SOLAR COLLECTORS USING TOTAL INTERNAL REFLECTIONS

N. S. Kapany
Oakes College
University of California
Santa Cruz, California 95064
and
KAPTRON, INC.
599 College Avenue
Palo Alto, California 94306

Abstract

This paper describes various configurations of solar collectors and components employing the phenomenon of total reflection. A double glazed window using "Optical Ribs" has been developed to yield high light transmission and ruggedness. Conical wedges are developed for use as energy concentrators as well as "Optical Valves" Dielectric compound concentrators with flat, parabolic, and elliptical reflecting surfaces will be described with various applications.

Introduction

In contrast to the classical flat plate collectors most non classical solar collectors make use of one or more reflections to perform the functions of focusing or light concentration. The classical parabolic tracking concentrator is a representative of this variety of metallic reflector. However, numerous non classical solar collectors have been devised that make use of one or more reflections. In this category lie (A) Winston's compound parabolic concentrator, (B) the power tower system, (C) Falbel's delta collector, and (D) the V-grooved concentrator.

Metallic reflections, though unavoidable for some solar collector configurations, suffer from the following limitations: (A) Absorption loss (B) Increased cost due to the metalization process, and (C) Deterioration in quality over extended periods of time.

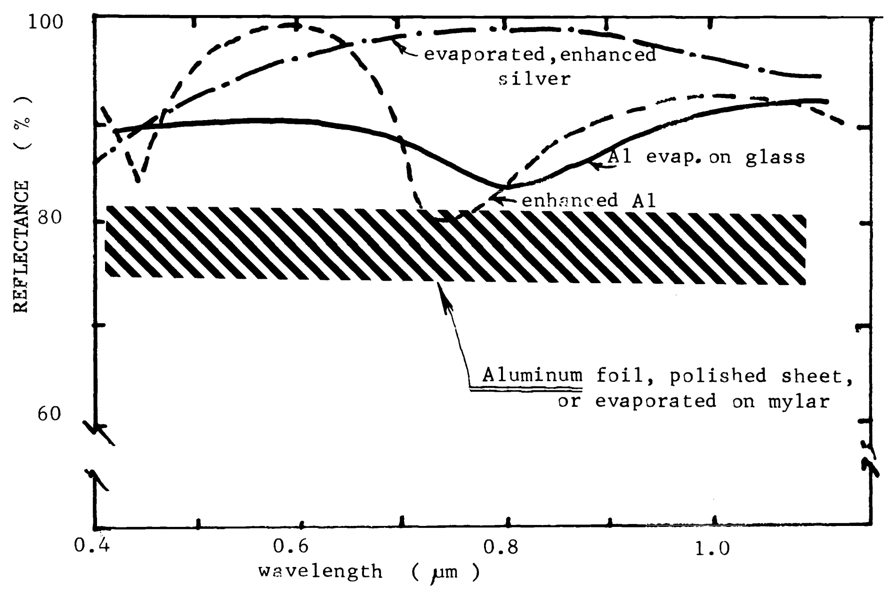

Fig. 1. Spectral reflectivity of various types of metallic reflectors.

Figure 1 shows the spectral reflectivity of various metallic surfaces. Vacuum deposited fresh aluminum surface yields reflectivity of the order of 90% over the solar spectrum. However, evaporated aluminum, unless protected with a second coating, suffers deterioration over a period of time. On the other hand, it is possible to enhance the reflectivity of aluminum by evaporating multilayer interference coatings upon it. With this technique the spectral reflectivity over a narrow spectral range can be increased to 99%, but the spectral reflectivity intergrated over the solar spectrum for enhanced aluminum is not particularly high. On the other hand, evaporated silver with an overcoating is shown to reach high reflectivity levels. However, evaporated metal surfaces with protective coatings in general tend to be too expensive for the solar collector application. But, inexpensive aluminum foil, polished aluminum and aluminized mylar yield reflectivity in the range of 80% over the solar spectrum. It is obvious from the data in Figure 1 that any solar collector utilizing more than one metallic reflection would be highly inefficient because of light losses in the vicinity of 15 to 20% per reflection.

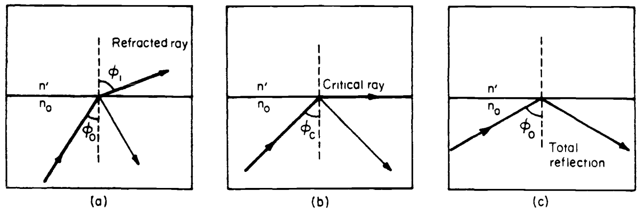

Figure 2. Ray incident at a plane interface between a high and low refractive index medium when (A) the ray is refracted (B) the ray traverses along the interface and (C) total internal reflection occurs.

