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ADVANCED OPTICAL AND THERMAL TECHNOLOGIES FOR APERTURE CONTROL

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ABSTRACT

Control of heat transfer and radiant energy flow through building apertures is essential for maximizing thermal and daylighting benefits and minimizing undesired heating and cooling loads. Architectural solutions based on current technology generally add devices such as louvers, shutters, shades, or blinds to the glazing system. This paper outlines the objectives and initial accomplishments of a research program the goal of which is to identify and evaluate advanced optical and thermal technologies for controlling aperture energy flows, thus reducing building energy requirements. We describe activities in four program areas: 1) low-conductance, high-transmittance glazing materials (e.g., heat mirrors, aerogels); 2) optical switching materials (e.g., electrochromic, photochromic); 3) selective transmitters; and 4) daylight enhancement techniques.

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INTRODUCTION

The energy-related performance of glazed apertures is generally seen as a major consideration in building energy use. These apertures have potentially positive and negative attributes with respect to heating loads, cooling loads, and lighting loads in buildings. As a basic approach, one would like to reduce undesirable heat losses and cooling loads to an absolute minimum. A better strategy is to balance useful gains against unavoidable losses so that the apertures make no net contribution to the energy cost of operating the building; that is, the gains and losses balance. Achievement of this goal would allow the major determination of the role of apertures to be based upon non-energy architectural and design constraints. The optimal use of a glazed aperture, however, would be to maximize the net energy benefits so that thermal gains and daylighting benefits can fulfill energy requirements elsewhere in the building. The identification of specific attributes of aperture systems that either minimize losses, break even, or maximize net energy benefits will be a sensitive function of climate, orientation, building type, and related operational parameters.

Most previous considerations of aperture performance have viewed the aperture as a static device having optical properties that are to be selected to optimize energy use in response to climate, building type, etc. But selection of this optimum level of performance based upon fixed thermal and optical properties almost always involves selecting a compromise solution, and the compromise will rarely be the solution that minimizes non-renewable energy consumption.

Aperture designs that minimize non-renewable energy consumption must be responsive to the hourly, daily, and seasonal climatic cycles that influence building energy consumption. The properties of elements of the ideal aperture system can be varied in response to climatic conditions, and the net performance of the total system can thus be timed to respond to thermal control and daylighting requirements. The aperture acts as an energy modulator, or controller, in the envelope of the building by rejecting, filtering, and/or enhancing energy flows, both thermal and daylighting. The functional role of the aperture at any given time is determined by intrinsic properties of the glazing elements, environmental conditions, and control responses by occupants.

Although a wide variety of specific functions can be assigned to any aperture, desirable performance characteristics can be organized into four broad functional categories.

1. Low-conductance, high-transmittance glazing.

   These systems minimize conducted and convected heat transfer while maximizing radiant transmission. These are the dominant desirable attributes of most passive solar heating systems.

2. Optical switching materials.

   These devices modulate daylight and/or total solar radiation on the basis of environmental conditions and building requirements. The significant feature of these materials is that they are active, changing properties over time.

3. Selective transmittance glazing.

   There are two categories of materials that control sunlight and daylight through selective transmittance. The first category contains angle-selective glazings that use optical techniques to control transmittance as a function of incident angle. These are designed to control undesired solar gain. The second category includes materials that are selective in a spectral mode, transmitting in some portion of the spectrum while reflecting or absorbing in other portions. These systems provide high daylight transmittance while minimizing total solar gain.

4. Daylight enhancement.

These systems provide optical collection, transmission, and distribution to enhance daylight utilization within a building.

For each of these four functional concepts we can identify a number of existing glazing options that provide some limited portion of the required control function. These options rely primarily on incremental improvements to existing glazing systems or on the addition of mechanically complex devices such as movable insulation. Even the new generation of heat-mirror coatings now entering the marketplace only begins to hint at potential improvements. Although new discoveries in optical sciences and engineering have advanced rapidly in some commercial fields, the architectural impacts have been limited. A broad range of advanced optical and thermal technologies has been largely unexplored in terms of ultimate application to building apertures.

