TRANSPARENT HEAT MIRRORS FOR PASSIVE SOLAR HEATING APPLICATIONS

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Publication Date
1978-03-01

Presented at the 2nd National Passive Solar Conference, Philadelphia, PA, March 16-18, 1978.

LBL-7829 c.2
EBB-W-78-03

Energy and Environment Division

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March 1978

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Prepared for the Consumer Products and Technology Branch of the U.S. Department of Energy under Contract W-7405-ENG-48.

LBL- 7829
EEB-W 78-03

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An expanded version of this paper will be published as Lawrence Berkeley Laboratory report LBL-7833.

The work described in this report was funded by the Department of Energy, Office of Assistant Secretary for Conservation and Solar Applications, Division of Buildings and Community Systems.

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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 promising savings of 25-75%, depending upon application, may be available to window manufacturers and homeowners in the next one to three years. Performance, applications and limitations are discussed.

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 (low emissivity) emitted by room temperature surfaces. These thin 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%. While the potential savings are quite large, there are a number of constraints and obstacles, both technical and institutional in nature, that must be overcome before transparent heat mirrors can be successfully commercialized. 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 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.

BACKGROUND

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 building 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.

Although each of the applications described above has some relevance to the goal of producing transparent heat mirrors for windows, none provides all the desirable 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. In early 1978, there now appear to be about ten firms with some level of serious interest and activity in the development and commercialization of transparent heat mirrors. Over the last eighteen months, 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.

The major 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. 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 configuratons were studied and tested, performance was measured, and cost-benefit calculations completed. Since the heat mirror is not sufficiently abrasion-and corrosionresistant, work is in progress to find a suitable protective overcoat to improve the heat mirror durability.

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. 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 testing is planned.

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.

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 should 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

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. A detailed discussion of the various methods for reducing the magnitude of each of these 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 1 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