Snell's law of refraction, which can be derived from basic electromagnetic theory, states that when light is incident on two homogeneous media that have a common plane boundary, the bending of light at the interface is governed by the expression, $n_o \sin\theta_o = n' \sin\theta'$. Figure 2 illustrates a ray incident at a plane interface $n_o n'$, where n_o is greater than n'. The ray incident at angle θ_o is refracted in the medium n' at an angle θ' to the normal in accordance with the above stated Snell's law. As the angle of incidence of the ray increased to a value of $\theta_c = \sin^{-1}(n_o/n')$ the ray proceeds along the interface as shown in the Figure 2(b). This is called the critical angle. When the angle of the incident ray in the denser medium N_o exceeds θ_c, no refraction occurs and there is total internal reflection as shown in Figure 2(c).

The intensity of energy flow in the totally reflected wave is exactly equal to the intensity in the incident wave; i.e. there is no average flow of energy into the medium of lesser refractive index for angles greater than θ_c. The field intensity in the less dense medium, however, is by no means zero. In fact, there is an instantaneous normal component of energy flow across the interface whose time average value is zero. This normal component is unattenuated in the direction of propagation but falls off exponentially with distance from the interface. This wave is referred to as the "evanescent boundary wave". The evanescent boundary wave is highly sensitive to the absorption and/or scattering characteristics of the less dense medium. If a total reflecting interface is bounded by a low index medium of complex refractive index, then the reflection coefficient is modified, resulting in loss of energy. This is obviously undesirable for systems requiring more than one total internal reflection. Experience in the field of fiber optics has demonstrated that high light transmission can be obtained over long lengths of fibers even though the light may suffer many hundreds of thousands of total internal reflections. This is an excellent demonstration of the fact that total internal reflection is the only form of reflection that is truly "total".

The analogs of wave propagation in plane and cylindrical geometry are illustrated in Figure 3. Figure 3 shows a plane wave incident upon a plane interface at an angle ϕ and the corresponding reflected and evanescent waves. The wave fronts (planes of constant

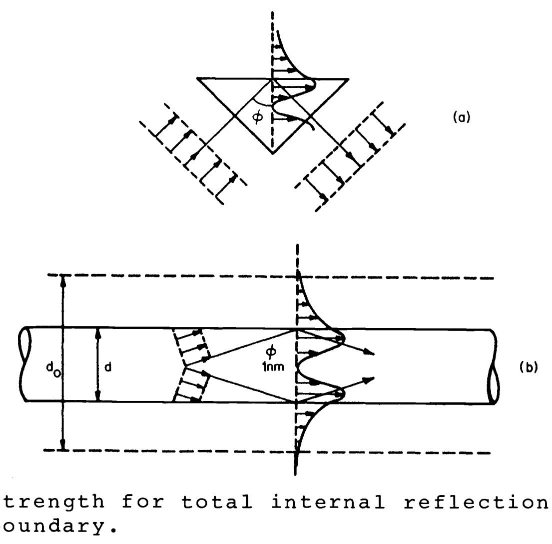

Figure 3. Electric field strength for total internal reflection at a) plane boundary, b) cylindrical boundary.

phase) are represented by dotted lines. The arrows designate the wave normal, their lengths indicate the time average Poynting vector (the flux of energy per unit area) and their directions indicate the flow of energy. In the incident medium, the superposition of incident and reflected waves gives a resultant wave whose planes of constant phase are perpendicular to the interface, and whose Poynting vector is parallel to the boundary and has a sinusoidally varying amplitude. In the second medium the wave front is also perpendicular to the boundary but with an intensity that decreases exponentially with distance from the interface. Although some energy is carried along the interface outside the incident medium, most of it is very close to the interface. Figure 3(b) shows the analogous phenomenon in dielectric waveguides. Depending on the mode of propagation and the characteristics of the optical waveguide the depth of penetration of the evanescent wave can be large. This points to the critical necessity for preserving the integrity and cleanliness of the totally reflecting interface. In most cases unless the total reflecting interface is protected by either a low refractive index coating or by sealing the surface, considerable light losses can occur because of environmental effects and dirt.

