic sheeting to take up and maintain the template contours. Also, many adhesives were not satisfactory. These problems and their solutions are detailed in Reference 1.

Thermal testing to determine the thermal efficiency of the prototype collector required the construction of an absorber shelf composed of water carrying copper tubes covered by black chrome. The usual difficulties of flow measurements involving pumps, thermocouples, solar insolation measurement, and data recording had to be overcome. It is hard to extrapolate thermal efficiency results made on a small model to those expected on large solar panels. We tried to estimate the avoidable optical and thermal losses and these estimates are presented in References 1 and 2. The solar thermal tests agree well with design predictions.

The Second Interim Scientific Report is primarily a study of the comparative performance characteristics of collectors designed using Stepped Prism Lenses with facets on the inside vs lenses with facets on the outer lens surfaces. Also a detailed study is presented on the shelf energy distributions for solar rays incident on the Fresnel lenses from different elevation and azimuth directions, data needed for photovoltaic applications especially.

Both the straight profile lens with prism facets on the outer surface and the more curved stepped lens with prism facets on the inside surface can be constructed such that one surface contour of the cylindrical lens can be well approximated by a circular arc. In order to achieve good focusing properties with a reasonably small F/D the facets on the inside lens designs must have a more curved profile as shown in FIG. 2. It is shown in Reference 2 that the curved lens has the advantage of less step shadow losses and also the lens is much easier to keep clean with facets on the inside surface. The straight lens has better concentration ratios and the depth of the concentrator is less than for the curved lens of the same aperture height.

Together the First and Second Interim Scientific Reports present a complete analytic picture of the new two point corrected stepped dielectric lenses with facets on either the inside or outside surfaces and of the shaped subreflectors for contracting the line focused fields onto a narrow shelf. Although the analysis is done for correction angles at $\theta = \pm 25^\circ$ and both the lens and subreflectors are dimensioned to a 12-unit high aperture the theories are extendable to many geometries. Suggestions for using the wide angle lenses for higher concentration and tracking using rotational rather than cylindrical symmetry are discussed. Applications using photovoltaic devices such as silicon ribbons are attractive. The 3 to 1 concentration of energy to a flat area with energy relatively well distributed over the shelf for most incidence angles makes the geometry especially interesting for 2-sided solar cells. As the shelf is located at the vertex of the subreflector, heat can be removed easily from the photovoltaic devices using radiation on the back surface of the subreflector.

The Internal Absorber Solar Collector

The wide angle lens with shaped subreflector (Stepped Prism Lens and Image Collapsing Subreflector or SPLICS) as described brings solar incident ray to fixed shelf absorbers but the design can lead to rather deep collectors and collector panels. As pointed

out in Reference 3, the SPLICS Collector element and panels composed of SPLICS can be scaled down in size by making the lens height smaller. For the SPLICS, the savings in materials resulting from shallower collector panels is not large because the lenses must have a certain minimum thickness for mechanical strength and by increasing the number of collector elements for a given aperture area the manifolding and heat removal problems are made more expensive.

SET, Inc. has investigated an alternative collector design called the Internal Absorber Solar Collector that has comparable concentration ratios and efficiencies to the SPLICS but has novel characteristics that make miniaturization of the collector elements and panels more attractive. Each collector rod has a circular exterior cross section and the absorber is placed inside the rod lens in an eccentrically extruded slot. The subreflector is the silvered back surface of the circular rod. FIG. 3 is a profile through a panel of internal absorber rod collectors showing representative positions of the absorber in the dielectric rod with a silvered mirror sprayed onto the rear surface of the rod. Because of the very wide angle characteristic of the rod lens, the array panel of collector elements can be vertically or wall mounted or inclined by the latitude angle for larger projected panel aperture. Because the rod dielectric material or weight is proportional to the radius R squared and the rod lens aperture or rod diameter is nearly equal to $2R$, the improvement of lens aperture to lens weight ratio is approximately proportional to $1/R$. As glass or plastic rods about one centimeter in diameter are easy to manufacture the problems in constructing such collectors are mainly (1) in insulating the absorber from the surrounding dielectric to prevent excessive conduction heat loss and (2) removing heat from the small crescent shaped or flat absorber which is covered with black chrome to reduce radiation heat losses. It will be shown analytically that heat can be extracted efficiently from the ends of the thin solid copper absorbers using the high thermal conductivity of the metal.