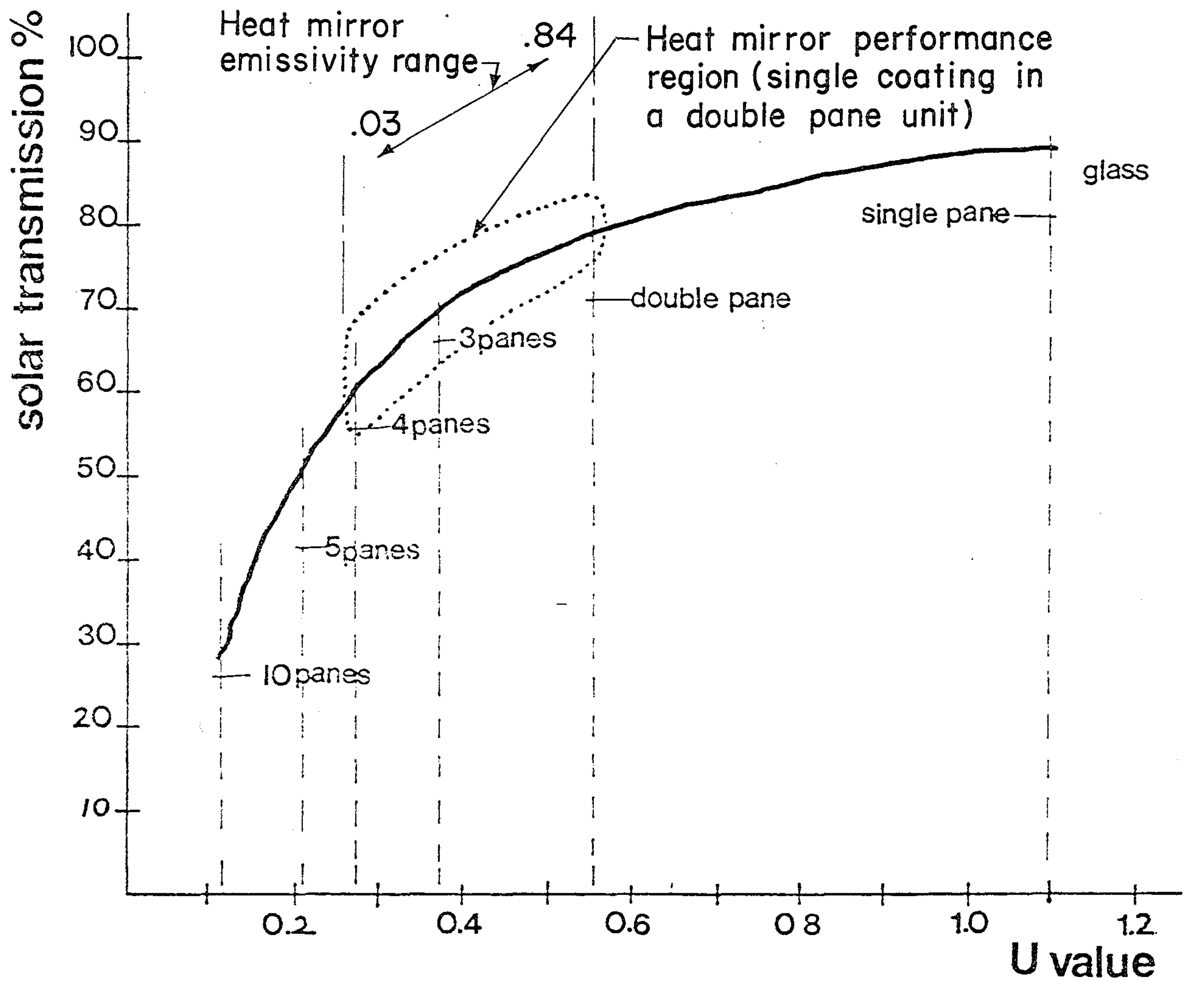

FIGURE 1: MULTIPANE THERMAL AND OPTICAL PERFORMANCE

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is non-absorbing, as it typically is for dimensions of architectural interest. The relative importance of each term depends upon physical dimensions, surface temperatures and surface properties, but in the range of typical architectural interest the radiative transfer is approximatlely equivalent to the convective transfer. Since the radiation loss term is directly proportional to emissivity, this suggests that heat mirror coatings with low emissivity (high thermal infrared reflectivity) may reduce the net thermal transfer across an air space or at a surface by roughly one half. Highly transparent heat mirror films might thus be capable of providing a higher solar transmission than multiple glazing for a given U-value.

The performance of an ideal transparent heat mirror is shown in Figure 2. For passive solar application, the transmission window should extend from .3 microns to approximately 2.5 microns while for other applicatons 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 from approximatley 5-20 microns.

Heat mirror coatings may be deposited on plastic or glass substrates using differing deposition processes depending on the materials used. Two basic materials systems are used. Multilayer 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 semiconductors are intrinsic transmitters of short-wave energy but are reflective to long-wave infrared. Multilayer heat mirrors can be produced by a variety of existing thin film deposition

