CURRENT STATUS AND FUTURE PROSPECTS OF NON-TRACKING SOLAR COLLECTORS.

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Abstract

The numerous potential applications of solar energy have been recognized widely for the past few decades. However, the sophisticated optical problems of an efficient collector, its integration with the overall system and the dominant economic constraints are not widely appreciated. This paper will briefly review the state-of-the-art of the non-tracking solar collectors with various performance criteria in mind. Also described in this paper are developments of some new components capable of producing high efficiency, lightweight and low cost non-tracking solar collectors. Windows with 'optical ribs' have been developed to yield high transmission, lightweight, ruggedness and efficient radiative and convective trapping. On the other hand, a new component termed 'optical valve' has been developed which is capable of transmitting the incident solar radiation and reflecting back to the absorber much of the emitted infrared radiation. Furthermore, an embossed absorber is shown to achieve almost complete absorption of solar radiation at large angles of incidence.

Introduction

The potential role of solar energy towards a partial solution of the overall energy problem is widely recognized. However, the role of sophisticated optics and the complex economic implications are not as widely appreciated. Various parameters of the optical problems as pertaining to the development of non-tracking solar energy collectors are:

(a) The incident solar radiation spectrum is equivalent to a blackbody source at 5500°C with spectral range extending from 0.3-2 μ.
(b) The nearly collimated beam angle varies over $\pm$ 90° in one azimuth (daily variation) and $\pm$ 23° in the other azimuth (seasonal variation) depending on the latitude of the site.
(c) Depending on location and weather conditions 30 to 100 percent of the incident radiation is diffuse scattered before reaching the ground.
(d) The Fresnel reflection losses at the transparent windows used to produce the 'greenhouse' effect vary from significant near normal incidence to severe at large angles.
(d) Depending on the solar collector design, a certain portion of the absorbed energy is lost due to radiative (IR), convective and conductive processes, and
(f) Some concentration of direct beam radiation is possible with non-tracking collectors, with potential reduction of heat loss at high temperatures.

On the other hand, the economic factors govern the potential widespread usage of solar energy systems. The salient economic factors may be enumerated as follows:

(a) The basic capital costs of the solar collector, the overall heat transfer unit, controls and installation. This includes cost of integration of the solar system with other energy supply systems,
(b) The interest costs for the capital borrowed over the period of amortization of the solar system including projected inflation rates,
(c) Projected competitive fuel costs, and
(d) The total efficiency of the solar system as a secondary source. This is determined by both the degree of sophistication of the system and the available year around insolation.

Superimposed on top of the technical and economic requirements are the problems of:
(a) reliability
(b) maintenance
(c) weight
(d) structural integration with the building
(e) architectural and aesthetic requirements.

The more imminent applications of non-tracking solar energy collectors lie in the areas of:
(a) heating (space and water) and cooling of buildings
(b) driving of heat engines for generation of power
(c) solar pumps for irrigation
(d) solar dehydration of agricultural commodities
(e) solar cold storage for increasing shelf life of perishable foods, and
(f) solar household devices, eg. cookers and washers, etc.

The temperature range required for most of these applications varies from 100°F to 500°F. It is oı paramount importance that the thermal energy be delivered efficiently and economically.

Low Temperature Solar Collectors

Among the multitudinous applications of solar energy, by far the least temperature rise above the ambient is required for solar swimming pool heating systems. This application of solar energy is particularly suitable since the swimming pool acts as a large thermal reservoir. Furthermore, due to the small temperature rise above ambient the convective and radiative losses are kept at a minimum, thus yielding high efficiency conversion without the need for cover plates and insulation. Figure 1 shows the plastic swimming pool solar heating systems being manufactured by Fafco, Inc. The overall swimming pool heating system is illustrated diagramatically in Figure 2. The black extruded plastic collector has a built-in water flow system which is linked to the swimming pool by automatic valves. Of particular interest are the solar sensor, the pinch valve and method of integration of the solar heater into the existing filter and gas heater system.

