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THIN-FILM FLAT-PLATE SOLAR COLLECTORS FOR LOW-COST MANUFACTURE AND INSTALLATION

JOHN W. ANDREWS
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March 1980

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ABSTRACT

A flat-plate solar energy collector design using thin-film plastics in both the absorber and glazing is described. The design approach proceeded in two steps. First, cost constraints on solar collectors were determined using reasonable economic projections. Second, engineering was applied only to those ideas which had hope of falling within those cost boundaries. The use of thin-film plastics appeared most attractive according to these criteria. The nature of the marketing and distribution network can be expected to have a strong impact on the final installed cost of the collector; the proposed design has characteristics which could make possible a reduced price markup.

I. EXECUTIVE SUMMARY

The flat-plate solar collectors proposed in this report depart radically from conventional designs. High-performance thin-film plastics (0.001 to 0.010 in.) are used in the glazing and absorber portions of these collectors in order to reduce cost. These plastic films are attached to a light rigid frame by means of a pressure-sensitive adhesive or other sealer which functions as both fastener and weather seal. The attached films form a set of stressed membranes that contribute to the overall strength of the panel. This monocoque construction provides a complement of physical properties which reduces material requirements and lowers fabrication costs.

In this solar collector design water is used as the liquid heat-exchange medium. It enters the absorber through manifolding integrated into the frame. The water enters the collector from the top manifold and flows between the two absorber films. A layer of aluminum foil laminated to the upper plastic layer in the absorber provides good lateral heat transfer from unwetted to wetted areas. Solar-heated water flows to the bottom of the collector and then out through manifolding similar to that at the top, but with larger porting to ensure adequate drainage.

The solar collectors made with thin plastic films have several advantages over conventional flat-plate collectors:

1. A reduction in material costs;
2. A large reduction in collector weight and bulk, which makes installation easier and less expensive;
3. Potentially enhanced performance because of good-to-excellent physical properties such as high glazing transmissivity (to 96%) and good thermal heat transfer;
4. Potentially high reliability and good production yield because the absorber requires essentially no internal pressurization and the construction is uncomplicated;
5. Tolerance of the absorber to freezing temperatures without the addition of antifreeze agents.

The major factor limiting the use of thin plastic films in a solar flat-plate collector is their environmental tolerance. The glazing films must be able to withstand high temperatures, weather, corrosive agents,

and ultraviolet light for an extended period. The absorber, which is somewhat protected from weather and ultraviolet, must be resistant to the effects of fluid flow and of long-term exposure to high temperatures under conditions of thermal stagnation.

A two-step design method was used. First, cost constraints were determined on the basis of the value of the energy which the collector could be expected to deliver. Second, materials and fabrication and installation methods were selected which not only would satisfy these constraints but also could be expected to provide a collector having performance and life consistent with the assumptions on which the cost constraints were based.

II. INTRODUCTION: THE ECONOMIC REALITIES OF SOLAR APPLICATIONS

The widespread application of solar energy cannot take place until two critical conditions are met: (1) a product must be developed that is competitive with existing and future energy systems, and (2) solar devices must be marketable at a profit high enough to initiate and sustain an industry. The efforts made so far to commercialize solar energy have generally been unsuccessful primarily because they have not met the above conditions.

Different types of solar systems (e.g. active, passive, photovoltaic) must be treated separately because of the different conditions under which they operate. What follows applies to active systems - those which make use of mechanical solar heat exchangers (collectors) activated by pumps and controls for building space and water heating.

It is a major thesis of this report that the wrong approach has generally been taken by solar designers. It is inappropriate to create a solar device first and then justify its cost by distorting economic reality. The more prudent approach is to establish the true domain of economic viability for the application of solar energy and then to apply engineering effort within this constraint. A number of factors are relevant to the domain of economic viability. The energy value of a square foot of collector must be quantified; the payback period must be realistic; and the solar energy must be related to the value of money, taking into account escalating fuel costs. Most of these factors cannot be

precisely quantified; one must be satisfied with a range of reasonable values. The evaluation methods must be kept simple so that they can be generally applied. To deny the reality of this necessity is only to prolong the time we must wait for widespread use of solar energy.

The amount of energy derived from a square foot of solar collector need not be obscure. It depends on several factors such as collector performance, physical orientation, geographical location, and system size relative to the load. Each of these factors may take on a range of values within which a benchmark value may be assigned. Values should be expressed in units of energy, just as the value of fuel oil can be expressed in terms of energy per gallon. Because available solar energy varies over both long and short time periods, it is generally averaged over a year; therefore, the usual unit for the energy value of a solar collector is Btu/ft²-yr. When such a value has been derived, the yield and cost can be compared with those of other energy sources.

