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Application of Large-Area Chromogenics to Architectural Glazings

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1. INTRODUCTION

Glass plays a significant role in the design of building envelopes today. Since its emergence during the last century as a major building material, glass has evolved into an ubiquitous and versatile building design element, performing functions today that would have been unimaginable a few years ago. The optical clarity and transparency of glass that we take for granted is one of its most unique features. Glass windows keep out the cold wind and rain without blocking the view, but also perform many more complex functions which require variable properties and tradeoffs between conflicting conditions. The glazing that provides view must also provide visual privacy at other times and must sometimes become totally opaque (for audiovisual shows, for example). Transparent glass admits daylight, providing good color rendition and offsetting electric lighting energy needs, but it can also create discomfort and disability glare conditions. The sun provides desirable warmth in winter but its heat is unwelcome in summer when it contributes to thermal discomfort and cooling energy requirements. And glass is an important element in the appearance and aesthetics of a building, both interior and exterior.

The problem confronting a building designer is one of tremendous variability in the environmental forces that impinge on the building exterior and the rapidly changing needs inside the building. For example, the intensity of sunlight varies on several timescales: by the seconds or minutes on a day with scattered clouds; by the hour as the sun follows its diurnal cycle; and over months as the seasons change. Since exterior daylight illuminance can vary by a factor of 10 to 20 during a day, from approximately 5000 lux (approx. 500 fc) under overcast sky to 100,000 lux (approx. 10,000 fc) in direct sun, optical controls must operate over this wide dynamic range.

There are many building envelope options to extend the intrinsic degree of optical and thermal control exhibited by glass alone. The glass selection will influence total transmittance, spectral properties, and directional properties. But these will be fixed properties and will satisfy some, but not all, of the performance requirements. *In order to provide a wide range of performance responses, dynamic control of one or more of the glazing properties is essential.* This is not a new thought; a vast array of window accessories can be added to glazing to alter its properties in response to changing external conditions and/or internal needs. Currentl research in a new field, large area chromogenics, is leading the way toward development of a new generation of glazing materials that will provide an intrinsic dynamic and responsive optical control capability within the glazing.[1,4] A recent approach is to provide this dynamic control using thin film coatings deposited on the glazing.

2. TRADITIONAL WINDOW CONTROL

People have rarely relied on glass alone to provide window control functions. The window covering (drapes, blinds and shades) industry has been based historically on the need to provide comfort, privacy, and aesthetics. Beginning in the 1960s, but accelerated in the mid-1970s in response to the energy shortages, new glazing products and new window coverings were introduced to the market to provide better control of heat loss and solar gain, which are major contributors to heating and cooling loads. Some entirely new product lines were created and existing products were improved to respond to new performance requirements. While heat loss has always been a concern with window performance, cooling loads resulting from windows became increasingly important as electricity costs rose dramatically. Throughout the world most commercial buildings, even in northern regions, have central air-conditioning systems that remove heat gains most of the year. Solar heat gain through windows is often the largest cooling load component in addition to internally generated sources, such as lights, office equipment, and people. Much of the new housing construction in sunny regions of the developed world use air conditioning, where more energy is used for cooling than for heating. Even in mild climates more central air conditioning is being installed in new homes. In the developing arid and tropical regions of the world there is increasing use of air conditioning.

Cooling loads from windows not only add to annual energy costs but also add the cost of the cooling system to the initial cost of the building. In North America annual cooling loads may be smaller than heating loads, but because the cost of electricity is normally much higher than the cost of furnace fuel, the annual cost for cooling can be higher than for heating.

In nonresidential buildings the cooling issues are even more important because of the higher internal heat loads. And nonresidential building owners often pay additional charges for electric demand, which is increased by cooling loads from windows. Furthermore, the charges for peak demand (this is during mid-day in many countries) can be even larger. When the available generating capacity during peak hours of the summer months is not sufficient to meet the demand, brownouts and blackouts may result.

The traditional window sun control methods consist of coated or heat absorbing glass, drapes, shades, blinds, and louver systems. Many of the operable shading systems are manually controlled, but some can be automatically controlled. The major sun control options are described below:

<u>Low-transmittance glass</u> is a traditional selection to reduce cooling loads in office buildings. This type of glass can be highly colored absorbing glass or glass coated with a semi-transparent metallic coating. This solution may help to reduce cooling loads, but it usually limits available daylight, requiring that electric lights be on whenever the building is occupied.

<u>Interior sun control systems</u> (shades, drapes, blinds, etc.) are relatively well known and widely used. Systems are often selected on the basis of appearance and cost, with insufficient attention paid to solar control and daylight control solutions. Operable systems managed by occupants have the potential to perform well given a conscientious user. However, limited studies and observed practice suggest that these systems are only rarely operated in an "energy efficient" manner.