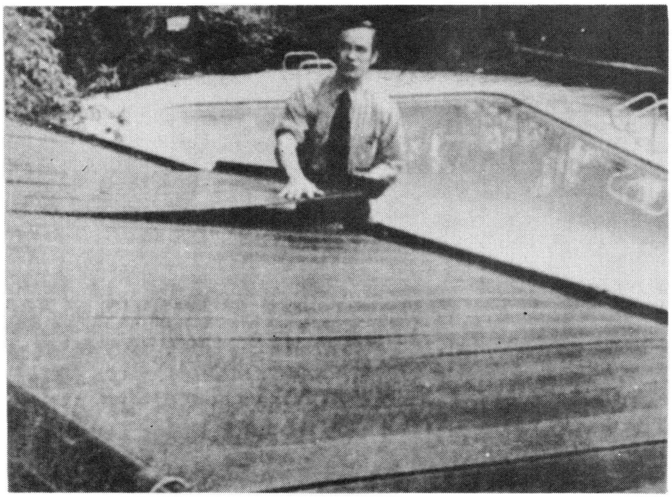


Figure 1

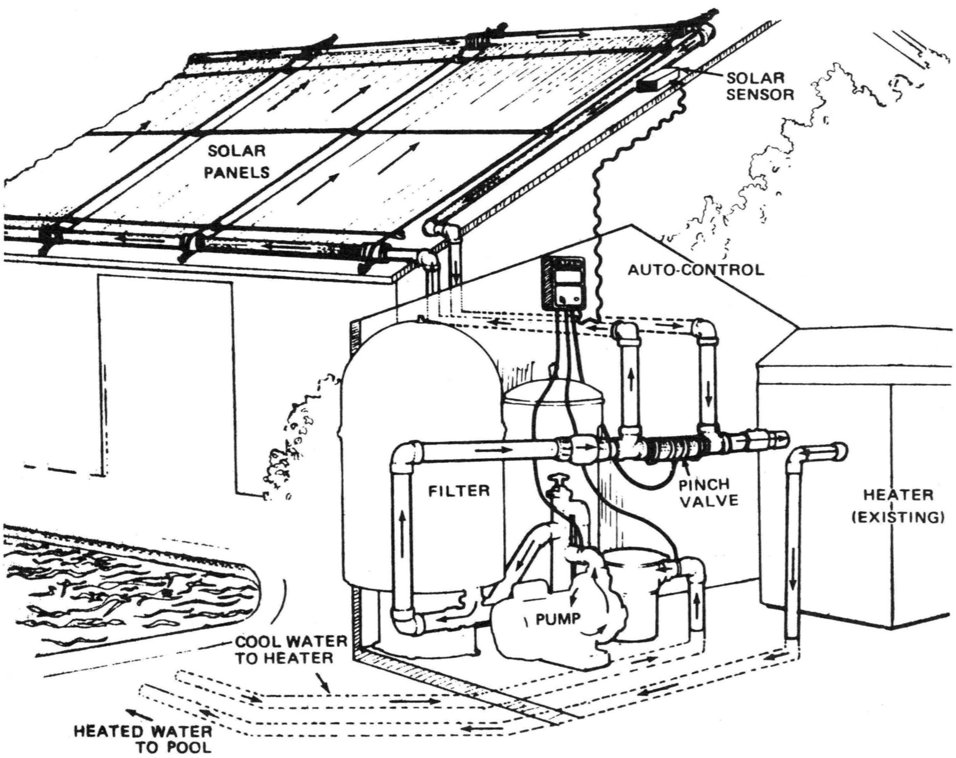


Figure 2. Schematic diagram of typical solar pool heater installation. (Fafco)

This unit is being used widely and has demonstrated a high degree of reliability, cost effectiveness and efficiency.

Another well known application of solar energy lies in dehydration of agricultural products. The temperature gradients required in the dehydration tunnel varies with the product. For example, prunes require a temperature gradient from 195°F to 160°F and grain requires a lower temperature range of about 100°F. Low cost and high efficiency solar collectors are capable of providing the required temperature ranges for dehydration. A very ingenious design of such a solar collector is illustrated in Figure 3.