Consider a typical system in which solar energy is applied to both water and space heating in a home. The energy value of a medium-performance collector in a typical system for this application is ~100,000 Btu/ft²-yr in many parts of the U.S.¹ For water heating only, the energy value would be considerably greater because this is a year-round use and the system could be better optimized for an almost constant load. The important consideration is that quantifying the energy value of a solar system permits energy comparisons with competing fossil fuels to be made. Such an energy value can be derived for any defined system at any location. With greater standardization such energy values will be important tools for comparing different energy systems.

The second factor, the payback period, must be placed in perspective. The question must be asked whether marketability can be established on payback periods of 15 to 30 years. Historically, industry has used periods of 3 to 5 years, except for highly capitalized ventures such as large-scale power generation. Acceptance of very long payback periods would require a significant alteration in marketing philosophy. One major difficulty is the uncertainty of long-term predictions of economic and technological trends. A prediction of fuel cost escalation for the next year may possibly be made with reasonable confidence; extension to 2

or 3 years diminishes the confidence; and, with extension to 20 to 30 years, the credibility of the prediction vanishes. The same is true of predictions about technology. Can one say whether advances in solar and non-solar technology will make solar either cheaper or otherwise more attractive than possible alternatives? The development of currently infant technologies could totally alter the economic picture and make long-term solar investment a very bad choice. The clear deduction is that engineering should be applied to designs that are constrained to relatively short payback periods.

In determining the longest payback period that will encourage a mass solar market, it is helpful to consider current industry practice. As noted above, in deciding whether to market a product with a higher first cost but lower operating costs than a competing product, industry generally requires a payback period no longer than 3 to 5 years. Occasionally somewhat longer periods are involved, but it seems unrealistic to use a payback period much longer than 8 years. Therefore, 8 years is used here as a reasonable compromise which allows for an expected increased energy consciousness on the part of the public but does not require total divergence from current practice.

The remaining considerations are the annual rate of fuel cost escalation and the value of money or discount rate. Many published studies use life-cycle methodology, which allows projection of the energy value as a function of the payback period. The input parameters for this method include the annual worth of money or discount rate and the annual fuel costs escalation rate. The general expression for the present value of the energy saved is²

$$V_0 = \sum_{J=1}^N \frac{(1 + F)^J}{(1 + I)^J} P_0 \quad (1)$$

where

N = period of analysis,

I = annual worth of money or discount rate,

F = annual fuel price escalation rate,

P_0 = value of energy saved in the first year (dollars),

V_0 = present value of the energy displaced over N years (dollars).

The energy value V_0 may be equated to the justifiable increment in cost of the solar system over the competing conventional one. This assumes that the effects of maintenance, which will tend to increase solar costs, and tax benefits, which will decrease them, will roughly cancel.³

If one sets $R=(1 + F)/(1 + I)$, then

$$V_0/P_0 = \frac{R^{N+1} - R}{R - 1} \quad (2)$$

It is significant that the value V_0/P_0 can be expressed approximately as a function of a single dependent variable represented by the difference $F - I$, rather than of F and I separately. Also, for the case $F = I$ it should be noted that the simple relation $V_0 = NP_0$ holds.

The initial value of the competing fuel (P_0) is determined from the product of the ratio of solar-derived energy E_s to the energy value of the displaced fuel E_F and the cost of the displaced fuel unit C_F :

$$P_0 = \frac{E_s}{E_F} C_F \quad (3)$$

The following case illustrates the value of P_0 for contemporary conditions.

Let

$E_s = 100,000$ Btu/ft²-yr (energy obtained from solar collectors)

$E_F = 100,000$ Btu/gal (#2 fuel oil at 72% furnace efficiency)

$C_F = \$1.00$ /gal (fuel cost during the first year of operation)

then

$$P_0 = \frac{100,000}{100,000} (1.00) = \$1.00/\text{ft}^2\text{-yr} \quad (4)$$

For the simple case where $F = I$, and $N = 8$ years,

$$V_0 = NP_0 = \$8.00/\text{ft}^2 \quad (5)$$

This is interpreted as the acceptable incremental cost of the solar energy system per square foot. For a hot-water-only application which derived 200,000 Btu/ft²-yr,

$$P_0 = \frac{200,000}{100,000} (1.00) = \$2.00/\text{ft}^2\text{-yr} \quad (6)$$

$$V_0 = 8(\$2.00) = \$16.00/\text{ft}^2. \quad (7)$$

Figure 1 shows the acceptable incremental cost for a solar energy system competing with fuel oil at a present \$1.00/gal, versus $F - I$, for an 8-year payback. This incremental cost is the difference between the solar system cost and the cost of the competing conventional one. Since the solar system will in general need a backup, this incremental cost to a first approximation may be expected to equal that of the solar portion of the system, less backup. The curve illustrates an energy value of 100,000 Btu/ft²-yr for the solar energy system. Note that we have used the term "payback" to mean the period of time required for the solar user to come to an even cash position with the user of the competing fossil-fueled system. This definition takes into account fuel cost escalation and future discounting. It differs from so-called "simple payback" which is just the time required for the incremental solar investment to be recouped, with no consideration of the time value of money.