Research on many elements of this program has been supported throughout the past six years by the Office of Buildings Energy Research and Development, Assistant Secretary for Conservation and Renewable Energy. The current program, initiated late in FY 82, builds upon this prior work and expands the scope and depth of these investigations. In each area detailed state-of-the-art reviews and technology assessments are underway. Results of these research overviews will be used in developing a comprehensive research plan to guide research activities in this field. The more promising technologies are being identified and will become the subject of new research investigations during the coming year.

The following discussion reviews preliminary results in three technical areas to suggest the importance and potential impact of these studies.

LOW-CONDUCTANCE, HIGH-TRANSMITTANCE GLAZINGS: HEAT MIRRORS

Coatings classified as heat mirrors, or transparent conductors, can be used to reduce radiative losses through architectural windows (1-3). Numerous thin-film systems exist which exhibit the potential for inclusion in energy-efficient glazings (4). Some of these coatings have been used as transparent electrical conductors and, to a lesser extent, as infrared radiation reflectors.

For our purposes a "heat mirror" is defined as a coating that is predominately transparent over the visible wavelengths (0.3 - 0.77 microns) and reflective in the infrared (2.0 - 100 microns). For the near-infrared (0.77 - 2.0), the material may exhibit combined properties depending upon design and end use. Heat mirrors fall into two classes based on design: single-layer doped semiconductors, and metal/dielectric interference films. Examples of the former are SnO_2:F, In_2O_3:Sn, Cd_2SnO_4, and CdO. Illustrative systems of the latter might be based on TiO_2/metal, Al_2O_3/metal, or ZnS/metal alternations.

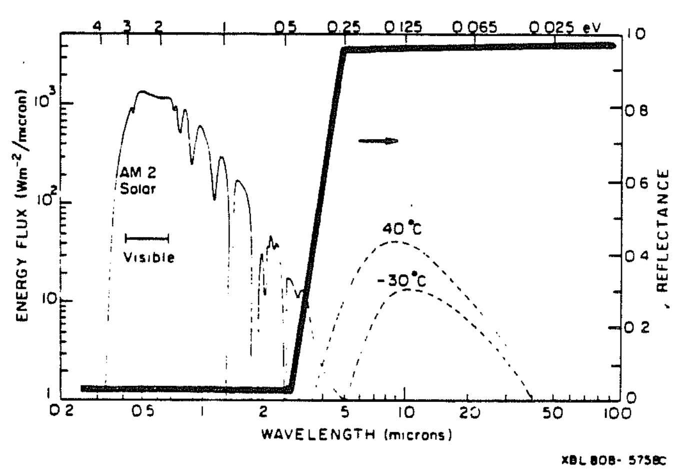

Figure 1. Solar irradiance (airmass 2) with two blackbody distributions (40°C, -30°C). Superimposed is the idealized reflectance of a heat-mirror coating.

Idealized properties of a heat mirror are shown schematically in Fig. 1 along with the solar (airmass 2) and blackbody spectra. With heat mirrors for windows, the coating's infrared reflectance provides a low-emittance (E) surface. The lower the emittance, the less the magnitude of radiative transfer by the window. Hence by using these nearly transparent coatings on a window surface, the thermal characteristics can be dramatically altered and energy can be more efficiently managed.

Figure 2 shows a triple- and a double- glazed window incorporating heat mirrors. In the separation between the glazing sheets a low-conductivity gas or vacuum may be used to further reduce convective heat transfer (2). Figure 3 shows the effect of multiple glazing and coating placement on overall thermal conductance, or U-value. Results were derived by computer modeling (5). For comparative purposes, a nonglass insulated wall has U = 0.6 W/m^2K (R-11) to 0.3 W/m^2K (R-19). New developments should make it possible to build R-5 to R-15 windows having a solar transmittance of 50 to 60%. Such windows would outperform insulated walls in any orientation for most climates.