To demonstrate that nearly all incident solar energy reaches the absorber surface and that a 60° elevation sector by 120° azimuth sector is covered with a concentration ratio of approximately three, we must study the optics of the geometry. This work was carried out making use of the vector ray tracing algorithms reported in References 1 and 2. When the incident solar rays on the front surface of the rod are refracted by the lens and then reflected by mirrored back surface of the rod, they focus very nearly to a point internal to the rod as shown in FIG. 4. When the change in incidence direction is in the elevation plane only the circular symmetry of the rod guarantees that the sharp focal line remains the same and the focal line moves along a circular arc about the center of the rod. For oblique incidence with azimuth and elevation angles both varied the rods with back mirror focusing characteristics are more complicated but nevertheless more than 90% of the solar incidence in the acceptance zones reaches the crescent shaped absorber when it is properly positioned. In fact for azimuth incidence at greater than 50° from the normal to the rod axis the sun's rays are focused directly onto the absorber without reflection from the rear mirror.

Turning now to the problems of efficient heat extraction from the miniature absorber it is necessary to prevent conduction losses through the dielectric rod or rear mirror whose surface temperatures are at ambient. An insulating zone, either evacuated or filled with low conductivity gas is shown in FIG. 3.

A detailed study was made to determine how much of the optical energy converted by the absorber surface into heat would flow by conduction to the ends of the absorber. In the analysis it was assumed that the main heat loss would be due to infra-red radiation from the absorber coated by a selective absorbing surface. A boundary value problem defined by differential equations was solved relating temperature along the absorber, emissivity of the selectively coated absorber, and heat flow for a model shown in FIG. 5 and defined by the following expressions.

Geometry of collector

FIG. 5

Referring to FIG. 5,

Let

$$r_1 = \rho_1 R$$

$$r_2 = \rho_2 R$$

Cross section area for conduction:

$$\pi R^2 (\rho_2^2 - \rho_1^2) \frac{\theta}{360}$$

Surface area for radiation:

$$\left[2\pi R (\rho_1 + \rho_2) \frac{\theta}{360} + R (\rho_2 - \rho_1) \right] \Delta x$$

where Δx is increment of length along axis of collector

Let

L = length of collector

Basic definitions of heat transfer used are:

A. Conduction

$$q_k = -kA \frac{dT}{dx}$$

q_k = rate of heat flow, Btu/hr

A = cross section area, ft^2

$\frac{dT}{dx}$ = temperature gradient, F/ft

k = thermal conductivity, Btu/(hr. ft. F)

B. Radiation

$$q_r = \sigma S E T^4$$

q_r = rate of heat radiation, Btu/hr

σ = Stefan-Boltzmann constant,
 0.1714×10^{-8} Btu/(hr. ft^2 R^4)

T = temperature in degrees Rankine

E = emissivity (dimensionless)

S = surface area, ft^2

C. Absorption

q_a = rate of heat absorption, Btu/(hr. ft.)

Assume steady state conditions and apply conservation of heat to a small element of the rod;

$$\begin{array}{c} \text{heat in} \\ -kA \frac{dT}{dx} \Big|_{x_1} + q_a \Delta x = -kA \frac{dT}{dx} \Big|_{x_1 + \Delta x} + \sigma E \bar{S} (T + 460)^4 \Delta x \end{array}$$

$$-kA \frac{dT}{dx} \Big|_{x_1} + q_a \Delta x = -kA \frac{dT}{dx} \Big|_{x_1} + \frac{d}{dx} \left(-kA \frac{dT}{dx} \right) \Big|_{x_1} \Delta x + \sigma E \bar{S} (T + 460)^4 \Delta x$$

$$-kA \frac{d^2 T}{dx^2} = q_a - \sigma E \bar{S} (T + 460)^4 \quad (1)$$

Boundary conditions:

$$T = T_0, \quad x = 0, L \quad (2)$$

Equation (1) is the basic equation to be solved subject to the boundary conditions. This was accomplished and results are summarized in FIG. 6.

FIG. 6 shows the efficiency of percentage of heat reaching a constant temperature sink (200°F) for different length rods and thicknesses of copper absorber.

REFERENCES (PART I AND APPENDIX I)

1. Interim Scientific Report No. 1, DoE Grant No. DE-FG04-77CS34163, 31 May 1979.
2. "Wide-Angle Lenses and Image Collapsing Subreflectors for Nontracking Solar Collectors," C. J. Sletten, F. S. Holt, and S. B. Herskovitz, APPLIED OPTICS, Vol. 19, page 1439 ff, May 1, 1980.
3. Interim Scientific Report No. 2, DE-FG04-77CS34163, 20 Jan 1980.
4. "Ray Tracing Algorithms for Doubly Curved Reflector Surfaces Defined by Discrete Points," C. J. Sletten, IEEE Antennas and Propagation Symposium, Quebec; June 1980 Digest, p. 409.
5. U. S. Patent Application No. 112953 filed 17 Jan 1980, "Internal Absorber Solar Collector," C. J. Sletten et al.

