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TRANSPARENT HEAT MIRRORS FOR PASSIVE SOLAR HEATING APPLICATIONS

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ABSTRACT

Recent progress in the development of transparent heat mirror coatings for energy-efficient windows and passive solar applications is reviewed. It appears that cost-efficient coatings deposited on glass and plastic may be available to window manufacturers and homeowners in the next one to three years. Depending upon the specific application, savings of 25-75% may be achieved. Heat mirror performance characteristics, product configurations, application limitations, cost benefit analysis and commercialization options are discussed.

1.0 INTRODUCTION

Windows and related glazing elements are essential components of passive solar systems. Architecturally, a window is a very complex building component which must perform multiple, often contradictory, functions. In order to function effectively in a passive solar heating role and maximize beneficial heat gain, the window must be highly transparent to the incident solar spectrum but must also have a high resistance to all thermal loss mechanisms. One approach to reducing thermal losses while maintaining high solar transmission involves the use of thin, transparent optical films which are reflective to the long-wave infrared radiation emitted by room temperature surfaces. These low emittance films, known as "heat mirrors," can be applied to glass or plastic glazing material, and depending on the application, will reduce thermal losses by 25-75%. Building designers already specify heat mirror products in the form of reflective glass and sun control plastic films, commercially available products which reduce winter thermal losses by varying amounts. However, since both products were developed to provide sun control functions, their reduced solar transmittance makes them generally unsuitable for passive solar heating applications in which winter solar gain must be maximized.

While the potential savings from the use of transparent heat mirrors are quite large, there are a number of constraints and obstacles, both technical and institutional in nature, that must be overcome before these products can be successfully developed and marketed. The Energy-Efficient Windows Program at the Lawrence Berkeley Laboratory, with funding provided by the U.S. Department of Energy, is in the process of supporting research, development and demonstration activities to assist private sector firms in the commercialization of heat mirror products. This paper summarizes the state of the art, describes work supported under the heat mirror commercialization program, and examines some of the issues relating to utilization of transparent heat mirrors for energy conservation and passive solar heating purposes.

2.0 BACKGROUND

2.1 Prior Applications

The reduction of heat transfer rates by the use of thermal infrared reflecting materials has been practiced in both architectural and non-architectural applications for many years. The best known examples are probably the multi-layer foil insulations used in buildings in the 1940's and their modern counterparts which find extensive use as spacecraft thermal insulators.

Heat reflecting surfaces that are also transparent have likewise been studied and utilized for some time. In 1958, heat mirror coatings were developed to be applied to furnace windows. Several types of solar control glass that are now marketed have low emissivity surfaces that reflect both the incident solar radiation and long-wave thermal radiation, with resultant U-value reductions. Since transparent heat mirrors are typically good electrical conductors, they find a host of applications when electrical leads are attached and power is pumped into them. They have been successfully used as defoggers and deicers for aircraft and automobile windshields as well as ski goggles, and as radiant heaters in other applications. A variety of electronic display devices require transparent conductive coatings. The optical industry utilizes transparent heat mirror coatings routinely, and the lighting industry, which now uses heat mirrors in low pressure sodium lamps, is studying the potential for improving the operation of incandescent light bulbs using heat mirror coatings. Other specific applications with some potential are glass refrigerator and freezer doors in supermarkets and glazings for flat plate and concentrating collectors.

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Although each of the applications described above has some relevance to the goal of producing transparent heat mirrors for windows, none provides all the desireable characteristics one would select for a product which might be expected to have a major market impact in the building industry. As with most products which must be successful in the marketplace, there is an evolutionary developmental process in which tradeoffs are made between a variety of performance characteristics and manufacturing/marketing costs before a product is offered for sale.

2.2 Current Activities

Windows incorporating transparent heat mirror coatings are now commercially available in several European countries. Colder climates, tighter building codes, and higher energy costs have resulted in market conditions more favorable to investment in building components with higher first cost but improved thermal performance. Transparent heat mirror coatings on plastic are being produced and tested in Japan. Coatings deposited on plastic can be retrofit to existing windows as well as incorporated into new windows. The flexibility of this approach formed the basis of our initial interest in heat mirror products deposited on plastic films.

In late 1978, there now appear to be about ten firms in the United States with some level of serious interest and activity in the development and commercialization of transparent heat mirrors. Over the last two years, the LBL program has supported one major development and assessment project and several smaller efforts, as well as conducting several small in-house studies. These projects are reviewed briefly here to provide a background for the more detailed discussion which follows.