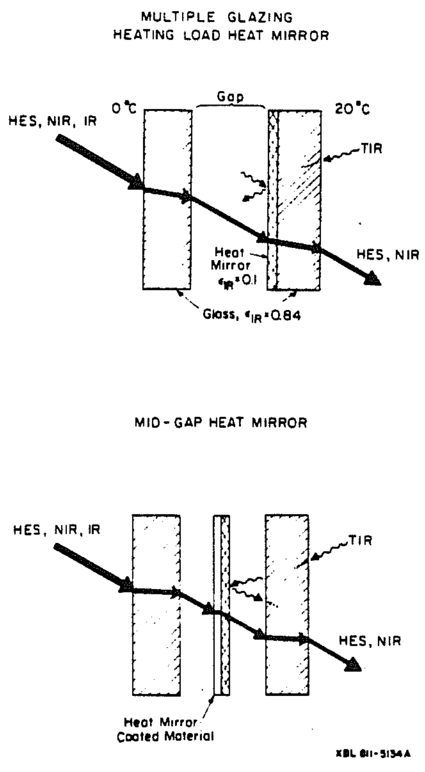

Figure 2. Multiple glazed windows employing heat-mirror coatings.

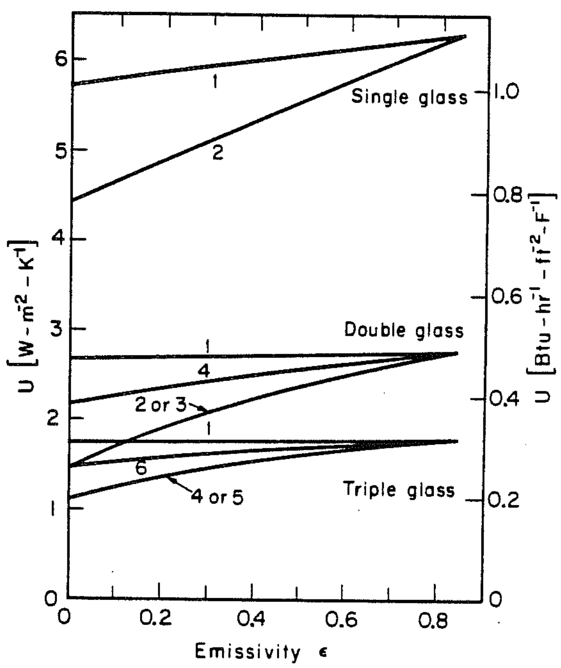

Figure 3. Modeled thermal conductance (U) for various window designs (5) using ASHRAE Standard winter conditions (T_{out} = 18°C, T_{in} = 18°C, wind speed = 24 km/hr). The effect of lowering the emittance of a single surface by the addition of a heat mirror. The surfaces on which the heat mirror appears are given as consecutive numbers, starting from the outside surface labeled 1. Air gap is 1.27 cm.

Active materials research centers around deposition processes and materials microstructural-property relationships. Development of cost-effective techniques to deposit such films on glass and plastic film materials is a major concern. Eliminating post-annealing treatments (to increase conductivity) would reduce expense. Improvement in chemical dip-coating processes and understanding of hydrolysis (CVD) chemistry as it relates to film properties are important research areas. Further development of plasma-assisted physical vapor deposition (PVD) is critical to room-temperature deposition on thin plastic film substrates. Lower deposition temperatures, along with near-atmospheric pressures, should be utilized for refined coating processes. An understanding of doping and defect properties in semiconductor films is necessary, with emphasis on durability and stability. There is also room for basic materials research of new binary and ternary compounds including boride, nitride, oxide, and carbide systems which may be better suited to simple deposition.