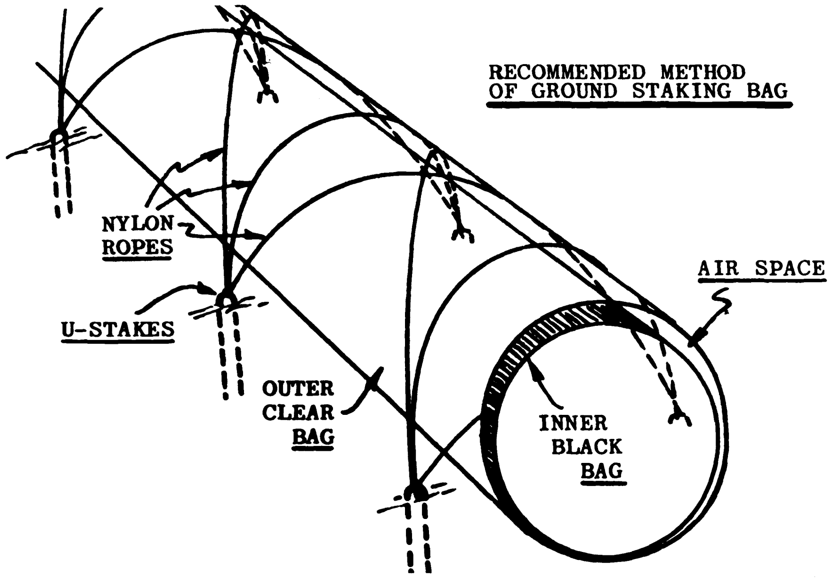


Fig. 3

Two concentric tubes of flexible plastic are inflated into cylindrical form by forced air from a pump. The inner tube is made of black plastic to absorb the solar radiation and the outer transparent tube provides both the 'hot house effect' as well as the desired air flow. Thus a high efficiency, low cost and easily portable system is achieved for various dehydration applications.

Medium Temperature Solar Collectors

Various designs of medium temperature (200°F - 500°F) non-tracking solar collectors have been evolved in recent years. They involve ingenious schemes for achieving reduction in convective, conductive and radiative loss with or without means for unidirectional concentration of incident solar energy. They differ from each other from the standpoint of efficiency, cost and achievable maximum temperature.

An interesting solar collector for hot water heating system is designed by Falbel Energy System Corp. Figure 4 shows the construction of the FES Delta Solar Collector.

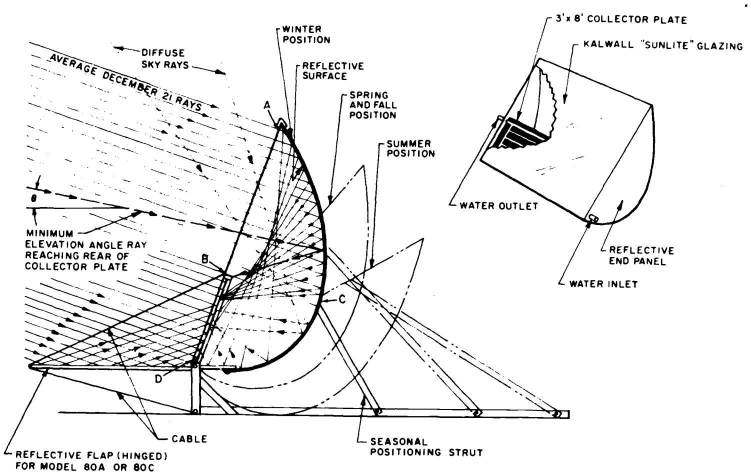


Figure 4

It makes use of an aluminum or copper flat plate collector, blackened on both sides, through which water is circulated. The collector is mounted in the lower part of a cylindrical reflective cavity whose cross section (when combined with the collector plate) resembles the Greek letter "delta". The cylindrical surface reflects most of the direct as well as diffuse solar rays to the rear side of the collector plate. Since the area above the collector plate is twice that of the collector plate, a solar irradiance gain of nearly two is schieved. When this is added to the direct rays absorbed by the front surface of the collector plate one could achieve an overall gain approaching three times. A net gain of 2.3:1 has been achieved using this system. A variation of this design makes use of partially reflecting and partially transparent film on the cylindrical surface. Such a system when mounted vertically in a wall provides a see-through window type solar collector.