2.3 LBL/DOE Program Activities

The major LBL/DOE contractual effort to date has been a twelve-month study with Suntek Research Associates, Corte Madera, California, to optimize cost-effective production systems for their proprietary multilayer heat mirror as part of a larger window retrofit product tradenamed Superpane.(1) The program was oriented toward high rate deposition systems suitable for depositing heat mirror coatings on plastic substrates. As part of this effort, a preliminary marketing study was completed to assist in identifying marketing strategies for successful market introduction. Several different window retrofit product configurations were studied and tested, performance was measured, and cost-benefit calculations completed. Since the heat mirror is not sufficiently abrasion- and corrosion - resistant, work was undertaken to find a suitable protective overcoat to improve the heat mirror durability. Some progress has been made in this area but the results to date indicate that initial heat mirror applications may be limited to window product configurations in which the coating is protected from most abrasive and corrosive stresses.

As part of a larger study to develop selective reflectance coatings for solar control purposes, Kinetic Coatings, Inc., Burlington, Massachusetts, has produced transparent heat mirror coatings on glass and plastic substrates.(2) Good performance has been obtained using an ion beam sputtering system to deposit two-layer coatings in which a dielectric layer is deposited over a very thin metallic layer. Due to the nature of the deposition process, the dielectric layer appears to provide good durability to the heat mirror coating. Additional sample production and life testing is planned. Studies are now in progress to determine if the deposition system can be scaled up to provide coating uniformity over much larger substrate areas.

Sierracin, Inc., Sylmar, California, currently sells an electrically conductive plastic film with high visible transmissivity which has good heat mirror characteristics. The coating utilizes a thin vacuum-deposited gold layer with a chemically applied TiO_x overcoat which acts as an antireflecting layer as well as providing some protection. Performance, deposition rates and production costs were reviewed to assess the viability of the Intrex film as a heat mirror.(3)

Since production rate is crucial to the ultimate product cost, investigations were made of high-rate thin film deposition processes which might be suitable for depositing known heat mirror materials. Several deposition processes, now in use by the glass and optical coating industry, appear to be able to meet the rate and performance requirements for heat mirror coatings. Since the solar control film industry already markets and installs metallized polyester films, they represent a plausible commercialization channel for retrofit heat mirrors. Based on contacts in the industry and a small marketing study, this approach will be pursued. Computer codes have been developed at LBL to model the performance of optical films and of heat mirrors integrated into window assemblies. Additional parametric studies are underway to provide cost-benefit figures for heat mirrors as a function of building type and climate.

Progress in the commercialization of transparent heat mirrors is reviewed in the following four categories:

1. Technical characteristics and performance issues
2. New and retrofit window applications
3. Cost-benefit issues
4. Marketing strategies and issues

3.0 TECHNICAL CHARACTERISTICS AND PERFORMANCE ISSUES

The primary function of large south-facing, glazed surfaces in a passive solar-heated building is to maximize solar gain while minimizing thermal losses during the heating season. Thermal losses can be classified into three major categories by basic heat transfer modes: radiation losses, convection/conduction losses and losses due to air infiltration. (FIGURE 1)

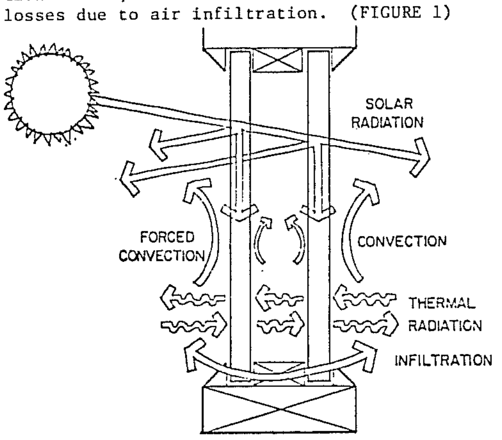

Fig. 1. Window Heat Loss/Gain Mechanisms

The overall heat transfer coefficient, the U value, combines all of these loss mechanisms except infiltration and excludes solar radiation effects. Note that the U value is a nominal performance figure defining an instantaneous heat transfer rate under specific temperature and wind conditions. Under "average" conditions, with a range of temperature and wind effects, the heat transfer rate may differ significantly from the nominal U value.