LOW-CONDUCTANCE, HIGH-TRANSMITTANCE GLAZINGS: TRANSPARENT AEROGELS

Transparent silica aerogels can be formed by supercritcially drying a colloidal gel of silica. The resulting material is highly transparent because the silica particles are much smaller than a wavelength of visible light. It is also an excellent thermal insulator because the material consists of 97% air trapped in pores smaller than the mean free path of air molecules. Basic studies of aerogel properties were initiated to determine its suitability for window glazing applications (6).

Aerogel Windows

For use in window systems, aerogel must be protected from moisture, shock, and handling. Although it can be fractured quite easily, aerogel is surprisingly strong in compression. Thus it can be protected by rigid glass panes on either side and should be sealed at the edges. Schmitt produced such a window by forming aerogel between panes of glass and drying through the edges (7). Even a large window can be dried by this method because the aerogel has a high permeability for ethanol under supercritical conditions. Other methods for protecting the aerogel should be investigated.

The thickness of glass in an ordinary window is determined by the size of the unsupported area. The sandwich structure of an aerogel window undoubtedly will permit thinner glass based on structural requirements alone. However, tests are needed to determine the thickness of glass required to protect the aerogel from damage. This thickness may prove to be greater than that required for standard windows unless transparent spacers are used.

Aerogel appears slightly yellow when viewed against a bright background, such as the sky or a white wall, because the blue light is scattered most efficiently. Against a dark background, the aerogel appears milky blue because the light is backscattered from the aerogel itself.

We have used the procedures of (8), together with optical measurements of aerogel samples, to calculate normal-hemispherical transmittance, T_h, for aerogel windows. Figure 4 shows the effect on aerogel thickness on T_h, averaged over the air-mass-2 solar spectrum. Aerogel by itself, despite scattering losses in the visible and O-H absorption in the infrared, has a higher transmittance than does window glass of equal thickness. The transmittance of an aerogel window made with low-iron glass and an aerogel thickness of 6 mm equals that of double glass. Doubling the thickness of aerogel reduces T_h to about 0.6, equal to triple glass. Increasing aerogel thickness reduces transmittance but also lowers the thermal conductance, U, of the aerogel window, while U for the double-glass window rapidly reaches a limiting value.

Using the measured thermal conductivity of aerogel, 0.019 $Wm^{-1}K^{-1}$, and the methods of (9), we can predict the heat transfer through an aerogel window. Figure 5 compares the thermal conductance of aerogel windows to that of ordinary double-glass windows as a function of the space between panes, D. At D = 0 the panes of glass touch, effectively becoming a single sheet of glass having U only slightly lower than for a single glass pane. For low D, heat flows only by conduction and radiation. The radiative term in U is much larger for the double-glass window, however, because the air is transparent to infrared radiation. As D increases further, convection heat transfer increases in the double-glass window but not in the aerogel window, so the overall conductance of the aerogel window continues to drop. Even lower conductance values can be achieved using low-conductance gases such as CO_2 and CCl_2F_2. The lowest reported heat transfer value is 0.011 $W^{-1}K^{-1}$, with CCl_2F_2. For this value, a window with 20 mm of aerogel would have a thermal conductance less than 0.5 $Wm^{-2}K^{-1}$.