In any case, the acceptable solar system cost does not go beyond the \$8-12/ft² range unless one is willing to assume very large fuel cost escalation rates in excess of 0.10 over the worth of money or discount rate. Most studies to date have used $F - I$ values greater than zero but considerably less than 0.10.

In summation, it is strongly suggested that the first imperative is to apply engineering to realistic economic constraints. If system material and labor costs can meet the necessary constraints, then rapid growth of the solar market is highly probable. In the balance of this report, material, design, and marketing approaches are suggested which will lie within the domain of economic viability.

III. DESIGNING FOR LOW COST

Contemporary industrial practices permit generalizations to be made regarding incremental cost breakdown in marketing a given product. For example, the consumer price for a product may reflect as much as a ten-fold increase over the manufactured cost of the product. This is a result of the marketing costs incurred in getting the product to the consumer. In segments of the industry with refined marketing procedures

Figure 1. Allowable incremental solar system costs for 8-year payback

this ratio may be reduced to about a factor of five. These markups are required to provide enough profits throughout the distribution chain to induce wholesalers and retailers to carry and sell the product.

In the benchmark example presented in the previous section an 8-year payback for a solar space-and-water-heating system permitted an acceptable system cost of $\sim \$10/\text{ft}^2$. If it may be acknowledged that half of the cost will reside with the component solar collector we may further extrapolate a manufacturing cost constraint. This may be accomplished by accepting the refined markup ratio of five for an installed solar collector cost of $\$5/\text{ft}^2$. The permissible manufactured cost based on such values is approximately $\$1/\text{ft}^2$.

As severe as this manufacturing cost constraint may appear it nevertheless follows from the assumptions made. It is only fair to note, of course, that given an application where more solar energy is collected (e.g. hot water systems in Southern California) or a higher initial cost exists for competing fuel, a more generous manufacturing cost may be tolerated for the given payback period. Such applications are appropriate for initial industrial involvement. A significant impact on the national energy budget, however, will require marketing of systems for space heating as well as hot water over the broad range of average weather conditions. It is for this reason that engineering applied to the $\$1/\text{ft}^2$ manufactured cost constraint is appropriate.

A cost constraint in the vicinity of $\$1/\text{ft}^2$ acts as an effective filter for eliminating materials candidates. When materials costs are measured intrinsically - in their price per pound - it becomes clear that the most desirable materials are those with the lowest intrinsic cost and the highest physical strength and endurance. Whenever these criteria are applied to conventional solar collector materials, such as copper and glass, it is clear that we must look elsewhere for materials candidates to meet the cost constraint.

Consistent with requirements to optimize the material cost-to-performance ratio was the exploration of polymeric-film materials like those presently used in the food packaging industry. Such films are characteristically strong and may be used structurally down to thicknesses of 0.001 inch. Examples of such films include common plastics such as

polypropylene and polyester. These materials and other similar plastics can exhibit impressive strength properties which would render them desirable for the glazing and absorber portions of a solar flat-plate collector. Unfortunately, common plastics often have properties not consistent with the requirements for solar application. These include physical and chemical instabilities and a generally poor physical tolerance to elevated temperatures. The inability of plastics to perform well in solar applications has in the past prevented rigorous exploration of these materials for possible means to make them usable in solar collectors. However, so attractive is the potential exhibited by these materials to meet the expressed cost constraints that engineering effort is now being applied towards the application of plastics to solar collectors. This effort is being complemented by the continuing development of new and more suitable materials by the plastics industry. It is highly desirable that such effort should continue and intensify in the future.

The design of a solar flat-plate collector using high-performance thin-film plastics is described below. By choosing appropriate materials and integrating them into a structure it appears to be possible to manufacture a collector of good to excellent performance at a cost of under \$1.00/ft². Two designs were originally conceived, a simple single-glazed unit suitable for solar heat-pump applications and some direct heating, and a high-performance unit suitable for direct heating even in northern climates.