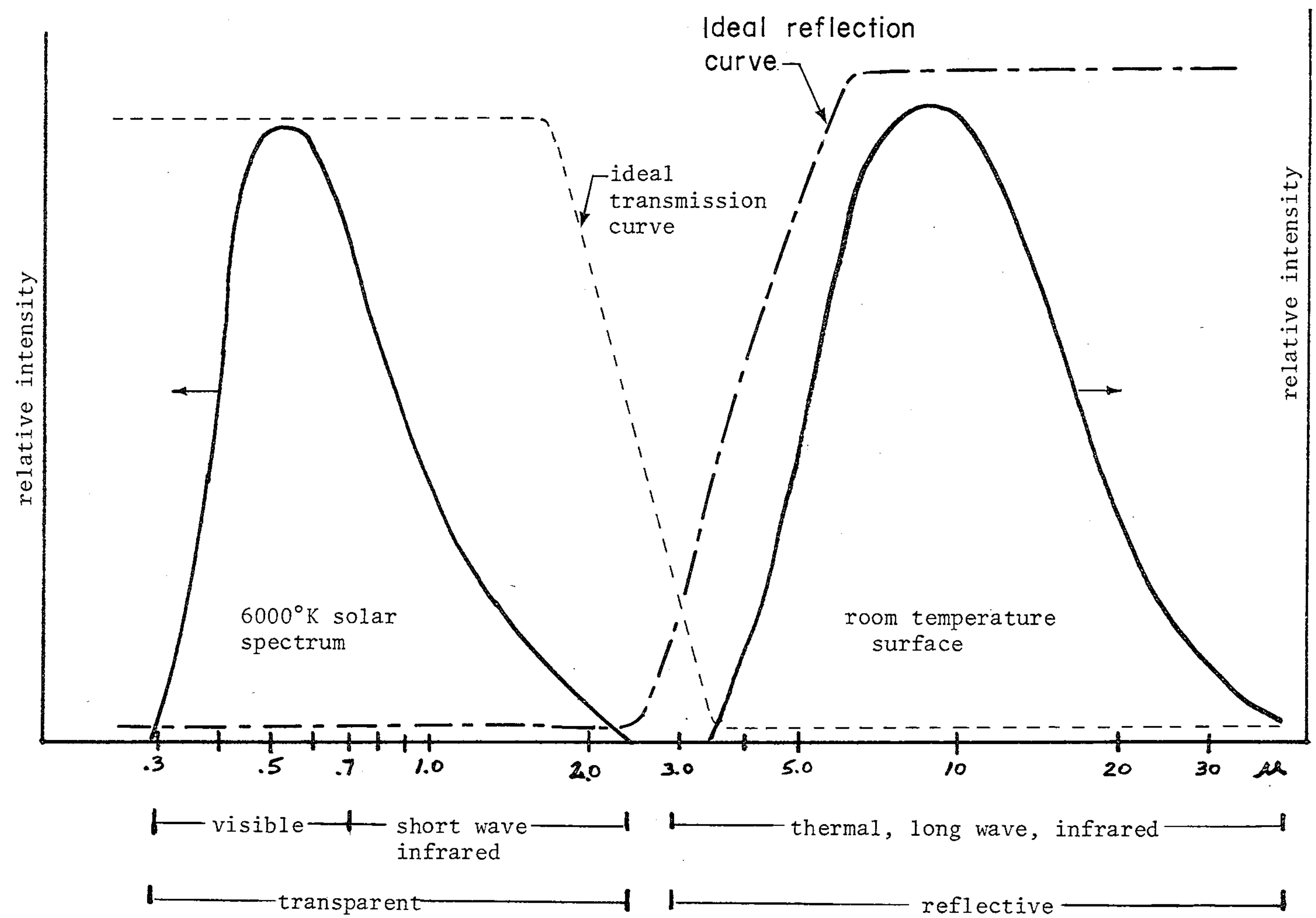

FIGURE 2: DESIRABLE HEAT MIRROR PROPERTIES

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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 process. 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.

To obtain optimal performance from a heat mirror, one must optimize both materials and production parameters to maximize solar transmissivity while minimizing emissivity. Improving transmissivity tends to degrade emissivity and vice versa. This can be visualized in Figure 2 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 transmission of 85-90% and associated emissivity of .15.

Given these figures for transmittance and emissivity, the resultant heat transfer rates can be computed. In typical winter conditions, double-glazed windows with transparent heat mirror coatings can be expected to lie within the boundaries shown in Figure 1. The general conclusion to be drawn from this analysis is that the addition of a heat mirror 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.

Reference to Figure 1 provides an indication of the number of air spaces or heat mirror surfaces required to provide a given U-value and the associated tradeoffs in transmission losses. We ignore for the moment (but consider later) moveable insulating devices which separate the interdependence of transmission and insulating value. Figure 3 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 $T_{ave} = 0^{o}F$, the U-value required to just balance thermal losses is .9 $Btu/ft^2\text{-}hr\text{-}^{o}F$ on a clear day, .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.