Part II - Collector Performance Measurements

Introduction

Thermal efficiency tests were conducted on the SPLICS (Stepped Prism Lens Image Collapsing Subreflector) collector with the absorbing shelf replaced by a tubular evacuated receiver. Two types of commercially available vacuum absorber tubes were employed -- the General Electric TC 100 and the Owens-Illinois SK-3092. Tests were conducted over a three-month period (May 23 - Aug. 17, 1980) on the roof top of the Hanscom Civil Airport Terminal Building, Bedford, Massachusetts.

The collector enclosure, which has been previously described (Reference 1), employs a square collection aperture 30.48 cm on a side. Since the absorber tubes were substantially longer than the collector enclosure, an insulated jacket was placed around that portion of the absorber which extended beyond the enclosure, Fig. 7.

Testing consisted of the measurement of the instantaneous efficiency, I.E., as a function of collector elevation angle, θ , and azimuth angle, ϕ . The instantaneous efficiency is simply the ratio of energy collected to energy incident. In these experiments the quantities of interest were fluid flow rate, fluid density, insolation, effective collector area, and temperature difference. The basic relation being

$$\text{I.E.} = \frac{\text{Flow rate} \times \text{fluid density} \times \Delta T}{\text{Insolation} \times \text{collection area}}$$

where ΔT is the difference between the exit and input fluid temperatures. All tests were conducted using water as the circulant.

Before considering quantitative results, three factors which have substantial impact must be considered. These factors deal with the construction of the stepped prism lens, the effect of azimuthal variation, and the substitution of a single vacuum

absorber for the conventional absorbing shelf.

a. Lens construction. Due to the fabrication technique used in constructing the prototype lens, a correction factor must be used when comparing the overall efficiency to other types of collectors. As has been previously described (Reference 2), the SPL was fabricated on a horizontal milling machine from a monolithic block of cast polymethyl methacrylate (Plexiglas). To withstand the rigors of this machining process, the lens was considerably thicker than required for correct optical performance. In optical transmission tests, transmission normal to the lens center was found to be 85.6%. This loss is attributed to 4% surface reflection from each plastic-air interface and ~7.3% due to optical absorption. Further, transmissional losses increased towards the upper and lower portions of the lens due to increased diffraction effects in the unpolished portions of the prism apexes. Although reflection losses would be essentially the same in a cast or extruded lens, that is about 8%, such a lens would be substantially thinner and have a totally polished surface. Thus, it is estimated that a mass-produced operational lens would have an average overall transmission at least 10% greater than the machined SPL.

b. Azimuthal variations. Experimental measurement of I.E. in the SPLICS collector revealed larger variations with azimuth position than was expected from design considerations. By placing an observation window in the collector itself, the actual focusing properties of the lens could be visually observed. When aligned with the optical axis of the lens corresponding to the sun's azimuthal position, a bright, linear image was produced directly on the absorber tube. This image, approximately 1 cm in width, is translated laterally across the absorber surface, as the azimuth angle is varied. Because of the small internal dimensions of the collector enclosure, the image is rapidly repositioned onto non-absorbing surfaces off the ends of the absorber. In a full-sized, operational collector, these losses would pose little problem during substantial periods of the

collection period. The subreflector is designed to compensate such variations in azimuth position on long collectors.

c. Use of vacuum tube. The SPLICS collector was designed to employ a shelf absorber approximately 7.6 cm in width. The substitution of a single tubular absorber, with a diameter of 5.3 cm, will produce variations in collector operation. Determination of the extent of these variations is a complex problem. The diameter of the tube is about 30% less than the width of the shelf. The tube, however, is a three-dimensional absorbing volume, rather than a flat surface. Rays which would be expected to intercept the shelf absorber will miss the tubular structure.

GE Absorber Results

A maximum instantaneous efficiency of 49.8%, with inlet temperatures in the range of 20 - 32°C, was measured using the GE absorber in the SPLICS geometry. The variation of I.E. with azimuth and elevation is plotted in Fig. 8. The plot is a smoothed curve resulting from many independent tests. For azimuth $\phi = 0$, an elevation angle variation of $\pm 15^\circ$ results in a variation of I.E. of from about 50% to 25%. The family of curves show a relatively high degree of I.E. sensitivity with variations in ϕ and θ .