Window with Optical Ribs

The window of a solar collector must maximize solar input for a non-tracking unit. It must be structurally sound, and it must protect the rest of the panel from the environment, withstand the environment itself, be durable, and resist projectiles (such as hailstones). A minimum projected 10-year service life is deemed necessary. The Kaptron window consists of at least two solar transparent plastic sheets or plates, separated from each other to form an air space insulator. The strength of the window is provided by ribs integrally molded with two plates. When properly dimensioned, these internal ribs also perform the second function of minimizing convective currents between the windows. The stiffening ribs are made of the same materials as the window panes and are transparent to the solar radiation. Thus, they do not cause reduction in the window area by shading; in fact, the light incident on the ribs is transmitted by total internal reflections. Since these optical ribs can be molded as part of the window panes, interface reflections and scatter will be eliminated.

One most important function of the solar window is that it transmit solar radiation. It is also desirable that it not permit retransmission of infrared radiation. Fortunately, as with glass, this desirable "greenhouse" characteristic is inherent in most optically transparent plastics. The solar transmission characteristics of many transparent plastics are equal to those of higher quality glass, and can be used in much thinner sections (due to their toughness) which, in most cases, makes for excellent transmission. For instance, where 1/8 inch thick glass is used, plastic films as thin as 0.02 inch are practical.

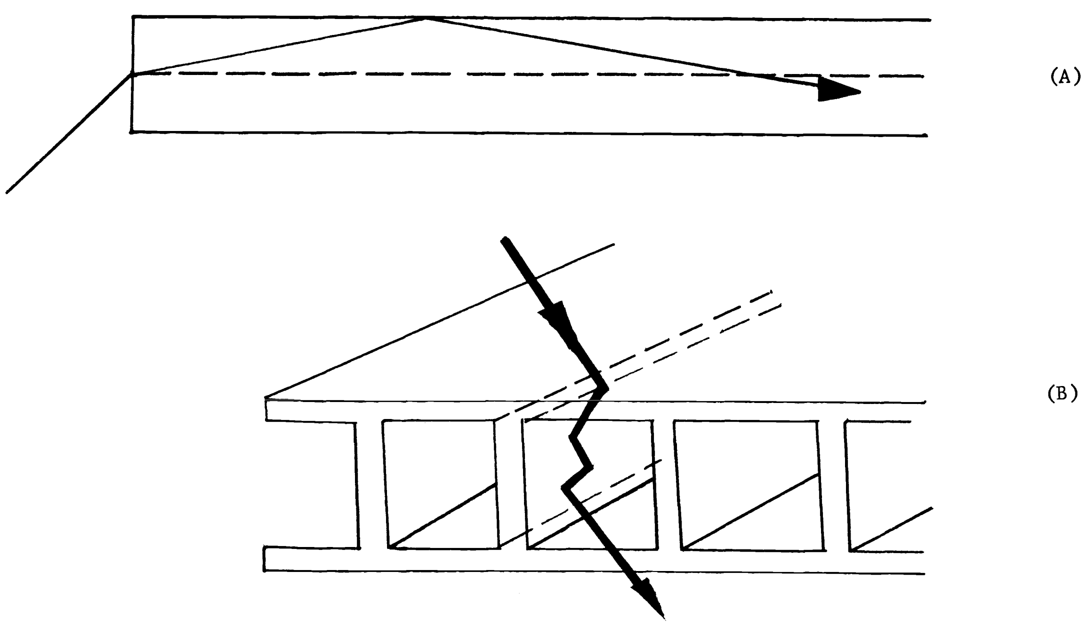

Figure 4. Solar collector window with optical ribs, (A) illustrating the conduction of solar radiation by total internal reflections and (B) a window with optical rib.

Measurements were made on a 12 in. × 12 in. acrylic window, with optical ribs as shown in Figure 4, in direct sunlight, with a large area radiometer having 100 cm^2 aperture to average the effects of the optical ribs. In one case, the optical ribs were oriented parallel to the plane of the incoming solar radiation, in the other ribs were perpendicular to the tilt axis, (⊥). Two sheets of window glass (total 0.2 inch) were measured for comparison with the two layers of acrylic (total 0.125 inch).

Table 1. Percentage of Solar Transmission at Various Sun Angles

	Angle of Window Relative to Sun				
Window Type	0°	15°	30°	45°	60°
1. Glass, 2 sheets	76.4	76.0	75.1	73.1	63.5
2. Acrylic, 2 sheets Ribbed Perpendicular (⊥)	86.8	84.2	81.6	79.3	72.0
3. Acrylic, 2 sheets Ribbed Parallel (‖)	86.8	86.0	85.6	82.4	72.1

Conical Wedges

A conical wedge has some interesting properties for use as a concentrator in solar collectors. It is clear that if the wedge is designed such that all the energy incident at the larger end of the wedge is conducted down to the smaller end of the wedge, without escaping from the side or suffering losses on reflections, a gain in flux per unit area can be achieved. However, it should be recognized that the solid angle of the cone of light at the smaller end is always greater than the solid angle at the larger end. Furthermore, for solar collector applications it is obviously essential to place the wedge in the east-west direction and to design it in such a way as to have large enough acceptance angle, thus avoiding undue seasonal adjustments. Such conical wedges can be made in three basic configurations (A) a hollow metallic wedge (B) an uncoated transparent dielectric wedge, and (C) an all-dielectric wedge using high refractive index and low refractive index dielectrics.

