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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.

INTRODUCTION

The energy-related performance of glazed apertures is generally seen as a major consideration in buildings energy use. These apertures can have positive or negative effects on 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. An effective strategy might be 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 on 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 selected to optimize energy in response to climate, building type, etc. But selection of this optimum level of performance based on fixed thermal and optical properties almost always involves selecting a compromise solution, and the compromise will rarely be the solution that maximizes the renewable energy contribution.

Aperture designs must be responsive to the hourly, daily, and seasonal climatic cycles that influence building energy consumption. The properties of the elements of an ideal aperture system can be varied in response to climatic conditions on an hourly, daily, or seasonal basis, 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 and are well suited for most glazing applications in cold climates.

2. Optical switching materials

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

3. Selective transmittance glazing

There are two categories of materials that control sunlight and daylight through selective transmittance. The first category, angle-selective glazings, uses optical techniques to control transmittance as a function of incident angle in order to control undesired solar gain and to improve daylight distribution in a room. The second category includes materials that are selective in a spectral mode, allowing transmittance in the visible portion of the spectrum while reflecting or absorbing the short-wave infrared energy. 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 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. Even the new generation of low-emittance 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 applications 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 some 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 in FY 82, with support from the Office of Solar Heat Technologies, builds on this prior work and significantly expands the scope and depth of these investigations. In each area, detailed state-of-the-art reviews and technology assessments have been completed. Results of these research overviews have been used to develop a comprehensive, multi-year research plan to guide research activities in this field [1]. The plan has been reviewed by a broad range of researchers and industry participants to ensure that it represents a consensus on research needs in this field. The research projects are conducted by private firms, universities, and national laboratories. In addition to undertaking several specific projects reviewed in this report, Lawrence Berkeley Laboratory assists DOE by providing scientific coordination of all the public- and private-sector research projects in the Aperture Materials Program.

The overall objective of this research program is to advance aperture research in several high-risk areas to the point where normal, private-sector R&D investments can carry an innovative concept to a commercial, marketable product. At present, many optical materials or techniques that are potentially useful in building applications are not fully explored because they represent unacceptable risks (with uncertain returns) to private firms. Any given technology will be advanced to the marketplace only after a substantial investment by the private sector that must be many times greater than the initial DOE-supported R&D. The federally supported phase of apertures research is thus seen as a highly leveraged undertaking designed to stimulate a private-sector commitment to market introduction once a need is established and fundamental technical obstacles are removed.

1. LOW-CONDUCTANCE, HIGH-TRANSMITTANCE GLAZINGS

Two approaches to developing low-conductance, high-transmittance glazings have been pursued in the past year.

A. Low-Emittance Coatings

Low-emittance (low-E) coatings can be used to reduce radiative loss through architectural windows [2-4]. Numerous thin-film materials systems exist that have the potential for inclusion in energy-efficient glazings [5]. Some of these coatings have been used as transparent electrical conductors and, to a lesser extent, as infrared radiation reflectors.

Our interest is in high-transmittance, low-emittance coatings that are predominantly 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 microns), the material may exhibit combined properties depending on design and end use. Low-E coatings fall into two classes based on design: single-layer doped semiconductors, and metal/dielectric multi-layer 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. Idealized properties of a low-E coating are shown schematically in Fig. 1 along with the solar (airmass 2) and blackbody spectra. The coating's high infrared reflectance provides a low emittance surface. The lower the emittance, the less the magnitude of radiative transfer in the window. By using these nearly transparent coatings on a window surface, the thermal characteristics can be dramatically altered and energy loss can be more efficiently controlled.

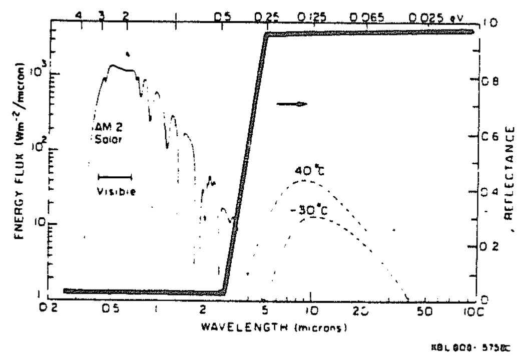
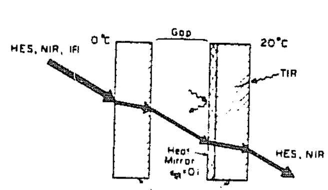


Fig. 1. Solar irradiance (airmass 2) with two blackbody distributions (40°C, -30°C). Superimposed is the idealized reflectance of a heat-mirror coating.