An effort was made to determine the effect of varying the SPLICS focusing properties on the variation of I.E. The lens-subreflector distance was altered from the design value of ~42 cm to 35 cm. The absorber tube axis was also moved about 3 cm rearward (toward the subreflector surface). The effect of this alteration was to produce a diffuse image of the sun. This diffuse image was about 4 cm in width, rather than the sharp 1 cm image which resulted from the design dimension. Fig. 9 shows the result of these changes. The maximum I.E. was reduced to 38%. The variation of I.E. with elevation for a given ϕ is considerably lower than in the previous case. Over a θ variation

of $\pm 30^\circ$, for $\phi = 0^\circ$, the I.E. varies from 38% to $\sim 24\%$. Thus, in the defocused case, although the maximum measured efficiency is lower, the variation with elevation is much more gradual. Thus, in the case of the SPLICS with the GE tubular absorber, the wide-angle properties, which were degraded with the sharply focused geometry, can be partially restored by defocusing.

The time constant of the GE tube was determined by covering the lens surface with aluminum foil. When the inlet and outlet fluid temperatures were identical, the lens was uncovered. With the geometry and flow rates employed, the collect required about 2 minutes to rise to the maximum temperature difference.

O-I Absorber Results

A maximum instantaneous efficiency of 48.4%, with inlet temperature variation of 20 - 32°C, was measured. Fig. 10 shows the variation of I.E. with azimuth and elevation angles. The O-I absorber, for a $\phi = 0^\circ$, varies in I.E. from about 48% to 33% over an elevation angle variation of $\pm 30^\circ$. Variation of I.E. with elevation angle is less pronounced in the O-I tube than with the GE. However, for a given θ , the variation in I.E. with azimuth angle is more rapid than with the GE absorber.

The O-I tube displays an anomalous dip in efficiency for $\theta = 0^\circ$ and $\phi = 0^\circ$. This variance was less evident at $\phi = 5^\circ$ and 10° . In general, the I.E. of the O-I tube is less sensitive to changes in elevation, but more sensitive to azimuth variation, than is the GE tube.

The time constant of the O-I tube was determined to be about 20 minutes. This relatively long time constant made determination of changes in operating quality of the O-I tube difficult to measure. Whereas a purposeful change in elevation or azimuth with the GE absorber produces rapid changes in the measured I.E., this is not so with the O-I absorber. The large thermal inertia of the O-I structure necessitates a long time period between cause (change in ϕ or θ) and effect (I.E.). In this period, the sun

would continue its passage across the sky, and compound the variation under consideration. The long thermal constant would be of little consequence if a solar simulator were to be employed, since the positioning of the source of insolation would be constant.

Heat Pipe Considerations

The heat pipe section of a solar absorber was secured from John Krall, the Grant Technical Monitor. The vacuum jacket which surrounded the heat pipe had been previously removed. Attempts to employ this heat pipe section proved to be ineffectual. Although energy was delivered to a water jacket, heat exchanger at the output side of the heat pipe, the quantity of heat delivered was much lower than expected. Use of the heat pipe was discontinued after discovery of this apparent malfunctioning.

The heat pipe provides an attractive mechanism for delivering heat from a concentrating collector to a heat exchanging manifold. In particular, the low thermal inertia of the heat pipe permits more rapid delivery of usable heat on collector start-up. Further the heat pipe displays a small temperature drop from the heat collecting to heat delivery ends and is lighter in weight than a water filled absorber, such as the O-I tube.

Use of heat pipes in solar collectors has not experienced the degree of utilization expected from their superior properties. This, in part, was due to their extremely high cost and relatively short lengths. In 1974, Hughes Aircraft Company offered the Series 1370H copper and water heat pipes at a price of \$50. for a 12-inch tube (Reference 3). This pipe was prohibitively expensive for all but the most critical cooling needs. Recently this situation has improved. Conversations with Dr. Donald Ernst of Thermacore, Inc., Leola, Pennsylvania, indicate that the development of cost effective heat pipes has been progressing satisfactorily under DoE sponsorship (Reference 4). Heat pipes based on trimethyl borate working fluid in carbon-steel tubes, and water in aluminum-steel, have been fabricated. The cost goal of \$51.50 (1975 dollars) for a four foot long heat pipe, apparently

can be met in production quantities. Such a heat pipe, coupled with a tubular vacuum jacket can be expected to produce a superior absorber and heat delivery system.

Conclusions

The coupling of a tubular vacuum absorber with the SPLICS concentrating collector has produced substantial improvement in operation. Maximum instantaneous efficiencies of 49.8% for the General Electric absorber and 48.4% for the Owens-Illinois tube were measured. This is compared to an instantaneous efficiency of 30%, maximum, recorded under similar conditions for the SPLICS employing the standard absorber shelf.