Several additional technical aspects of window performance deserve mention. The horizontal scale of Figure 3 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 $Btu/ft^2\text{-}hr\text{-}^{o}F$ 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

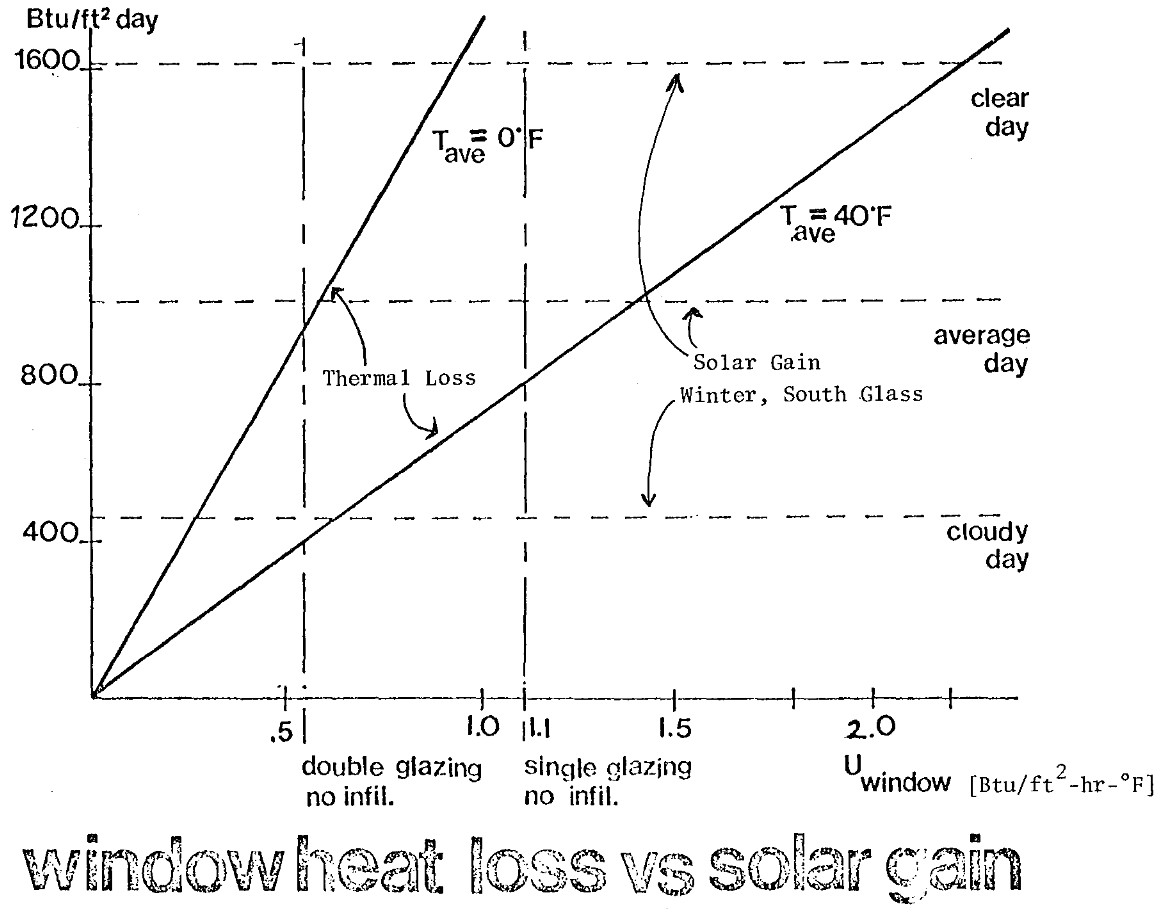

FIGURE 3: HEAT LOSS VS. SOLAR GAIN

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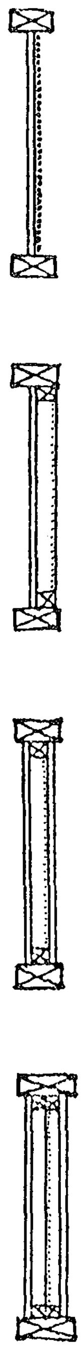
small window is more than twice as high as for a larger unit. To the extent that many passive systems will use large, inoperable, glazed surfaces, this may not present a major problem. However, it is clearly senseless to put substantial funds into reducing the glazing conductance if infiltration through loose fitting windows remains uncorrected.

Condensation and frost on windows are undesirable 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. For an outside temperature of 10^{o}F, the indoor relative humidity can be as high as 60%, compared to 45% with an uncoated glass surface, before undesired condensation will occur. It appears that in cold climates heat mirrors on single glazing 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.