A. Light-weight Support Frame for the Thin Plastic Films

The basic structure supporting the thin plastic films which comprise the glazing and absorber consists of a light, low-cost, bent metal frame. This frame can be made from galvanized steel and can meet the requirements of structural integrity for a mass-production cost as low as \$0.10 per linear foot. Its cross-section is U-shaped, with the open portion facing outward (Figure 2). Its upper and lower flat portions form the surfaces onto which the glazing and absorber films are attached. Attachment made either thermally or with adhesive forms a seal of exceptional shear strength. The composite of attached films and frame forms a structure having physical properties consistent with the requirements of the

Figure 2. Construction details of thin-film collector panel

installed collector panel. Additional internal linear members help stiffen the frame and divide the glazing surface into sections of reduced flexure area to lower the fatigue stresses on the films due to fluctuating wind loads; they also improve the appearance of the panel.

B. Thin-Film Plastic Glazings

A number of glazing candidates appear to meet the requirements of relatively low cost and high performance. It is desirable that the glazing tolerate solar and environmental exposure for at least 5 years. Glazing performance is specified by transmissivity, strength, temperature tolerance, and ultraviolet resistance. Some of these candidate glazing films are listed in Table 1; their transmissivities are between about 86 and 96%.

Of these films, polyesters are among the strongest; they are generally low in cost and can be made physically taut on a frame (oriented polyester shrinks at elevated temperatures). The fluoroplastics have the highest general performance but cost more. What is most important is the high potential for engineering a polymer for the desired characteristics. What may not represent the ideal material today is within the range of polymer engineering.

In the simplest BNL design, with only one glazing, the polyester film glazing has shown promise. It can easily be attached with high-performance, weatherable, pressure-sensitive adhesives, and heat curing tightens the attached film and improves its appearance. A double-glazed design using fluoroplastic glazings has also been fabricated and tested. Figures 3 and 4 illustrate the strength and weight advantages obtainable with these designs.

C. Thin-Film Plastic Absorbers

The use of thin plastic films in the absorber gives rise to problems not encountered with metal absorbers, such as the ability of the material to tolerate high temperatures. In a flat-plate collector designed for high performance through the reduction of heat loss, the absorber can experience very high temperatures. These can approach 450°F and any plastics considered for use in the absorber must be able to withstand the temperatures anticipated in the design. These high temperatures are not encountered during normal operation, when the absorber must remain below

Table 1
Leading Commercial Candidates for Thin-Film Glazings

Trade Name	Flexigard	Halar	Kynar	Llumar	Melinex OW	PAN*	Tedlar	Teflon
Material	Polyester/ Acrylic	Fluoro- plastic (ECTFE)	Fluoro- plastic (PVDF)	Polyester	Polyester	Polyacry- lonitrile	Fluoro- plastic (PVF)	Fluoro- plastic (FEP)
Source	3M	Allied Chemical	Penvalt	Martin Processing	ICI Americas	Trian	DuPont	DuPont
Thickness (mils)	7	5 (1,2,4,10)	5 (3,10,15,20)	5 (7)	5-7		4 (1/2-4)	1 (2)
Tensile Strength at Yield ASTM D-882 (psi)	7280	4000-5000	5900-6100	14000	15300- 16300	20000	4900- 6000	1700
Service Temperature Range (°F)	to 275	cryogenic to 330	-80 to 275 continuous	-70 to 350	to 300	to 482	-100 to 225 continuous	-425 to 400 continuous
Expected Lifetime (yr)	>10	3000 hr in weather- ometer (no change)	20-25	10-15	15	20	8	>15
Water Absorption ASTM D-570		<0.1%	0.04%	0.08%			<0.5%	<0.01%
Solar Transmissivity	82-90%	85%	93%	88-90% visible	87%	92%	90%	96%
Approximate Cost (\$/lb)	\$5-7	\$20	\$7	\$6	\$4	\$3	\$10	\$20
Specific Gravity		1.66	1.74- 1.78	1.38	1.40	1.17	1.38- 1.57	2.1- 2.2

*Not yet made into commercial film.

Figure 3. Technician demonstrating strength of the thin-film collector panel

Figure 4. Technician demonstrating portability of the thin-film collector panel

the boiling point of water. However, if for any reason the collector is not operating on a sunny day, its temperature will rise until its rate of heat loss equals the rate of heat absorption. This maximum temperature condition is called stagnation.

In designing pressurized absorbers made of plastics, the material's ability to tolerate the working pressure of the fluid at any anticipated working temperature must be considered. To meet this requirement pressurized plastic absorbers must be channeled and made thick enough to ensure structural integrity under design pressure and temperature. Making the wall thicker requires more material and therefore costs more, and it lowers the heat transfer rate.