Another ingenious non-tracking solar collector has been developed by Professor Roland Winston of the University of Chicago. Figure 5 illustrates diagramatically the Compound Parabolic Concentrator of Winston. The plane profile of this morror consists of two distinct parabolic sections whose axes are inclinced at angles $\pm\ \theta_{max}$ with respect to the optical axis of the collector. A concentration ratio of 10:1 has been achieved using this design. Such a collector needs no diurnal tracking; only seasonal tracking is required. Furthermore, the efficiency of the scattered sky light collection is the reciprocal of the concentration ratio.

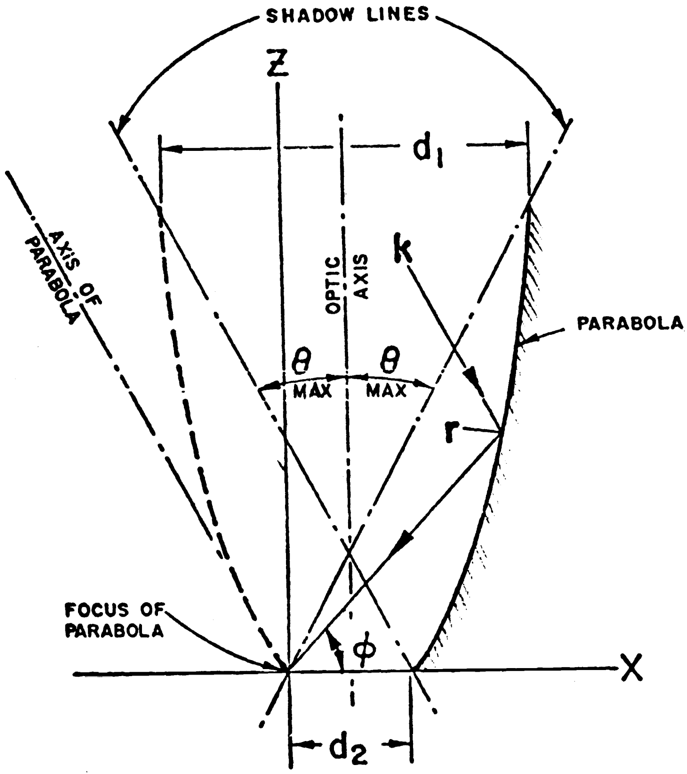


Figure 5. Cross section diagram of the Compound Parabolic Concentrators.

Yet another new non-tracking solar collector has been developed by Corning Glass Co. This system consists of two concentric tubes in which the space is evacuated. The outer tube is transparent on the top and reflecting at the bottom in order to focus the solar radiation on the smaller inner tube, through which the heat transfer fluid flows. This system substantially eliminates both the convective and conduction losses by means of the vacuum jacket, and reduces radiative loss by the small collector area and selective absorption coating. Cost and reliability appear to be the primary problem areas requiring resolution for these high technology collectors.

Kaptron Solar Collector

The Kaptron solar collector is unique in terms of (a) the design of the window, (b) a means for providing solar energy transmission and infrared reflectivity (c) a more efficient absorber and (d) a soundly based insulating and attachment system. Specifically the parts of the Kaptron solar panel are:

.. window with optical ribs
.. an optical valve
.. a multiple reflection absorber, and
.. insulation case.

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 deem 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 the 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 0.004 inch are practical.