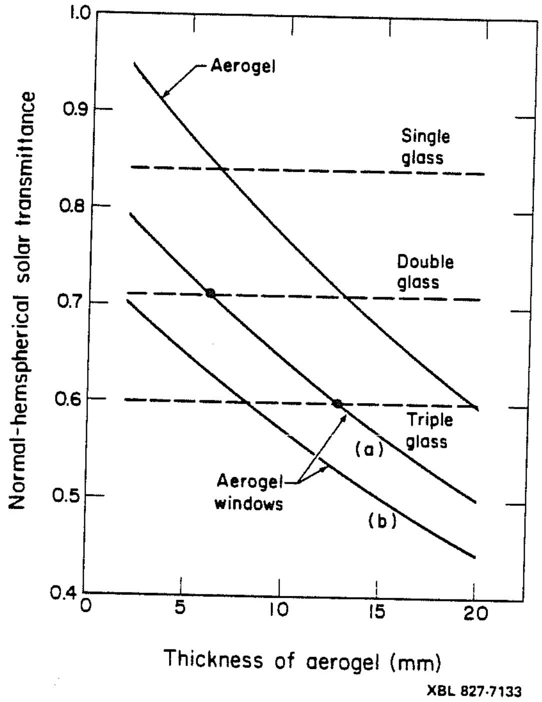

Figure 4. Calculated solar transmittance of aerogel windows vs. aerogel thickness compared to solar transmittance of conventional glass except for the 3-mm windows. All glass is 3-mm clear float glass except for the low-iron glass of aerogel window (a).

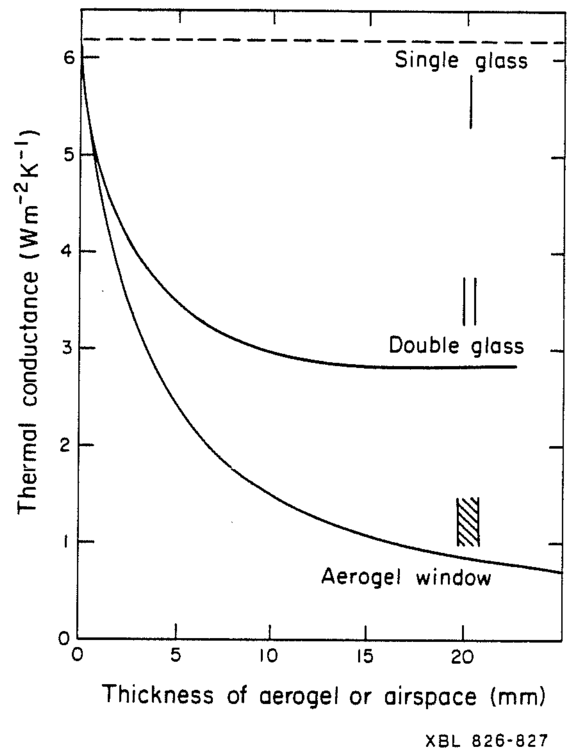

Figure 5. Calculated thermal conductance of aerogel window and of conventional single- and double-glass windows vs. spacing between glass panes.

In principle, we could increase the thickness of the aerogel until reaching the desired conductance, but unless scattering can be reduced, the solar transmittance and optical quality degrade to unacceptable levels for thickness greater than a few centimeters. In any case, it may not be possible to make layers thicker than a few centimeters by the process described above; experiments with tall columns of aerogel produced defects at the base of the column. The optimum thickness in window systems will depend on climate, building type, and window orientation.

OPTICAL SWITCHING MATERIALS

Optical switching materials or devices can be used for energy-efficient windows or other passive solar devices. An optical shutter provides a drastic change in optical properties under the influence of light, heat, or electrical field or by their combination. The change can occur as a transformation from a material that is highly solar transmitting to one that is reflecting either totally or partly over the solar spectrum. A less desirable alternative might be a film that converts from highly transmitting to highly absorbing. An optical shutter coating would control the flow of light and/or heat in and out of a building window, thus performing an energy management function. Phenomena of interest to optical shutters are electrochromic, photochromic, thermochromic, and liquid crystal processes (10).

Electrochromic Devices

Electrochromism is exhibited by a large number of inorganic and organic materials. The electrochromic effect is of current research interest mainly because of its application to electronic display devices, although some studies for window applications have been completed (11). An electrochromic material exhibits intense color change due to the formation of a colored compound formed from an ion-insertion reaction induced by an instantaneous applied electric field. The reaction might follow: $MO_x + yA^+ + ye \longleftrightarrow A_yMO_x$.

There are three categories of electrochromic materials: transition metal oxides, organic compounds, and intercalated materials. The materials that have attracted the most research interest are WO_3, MoO_3, and IrO_x films. Organic electrochromics are based on the liquid viologens, anthraquinones, diphthalocyanines, and tetrathiafulvalenes. With organics, coloration of a liquid is achieved by an oxidation-reduction reaction, which may be coupled with a chemical reaction. Intercalated electrochromics are based on graphite and so are not useful for window applications.