Figure 5. Ray passage along a reflecting wedge: (a) Illustrating the limiting ray and the returning ray passage; (b) Geometrical construction used for calculating the acceptance angle of a reflecting wedge.

Let us consider a hollow conical wedge in which reflections occur at a metallic surface. Figure 5 shows a metallic wedge in which two rays enter at different angles to the axis. No refraction or total internal reflection occur in this system. The dotted ray suffers multiple reflections inside the wedge and emerges from the other end. On the other hand, a solid ray inclined at an angle greater than the "returning angle" undergoes reflections within the cone and as shown in Figure 5 changes its direction on the fifth reflection and is lost to the system. The condition for a ray that is transmitted through a hollow reflecting wedge is most easily found by means of a simple geometrical construction (Fig.5(b)). Successive images of the sides of the wedge are shown with an indication of the path of the ray inside the wedge. If the ray projection intersects the polygon formed by successive reflections of the output end, then the ray will emerge from the output end. Simple geometrical considerations yield the following expression; relating the diameter of the cone entrance end and exit end to the acceptance and emerging angles.

$$\sin\theta_{max} = \frac{BD}{AC} = d_2/d_1$$

As already stated such a metallic wedge is undesirable because of light losses at the reflections.

An all-dielectric wedge has two advantages, viz.; no loss due to the internal reflection at the interface and secondly, a large acceptance angle due to the refraction at the entrance surface of the wedge. The acceptance angle of an all-dielectric wedge is given by the following expression;

$$n_o \sin\theta_{max} = (n_1^2 - n_o^2)^{1/2}(d_2/d_1) ,$$

where d_1 is the input width and d_2 is the output width, as shown in Figure 6.

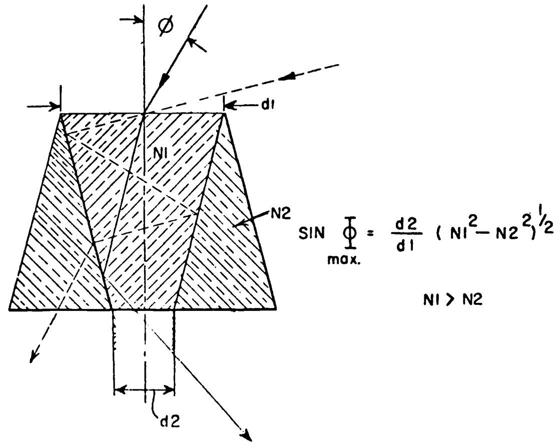

Figure 6. Dielectric total internal reflection concentrator diagram.

The Optical Valve

The "Optical Valve" incorporates a novel optical design, providing increased high temperature efficiency for the otherwise relatively low efficiency of the flate plate collector. In the rudimentary form of the device, use is made of reflecting wedges or inverted V's between the window and the absorber, maximizing the entrapment of heat in the solar panel. This is done by utilizing infrared reflecting surfaces on the bottom of the valve. The reflection paths of the infrared ray from the bottom surfaces of the triangular shaped valve are obvious. The optical path of the incident solar radiation through the valve is illustrated in Figure 7. This is accomplished by solar reflective surfaces on the top of the valve. Adjustment of the space between the valve and the absorber provides for a uniform redistribution of the solar radiation on the absorber. This case shown in Figure 7(a) is for normal incidence of the sun to the collector. The slits in the valve are set east-west so the incident solar radiation varies little from that on a normal flat plate collector during the day. It does vary with the seasons, but the valve continues to operate with only reduced effectiveness. Figure 7(b) shows a 10° incidence angle, for example.