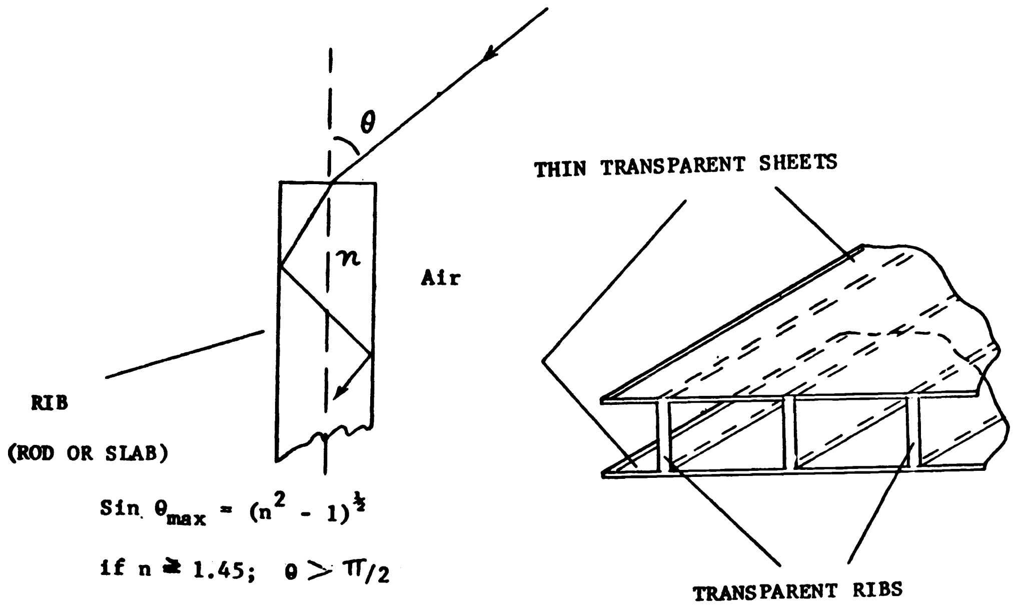


Figure 6. Solar collector window with optical ribs, (a) illustrating the conduction of solar radiation by total internal reflections and (b) a window with optical ribs.

Measurements were made on a 12 in. x 12 in. acrylic window, with optical ribs as shown in Figure 6, in direct sunlight, with a large area radiometer having a 100 cm^2 aperture to average the effects of the optical ribs. In one case, the optical ribs were oriented parallel to the direction of the incoming solar radiation, in the other the 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).

	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

Table 1. Percentage of Solar Transmission at Various Sun Angles

The Optical Valve

The "optical valve" incorporates a novel optical design, providing increased high temperature efficiency for the otherwise relatively low efficiency of the flat plate collector. In the rudimentary form of this device, use is made of reflecting wedges or inverted V's between the window and the absorber. The primary function of this "valve" is to reflect infrared radiation emitted from the absorber back to the absorber, thus maximizing the entrapment of heat in the solar panel. This is done by infrared reflecting surfaces on the bottom of the valve. The reflection paths of the infrared rays 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 of the absorber. The case shown in Figure 7 (a) is for normal incidence of the sun to the collector. The slits in the valve are set east to 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 slightly reduced effectiveness. Figure 7 (b) shows a 10^{o} incidence angle.