A solid-state window device can be fabricated containing the elements shown in Figure 6: transparent conductors (TC), an electrolyte or fast-ion conductor (FIC), counter electrode (CE), and electrochromic layer (EC). Much research is needed to develop a usable panel and better electrochromic materials having high cycle lifetimes and short response times. Fast-ion conductors and electrolytes also require further study.

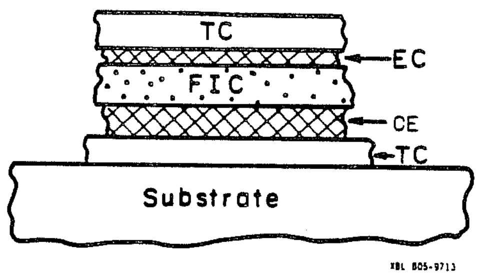

Figure 6. Model of solid-state electrochromic cell.

Photochromic Materials

Photochromic materials change their optical properties or color with light intensity. Generally, photochromic materials are energy-absorptive. The phenonemon is based on the reversible change of a single chemical species between two energy states having different absorption spectra. This change in states can be induced by electromagnetic radiation. Probably the best known application is photochromic glass used in eyeglasses and goggles. Photochromic materials are classified as organics, inorganics, and glasses. The organics include stereoismers, dyes, and polynuclear aromatic hydrocarbons. The inorganics include ZnS, TiO_2, Li_3N, HgS, HgI_2, HgCNS, and alkaline earth sulfides and titanates, with many of these compounds requiring traces of heavy metal or a halogen to be photochromic. Glasses that exhibit photochromism are Hackmanite, Ce, and Eu doped glasses (which are ultraviolet sensitive), and silver halide glasses (which include other metal oxides). The silver halide glasses color by color-center formation from an AgCl crystalline phase.

For windows, development work is needed to utilize commercially available silver halide glasses. Deposition of such glasses as film compounds requires more research for possible utilization as films and suspensions in polymeric materials.

Reversible Thermochromic Materials

Many thermochromic materials are used as nonreversible temperature indicators, but for an optical shutter one can consider only the reversible materials, although their cyclic lifetime is limited by non-reversible secondary reactions. Organic materials such as spiropyrans, anils, polyvinyl acetal resins, and hydrozides are examples of thermochromic materials. Inorganic materials include HgI_2, AgI, Ag_2HgI_4, $SrTiO_3$, Cd_3P_3Cl, and Copper, Tin, and Cobalt complexes. Work is suggested on compounds that exhibit both photo and thermochromism. Identification of limiting reactions, development of film materials, and polymeric and glassy dispersions are necessary.

Liquid Crystals

Liquid crystals have been extensively researched for use as electronic and temperature displays. Liquid crystals are characterized as one of three structural organic mesophases: smectic, nematic, or twisted nematic (cholesteric). The most widely used is the twisted nematic. From a materials standpoint, liquid crystals are based on azo-azoxy esters, biphenyls, and Schiff bases. Passive liquid crystal films can be solidified into solid films by polymerization, giving preset optical properties. A liquid crystal in the form of a light valve could be used to modulate transmittance and reflectance of light. Unlike the electrochromic device, a liquid crystal would require continuous power to stay reflective. Both cost and fabrication problems must be considered for large-area liquid crystal optical shutters.

SUMMARY

The research program described above is designed to identify, develop, and evaluate new optical technologies that promise to increase the energy efficiency of building apertures and enhance the performance of all passive systems in buildings. Although the program started late in FY 82, it builds upon six years of prior work on aperture performance so that we expect additional results to emerge quickly in FY 83. New state-of-the-art reviews have already identified promising technical concepts in each of the four major areas of aperture function that will be further explored in FY 83.

ACKNOWLEDGEMENT

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