Low-E coatings can be applied directly to glass in double and triple glazing or may be applied to plastic films that are glued to glass or are suspended in a double-glazed air space. In the air space between the glazing sheets a low-conductivity gas or vacuum may be used to further reduce convective heat transfer [3]. Figure 2 shows the effect of multiple glazing and coating placement on overall thermal conductance, or U-value. Results were derived by computer modeling [6]. New developments, such as using low-conductance gases and two low-E coated plastic inserts, 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.



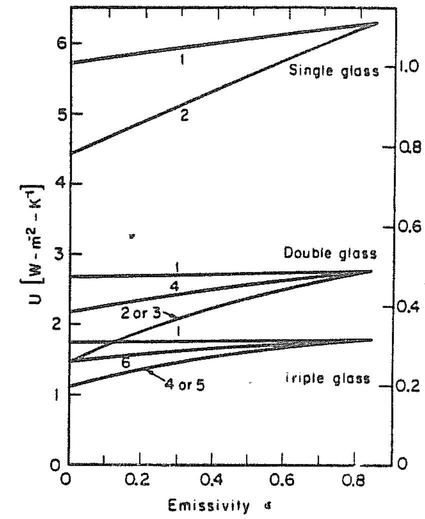


Figure 2. Modeled thermal conductance (U) for various window designs (5) using ASHRAE Standard winter conditions (T_{out} = 18°C, T_{in} = 18°C, wind speed = 24 km/hr).

After almost 10 years of research, windows incorporating the first generation of low-E (E = 0.1 -0.2), high-transmittance films have become commercially available. The commercial products, based on multi-layer designs, are not sufficiently durable to withstand the abrasion and atmospheric exposure of unprotected environments. This limits their applicability to hermetically sealed windows, thereby missing the enormous potential savings in the retrofit market. Glue-on plastic films with a low-E surface (E = 0.25 - 0.3) are commercially available for retrofits but exhibit only low to moderate solar transmittance.

We have been exploring the use of new types of hard refractory materials as low-E coatings. Materials such as transition metal nitrides (e.g., TiN) have excellent durability but do not have the desired emittance and solar transmittance properties. Our approach has been to investigate techniques for improving the thermal and optical properties of these materials while maintaining their inherent stability and durability.

Our initial research in FY 83 focused on TiN and TiN_x. Our approach was to examine 1) gradient index profiles to reduce reflection losses from TiN and 2) oxygen substitution for nitrogen to produce TiN_xO_y films having reduced absorption in the solar spectrum but high reflectance for longwave infrared radiation (i.e., low-emittance). The first stage was to better characterize the optical properties of TiN, TiN_x, and TiN_xO_y films. Samples of TiN were fabricated using reactive RF sputtering. Optical measurements were made on several film thickness of TiN from which basic optical constants were calculated. This allowed calculation of the optical properties for any film thickness. We have also measured the optical properties of TiO_2. We can now calculate the optical effects of multilayer and gradient index coatings utilizing various combinations of these materials. The film's microstructure is examined using electron microscopy and its chemical composition studied using Auger spectroscopy. These investigations enable us to relate the film's optical and thermal properties to physical structure and chemical composition.

In FY 84 we will extend this analysis to films produced by plasma-assisted chemical vapor deposition. Different coating techniques are expected to produce a range of film properties. We will also expand our investigation to ZrN/ZrN_xO_y films and examine other related transition metal nitride/oxide films that may have promise as low-E coatings. We will also investigate the possibility of improving the optical properties of SnO_2 and In_2O_3 semiconductor films using similar gradient index structures.

B. Transparent Aerogels

Transparent silica aerogels can be formed by supercritically 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 undertaken to determine its suitability for window glazing applications [7-8]. This work is a joint effort between the Solar Group and the Windows and Daylighting Group at LBL. More detail on the project can be found in [12].