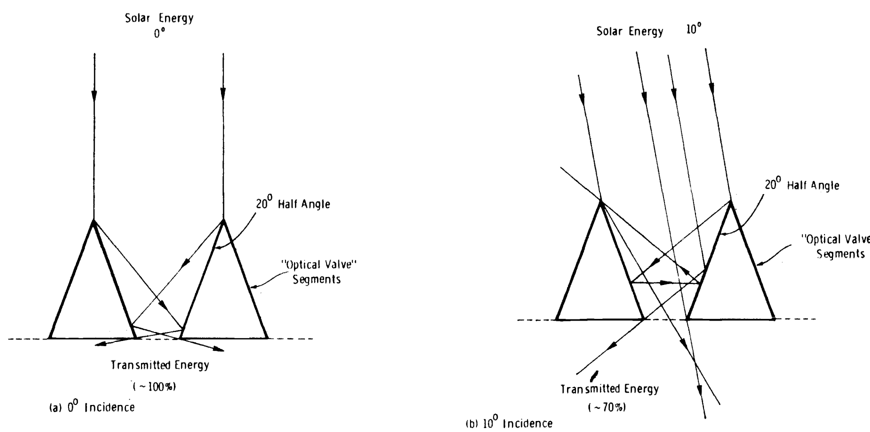

Figure 7. Path of normal incidence rays (a), and rays inclined at 10° (b), through the optical valve.

Alternate valve designs using total internal reflection are illustrated in Figures 8(a) and 8(b). This "Valve" type consists of solar transparent solid flat bottom "V" channels joined at the upper surface and having a relatively high refractive index interspersed with inverted "V" channels consisting of a low refractive index transparent solid or gas. The bases of the low index channels have a thin metal strip on them to reflect IR from the collector plate. Such "all-dielectric" valves have a negligible reflection loss for incident solar radiation and considerably higher acceptance angle than comparable metal reflector types shown in Figure 7. They have the further advantage of being readily produced in large sheets by continuous extrusion processes.

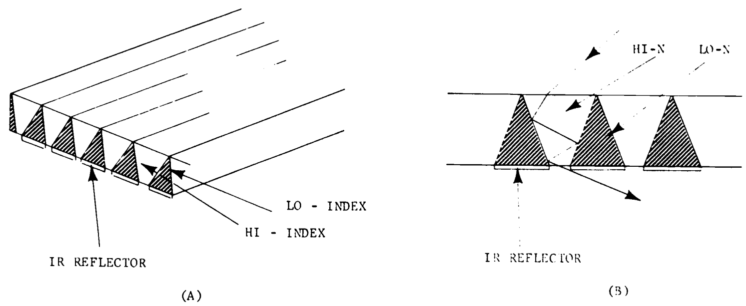

Figure 8. Design of the total internal reflection optical valve (a) continuous sheet structure and (b) ray path.

Design analysis has been conducted to evaluate the efficiency of an optical valve consisting of thin reflecting laminates formed in the V shape. The number of reflections, fractions of incident energy transmitted (μ_{in}), the fraction of thermal energy escapement (μ_{out}) as a function of the angle of the V-groove (ϕ), and the angular deviation of the sun from the center plane of the device (α) are shown in Table 2.

Table 2. Efficiency of "Optical Valve" as a Function of Angle of the Rays.

Half Angle ϕ	Max. # of refl.	μ_{out}	μ_{in}					
			α =	0°	2.5°	5°	7.5°	10°
20°	2	0.35		1.00	0.94	0.90	0.86	0.83
15°	2	0.27		1.00	0.93	0.88	0.85	0.81
10°	4	0.17		1.00	0.90	0.83	0.79	0.75

The Optical Valve can be fabricated by using thin sheets of highly reflecting plastic or metal assembled in the form of V-grooves. The actual size of the grooves is governed by the thermal, structural and manufacturing cost considerations. V-groove widths of a few mm's appear to be optimum from all these considerations.

Compound Dielectric Concentrators

Solar energy collectors consisting of an array of cylindrical elements have been proposed in the past, where concentration of incident solar energy is required to produce high temperatures or current without the need for tracking. Most cylindrical designs (refractors or reflectors), however, suffer from considerable aberrations resulting in loss of energy density. In an attempt to provide a high concentration ratio without the requirement for tracking, a compound parabolic reflector has been developed by Professor Roland Winston. Such a radiant energy collector basically uses two opposed concave metallic reflective walls which have a parabolic contour and which are spaced from each other to define a hollow trough therebetween (Figure 9). Depending upon the application, the heat absorbing elements in the form of a linear array may be placed between the focii of the collectors. This remarkable concept of a solar energy concentrator suffers from three disadvantages in certain situations. Firstly, the acceptance angle for incident light is limited, thereby requiring seasonal adjustment of the collector. Secondly, because metal reflective surfaces are utilized a substantial light loss can occur at each reflection due to absorbtion. Thirdly, due to the hollow through design a substantial amount of