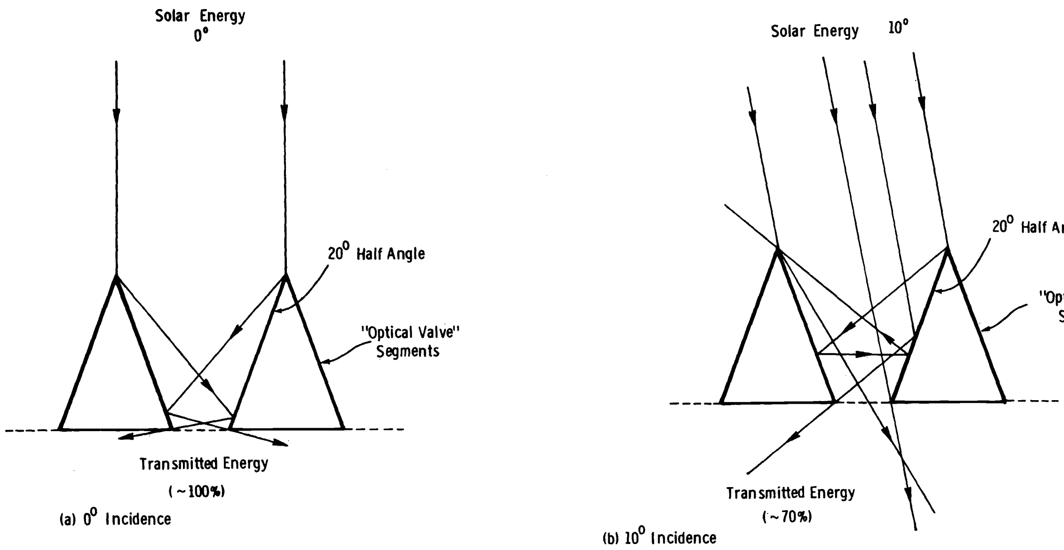


Figure 7. Path of normal incidence rays (a) and rays inclined at 10^{o} (b) through the optical valve.

Alternative valve designs using total internal reflection are illustrated in Figures 8(a) and 8(b). This "valve" type consists of solar transparent solid flat bottomed "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 layer 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 such as shown in Figure 7. They have the further advantage of being readily produced in large sheets by continuous flow processes.

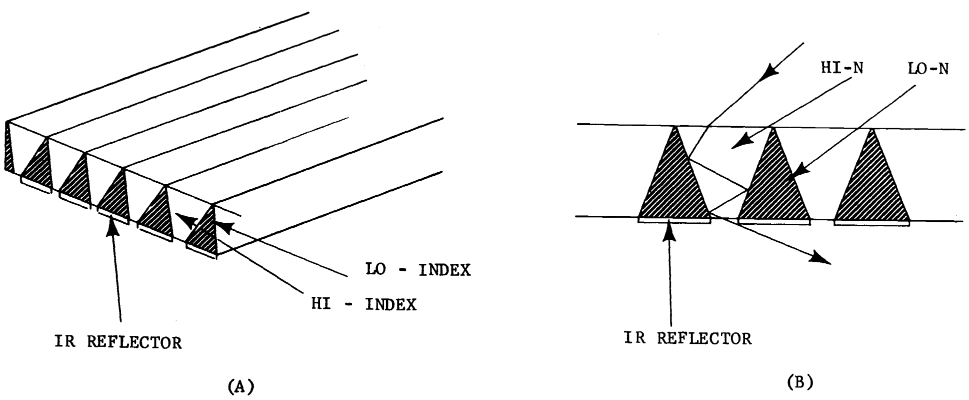


Figure 8. Design of the total internal reflection optical valve (a) continuous sheet structure and (b) ray path.

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 half 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 II.

Half Angle Ø	Max. # of Refl.	μ Out	(μ in) for α = 0°	2.5°	5°	7.5°	10°
20°	2	0.35	1.00	0.94	0.90	0.86	
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

Table II. Efficiency of "optical valve" as a function of angle of the rays.

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 thermal, structural and manufacturing cost considerations. V-groove widths of a few mm's appear to be optimum from all of these considerations. Figure 9 shows photograph of an 'optical valve' experimental prototype.