The two types of tubular absorbers tested in the SPLICS displayed essentially similar performance. The GE absorber displays rapid thermal response and high efficiency. This tube, however, exhibited a stronger angular dependence than expected. This dependence could be decreased to a large extent by defocusing the optical system. The O-I absorber, being water filled, displayed a sluggish response to rapid changes in insolation. Although this property produced experimental difficulties, in actual operation, this thermal inertia would smooth out variations in delivered energy during transient insolation conditions. The O-I absorber also displayed an inherently wider acceptance angle capability than the GE tube when used in the SPLICS geometry.

The SPLICS structure employed in these tests was less than optimum for use with the tubular absorber. Nevertheless, a marked improvement in efficiency was noted. The wide-angle properties of the design have been demonstrated. The combination of a stepped prism lens coupled with an image collapsing subreflector specifically designed for use with a tubular vacuum absorber can offer superior properties in a non-tracking concentrating collector.

REFERENCES (PART II)

1. Interim Scientific Report No. 2, DE-FG04-77CS34163,
20 January 1980.
2. Ibid
3. Hughes Aircraft Company, Electron Dynamics Division,
Series 1370H Literature dated March 1974.
4. Private conversation with Dr. Donald Ernst, Sep. 19, 1980.

Part III - Comparative Cost Analysis

Introduction

In general, as the cost of fossil fuels rises, the manufacturing costs of solar energy conversion components will also rise, so that one may not find a clear intersection point, at which it will become economically sound to switch from oil or gas heat to solar heat. For example, over the past two years, the average cost of basic materials -- such as copper, aluminum, steel and glass -- has risen at about the same rate as the cost of energy while transportation and labor costs have risen even more sharply.

In a cost study, accurate data must be available regarding the effect of production volume, manufacturing methods and transportation costs on the total cost of a solar concentrating system using a stepped prism concentrating collector. We could get accurate cost data only on the fabrication costs of the stepped prism concentrator. The other system costs were less firm, however the costs of the aluminum reflectors, support structures and installation costs should not be very much different from the data arrived at by Evans and Florschuetz (Reference 3) for a photovoltaic system, except that the heat transfer efficiency in a heat transfer system approaches 80% while photovoltaic cells provide, at best, 15% conversion efficiencies. Winston V-Trough and Compound Parabolic Concentrators (Reference 6) are somewhat more costly to fabricate than the subreflectors used with the stepped prism system because of Winston's much greater aspect ratio (depth of reflector as compared to its aperture for 60° elevation angle coverages) and will also require more costly bracing and support structures. The cost of \$47.80/M² shown on Table I would not be sufficient for the Winston type collector system.

The stepped prism heat concentrating system has performance advantages over the flat plate collector because of the higher

temperatures obtainable with a concentrating system. Higher temperatures result in smaller liquid storage tanks and make solar energy available for air conditioning. The advantages of concentrators over flat plate collectors are shown in Roy's cost analysis (Reference 5) for photovoltaic cells. He separates the costs of the conversion cell from the cost of the other components, and finds that the cost of the generated electricity is largely controlled by the concentrator cost. We have, therefore, concentrated our cost study on the stepped prism lens concentrator.

Cost Analysis - SET, Inc. Technology

In the 8th Quarterly Progress Report we pointed out that lens fabrication by extrusion, as suggested by Sheffield Plastics Corporation of Sheffield, MA. (Reference 1) was less costly than the die casting process quoted by the Swedlow (Reference 2) engineers of Garden Grove, California. According to Swedlow engineers, the life of the casting die was limited by the risks in handling rather than wear, and was, therefore, less predictable than the life of the extrusion die.

A casting die built to fabricate 0.37 M^2 stepped lenses would cost \$65,000. and is expected to produce 3,000 to 10,000 units before it has to be replaced. The added die cost of \$17.56 per M^2 used to calculate the cost of the lens assumes that the die will not be damaged before the 10,000 units have been produced (3700 M^2). Should the die fail prematurely the cost of the stepped lens fabricated by the die casting process could easily be double the cost in Table I.