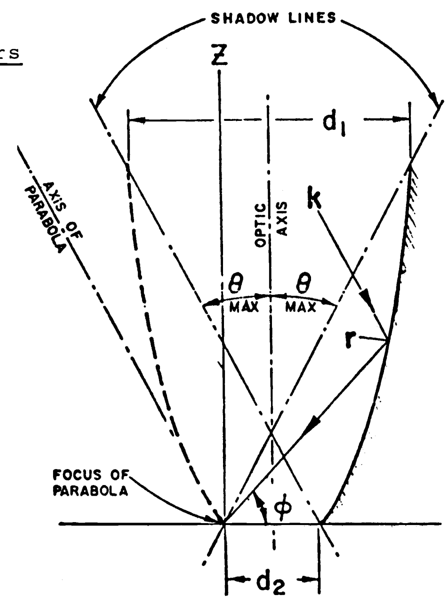

Fig. 9. Compound parabolic concentrator cross-section.

energy can be lost due to radiative and convective process thereby requiring the use of transparent windows.

Some of the above described disadvantages may be overcome and the requirement for a high efficiency solar collector can be met by the use of a radiant energy concentrator consisting of a plurality of opposed converging, reflective surfaces utilizing the principle of total internal reflections. The simplest version of such a dielectric concentrator is a panel of reflecting surfaces which includes a parallel set of truncated triangularly shaped wedges, as discussed above and shown in Fig. 8. Figure 10 shows an array of dielectric compound concentrators in which the cross sectional contour of the convex surfaces is a truncated parabola, as in the compound parabolic concentrator of Winston. The incident

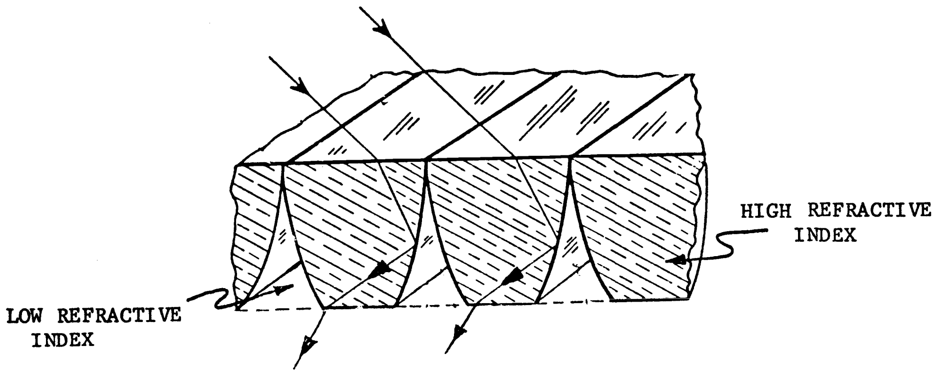

Figure 10. Diagram of dielectric compound parabolic concentrator.

solar energy refracts at the entrance flat surface of the dielectric concentrator thereby increasing the acceptance angle of the system. The refracted ray is then incident on the parabolic dielectric surface where it suffers total internal reflection and is directed towards the bottom end of the concentrator. An array of solar cells or heat transfer channels may be placed at the bottom of each of the dielectric parabolic concentrators to receive the solar energy. The critical angle for total internal reflection is determined by the ratio of refractive indices of the two media. Hence, the acceptance angle of the dielectric compound concentrator is determined both by the refractive indices of the media as well as the ratio of the width at the top and bottom of the concentrators. The light ray passing through the element along a line which is parallel to the axis of symmetry of the parabolic section will be reflected to the focus at the opposite edge. All rays making smaller angles with the vertical axis will pass through the bottom aperture and be absorbed, if the absorber is properly coupled.

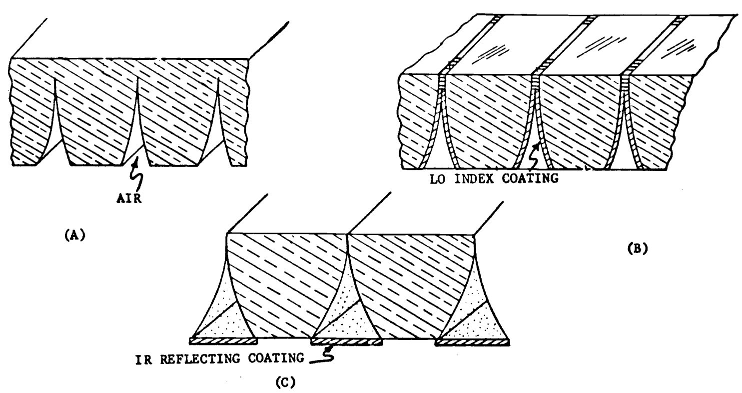

Figure 11. Various configurations of the dielectric compound parabolic concentrator.