<u>Fixed exterior shading devices</u>, such as overhangs, fins, or shade screen materials, are often employed. These typically shade the window from direct sun but allow some view of the sky so that daylight can be admitted. In addition, they often break up and diffuse the incident solar beam so that diffused and attenuated direct sunlight is also introduced. However, because they are fixed, these solutions invariably represent a compromise between the requirements of sun control, daylight admittance, and glare control.

<u>Operable exterior sun control systems</u> should provide better performance than fixed systems. Operable systems include a variety of movable awnings, operable slats, fins and louvers, shade systems, and exterior venetian blinds. Systems can be manually or automatically controlled. Automatic controls with manual overrides would appear preferable, ensuring that the systems function properly to meet occupant needs at all times. Exterior operable sun control systems have been used successfully in Europe for some time and to some degree in Asia and are recently attracting attention in North America. They are relatively costly compared to interior treatments or reflective glass, but since they may allow reductions in cooling system sizing as well as permitting daylight utilization, they may be economically beneficial if all costs are accounted for. Some of the additional costs that have to be factored into this shading system are servicing costs and problems with frost and freezing of the system. Operable shading systems should also provide improved thermal and visual comfort relative to most fixed shading solutions. While it is difficult to estimate the economic benefits of comfort directly, the cost of unhappy and uncomfortable office occupants is clearly large.

<u>Between-glass window shading controls</u> are also available. Simple systems employ fixed louvers between glass; other devices such as thin venetian blinds may be operated manually or with a magnetic device without opening the glazing. In the case of exhaust air or air-flow windows, the ventilation air from the room is exhausted between the panes of a glazing system over a venetian blind and either exhausted to the outdoors or returned to a heating and cooling system. In the winter, this provides an interior glass surface temperature that closely matches the room air temperature, thus providing good thermal comfort. In the summer, the blinds, if adjusted properly, absorb the sun's energy; the resultant heat is then carried off in the moving air stream. On sunny days in the winter, the blind acts as a solar air collector and the heat collected may be used in other parts of the building. These systems have been rather extensively used in Europe and are beginning to be introduced also into North America.

3. NEW TECHNOLOGY OPTIONS

Advanced coatings deposited directly on glass or plastic can provide the window systems of the future with the same sophisticated solar control that now requires mechanical devices. The performance requirements for such an ideal glazing are complex because of the multiple functions it must serve. An ideal coating will control adverse cooling loads while maximizing daylighting and heating benefits. In some climates better heat loss control will also be an important issue. Several control strategies may be used to address important performance issues:

1. Issue: Reduce Adverse Cooling Impacts

   a) Reduce cooling energy
   b) Reduce peak cooling loads and air conditioning system size
   c) Reduce peak electric demand
   d) Improve thermal comfort

   Approaches:

   a) Active modulation of transmittance--e.g., chromogenic materials
   b) Passive rejection of solar gain--e.g., spectral and angular control

2. Issue: Increase Beneficial Impacts of Daylight

   a) Reduce lighting energy
   b) Reduce peak electric demand
   c) Simplify lighting control hardware
   d) Improve visual comfort

   Approaches:

   a) Spatial and spectral control in perimeter zone--e.g., spectral and angle selective transmittance
   b) Glare control-e.g., chromogenic materials
   c) Daylight intensity control, e.g., chromogenic materials
   d) Collect and distribute light to core of building–e.g., concentrators and light guide systems

3. Issue: Provide Heat Loss Control

   a) Reduce heat loss
   b) Maintain solar heat gain potential
   c) Improve thermal comfort

   Approaches:

   a) Low-emittance (low-E) coatings
   b) Aerogel
   c) Gas fills or vacuum

The most important control function is control of the intensity of transmitted solar energy. It is possible to produce chromogenic materials having transmittance properties that change from clear to reflective or absorptive as a function of exterior climate conditions, such as sunlight intensity or temperature, or to use an electro-optical control system that controls transmittance as a function of climate and building conditions. Examples of such classic materials are well known: photochromic sunglasses switch as a function of light intensity; nematic liquid crystal temperature indicators change optical properties in response to temperature changes; and twisted nematic liquid crystal watch displays switch from transparent to reflective as each digit changes. However, there are several technical and economic barriers that must be overcome before this existing technology could be used for large area glazing.