NEW AND RETROFIT APPLICATIONS

Heat mirror coatings may be applied directly to glass and installed in new and retrofit applicatons or they may be applied to thin plastic films and then glued to existing windows, much as solar control films are applied. A variety of different window configurations utilizing heat mirrors are possible. Several are shown in Figure 4 with associated U-values and solar transmittance properties. Since there is a tremendous inventory of single-glazed windows in the United States, retrofit options for single-glazed windows should present good sales opportunites. Figure 4a shows nominal performance values for a heat mirror applied directly to the interior of an existing window. The nominal U-value is reduced from 1.14 Btu/ft^2-hr-^{o}F to a range of .72-.63 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 and some fluorinated polymers have acceptable IR transmission characteristics but lack the mechanical strength, UV resistance or other desirable properties of polyester, which is the mainstay of the solar control film industry. 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.

WINDOW/HEAT MIRROR CONFIGURATIONS



	U BTU/FT^2-HR-^oF E=.2	U BTU/FT^2-HR-^oF E=.05	TRANS.
(a) SINGLE GLAZED INNER SURFACE	.72	.63	.78
(b) PLASTIC FILM + AIR GAP RETROFIT	.31	.26	.75
(c) DOUBLE GLAZED AIR GAP	.32	.27	.77
(d) DOUBLE GLAZED MID-GAP PLASTIC FILM	.21	.17	.66

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FIGURE 4: HEAT MIRROR APPLICATIONS

Figure 4b 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%.

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 4c). The resultant U-value is lower than that to be expected from triple glazing and may thus represent an attractive option.

A more attractive approach to modifications of factory assembled double glazing would add the polyester film with heat mirror to the center of the double-glazed unit (Figure 4d). If the plastic is coated on both sides with a heat mirror (or if a suitable IR transparent plastic with a single heat mirror coating is used), the window will exhibit an extremely low rate of thermal transfer, approximately .17-.21 Btu/ft^2-hr-^{o}F, depending on the heat mirror emissivity (.05-.20).

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 emissivity 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 views. 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, venetian 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.

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/$foot^2$. Cost estimates for similar production by Sierracin for their gold-coated polyester fell in the range of \$.40-\$.60/$foot^2$ where the gold evaporant alone costs \$.12/$foot^2$ at current gold prices. Production costs for most solar control films (which are coated at speeds of 400-600 feet/minute) fall in the range of \$.25-\$.40/$foot^2$ 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/$foot^2$ 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/$foot^2$ 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/$foot^2$, 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 5 presents results of a simplified analysis for a heat mirror retrofit to an existing single-glazed window.