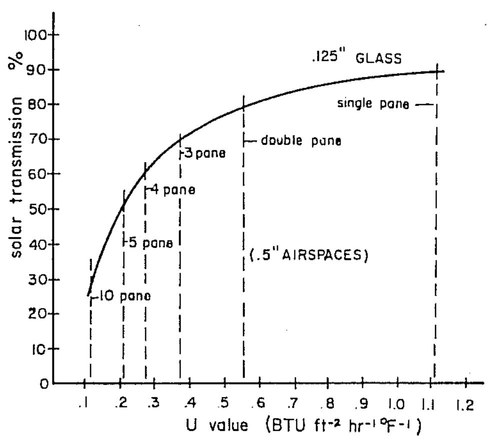

Fig. 2. U value/Transmittance of Multilayer Glass

A detailed discussion of the various methods for reducing the magnitude of each of the window heat loss mechanisms is beyond the scope of this paper. Multiple glazings are used routinely to reduce thermal transfer but at the cost of a loss in transmission of incident sunlight. Figure 2 shows the reduction in U-value and resultant loss in solar transmission for up to ten panes of glass. The incremental thermal value of each additional glazing layer decreases as layers are stacked in series. Convective and radiative transfer in an airspace or at a surface can be assumed to be independent and operating in parallel if the assumption is made that the air slab is non-absorbing to solar and IR radiation, as it typically is for dimensions of architectural interest. The relative importance of each thermal loss term depends upon physical dimensions, surface temperatures and surface properties, but in the range of typical architectural interest the radiative transfer is approximately equivalent to the convective transfer. Since the radiation loss term is directly proportional to emittance, this suggests that heat mirror coatings with low emittance (high thermal infrared reflectance) may reduce the net thermal transfer across an air space or at a surface by roughly one half. (FIGURE 3)

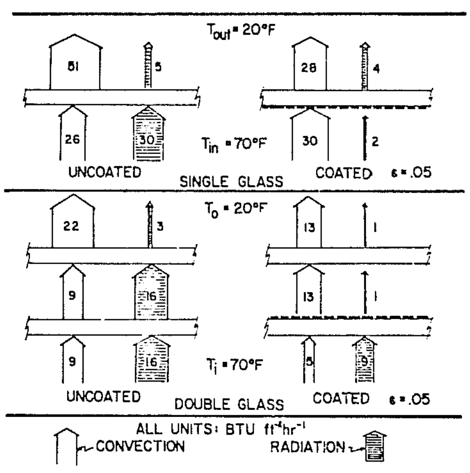

Fig. 3. Radiative/Convective Heat Loss Breakdown

(Further improvements may be obtained by replacing the air or dry nitrogen gas fill in sealed insulating glass units with gases such as krypton or argon which have lower thermal conductivity.) If the radiative transfer across the air space can be reduced by a heat mirror coating with less solar optical loss than additional glass layers, heat mirror films might then be capable of providing adequate solar transmission while achieving very low U values without the use of large numbers of glass or plastic layers.

The performance of an ideal transparent heat mirror is shown in Figure 4. For passive solar applications, the transmission window should extend from .3 microns to approximately 2.5 microns while for other applications where illumination is important but heat gain may not be, the transmission window need only extend to .7 microns. The coating should exhibit high reflectivity to long-wave infrared radiation from approximately 5-20 microns.

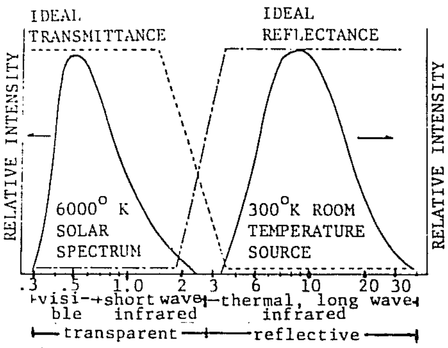

Fig. 4. Ideal Heat Mirror Properties

3.1 Materials and Deposition Systems

Heat mirror coatings may be deposited on plastic or glass substrates using differing deposition processes depending on the materials selected. Two basic materials systems are used. Multi-layer coatings utilize a metallic layer (such as copper, silver or gold) reflective to the infrared and one or more dielectric layers as antireflection layers to improve visible transmittance and increase durability. Single layers of some doped semiconductors are intrinsic transmitters of short-wave energy but are reflective to long-wave infrared. Multi-layer heat mirrors can be produced by a variety of existing thin film deposition processes such as thermal evaporation and sputtering. Semiconductor type heat mirrors have been produced primarily by high-temperature pyrolysis processes which has restricted their use to glass substrates although some can also be produced at lower substrate temperatures using sputtering processes. Material systems and deposition processes are reviewed in more detail in reference 4. The selection of materials and production process has an important impact on ultimate product cost as well as influencing factors such as performance and durability. Rapid advancements in the thin film deposition field reinforce our view that high rate deposition systems capable of depositing a wide range of coatings on large area glass and plastic substrates are currently available or will be available in the near future.

3.2 Net Window Thermal Performance

To obtain optimal performance from a heat mirror, one must optimize both materials and production parameters to maximize solar transmittance while minimizing emittance. Improving transmittance tends to degrade emittance and vice versa. This can be visualized in Figure 4 by imagining the ideal transmission curve being shifted to the left or right. Typical performance that has been achieved for the heat mirror coating alone (without substrate losses) is a solar transmittance of 85-90% and associated emittance of 15%.