In the absorber design described here, the water is supplied at the top manifold and passes down between the two absorber films by gravity, so that in a vented system the absorber remains at atmospheric pressure. This permits the use of very thin films with low material cost and good heat transfer. The relaxed operating requirements of such an absorber can improve production yield (the fraction of a production run which is of acceptable quality) and increase operating reliability. With non-pressurized operation, plastics can be ideal materials for the absorber.

The critical factor affecting performance is the ability of the absorber to remain adequately wetted; incomplete wetting lowers the efficiency. Several designs have been studied to ensure sufficient heat exchange, with variations including geometric alterations in the seal pattern of the two absorber films, conditioning of the wetted surface, the use of wetting agents, and lamination of metal foil to the polymer film. The metal foil will improve the lateral heat transfer should small non-wetted voids be present due to air bubbles or uneven flow so that incomplete wetting can be tolerated. The polymer side of the laminated film will be in contact with the heat transfer water in order to protect the metal foil from corrosion by the water and improve the tear resistance of the foil. The foil also improves moisture imperviousness and provides a substrate suitable for various absorber coatings.

A configuration incorporating many of the above features is made as follows: An absorber film is fabricated by laminating 0.002-inch aluminum foil to a polymer film.

Two sheets of the laminate are attached on their polymer sides with adhesive to form long thin channels, which will permit water to flow down between the sheets. The combination of a wettable surface and good lateral heat transfer will allow this thin-film absorber to perform well with gravity feed. This absorber is expected to cost about \$0.25/ft² and to endure for at least 15 years.

These films can be attached to the frame with pressure sensitive adhesive. Holes are then drilled or punched through the first film, frame, and manifold bonding material, into the manifold pipe, at the top and bottom of the frame for supply and return manifolding. Sealing of the second absorber film around the edges forms a fully enclosed envelope preventing escape of moisture out of the absorber (see Figure 2).

Plastic materials that are promising candidates for use in this low-cost absorber include polypropylene, polyester, fluorinated ethylene-propylene, and polyacrylonitrile. Although much work remains to be done in the development of absorber films, these materials appear to offer good performance and lowest cost. Since polypropylene and polyester can withstand temperatures only up to about 250°F, the performance of solar collectors designed around these materials is limited; higher performance requires more expensive materials such as fluorinated ethylene-propylene or polyacrylonitrile. Even with the latter materials, the cost is very modest, and a properly designed solar collector offers superior performance, allowing stagnation temperatures as high as 450°F, if the absorber material is laminated with metal foil. Advanced film development shows great promise as selective absorber coatings are already being applied to thin films at a very low cost. This effort will significantly enhance the use of plastics in solar applications.

Production of the absorber described above is easily adaptable to high-speed fabricating machines of the type now used in the food packaging industry to make plastic bags for potato chips and similar products, which laminate and print at a rate of hundreds of feet per minute. Manufacture of the absorber by such machinery is considered possible, including the entire process of laminating the films, printing the optically selective absorber surface and sealing the two films with the proper flow pattern. The fabrication cost for such a process, including the costs of labor, machinery, and materials can be measured in pennies

per square foot. A projected manufactured cost breakdown is shown in Table 2, for the single glazed collector, and Table 3, for the double-glazed collector.

Table 2
Cost Breakdown for Single-Glazed
Polyacrylonitrile Thin-Film Solar Flat-Plate Collector, Panel Area 20ft²

Frame: Galvanized steel, 26 gage, 32 in. x 92 in., at \$0.10/ft	\$2.10
Cross supports: Galvanized steel, 26 gage, 32 in., 3 ea. at \$0.09	0.72
Glazing film: Polyacrylonitrile 0.004 in. at \$0.02/mil-ft ²	1.60
Absorber: 2 ea. Polyacrylonitrile, 0.001 in., at \$0.02/mil-ft ²	0.80
2 ea. Aluminum foil. 0.002 in. at \$1.00/lb or \$0.028/ft ²	1.12
absortive coating at \$0.05/ft ²	1.00
Manifold: 2 ea. at \$0.50/ft	2.67
Liquid Coupling: 2 ea. at \$0.50	1.00
Adhesives: (estimated)	0.75
Production and Labor: (see below)	1.10
	Subtotal 12.86
	15% Overhead 1.93
	Total \$14.79
	Cost Per Square Foot \$ 0.74

Production and Labor Cost Breakdown

It is assumed, on the basis of similar processes, that a machine can be built which will automatically construct the simple frame and attach the thin-film absorber, glazing, and manifold.