Three variations of the dielectric compound parabolic concentrator are illustrated in Figure 11. The type illustrated in Fig. 11(a) consists of an extruded single sheet having integral connections struts adjacent to the entrance surface. It is not always necessary that the interspace between the elements be completely filled with air. Figure 11(b) illustrates a system in which a low refractive index coating is used to protect the total reflecting surface. Figure 11(c) shows a system in which the interspace is sealed off by a film, thus protecting the TIR interface. Furthermore, it is possible to place an infrared reflective coating on the film used for closing off the interspace. This I.R. reflective coating is useful in reducing radiative losses from an absorber placed below the concentrator. It is possible to vary the acceptance angle of the dielectric compound concentrator by changing the shape of the entrance surface. Figure 12(a,b) illustrates the use of positive and negative cylindrical surfaces at the entrance of each of the dielectric parabolic concentrators. Figure 12(c) illustrates the use of fresnelized cylindrical or aspheric surfaces for the entrance end of the dielectric compound concentrator.

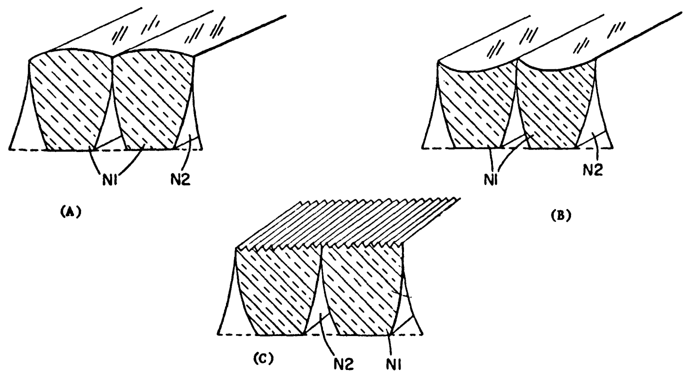

Figure 12. DCPC with various entrance aperture modifications.

A design variation of dielectric parabolic concentrators for use with a finned absorber (heat transfer or photoelectric) is shown in Figure 13. The incident radiation, after refraction at the entrance surface and total internal reflection at the parabolic surface, impinges on the circumference of the transparent cylindrical cavity inserted into the exit face of the concentrator. The light is refracted through the cylinder tube onto the absorbing element, which can be vacuum insulated from the tube for higher efficiency. TIR CPC concept can also be applied to a class of concentrators which use elliptical surfaces for use in concentration of light from large area finite distance sources. In these cases, however, the reflection angles at the elliptical surfaces can approach 90%. Therefore, it is not possible to use total internal reflection for the entire reflector. In the system illustrated in Figure 14, low loss internal reflection improves the performance by permitting lossless reflection from a large fraction of the surface. The boundary of the total internal reflection region is determined by the ratio of a concentrator refractive index N_1 to the surrounding medium N_2 and by the concentration ratio.

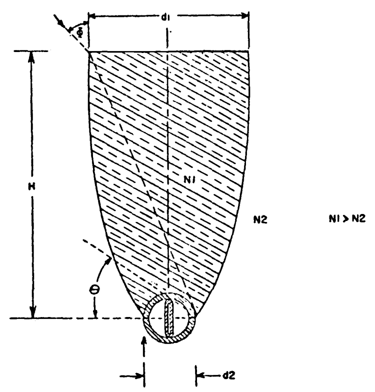

Fig. 13. DCPC with vacuum insulated absorbing element.

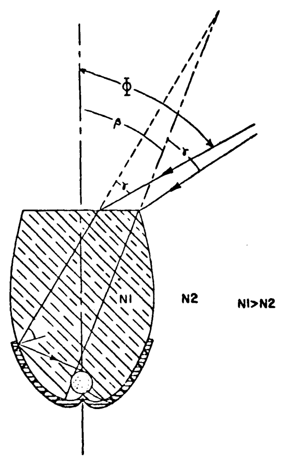

Figure 14. Partial TIR compound elliptical concentrator.