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 has produced such a window by forming aerogel between panes of glass and drying through the edges [9]. 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 will be investigated.

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 [10] together with optical measurements of aerogel samples, to calculate normal-hemispherical transmittance, T_h, for aerogel windows. Figure 3 shows the effect of 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.

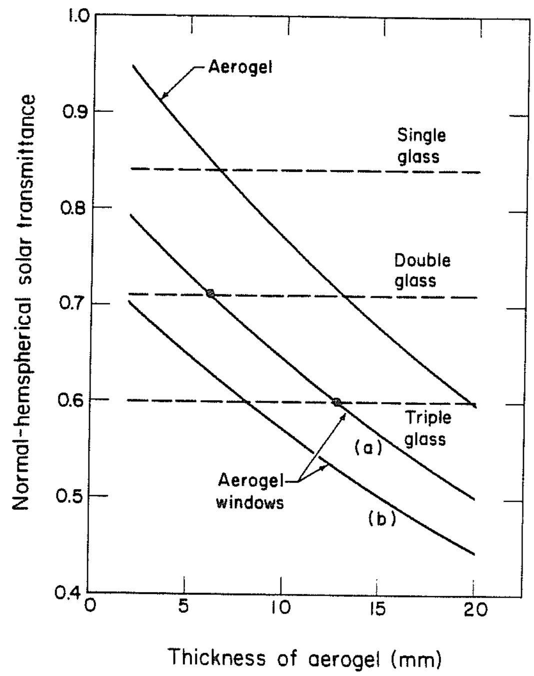


Fig. 3. Calculated solar transmittance of aerogel windows vs. aerogel thickness compared to solar transmittance of conventional glass windows. All glass is 3-mm clear float glass low-iron glass of aerogel window (a).

Using the measured thermal conductivity of aerogel, 0.019 $Wm^{-1}K^{-1}$, and the methods of [11], we can predict the heat transfer through an aerogel window. Figure 4 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 radiation and conduction. 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 $Wm^{-1}K^{-1}$, with CCl_2F_2. For this value, a window with 20 mm of aerogel would have a thermal conductance less than 0.5 $Wm^{-2}K^{-1}$.

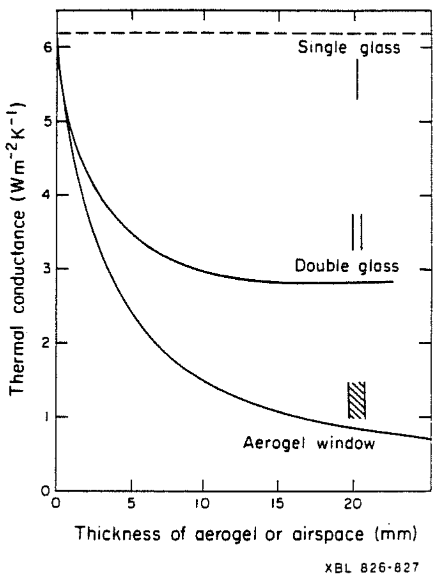


Fig. 4. Calculated thermal conductance of aerogel window and of conventional single- and double-glass windows vs. spacing between glass panes.

Even lower conductance values could be obtained if the sealed unit was evacuated. Aerogel has more than sufficient mechanical strength to act as its own transparent spacer to separate two sheets of glass. Studies are under way to investigate the performance of an evacuated aerogel windows.

Advances in understanding the optical and thermal performance of aerogels require the ability to alter the synthesis process. A supercritical dryer was designed and built so that aerogel samples could be custom-fabricated and so that the effects of processing conditions on aerogel properties could be studied. A polar nephelometer was built so that optical scattering properties could be determined. More details on results of optical analysis and plans for FY 84 are provided in Reference 12.

2. 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 reflects over part or all of the solar spectrum. (Figures 5, 6, and 7). A less desirable alternative would be a material that switches 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. Depending upon design, such a coating could control glare, modulate daylight admittance, and limit solar heat gain to reduce cooling loads, prevent overheating, and improve thermal comfort.