Estimated machine cost,
including interest, for 7 years \$1,500,000

Labor at \$40/hr, 480 eight-hour shifts/year
for 7 years 1,075,200

Seven-year total 2,575,200

Number of units produced in 7 years,
at 1 unit per 30 seconds 3,225,600

Production and labor cost per unit \$0.80

Breakdown and setup at \$0.30 per unit \$0.30

Total production and labor cost per unit \$1.10

This cost is included in the overall cost breakdown above.

Table 3
Cost Breakdown for Double-Glazed
Polyacrylonitrile Thin-Film Solar Flat-Plate Collector
(Panel Area = 20ft²)

Frame: Galvanized steel, 26 gage, 32 in. x 92 in., at \$0.20/ft	\$4.20
Cross supports: Galvanized steel, 26 gage, 32 in., 3 ea. at \$0.15	1.20
Glazing film:	
(Upper) Polyacrylonitrile 0.004 in. at \$0.02/mil-ft ²	1.60
(Lower) Polyacrylonitrile 0.001 in. at \$0.02/mil-ft ²	0.40
Absorber: 2 ea. Polyacrylonitrile, 0.001 in., at \$0.02/mil-ft ²	0.80
2 ea. Aluminum foil. 0.002 in. at \$1.00/lb	1.12
absorptive coating at \$0.05/ft ²	1.00
Manifold: 2 ea. at \$0.50/ft ²	2.67
Liquid Coupling: 2 ea. at \$0.50	1.00
Adhesives: (estimated)	0.75
Production and Labor: (estimated) x2	2.20
	Subtotal 16.94
	15% Overhead 2.59
	Total \$19.48
	Cost Per Square Foot \$ 0.97

IV. PERFORMANCE EXPECTATIONS OF THIN-FILM SOLAR COLLECTORS

The following evaluation illustrates some realistic possibilities for the performance of the thin-film collectors, under development at Brookhaven National Laboratory. The specifics are indicative of the present level of design and will no doubt be altered by future development.

The plastic materials being considered for use in the low-cost designs are polyesters such as Llumar and Melinex OW in low-temperature collectors and fluoroplastics such as Kynar and Teflon FEP in collectors suitable for direct heating. These materials are being considered for use in the absorber as well as the glazing. As absorber materials they will be laminated with a thin layer of aluminum foil to improve lateral heat transfer in case bubbles or voids form between the two absorber

films. Two sheets of laminated foil films will be attached on their polyester sides to form an envelope with long vertical channels constraining the water flow. The low-temperature design will consist of one UV-stabilized polyester glazing film (0.04 in.) and two polyester-aluminum laminate films (0.003 in. each). The collector losses will be controlled to ensure that the absorber temperature under stagnation does not exceed 250°F. The absorber will be coated for an absorptivity α of 0.95. A selective coating will be attempted, though it is understood that a successful selective coating would raise the stagnation temperature and require the substitution of plastics able to tolerate the higher temperatures. A solar transmissivity τ of 0.86 is assumed. The worst-case conditions under which stagnation is anticipated would be a solar intensity $I = 300 \text{ Btu/ft}^2\text{-hr}$ and an ambient air temperature $t_a = 100^\circ\text{F}$.

Under stagnation conditions the collector inlet temperature t_i is equal to the absorber temperature. The overall heat loss coefficient U_L can be determined from the expression for the horizontal intercept of the Hottel-Whillier collector efficiency curve:

$$\frac{t_i - t_a}{I} = \frac{\tau\alpha}{U_L} \quad (8)$$

Using the above values for τ , α , I , t_a , and with t_i equal to the 250°F stagnation temperature, one obtains $U_L = 1.63 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ for a collector with a horizontal intercept $\tau\alpha/U_L$ equal to $0.5^\circ\text{F-ft}^2\text{-hr/Btu}$. A single plastic glazing at 250°F is expected to have an upward heat loss⁴ U_{up} of $1.4 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$.

The difference $U_L - U_{up}$ is a measure of the allowable net heat loss through the back and edges. An effective thermal resistance R value for this insulation is given by

$$R = \frac{1}{U_L - U_{up}} \quad (9)$$

For the conditions described above, a value $R = 4.4^\circ\text{F-ft}^2\text{-hr/Btu}$ is obtained.

The collector performance is characterized by the Hottel-Whillier curve of collector efficiency vs $(t_i - t_a)/I$. The vertical intercept gives the collector efficiency when the collector fluid inlet temperature

is equal to the ambient. This intercept is equal to $F'F''\tau\alpha$, where F' is the collector efficiency factor and F'' is the collector flow factor.⁵ For predicted values of $F' = 0.95$ and $F'' = 0.95$, the vertical intercept is equal to 0.72. The horizontal intercept relates the collector temperature difference above ambient to the insolation rate under stagnation. As previously shown, it was fixed at the value $0.5^\circ\text{F-ft}^2\text{-hr/Btu}$ by the 250°F upper temperature limit for the plastic absorber. The configuration of this collector in cross section is shown in Figure 5.