Given these figures for transmittance and emittance, the resultant heat transfer rates can be computed. In Figure 5 the thermal performance of a variety of window designs (see Figure 9) incorporating heat mirrors is compared to multiple layers of glass.

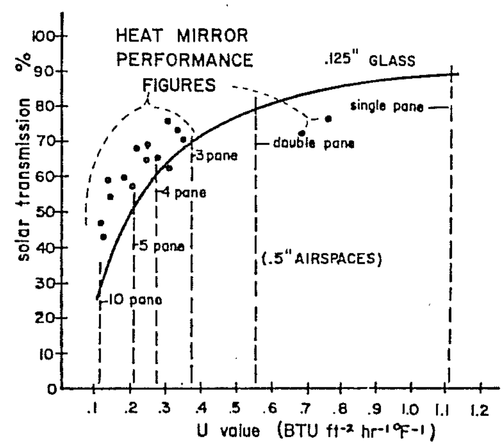

Fig. 5. Heat Mirror Thermal Performance (see Fig. 9 for window details)

The general conclusion to be drawn from this analysis is that the addition of a single heat mirror coating to either a single or double-glazed window has roughly the equivalent thermal effect to adding an additional glazing layer plus an air space. Cost, weight, lifetime, retrofit capability, etc. might then become the key factors in deciding which option to choose. However, double glazed windows incorporating heat mirror inserts are capable of achieving extremely low U-values, normally associated with insulated walls, which cannot be attained in a practical manner by multiple glass or plastic layers. A relatively small three foot by four foot window with ten layers of glass would weigh a minimum of 250 pounds. A window incorporating eight plastic layers between two sheets of glass would weigh much less but would be about six inches thick and have undesireable visual and optical properties, particularly when viewed at oblique angles. Thus if very low U values are desired, high performance heat mirror coatings appear to have significant practical advantages compared to a brute force, multi-layer glass or plastic approach.

Other window options such as moveable insulating devices achieve low heat transfer rates and high solar transmittance values by separating the insulating and transmitting functions. Such devices however require manual or automatic operation and must have adequate air seals when deployed to minimize convective thermal short circuits. Some characteristics of these devices relative to heat mirrors are shown in Figure 11.

Figure 6 provides a highly simplified view of the relationship between window solar gain and thermal losses. The daily energy transfer is shown in the vertical dimension and the window U-value is taken as a variable on the horizontal axis. Solar gains, which for simplicity are shown as independent of U-value, are shown as horizontal lines. Window thermal losses are shown for two average outside temperature conditions. On a cold day, where Tave = 0°F, the U-value required to just balance thermal losses is .9 Btu ft^{-2} $^{o}F^{-1}$ under clear sky conditions, .6 on a day with average solar gain and approximately .3 on a cloudy day. Of course, to collect additional useful energy, the U-value must be lower than those given above. This simplified perspective is not intended to substitute for more rigorous analysis of the annual thermal performance of windows which is now in progress. It is, however, useful in providing insights into performance goals for effective windows in both passive and related energy conservation roles.

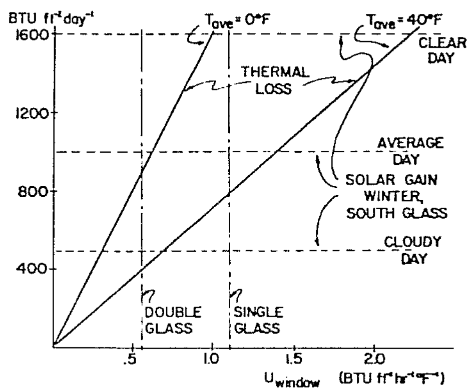

Fig. 6. Window Thermal Loss vs. Solar Gain

3.3 Other Performance Issues

Several additional technical aspects of window performance deserve mention. The horizontal scale of Figure 6 extends well beyond the U-value of a nominal single-glazed window since infiltration losses on loose fitting windows can drastically increase thermal losses. At rated wind speed (25 mph) these losses can amount to an equivalent U-value of 1.9 Btu ft^{-2} hr^{-1} $^{o}F^{-1}$ due to infiltration only. The relative impact is much larger on small windows since infiltration occurs through perimeter cracks and the ratio of crack length to window area in a small window is more than twice as high as for a larger unit. To the extent that many passive systems will use large, inoperable, glazed surfaces, this may not present a major problem. However, it is clearly senseless to put substantial funds into reducing the glazing conductance if infiltration through loose fitting windows remains uncorrected.