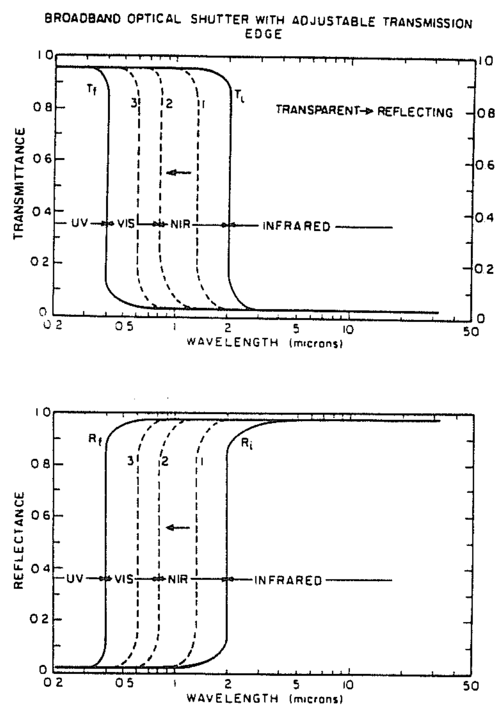


Fig. 5. Schematic of idealized optical shutter spectral response with adjustable transmission properties (absorptance is neglected).

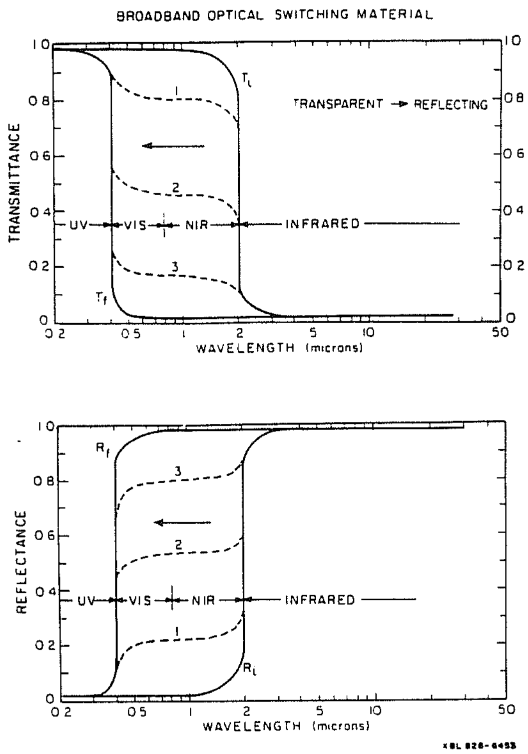


Fig. 6. Schematic of idealized broadband optical switching effect showing successive intervals of transformation (absorptance is neglected).

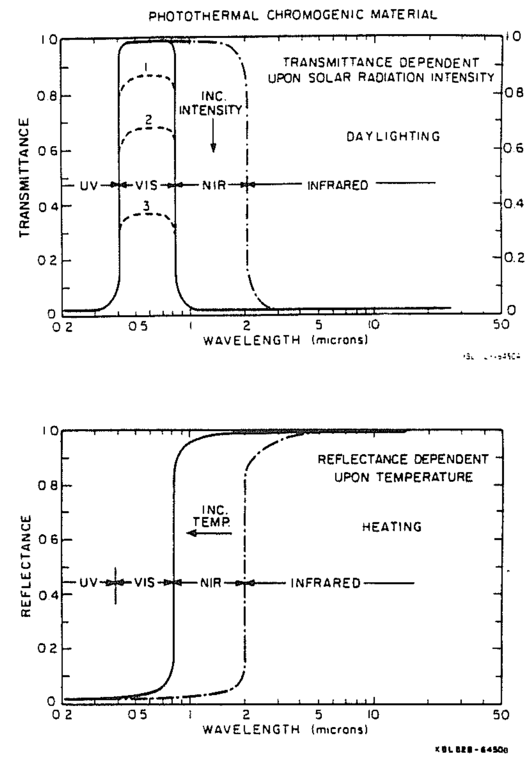


Fig. 7. Behavior of a photothermal chromogenic material. The transmission decreases with incident solar radiation intensity and the reflectance property rejects the solar near-infrared as temperature increases. This action stabilizes incident lighting levels and solar gain through the glazing.