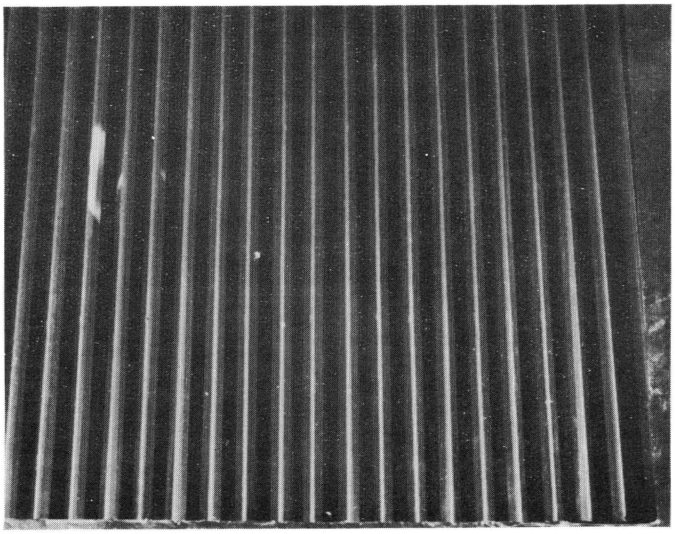
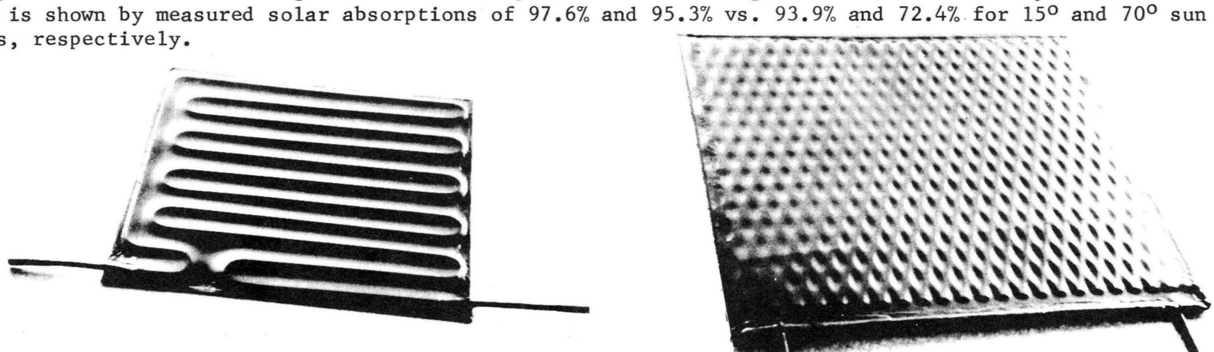


Figure 9.

The Absorber

Optimization of the absorber in a solar panel includes maximizing absorptivity (α), minimizing the emissivity (ϵ), and maximizing thermal transfer within and through the unit (all with due regard to efficiency and cost). The ideal absorber would have a high absorptivity in the 0.3-2μ and 10μ (for reabsorption) range and low emissivity at approximately 10μ. For a black body α/ϵ is approximately equal to 1, whereas for a polished metal surface this ratio is approximately 3. Ratios on the order of 15 (special black nickel) have been obtained by coating a thin absorption layer over a reflecting surface. This layer is thick enough to absorb the solar radiation, but thin compared to the wavelength of the infrared radiation.

Design of the absorber surface can be used to maximize thermal transfer and also enhance the absorption of the solar radiation. A fluid transfer design shown in Figure 10 (a) has been constructed. This design is much like the tube sheets used in commercial refrigerators and freezers. The absorptive surface is fabricated of roughened aluminum. The heat transfer fluid goes through the incorporated channels that are designed in number and dimension to minimize back pressure and maximize area for transfer of heat. The above mentioned absorber is very low in cost and lacks some thermal efficiency due to its simplicity. The design of an embossed absorber is shown in Figure 10(b), wherein honeycombs of pyramidal shape are embossed directly on the heat exchanger surface. Advantages of the embossed honeycomb are that it provides multiple bounce absorption and increases integrated solar absorption. The advantage of the embossed honeycomb vs. a flat plate is shown by measured solar absorptions of 97.6% and 95.3% vs. 93.9% and 72.4% for 15° and 70° sun angles, respectively.



(a) Bottom Tube Sheet

(b) Top Embossed Surface

Figure 10. Multiple absorber and heat transfer unit.