The U-values quoted throughout this paper refer to heat transfer rates through glazed areas only. U-values for typical windows obtained by laboratory hot box tests will frequently exceed calculated values if the thermal transfer through sash and frame elements is not properly accounted for. Existing sash and frame materials have thermal conductances in the range .3-1 Btu $ft^{-2}hr^{-1}{}^{o}F^{-1}$. If the designs discussed in this paper prove feasible and glazing assemblies with conductances less than .3 are introduced, poorly designed sash and frame (representing 10-25% of the gross window area) may adversely effect the overall window U-value. Thus, development of highly insulating glazing assemblies may focus additional attention on the development of low thermal loss frames.

Condensation and frost on windows are undesireable due to their effects on window frame materials. In addition, condensation on a heat mirror surface has a significant functional effect on the heat transfer rate. Due to the high emissivity of water, a heat mirror surface covered with condensation or frost will, to first approximation, behave thermally like an uncoated glass surface. The impact of a heat mirror on the glass surface temperature (and thus the likelihood of forming condensation or frost) varies with the application. With single glazing, the surface temperature will drop when a heat mirror is added whereas in a double-glazed unit the addition of a heat mirror to the air space side of the inner glazing will raise the inner glass surface temperature. Typical temperature profiles across double glazing, with and without heat mirror coatings, are shown in Figure 7.

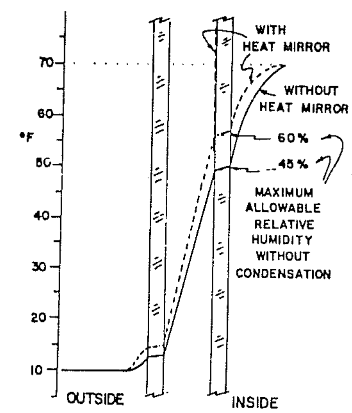

Fig. 7. Temperature Gradient Across Double Glazing

For a double glazed window and an outside temperature of 10°F the indoor relative humidity can be as high as 60%, compared to 45% with an uncoated glass surface, before undesired condensation will occur. For single glazed windows with heat mirror retrofits, surface temperatures will be lower than with uncoated glass. Condensation or frost is thus more likely to occur in the coldest portion of the winter, rendering the insulating properties of the heat mirror useless. Thus in cold climates, single glazing with heat mirrors may not be a good substitute for double glazing due to frequent condensation and frosting. A related issue is the impact of large glazed areas on mean radiant temperature (MRT) and thus perceived thermal comfort. Increased MRT should allow reductions in room air temperature and thus provide additional energy savings. Studies are underway to quantify these results.

4.0 NEW AND RETROFIT APPLICATIONS

Heat mirror coatings may be applied directly to glass and installed in new and retrofit applications or they may be applied to thin plastic films and then 1) glued to existing windows, much as solar control films are now applied, 2) glued to glass which is then incorporated into new windows by window manufacturers, and 3) attached to existing windows or new windows as an unsupported plastic film. Although there are some uncertainties pertaining to the effective lifetime of plastic films, their versatility in both new and retrofit applications and their potential low production cost has made them the focus of our investigations to date.

4.1 Window Configurations

A variety of different window configurations incorporating heat mirror coatings have been examined. Several are shown schematically in Figure 9 with associated U values and solar transmittance properties. There are as yet no standardized performance values for heat mirror coatings. The results shown in Figure 9 are based upon a solar transmittance of 90% for an emittance of .2, and a solar transmittance of 80% for an emittance of .05, all figures for the coating only without substrate. Both results have been obtained experimentally. The coating with E=.05 is probably the best that could be obtained in a product; E=.2 is more likely to be a practical goal for volume production. Coating and substrate properties are summarized in Figure 8 below. Several approximations and simplifying assumptions are incorporated into the results shown below which are meant to be illustrative of the performance range, rather than definitive product performance values.

LAYER	THICKNESS	TRANS.1]	E 2]	E_{net} 3]	E_{net} 4]
Heat Mirror	200-2000Å	.80	.05	--	--
Heat Mirror	200-2000Å	.90	.20	--	--
Polyester	.001 inch	.92	~.9	.65	.55
FEP	.001 inch	.96	~.9	.35	.25
Glass	.125 inch	.88	.84	.84	.84

Notes: 1] TRANS. : Normal Solar Transmittance

2] E : Hemispherical emittance of coating or substrate.