We consider materials that possess variable, reversible optical properties as potential candidates for an optical shutter. There are three classes of phenomena that may prove useful:

- Chromogenic, including electrochromism, photochromism, and thermochromicsm;
- Physio-optic, including mesogenic molecules/liquid crystals, magneto-optic, electro-optic, and mechano-optic or deformable media;
- Electrodeposition, including reversible electrodeposition and electrophoresis.

In FY 83 our research program focused on electrochromic coatings because they offer the potential for active control (by an applied voltage) in response to building conditions and because there is sufficient experience with optical displays and related applications to suggest that they would be good candidates for glazing applications. Expanded efforts on photochromic, thermochromic, and liquid crystal systems are planned in FY 84.

A. Electrochromic Devices

Electrochromism is exhibited by a large number of inorganic and organic materials [13,14]. 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 8: transparent conductor (TC), an electrochromic layer (EC), an electrolyte or fast-ion conductor (FIC), counter electrode (CE), and a second transparent conductor. A number of variations on this device configuration is possible, although several of the approaches used for small electronic displays cannot be scaled up successfully to the dimensions required for windows.

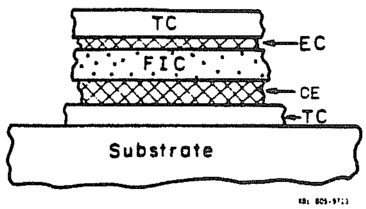


Fig. 8. Model of solid-state electrochromic cell.

An expanded technical review of candidate electrochromic systems was completed [14]. Research programs on the properties of WO_3- based electrochromic systems were continued in 1983 at EIC Laboratories, Inc [15]. and in the Department of Electrical Engineering, Tufts University [16]. Measurements of the optical properties of polycrystalline electrochromic oxide H_xWO_3 showed much higher reflectivity than is characteristic of amorphous electrochromic materials. The optical properties can be explained in part by the free-electron Drude model. This demonstrates that the reflectivity modulation observed in polycrystalline films is associated with a high degree of modulation in the free-electron density. Continuing studies are planned to better understand the source of free electron scattering so as to maximize the achievable reflectivity. Related work in these contracts is oriented toward identifying and testing suitable materials for use as fast ion conductors and as counter electrode materials. In FY 84 additional studies are planned to characterize the optical properties of less well known electrochromics such as NiO_2 (LBL) and to investigate other device configurations and deposition techniques based on WO_3 (SERI).

B. 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 state having different absorption spectra. This change in state 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. Within the organics are stereoismers, dyes, and polynuclear aromatic hydrocarbons. The inorganics include ZnS, TiO_2, Li_3N, H_gS, 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.

A literature survey and review of photochromic materials was completed in 1983 [17]. Results of this study were used to define future R&D in the multi-year plan [1]. It is anticipated that competitive solicitations will be issued in FY 84 for additional work in this area.

C. 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 often limited by nonreversible secondary reactions. Organic materials such as spiropyrans, anils, polyvinyl acetal resins, and hydrozides are examples of thermochromic compounds. Inorganic materials include HgI_2, AgI, Ag_2HgI_4, $SrTiO_3$, Cd_3P_3Cl, and Copper, Tin, and Cobalt complexes. A review of thermochromic materials was completed in FY 83 [17]. Work is suggested on compounds that exhibit both photo and thermochromism. Identification of limiting reactions, development of film materials, and polymeric and glassy dispersions appear to be useful directions for future research. It is anticipated that additional work will be undertaken in this area in FY 84. Further discussion of promising future directions for this research is contained in [1].

D. Other Switching Film Mechanisms

A number of other materials systems have been reviewed to determine their suitability as optical switching materials. These include physio-optic processes (i.e., liquid crystals, magneto-optic materials, and electro-optic materials) as well as processes based on reversible electrodeposition and electrophoresis. Each of these approaches has one or more attractive features, but in general they appear less promising than the alternatives described above. We will, however, continue to follow development of these novel approaches to determine if research results in other applications have relevance to aperture requirements.

3. SELECTIVE TRANSMITTANCE MATERIALS

Our objective is to identify, develop, and characterize materials and techniques to produce glazing materials having angular and spectral control that minimize cooling energy requirements and maximize the efficiency of daylight utilization. In most cases the materials envisioned should not degrade the desirable optical properties of apertures (optical clarity, neutral color rendition, etc.). In some specific, non-view glazing applications, requirements could be significantly relaxed.