The system cost of solar concentrators, supporting structures, reflectors material and labor cannot be as accurately determined as the fabrication cost of the acrylic lens alone, and may vary considerably from location to location and also with seasonal labor cost fluctuations. The figures quoted here were arrived at by inquiries made to local (Massachusetts) Solar Energy Systems installers such as Solar Solutions, Inc. in Bedford, MA., Power

Solar Engineering in Malden, MA., and Solar Powered Energy Systems in Newton, MA. These costs are normalized for retrofit on a single family or two story dwelling of medium size (3 to 4 bedrooms), which is at most 10 years old and has sufficiently strong roof construction to accomodate the additional collector weight. If more accurate cost comparisons with other possible energy sources are required, one could use the "Parametric Cost Analysis" developed by Evans and Florschuetz (Reference 3) for sunlight concentrators used with photovoltaic cells and V. Evtuhov (Reference 4) for photovoltaic systems in general.

TABLE I - PART III

	Die Casting		Extruding	
	Cost \$ per M ²		Cost \$ per M ²	
	1,000 Units	10,000 Units	1,000 Units	10,000 Units
Stepped Acrylic Lens	\$ 38.94	\$ 33.60	\$ 31.31	\$ 30.64
Glass Absorber Tubes	84.00	50.00	84.00	50.00
Frame and Supports	47.80	28.00	47.80	28.00
Aluminum Reflectors	5.38	4.18	5.38	4.18
TOTAL COST of Lens, Frame and Tubes	\$176.12	\$115.78	\$168.49	\$112.82
COST OF INSTALLATION X 2.5	\$440.30	\$289.45	\$421.23	\$282.05

REFERENCES (PART III)

1. Private communication from William Preston, Sales Manager, Sheffield Plastics, Sheffield, MA., March 6, 1980
2. Private communication with William Yamaguchi of Swedlow, Inc., Garden Grove, California, April 17 and May 14, 1980.
3. D. L. Evans and L. W. Florschuetz, "Cost Studies on Terrestrial Photovoltaic Power Systems with Sunlight Concentration," Solar Energy, Vol. 19, No. 3, 1977.
4. V. Evthuhev, "Parametric Cost Analysis of the Photovoltaic Systems," Solar Energy, Vol. 22, No. 5, 1979.
5. Aharon S. Roy, "Econometric Analysis of Concentrators for Solar Cells," Solar Energy, Vol. 21, No. 5, 1978.
6. D. L. Evans and L. W. Florschuetz, "Cost Studies on Terrestrial Photovoltaic Power Systems with Sunlight Concentration," Solar Energy, Vol. 19, No. 3, 1977.
7. A. Rabl, N. B. Goodman and R. Winston, "Practical Design Considerations for CPC Solar Collectors," Solar Energy, Vol. 22, No. 4, 1979.

FIGURES AND ILLUSTRATIONS

- FIG. 1 Image Collapsing Concentrator with prism facets on outside lens surface (cross section)
- FIG. 1A Photograph of Straight Stepped Prism Lens and Image Collapsing Subreflector
- TABLE I Dimensions for constructing straight lens with facets on outer surface
- TABLE IA Profile dimensions of Image Collapsing Subreflector Contour for Straight Lens
- FIG. 2 Detail Drawing of Stepped Prism Lens with facet on inner lens surface
- TABLE II Dimensions for constructing curved lens with facets on inner surface
- TABLE IIA Profile dimensions of Image Collapsing Subreflector Contour for Curved Lens
- FIG. 3 Cross sectional view of the dielectric rod internal absorber collector
- FIG. 4 Focusing by mirror backed dielectric rod with incident solar rays normal to lens axis
- FIG. 5 Model geometry used in heat flow analysis on Internal Absorber Solar Collector
- FIG. 6 Efficiency of Heat Transfer for a Selective Surface Copper Absorbing Strip
- FIG. 7 SPLICS collector modified for tubular vacuum absorber.
- FIG. 8 Performance of G.E vacuum absorber: Instantaneous efficiency as a function of elevation and azimuth angles.
- FIG. 9 Performance of G.E vacuum absorber with defocused SPLICS optical system.
- FIG. 10 Performance of O-I. vacuum absorber: Instantaneous efficiency as a function of elevation and azimuth angles.

FIG.1 IMAGE COLLAPSING CONCENTRATOR WITH PRISM FACES ON OUTSIDE LENS SURFACE

FIG. 1A PHOTOGRAPH OF
STRAIGHT STEPPED PRISM LENS
AND IMAGE COLLAPSING SUBRE_
FLECTOR.