Other Applications

Figure 15 illustrates the use of low loss fiber optics in conjunction with the dielectric concentrator in order to transform the shape of the illuminated surface from a strip into a more convenient shape such as a circle or a square to match the shape of the solar cells. Low loss fiber optics have now been developed with loss below 2db/km. Such fiber optics, when they become commercially available at low cost, could find some useful applications in the field of solar energy. When used with cylindrical concentrators, only small area of collectors can be conveniently fabricated using such fiber optics. This limitation is set primarily because dielectric concentrators of the non-tracking variety cannot exceed concentration ratios of 10. On the other hand, the tracking type of concentrator coupled to low loss fibers potentially could be extremely practical and useful in order to conduct solar radiation to remote regions in buildings, such as basements and corridors, and is shown in Figure 16. Conceivably the fiber optics could be installed in the building much as the electrical cables which are presently used.

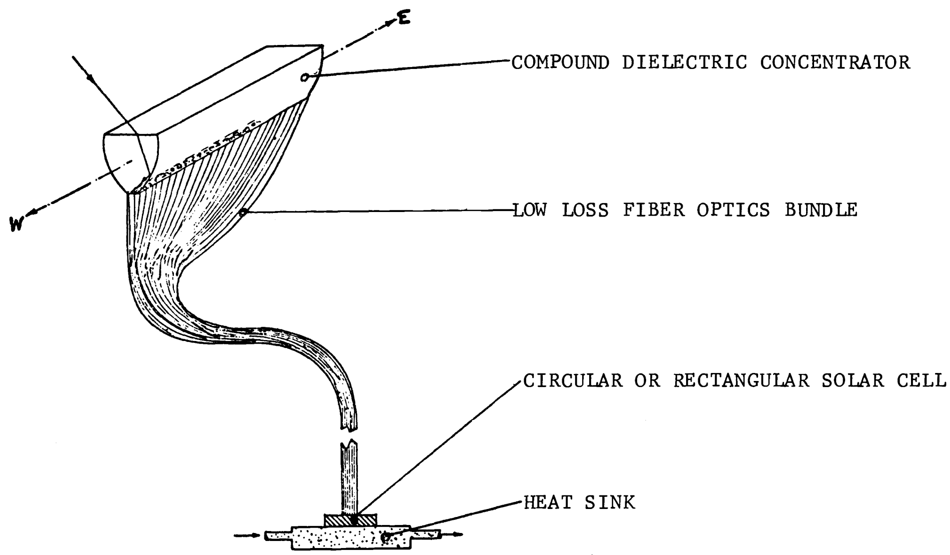

Figure 15. Compound dielectric concentrator coupled to solar cell for geometrical matching and heat isolation purposes.

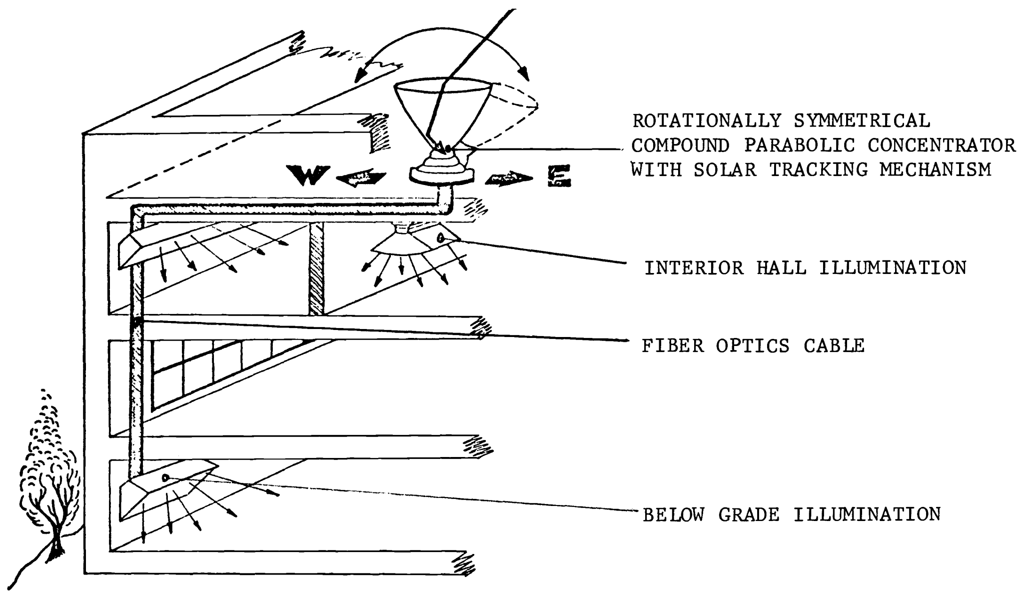

Figure 16. Tracking solar concentrator used with low loss fiber optics to illuminate the interior portions of buildings.