Spectral control cabilities are useful to improve the luminous efficacy of transmitted solar radiation. Since approximately 50% of the energy in incident solar radiation is in the visible wavelength, the efficacy of sunlight and daylight could, in principle, be doubled to more than 200 lumens/watt. As a spinoff of solar control films and low-emittance coatings, several selective films have been commerically developed and appear to meet current market needs. The most durable plastic-coated films do not have very high transmission; the highest transmittance films are not durable enough to be used in exposed applications. Continued privately supported activity should improve the commercially available options.

Angle-selective films offer the possibility for modifying the cosine response of specular glazings to reflect or admit solar radiation as a function of solar altitude or angle of incidence. Such films could regulate or control the hourly and seasonal patterns of solar gains. In passive systems, angle-selective films could enhance winter collection with high transmittance and reduce summer transmittance in the cooling season.

Several approaches that appear promising are: growth of oriented dendritic films using off-axis sputtering; shadow metallized grating profiles; holographic coatings; and oriented microparticulate structures incorporated into the glazing substrate. In FY 84 exploratory investigations of these approaches will be continued.

4. MATERIALS FOR ENHANCED DAYLIGHT UTILIZATION

Energy requirements for electric lighting account for a major fraction of electricity use in non-residential buildings. Since most illumination requirements occur during daylight hours (unlike in residential buildings), light from the sky and sun could satisfy much of the illumination requirements in commercial buildings.

Although the potential benefits of available technology and improved design are not yet routinely achieved, this research program is designed to explore the next set of technical barriers to effective daylight utilization. The light flux arriving at a building skin is generally greater than the total interior illuminance requirements. The general problem can be viewed as one of collecting, transmitting, and distributing available daylight to meet the temporal and spatial variation in interior illuminance requirements. If these functions could be performed with optical efficiency, two benefits would emerge. First, the efficiency of daylight utilization in perimeter zones and low-rise buildings would improve. This would fulfill illuminance requirements while minimizing the adverse effects of glare and solar gain (which contribute to cooling loads), and would greatly improve the attractiveness of daylighting solutions. Second, daylight could be used deeper in large buildings, in areas far removed from light-admitting apertures. Removing the restriction on physical proximity to the building skin would allow a greater fraction of non-residential floor space to be illuminated with daylight.

Optical systems must also be developed within the context of actual use in buildings, so that needs for reliability and low maintenance are considered. Particular emphasis is placed on components that have no moving parts and for which precise alignment is not critical. For this reason, we focus attention on light-pipe and optical fiber systems, and on other refractive and diffractive systems.

Optical systems have four major functional elements:

- Light collection: most systems use direct beam illumination, although some use diffuse sky or ground-reflected light.
- Light transmission: the major appeal of these optical systems is their ability to transmit light to locations where direct access to the sun and sky is not possible.
- Light distribution: once light is transferred to the space in which it is to be used, it must be distributed in a manner consistent with the functional and aesthetic requirements of that space.
- Electric light integration: because few daylighting systems will be operated without a full electric lighting system, the proper integration of the two systems is essential to ensure user satisfaction and substantial savings.

There are several other general criteria that characterize good daylighting systems. First, there should be no unusual (or at least undesirable) color effects. Although the spectral composition of sunlight is desirable, some optical techniques may be wavelength-dependent and may enhance or reject some spectral elements. Second, the "stability" of the daylight source is critical. Slow variations of moderate magnitude may be acceptable. Although there is no 60-cycle flicker, wind-induced vibration of light-collecting elements or building-induced vibration (e.g., fans, chillers) of transmission/distribution systems could create unpleasant "flicker". Third, lighting quality concerns will always be important. Daylighting systems must not increase discomfort and disability glare over accepted standard practice. Due to the intensity of the sun as a source, control of light distribution is a critical element. Finally, since there is no single "correct" way to light a space, advanced daylighting systems must be developed recognizing that the best designs combine functional and architectural/aesthetic criteria. Properly utilized, this could represent an advantage and an opportunity, rather than a limitation.