3] E_{net} : Net substrate emittance from uncoated side when heat mirror emittance = .2

4] E_{net} : Net substrate emittance from uncoated side when heat mirror emittance = .05

Fig. 8. Heat Mirror/Substrate properties for Fig 9

FIG.		HEAT MIRROR EMITTANCE	U VALUE	SOLAR TRANS. (NORMAL)
9a	SINGLE GLASS, PLASTIC RETROFIT (H.M. on polyester, on inside surface)			
		.20	.76	.77
		.05	.67	.69
9b	DOUBLE GLASS (H.M. on air gap surface, glass)			
		.20	.35	.70
		.05	.30	.62
9c	SINGLE GLASS, PLASTIC RETROFIT & AIR GAP (H.M. on air gap surface, polyester)			
		.20	.34	.73
		.05	.28	.65
	(H.M. on air gap surface, FEP)			
		.20	.31	.76
		.05	.26	.68
9d	DOUBLE GLASS, MID AIR GAP PLASTIC FILM (single H.M. on polyester)			
		.20	.24	.64
		.05	.21	.57
	(single H.M. on FEP)			
		.20	.22	.67
		.05	.19	.59
9e	DOUBLE GLASS, DOUBLE MID GAP FILM (single H.M. coating, folded polyester)			
		.20	.16	.53
		.05	.13	.42
	(single H.M. coating, folded FEP film)			
		.20	.15	.58
		.05	.12	.46

Note: All air gaps .5"; T_{out}=0°F, T_{in}=70°F

Fig. 9. Window/Heat Mirror Configurations

Since there is a tremendous inventory of single glazed windows in the United States, retrofit options for single-glazed windows should present good sales opportunities. Figure 9a shows nominal performance values for a heat mirror retrofit applied to the interior of an existing window. The nominal U-value is reduced from 1.14 Btu $ft^{-2}hr^{-1}$ $°F^{-1}$ to a range of .76 - .67 depending upon the emissivity of the heat mirror surface. Note that the heat mirror must face the room side to be effective and must therefore be adequately protected from abrasive and corrosive stresses. A second option to increase durability involves depositing the heat mirror coating on long-wave infrared transparent plastic substrates and then laminating the coated plastic to the glass with the heat mirror sandwiched between. Polyethylene, polypropylene and some fluorinated polymers have acceptable IR transmission characteristics but lack the mechanical strength, UV resistance or other desireable properties of polyester, which is the mainstay of the solar control film industry

We might anticipate the development of improved polyethlene, polypropylene and fluorinated polymer films as interest in this market increases. The sputtered dielectric overcoats used by Kinetic Coatings have successfully withstood initial weathering tests and show some promise of providing adequate protection for exposed heat mirrors, although additional testing is required.

Factory assembled double glazing could incorporate a heat mirror surface applied directly to the glass, facing the air space or applied to plastic and then laminated to glass (Figure 9b). The resultant U-value is lower than that to be expected from triple glazing and may thus represent an attractive option.

Figure 9c shows a generic configuration for a window retrofit which was extensively explored in the Suntek contract. The plastic film substrate with a heat mirror coating is glued to a plastic or metal frame, which is in turn attached to the glass in an existing window. This can be permanently attached with adhesives or attached with a removable mechanism such as a magnetic seal. The heat mirror surface is protected by facing the air gap. If the unit does not hermetically seal to the glass and incorporate a desiccant, there are potential condensation problems. Rigid plastic may be substituted for the polyester film if the "soft" characteristic of this retrofit is not acceptable. By creating an air space and adding a heat mirror at the same time, the thermal loss of a single-glazed window is reduced by approximately 75%. The use of an IR transparent plastic such as FEP provides a further small reduction in U-value by reducing the interior surface film coefficient.

An attractive approach to modifications of the factory assembled double glazing would add the polyester film with heat mirror to the center of the double-glazed unit (figure 9d). If the plastic is coated on both sides with a heat mirror (or if FEP or equivalent IR transparent plastic with a single heat mirror coating is used as shown), the window will exhibit a very low rate of thermal transfer, approximately .19-22 Btu $ft^{-2}hr^{-1}{}^{o}F^{-1}$, depending upon the heat mirror emittance (.05-.20).

An even more attractive window assembly (Figure 9e) would incorporate a single sheet of heat mirror coated polyester or FEP stretched and wrapped around a frame which is then secured in the air space of a double glazed window. With a good heat mirror coating, the U value may be as low as .12 Btu $ft^{-2}hr^{-1}{}^{o}F^{-1}$, or an R value of 8, without the necessity for operable devices of any sort. Normal solar transmittance would lie in the range of 40-60%, depending upon heat mirror properties and the choice of plastic substrate. That fraction of the apparent solar loss which is absorbed in the coatings and substrates serves a useful purpose in reducing convection/conductive losses, even though it may not be available for room side thermal storage. However, as the solar incidence angle departs from normal, optical losses will increase, and for a multilayer system will become quite significant at large angles of incidence. The question of whether the reduction in thermal losses will more than compensate for the attenuated winter solar gain awaits further analysis.