Insulation

The whole solar panel itself must be an infrared insulator for the absorber. The way in which the window and valve perform this function has been discussed, along with their dual role of being transparent to solar radiation. It is then necessary to provide insulation to the back of the absorber and to the sides of the solar array. It is also desirable in many cases that this insulation be a structural element to provide support and a case for the rest of the solar panel (both for installation and shipment).

Figure 11 illustrates the insulation design consisting of a structural plastic foam which has good insulating characteristics backed up with highly effective polyurethane foam. These foams must be closed cell, filled with gas (preferably Freon), able to withstand the anticipated absorber temperatures (250°F), and durable in the anticipated environment (either by themselves or with appropriate coatings). Use of reflecting surfaces on the absorber side not only protects the foam but concentrates the infrared radiation on the absorber (where it is desired). The foam may directly contact the absorber, or an air space may be provided to give additional insulation to the absorber. Figure 11 illustrates the solar collector with "optical ribs", "optical valve", "multiple absorber and an insulating case". These collectors are capable of being manufactured with high ruggedness and low weight (2 lbs/sq.ft.).

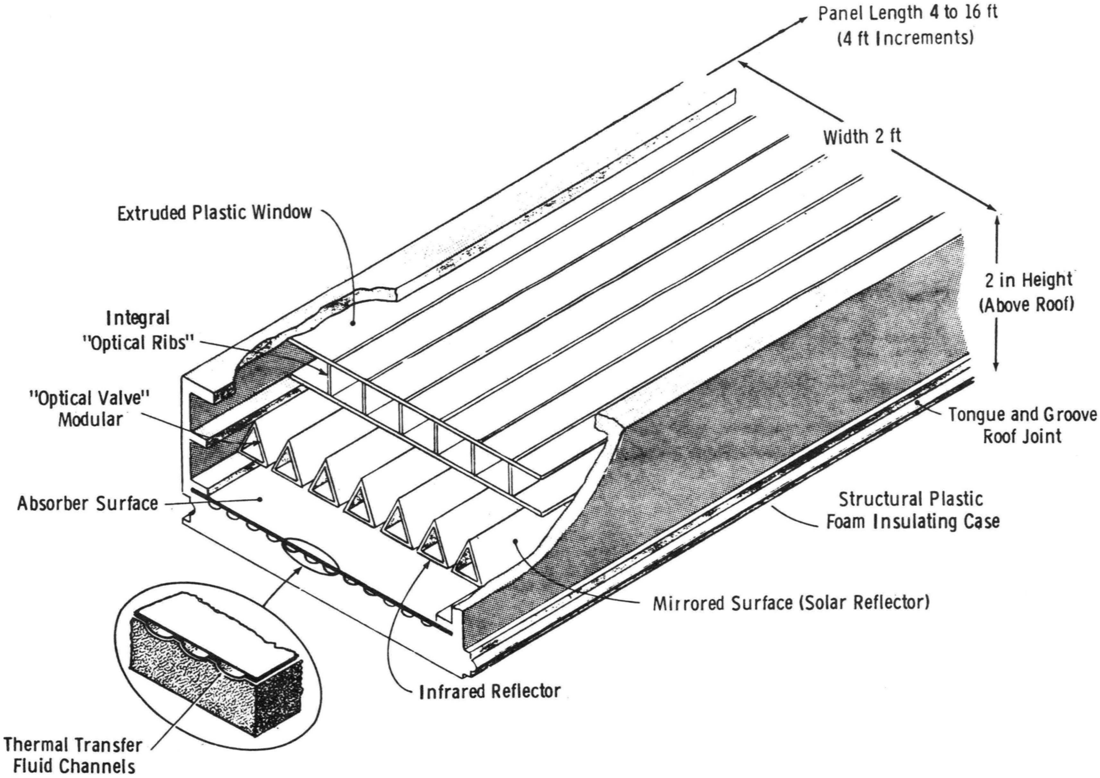


Figure 11. Schematic of a solar panel incorporating a window with "optical ribs", and "optical valve", a "multiple absorber" and insulating case.

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