In FY 83 we examined the overall problems of light collection, transmission, and distribution as well as integration with electric light. Our studies focused on collection and transmission, which we believe to represent the most fundamental technical problems and constraints. Several promising options for solid and hollow light guides were examined [18]. Although currently available light guide systems are not adequate, further R&D seems likely to lead to several viable approaches. The outlook for viable options for collecting skylight and sunlight that involve no moving parts (or minimal mechanical complexity) is less promising. Fundamental optical principles and thermodynamic considerations limit the ability of a fixed reflective, refractive, or diffraction system to provide the desired light collection and concentration. Several approaches are being examined; one is the subject of an LBL patent disclosure. Continuing work in FY 84 will be directed toward further analysis and development of promising collection and light guide systems.

SUMMARY

The Aperture Materials Research Program is designed to identify, develop, and evaluate new optical and thermal technologies that promise to increase the energy efficiency of building apertures and enhance the performance of all passive systems in buildings. We review recent technical progress in several applications areas and discuss plans for future aperture materials research.

ACKNOWLEDGEMENT

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REFERENCES

[1] Research Opportunities in Advanced Optical and Thermal Materials for Aperture Control, Draft Multi-year Research Program Plan, U.S. Dept. of Energy 1983.

[2] Selkowitz, S., Transparent Heat Mirrors for Passive Solar Heating Applications, Proceedings of the Third Passive Solar Conference, San Jose, CA. Jan. 1979, pp. 124-132. LBL-7833.

[3] S. Selkowitz, Thermal Performance of Insulating Window Systems, ASHRAE Transactions (1979) Vol 85, No. 2, 1979, p.669.

[4] R. Johnson, S. Selkowitz, F. Winklemann, and M. Zenter, Glazing Optimization Study for Energy Efficiency in Commercial Office Buildings, Proceedings of the Third International Symposium on Energy Conservation in the Built Environment Dublin, Ireland, March 1982. LBL 12764.

[5] C.M. Lampert, Heat Mirror Coatings for Energy Conserving Windows, Solar Energy Materials, Vol. 6, No. 1, pp. 1-42, 1981.

[6] M. Rubin, R. Creswick, and S. Selkowitz, Transparent Heat Mirror for Windows: Thermal Performance, Proceedings of the Fifth National Passive Solar Conference, Amherst, MA. Oct. 1980.

[7] M. Rubin and C. Lampert, Transparent Silica Aerogels for Window Insulation, Solar Energy Materials.

[8] A. Hunt, Light Scattering Studies of Silica Aerogels, to be published in Science of Ceramics, John Wiley & Sons, 1983.

[9] W.J. Schmitt, presented at the Annual Meeting of the AIChE, New Orleans, LA, 1981.

[10] M. Rubin, Solar Optical Properties of Windows, Energy Research Vol. 6, p.123, 1981.

[11] M. Rubin, Calculating Heat Transfer through Windows Energy Research, (1981).

[12] A. Hunt, Transparent Aerogels for Low-Conductance Windows, Proceedings of the 1983 Passive & Hybrid Solar Energy Update, Wash. D.C., Sept 26-28, 1983, (Nov. 1983). GPO Washington, D.C.

[13] C.M. Lampert, Thin Film Electrochromic Materials for Energy-Efficient Windows, 1980, LBL-10862.

[14] C. M. Lampert, Electrochromic Materials and Devices for Energy-Efficient Windows, draft.

[15] R. D. Rauh, Variable Transmittance Electrochromic Windows, Proceedings of the 1983 Passive & Hybrid Solar Energy Update, Washington, DC, Sept 26-28, 1983, (Nov. 1983). GPO Washington, D.C.

[16] R.B. Goldner, Optics and Materials Research for Controlled Radiant Energy Transfer in Buildings, Proceedings of the 1983 Passive & Hybrid Solar Energy Update, Wsington, DC, Sept 26-18, 1983, (Nov. 1983). GPO Washington, D.C.

[17] C.M. Lampert and S.M. Li, Photochromic and Thermochromic Phenomena for Switching Glazing, Lawrence Berkeley Laboratory Report LBL 16886.

[18] S. Selkowitz, et. al., Optical Materials for Enhanced Daylight Utilization in Buildings,, Lawrence Berkeley Laboratory Report LBL 16894