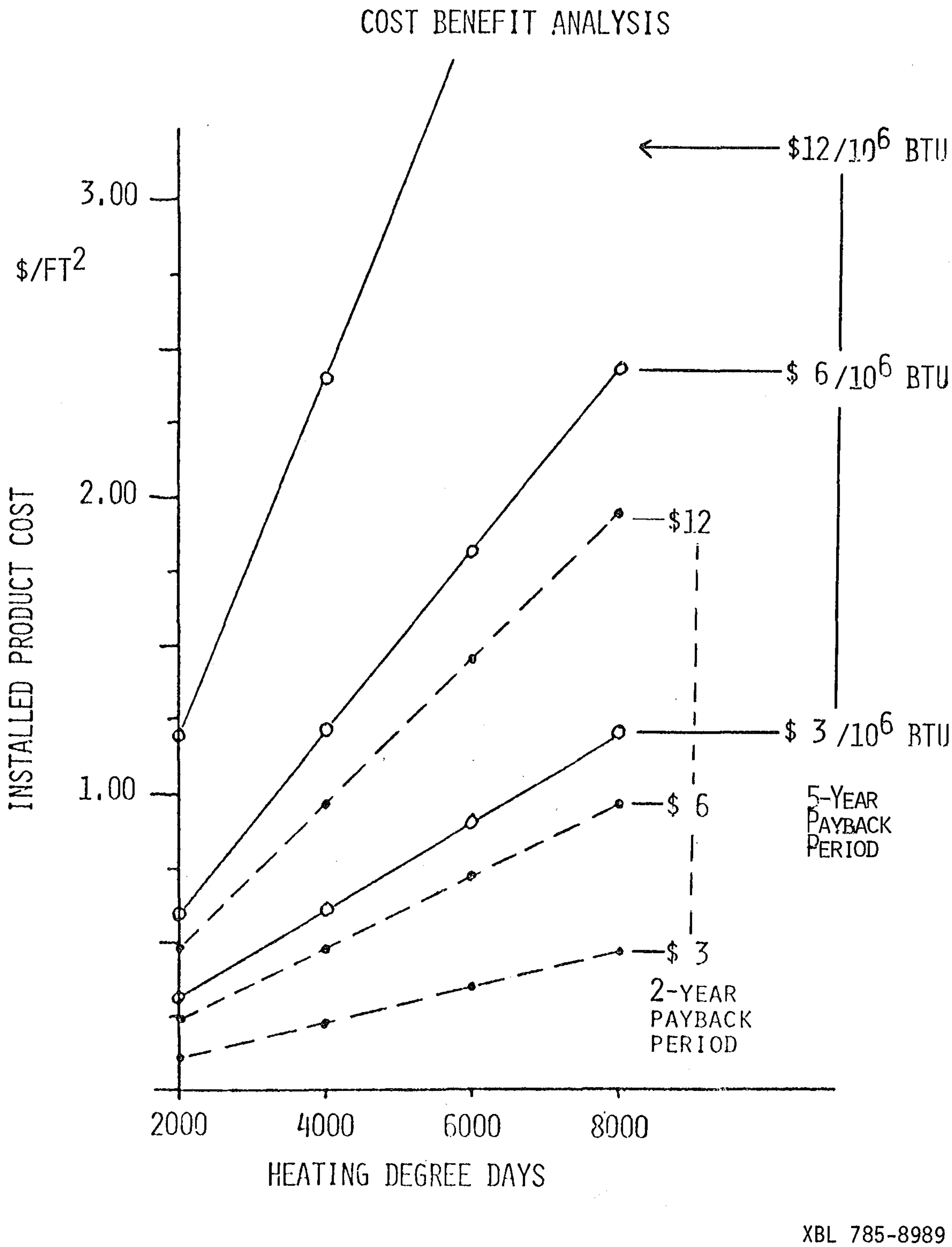

FIGURE 5: COST BENEFIT ANALYSIS

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 (typical oil heating cost), the maximum that can be spent on retrofit heat mirror would range from \$.60 per foot^2 in a mild, 2000 degree day climate to \$2.40/foot^2 in a cold, 8000 degree day climate.

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.

MARKETING STRATEGIES AND ISSUES

Technical excellence and desirable 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. 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% savings in winter heating bills due to the lowered emissivity of the laminated metallized film. 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 additional support to assist in overcoming additional technical and institutional obstacles to successful market introduction.

SUMMARY

In the next one to three years, windows incorporating "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 slight reduction in desired solar gain. Although final manufacturing cost and selling price are uncertain, payback periods of one to five years are 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, offer additional insulating options. Heat mirror applications are compared to more conventional insulating windows and accessories in the table.

The ultimate product selections will be made by building designers and consumers on the basis of perceived product cost, durability, performance and other factors. It appears likely that in the next few years, transparent heat mirrors will become a valuable design option for energy conservation and passive solar applications.

HEAT MIRROR VS. ALTERNATIVE WINDOW MANAGEMENT STRATEGIES

	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
• 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	+ .50-3.00	.1 - .5	++	DAILY	MODERATE
• SHUTTERS	+1.00-5.00	.1 - .5	++	DAILY	MODERATE

NOTES:
1) INCREASED COST SHOWN RELATIVE TO SINGLE GLAZED UNIT
2) U VALVE: BTU/HR-FT^2-^{o}F, NO INFILTRATION
3) COMPARATIVE RANKINGS: +++: HIGH, ++: MODERATE, +: UNCERTAIN
4) SHADES AND SHUTTERS DESIGNED FOR HIGH THERMAL RESISTANCE

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