TABLE I DESIGN DATA, STRAIGHT LENS		
Y	X1	X2
6	48827	
5.7	51917	82532
5.4	54847	83486
5.1	57619	84351
4.8	60231	85122
4.5	62684	85792
4.2	64977	86357
3.9	67111	86814
3.6	69085	87156
3.3	709	8738
3	72554	87483
2.7	7405	87459
2.4	75386	87306
2.1	76563	87019
1.8	77581	86598
1.5	7844	86036
1.2	7914	85333
.9	79681	84485
.6	80061	83491
.3	80269	82351
0	803	81115

TABLE IP SUBREFLECTOR CONTOURS	
Y	-X
4.8	7.5
4.846	7.86
4.8806	8.22
4.9038	8.58
4.9154	8.94
4.9152	9.3
4.9029	9.66
4.878	10.02
4.8402	10.38
4.7887	10.74
4.723	11.1
4.6421	11.46
4.545	11.82
4.4303	12.18
4.2964	12.54
4.1414	12.9
3.9627	13.26
3.7568	13.62
3.5192	13.98
3.2435	14.34
2.9265	14.7
2.535	15.06
2.1475	15.38
1.6688	15.66
1.237	15.87
.8874	15.99
.4763	16.08
0	16.125

INNER SURFACE CIRCLE

RADIUS $R=57.2$ UNITS

WITH CENTER AT $X=-56.9$

$Y=0$

MINIMUM LENS THICKNESS

$= 0.5$ UNITS

INDEX OF REFRACTION $= 1.49$

LINEAR 40-PRISM IMAGE CONCENTRATING LENS MATERIAL: OPTICAL GRADE
CAST ACRYLIC

FIG. 2. DETAIL DRAWING OF
STEPPED PRISM LENS WITH
FACETS ON INNER LENS SUR-
FACE

PRISM GEOMETRY SUPPLIED ON SEPARATE SHEET

MRS1279

TABLE II
DESIGN DATA, CURVED LENS

Y	X1	X2
6		.009852
5.7	-.009852	.246984
5.4	.227082	.46605
5.1	.446148	.668526
4.8	.648798	.855462
4.5	.83607	1.02774
4.2	1.008834	1.186128
3.9	1.167834	1.33125
3.6	1.313694	1.463676
3.3	1.446966	1.583874
3	1.568106	1.692252
2.7	1.67751	1.789158
2.4	1.775532	1.874904
2.1	1.862454	1.949736
1.8	1.938534	2.013894
1.5	2.003958	2.067498
1.2	2.0589	2.110758
.9	2.103534	2.143788
.6	2.137938	2.166672
.3	2.16216	2.179626
0	2.175936	2.175936

TABLE IIA
SUBREFLECTOR CONTOUR

Y	-X
5.65	7.03
5.7146	7.45
5.7665	7.87
5.8054	8.29
5.8311	8.71
5.8477	9.13
4.8	9.55
5.8213	9.97
5.7977	10.39
5.753	10.81
5.6927	11.23
5.6159	11.65
5.5217	12.07
5.4087	12.49
5.2756	12.91
5.1206	13.33
4.9414	13.75
4.7352	14.17
4.4982	14.59
4.2255	15.01
3.9101	15.43
3.626	15.76
3.3335	16.06
3.0003	16.36
2.6558	16.63
2.3022	16.87
1.886	17.11
1.5134	17.29
1.2096	17.41
.9093	17.5
.6333	17.56
.152	17.62
0	17.63

OUTER SURFACE CIRCLE

RADIUS $R = 9.36$ UNITS

WITH CENTER AT $X = -7.03, Y = 0$

MINIMUM THICKNESS = .15 UNITS

INDEX OF REFRACTION = 1.49

FIG.3 CROSS SECTIONAL VIEW OF DIELECTRIC ROD INTERNAL ABSORBER COLLECTOR

FIG. 4 FOCUSING BY MIRROR
BACKED DIELECTRIC ROD WITH
INCIDENT SOLAR RAYS NORMAL
TO LENS AXIS.

FIGURE 6 EFFICIENCY OF HEAT TRANSFER FOR A SELECTIVE SURFACE COPPER ABSORBING STRIP.

FIG. 7 SPLICS collector modified for tubular vacuum absorber.

FIG. 8 Performance of G.E. vacuum absorber: Instantaneous efficiency as a function of elevation and azimuth angles.

FIG. 9 Performance of G.E. vacuum absorber with defocused SPLICS optical system.

FIG. 10 Performance of O-I. vacuum absorber: Instantaneous efficiency as a function of elevation and azimuth angles.

Appendix I

Detailed Design Procedure for Curved Stepped Prism Lens

This lens has a smooth outer face and a stepped inner face. It is assumed that the following quantities are prescribed:

d_0 = lens aperture

n = index of refraction of lens material

$F(x_0, y_0)$ = focus point

θ = correction exit angle

These quantities together with prism vertex coordinates will determine the angles β and γ for a symmetric prism pair with two-point focusing properties as described in Reference 1 (see Fig. A).