A solar collector capable of operating at higher temperatures, which would be suitable for direct heating, even in cold climates, can be constructed with fluoroplastic films such as Kynar and Teflon FEP. With Teflon FEP in the absorber the tolerance to stagnation temperatures can easily be increased to 350°F on a continuous basis. Two thin-film glazings are needed to ensure the performance required for winter direct heating.

The horizontal intercept of the Hottel-Whillier curve is now given, very nearly, by

$$\frac{t_1 - t_a}{I} = \frac{\tau_1 \tau_2 \alpha}{U_L} \quad (10)$$

where τ_1 and τ_2 are the solar transmissivities of the outer and inner glazings. For the materials chosen $\tau_2 = 0.96$ (Teflon FEP), and $\tau_1 = 0.93$ (Kynar). With $t_1 = 350^\circ\text{F}$ at stagnation, and $t_a = 100^\circ\text{F}$, $I = 300 \text{ Btu/ft}^2\text{-hr}$, and $\alpha = 0.95$, a value of U_L equal to $1.0 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ is obtained. The horizontal intercept of the collector efficiency curve is then calculated from Eq. 9 to equal $0.85^\circ\text{F-ft}^2\text{-hr/Btu}$. The vertical intercept, given by $F' F'' \tau_1 \tau_2 \alpha$, is equal to 0.76, for $F' = F'' = 0.95$ as before.

The upward heat loss factor for the double plastic glazing is expected⁴ to be $0.8 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$. Using Eq. 9, the effective R value for the collector back and edge insulation is calculated to be $5^\circ\text{F-ft}^2\text{-hr/Btu}$. The configuration of this collector in cross section is shown in Figure 6.

Calculated collector efficiency curves for the single and double glazed collectors described above are shown in Figure 7. Test data points for an actual double glazed panel are also shown.

Figure 5. Single glazed thin-film collector configuration

Figure 6. Double glazed thin-film collector configuration

Figure 7. Calculated collector efficiency curves for single and double glazed collectors, with test data points for double glazed collector

These values do not represent the ultimate in achievable performance for thin films, but rather, the potential now available to the designer. Performance could be improved by adding more optical covers and insulation. The upper stagnation limit for Teflon is in the vicinity of 450°F continuous. With a collector angle optimized for winter solar collection, a low-loss design could be implemented which would avoid stagnation greater than 450°F and achieve a horizontal intercept greater than 1.0°F-ft²-hr/Btu. The benefits of such enhanced performance will have to be weighed relative to the cost to the consumer.

V. MARKETING FOR LOW COST

The cost of solar technology relative to that of other energy sources has been a primary impediment to its widespread utilization. The solar industry, being new, has not fully integrated a marketing model for its products. One problem, pointed out above, was to determine the value of the product to be sold. For the solar collector, this value is the energy contribution of the collector relative to its cost. When this value is understood, it becomes clear how the product should be priced, consistent with a demand sufficient to stimulate a mass market. The collector design presented here addresses the correct economics, but can fail if an appropriate marketing plan is not developed.

Marketing involves the facilities, people, institutions, and functions concerned with the movement of goods from the point of production to the point of ultimate utilization and includes a variety of activities, not only handling, storage, transportation, warehousing, delivery, and retailing, but also research, advertising, promotion and financing. Since each activity has a finite cost, it is important to optimize the costs relative to the market demand. The collector design presented here can lower the marketing cost contribution to the total cost of installed solar collectors, which has been a hindrance to widespread acceptance. With the proper marketing plan, it should be possible to meet the cost constraint on a high-performance solar collector.

The marketing plan developed for this design is based on the shipment of the materials for building the finished collector to regional locations for fabrication. The glazing and absorber components can be

shipped in large rolls, ~500 lb each. The metal stock for the frame can also be shipped in rolls, as the simple U-channel shape can easily be bent from roll stock by an automated rolling die of the type used for rain gutters. In this way, the materials for 10,000,000 ft² of solar collector could be shipped in a single railroad box car. Bulk shipment over most of the transport distance minimizes the unit cost of transportation per square foot of collector. The destination will be a small factory and distribution center, where automatic machinery will fabricate the frame from the roll stock and attach the manifolds, absorber, and glazing. The collector design is so simple that the machinery for fabrication will represent a modest capital expenditure relative to the amount of solar collector produced over its lifetime, and the machinery will be small enough to require very little production space. The bulk transport of materials will have the added advantage of reducing warehouse space requirements by allowing automated collector production to match the rate of collector installation.