4.2 Other Applications

A variety of other heat mirror applications are possible. Both interior and exterior storm windows might incorporate heat mirror coatings but the reduction in U-value will depend on heat mirror emittance as well as on the degree of air movement in the air space that is created if the storm window is not very tight fitting. Several different types of single and multi-layer roll-up shades are being introduced to the marketplace and these typically incorporate one or more metallized plastic layers to reduce thermal transfer. With the use of transparent heat mirrors, these devices could maintain their good thermal performance and still provide some light and view. In fact, a transparent heat mirror provides the option of turning virtually any smooth, colored surface in a building into a thermal heat reflecting layer and the performance of drapes, venetial blinds, shutters, and other window accessories might be improved accordingly. In each case, ultimate heat mirror cost and performance characteristics would appear to be crucial factors in determining tradeoffs. In many circumstances the advantage of light transmission through heat mirrors may not justify the added cost compared to much cheaper light reflecting metallized plastics.

5.0 COST BENEFIT ISSUES

The issues of cost and cost effectiveness have occurred frequently throughout this paper and indeed occur throughout most energy-related discussions. A detailed discussion of heat mirror production cost analyses is beyond the scope of this paper. Most of our effort to date has focussed on costs for vacuum coating plastic film. Production costs for coating glass directly might be expected to be somewhat higher due to the more complex handling requirements and the higher value of unacceptable finished product. Suntek has estimated production costs at \$.50 ft^{-2} for a sales volume of one million square feet per year at a production rate of one foot per minute. It is our estimate that these rates can be increased tenfold, which should drop the production cost to perhaps \$.35 ft^{-2}. Cost estimates by Sierracin for similar production of their gold-coated polyester fell in the range of \$.40- \$.60 ft^{-2} where the gold evaporant alone costs \$.12 ft^{-2} at current gold prices. Production costs for most solar control films (which are coated at speeds of 400-600 feet $minute^{-1}$) fall in the range of \$.25-\$.40 ft^{-2} where the basic material and labor cost is quite low but the handling, quality control trimming, laminating, adhesive coating and general merchandising overhead costs constitute the largest fraction of the cost. Solar control films are sold to the consumer as low as \$.60 ft^{-2} but more typically at \$.75-\$1.50 for homeowner installation and \$1.50-\$2.50 for professionally applied films.

These would appear to constitute lower limits for heat mirror retail costs in the retrofit market. In the OEM window market it appears heat mirrors might add \$1.50 - \$3.00 ft^{-2} to the retail cost of new windows. Estimates are necessarily vague in this entire discussion because of the large number of variables which may ultimately affect production cost. Since the incremental cost of adding an additional glazing typically lies in the range of \$2.00 - \$4.00 ft^{-2}, it is apparent that heat mirror coatings are potential competitors in this area.

The question of heat mirror costs can also be approached from the point of view of a cost-benefit analysis of potential savings to determine allowable costs. Figure 10 presents results of a simplified analysis for a heat mirror retrofit to an existing single-glazed window. Two allowable payback periods are shown, two years and five years, and three fuel cost scenarios, \$3, \$6 and \$12 per million Btu, are considered. If, for example, we require a five-year payback in a region with heating fuel costs of \$6 million Btu^{-1} (typical oil heating cost), the maximum that can be spent on retrofit heat mirror would range from \$.60 ft^{-2} in a mild, 2000 degree day climate to \$2.40 ft^{-2} in a cold, 8000 degree day climate. This discussion reminds us that the product lifetime must be comfortably in excess of the anticipated payback period if it is to save money for the consumer or building owner.

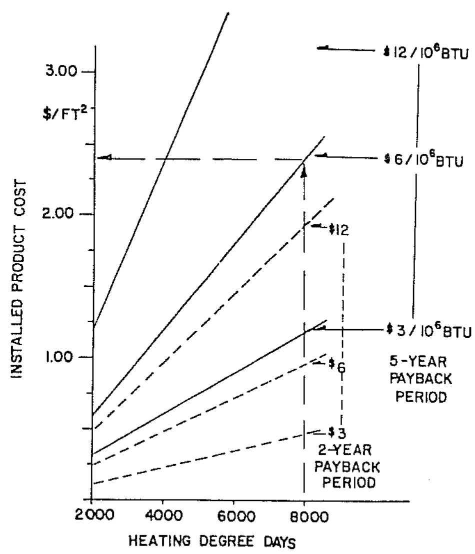

Fig. 10. Simplified Cost Benefit Analysis

For these short-term analyses using simplified load calculations, fuel escalation, inflation and interest charges are ignored. Studies are now in progress utilizing more sophisticated hour-by-hour calculation procedures and considering long-term amortization of heat mirror expenditures with appropriate economic modeling. It is apparent from our preliminary studies, however, that heat mirrors will be good investments for consumers with average to high fuel costs in moderate to cold climates.