FIG.A PRISM PAIR

For the curved stepped prism lens the following additional quantities must be prescribed

$$q_0 = \text{prism height}$$

$$s_0 = \text{prism overlap}$$

The number of prisms in the lens will then be d_0/q .

The first prism pair is determined (i.e., β_1 and γ_1) using vertices at the points

$$V_1 = (0, \frac{d_0 - q_0}{z})$$

and

$$V_{-1} = (0, -\frac{d_0 - q_0}{z})$$

The upper prism is modified in the following manner.

The upper prism inner face is extended upward until it intersects the line $y = d_0/z$ (see Fig. B). This point of intersection is denoted by $(u(1,1), v(1,1))$. The upper prism outer face is extended upward and moved to the right parallel to itself until it intersects the line $y = d_0/z$ at the point $(r(1,1), (v(1,1))$

where $r(1,1) = u(1,1) + s_1$

$$s_1 = s_0$$

and $v(1,1) = d_0/z$.

Note that moving the outer face to the right parallel to itself does not change the final exit angle for a ray starting at F and passing through V_1 .

FIG.B FIRST UPPER PRISM

The first upper prism is completed (i.e. lower corners $[u(1,2), v(1,2)]$ and $[r(1,2), v(1,2)]$ prescribed) by extending the inner and outer faces downward until they intersect the line $y = d_0/2 - q_0$. Thus, the first prism lies between $y = d_0/2 - q_0$ and $y = d_0/2$ with upper edge of length $s_1 = s_0$. The first lower prism is merely the mirror image relative to the x-axis of the first upper prism. Since all lower prisms are mirror images of upper prisms we will from here on discuss only the design of the upper prism.

Assume that the first through the k^{th} prisms have been designed as shown in Fig. C and it is now desired to design

the $(k+1)^{st}$ prism. The $(k+1)^{st}$ vertex position v_{k+1} is located as shown in Fig. C using β_k from the k^{th} prism.

FIG.C START OF DESIGN OF $(k+1)^{st}$ PRISM

A prism pair is now designed using the vertex v_{k+1} . i.e., β_{k+1} and γ_{k+1} are calculated.

FIG.D COMPLETION OF DESIGN OF $(k+1)^{st}$ PRISM

Starting from V_{k+1} construct the $(k+1)^{\text{st}}$ prism inner face at angle β_{k+1} and starting at $[r(k,1), v(k,1)]$ construct the prism outer face using angle γ_{k+1} . The upper edge of the prism has y coordinate $d_0/2 - kq_0$ and the lower edge has y coordinate $d_0/2 - (k+1)q_0$. The length of the upper edge s_{k+1} is different generally from s_0 because β_{k+1} is different from β_k . However, for lens designs with many prisms the change in successive β 's is small and all s_β 's are very nearly equal to s_0 . Thus, the overlap between prisms is essentially constant.

The following formulas determine the coordinates of the $(k+1)^{\text{st}}$ prism given the k^{th} prism coordinates.

$$P_{k+1} = [r(k,2) - s_0, v(k,2)]$$

$$V_{k+1} = [r(k,2) - s_0 - q_0/2 \tan \beta_k, v(k,2) - q_0/2]$$

β_{k+1} and γ_{k+1} are determined from Reference 1 using V_{k+1}, n, x_0, y_0 and θ .

$$u(k+1,1) = r(k,2) - s_0 + q_0/2 (\tan \beta_{k+1} - \tan \beta_k)$$

$$v(k+1,1) = v(k,2) - q_0$$

$$r(k+1,1) = r(k,2)$$

$$v(k+1,1) = v(k,2) = d_0 - kq_0$$

$$v(k+1,2) = v(k+1,1) - q_0 = d_0 - (k+1)q_0$$

$$u(k+1,2) = u(k+1,1) - q_0 \tan \beta_{k+1}$$

$$r(k+1,2) = r(k+1,1) - q_0 \tan \gamma_{k+1}$$

Note that the β 's and γ 's are measured positive CCW from the prism faces to the negative y axis. Thus β_k and γ_k as shown in Fig. C are negative.

It generally happens that as this design is carried out the prism faces near the x axis are not perpendicular to the x axis and the lens curves sharply to the right or left. An optimum design (i.e., central prism faces nearly normal to the x axis) can be achieved by successively adjusting the focal point y coordinate. When an optimum design is achieved the design procedure guarantees that the outer face is a continuous broken line curve that can be approximated by a smooth curve or a circle. The circle is, of course, not as accurate as the continuous curve but for solar work it is generally adequate.