The regional facility could serve as a franchised installer as well as fabricator. This would reduce the number of middlemen in the distribution chain, and would also make possible more uniform quality control in system installation and maintenance.

Since one of the prime functions of the regional facility will be professional installation of collectors, it should always have a ready supply of collector panels. About 5 panels will be folded into a bundle, weighing ~50 lb, that can be carried and installed by one person (Figure 8). This will permit speedy installation of the collector array in units of ~100 ft² at a time. To match this ease of handling, an integrated track and flashing member will be installed on the mounting structure for the collector (Figures 9 and 10) to allow easy setting in and unfolding of the collector array. The simple manifold scheme will permit rapid attachment of liquid conduits. Attachment of the hold-down strip will complete the securing of the collectors to the mounting surface while permitting thermal expansion and contraction of the frames. The addition of thin-film sealing strips (Figure 11) will provide redundant sealing and increase the overall strength of the array. The panel has no fastenings other than the holddown strip; this will facilitate repair or replacement of the panels if necessary.

ILLUSTRATION OF HOW THIN FILM SOLAR COLLECTOR
PANELS MAY BE INSTALLED AS A BUNDLE AND
UNFOLDED ON THE ROOF FOR QUICK INSTALLATION.

Figure 8. Five-panel assembly of collector array

Figure 9. Track and flashing assembly, single glazed collector

Figure 10. Track and flashing assembly, double glazed collector

Figure 11. Final sealing joint between panels

The supply and return lines to the collector array are connected at one corner of the array, with all piping and manifolding within the frame of the array. The external connection is coupled to an insulated two-pipe modular section, which is attached to the outside of the house if the collectors are roof mounted. It resembles a rain gutter downspout and will allow fast and economical installation with a minimum of penetrations.

VI. CONCLUSIONS

The major conclusion of this paper is that, although realistic cost constraints on active solar systems utilizing collectors are severe, there is nevertheless reason to believe that these constraints can be met. The use of plastics in both the absorber and glazings is seen as an attractive pathway toward meeting these cost goals. An integrated marketing plan, including consideration of distribution methods and installation procedures, is essential to successful commercialization.

VII. REFERENCES AND NOTES

1. For example, using the Balcolm-Hedstrom load-collector ratio method (Solar Engineering, January 1977, p. 18) the median collectable solar energy was 99,000 Btu/ft²-yr over a sample of 84 cities, for systems providing 50% of the building heating load from solar energy. All but 6 cities fell in the range 70,000 to 160,000 Btu/ft²-yr. See also the editorial by Bruce Anderson in Solar Age, January 1978: "...there is no evidence, and little possibility, that any solar space-heating system will ever deliver more, annually, than 100,000 Btus per square foot of aperture area in a climate where sunshine is possible 50 percent of the time."
2. W. Kahan and R.C. Estes, The economic constraints on solar energy, heat pump, and solar assisted heat pump systems, Proc. 1978 Annual Meeting of the American Section of the International Solar Energy Society, Denver, August 28-31, 1978, p. 288.
3. There are two distinct tax benefits available to the solar energy user. The first is the solar tax credit, which is 30% of the first \$2000 of system cost and 20% of the next \$8000. At present this

REFERENCES AND NOTES (Cont.)

credit is not viewed as a permanent part of the tax structure, and there is some question whether the IRS will hold that upon transfer of the property the seller's basis will be reduced by the amount of the credit. Many manufacturers are reluctant to include the credit in assessing the marketability of solar systems. The second tax benefit is the tax deductibility of interest paid on money borrowed to finance the solar system. For example, if the solar system is mortgaged at 12% and the consumer is in a 40% marginal tax bracket a saving of approximately 5% of the system cost will accrue the first year (assuming no down payment). This saving will decrease in following years as the loan is amortized. Maintenance costs, on the other hand, can be expected to increase with time once the system is out of warranty.

4. A. Whillier, Design factors influencing solar collector performance, in Low Temperature Engineering Application of Solar Energy, R.C. Jordan ed., American Society of Heating, Refrigerating, and Air-Conditioning Engineers, New York (c. 1966), p. 32. The values of U_{up} of 1.4 and 0.8 Btu/hr-ft²-°F for the single and double glazed collectors includes a 20% increase over the values in Fig. 3.5 due to the long-wave transmissivity of plastics, discussed on p. 34.
5. J.A. Duffie and W.A. Beckman, Solar Energy Thermal Processes, Wiley, New York, 1974, pp. 138-151.