6.0 MARKETING STRATEGIES AND ISSUES

Technical excellence and desireable performance characteristics will not be sufficient to guarantee consumer acceptance of heat mirror coatings for windows. The manufacturing technologies are sufficiently complex so that there are only a limited number of firms that might successfully make the product. A more significant problem is the fragmented structure of the window market and the uncertain reactions of the buying public. In total, the window market is very large but its sectors vary both in size and technical sophistication. To successfully market the product, a firm must provide multi-level distribution channels for OEM users as well as professional and do-it-yourself installation, and must back those with extensive promotional efforts. In the retrofit market, consumer education will be a critical factor. Selling transparent heat mirrors might be compared to selling the "emperor's clothes," an "invisible" product for which tremendous performance claims will be made. This factor alone may argue for reducing solar transmissivity by adding a slight color or tint. There is no prior consumer experience with heat mirrors, although for the plastic film retrofit application there is a growing acceptance of a related product solar control films. Preliminary market studies have indicated some level of confusion between the function of heat mirrors and solar control films. In addition, solar control film manufacturers already claim 10-20% savings in winter heating bills due to the lowered emittance of the laminated metallized film. And recently, several solar control film manufacturers have introduced "insulating" solar control films, that is, sun control films that are also heat mirrors. (E=.25). These films, laminated to the inside of windows result in U values in the range .65-.70 Btu ft^{-2} hr^{-1} $^{o}F^{-1}$. Rather than introducing transparent heat mirror film as a novel product, the connection to a known and proven product should probably be exploited. This consumer experience plus the existing marketing and distribution networks of the firms selling solar control film might be translated into a very viable marketing option for heat mirror retrofits. Most of the larger solar control firms are indeed interested in manufacturing and/or marketing this product. Marketing and commercialization studies have been conducted as part of the Suntek contract with the assistance of a marketing research firm. Additional studies are now in progress at LBL. It is the intent of the LBL/DOE research program to provide continued support to assist in overcoming additional technical and institutional obstacles to successful market introduction.

7.0 SUMMARY

In the next one to three years, windows incorporating transparent "heat mirror" films for passive solar heating applications should become available on the marketplace. Due to their high reflectivity to thermal infrared radiation, heat loss may be reduced 25-75%, depending upon application, with only a modest reduction in desired solar gain. Although final manufacturing cost and selling price are uncertain, payback periods of one to five years appear to be attainable, depending upon climate, fuel costs and application.

Passive solar designers have a variety of options available to reduce undesired thermal losses, through glazing. Heat mirrors, in several different product configurations, will offer additional useful insulating options. To be successful in the marketplace, heat mirrors will compete against a growing variety of existing and new insulating window products. No single product is likely to dominate the field since product selection is based upon tradeoffs among a wide range of parameters to satisfy an equally wide range of demands. Products incorporating heat mirrors will further strengthen the diversity of window management options. Heat mirror applications are compared to more conventional insulating windows and accessories in figure 11 below.

No single window management strategy stands out as superior to all others. The ultimate product selections will be made by building designers and consumers on the basis of perceived product cost, durability, performance, convenience, aesthetics and other factors. Heat mirrors will not be the magic technical triumph which spares designers the effort and responsibility associated with good building design and wise product selection but rather they will become one more in an array of valuable design options for energy conservation and passive solar heating applications.

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	RELATIVE COST[1] $ Ft^{2}	PERFORMANCE[2]	DURABILITY[3]	OPERATION	CONSUMER ACCEPTANCE
•SINGLE GLAZING	0	1.14	+++	No	Too High
•HEAT MIRROR					
EXPOSED	+1.50-2.50	.65	+	No	Uncertain
SEALED AIRSPACE	+2.50-4.00	.35	++	No	Moderate
TRIPLE AIRSPACE	+3.00-5.00	.12 - .15	++	No	Moderate
•DOUBLE GLAZING	+2.00-3.00	.56	+++	No	Increasing
•STORM WINDOWS	+1.50-3.00	.5 -.6	+++	Seasonal	Moderate
•TRIPLE GLAZING	+4.00-5.00	.36	+++	No	Increasing
•QUAD GLAZING	+5.00-6.00	.27	+++	No	Uncertain
•SHADES [4]	+ .50-3.00	.1 - .5	++	Daily	Moderate
•SHUTTERS [4]	+1.00-5.00	.1 - .5	++	Daily	Moderate

NOTES: 1) Increased cost shown relative to single glazed unit
2) U value: Btu Hr^{-1} ft^{2} $^{o}F^{-1}$, no infiltration
3) Comparative rankings: +++high, ++moderate, +uncertain
4) Shades and Shutters designed for high thermal resistance

Figure 11. Heat Mirror vs. Alternative Window Management Strategies