The topics in this book detail the state-of-the-art in the development of such large-area devices. Research is in progress at a number of research institutions worldwide to perfect chromogenic technology for what are known as "smart windows." Light-sensitive (photochromic), heat-sensitive (thermochromic), and electrically activated (electrochromic and dispersed liquid crystal) devices will respond differently in a building to different environmental forces. This will result in different effects on lighting energy requirements and cooling energy requirements as illustrated schematically in Figure 1 (lighting savings assume the use of a switched or dimmable electric lighting control). Relative requirements for cooling and lighting are shown for three types of conventional glazings and for three types of chromogenic glazings. The data are typical for a building in a climate requiring significant cooling. A climate with less cooling would tend to compress the cooling energy axis. Photochromics have low lighting energy requirements since they respond to light, but may have higher cooling loads. Conversely, thermochromics could be selected to respond properly to minimize cooling, but may not provide large lighting savings. The lowest total energy consumers are the electrochromics shown in the lower left. Electrochromic coatings can be actively controlled throughout the year to minimize both lighting and cooling, and thus appear to be the technology of choice.

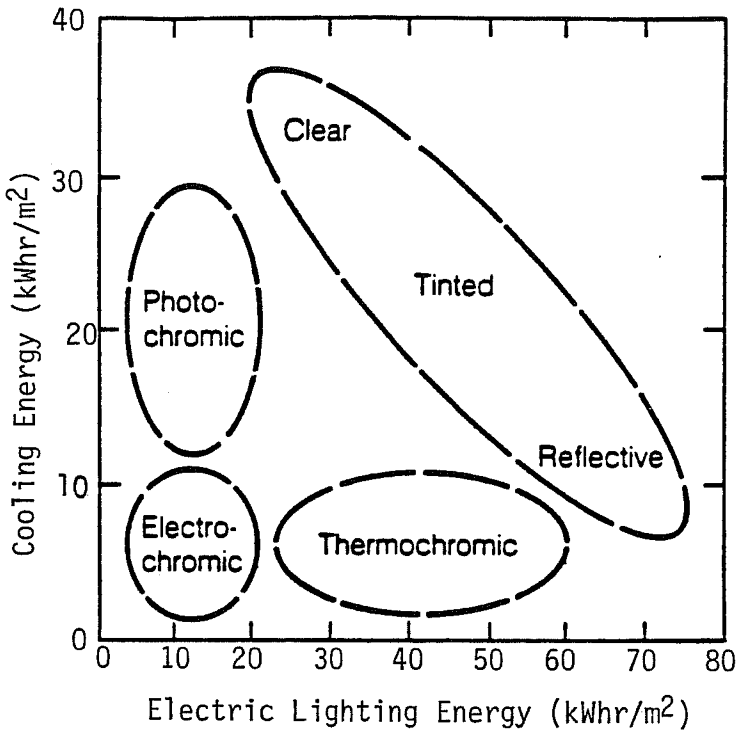


Figure 1. Schematic representation of projected cooling energy and electric lighting requirements. Relative requirements for cooling and lighting are shown for three types of conventional glazings and for three types of chromogenic glazings. Specific energy requirements depend on glazing properties, building type and location, window orientation, etc.

3.1 Spectrally Selective Coatings

Spectral control capabilities may be integrated into some of the chromogenic materials discussed in this book. Ideally, one would like to control the intensity of the transmitted radiation, its spectral content, and perhaps its spatial distribution in the room. Since the sun's spectrum is approximately 50% visible energy and 50% near infrared, one could reject more than half the total energy content with a spectrally selective coating while having only a minor effect on light transmission. The overall transmission of any chromogenic device is dependent on the optical properties of the substrate. For comparison, the properties of common glasses used in windows[5] are shown in Figure 2 and properties of polyethylene terephthalate (polyester)[6] used as a substrate for many coatings and in dispersed liquid crystal devices are shown in Figure 3. Blue-green glass and some metallic coatings exhibit spectral selectivity, allowing higher transmittance in the visible portion of the spectrum than in the near-infrared. Low-E (low-emittance) coatings generally have some spectral selectivity that can be enhanced by altering the design of the coating.[6-8] A low-E coating generally has a high transmittance in the visible and solar spectrum but high reflectance (low emittance) in the long-wave infrared wavelengths. Chromogenic coatings may have spectrally selective properties in the electrochromic layer itself or in the transparent conductors that make up the overall coating stack. Future improvements in coating design should further increase spectral control. Thin film coating technology can also be used to apply interference coatings to produce any desirable color or tint.

3.2 Angle Selective Coatings

Window materials whose transmittance is a specially tailored function of solar incidence angle are also potentially important. The coating might perform like a series of fins or overhangs, rejecting light that arrives at greater than critical incident angles and admitting light otherwise. It may be possible to produce such effects using materials embedded within glazing substrates or with oriented coatings or holographic films. Refractive optical systems, e.g., linear Fresnel prism elements, could also be used for light control. Although these approaches might be used in conjunction with chromogenic films, there is currently no direct connection between these technologies and chromogenic materials.

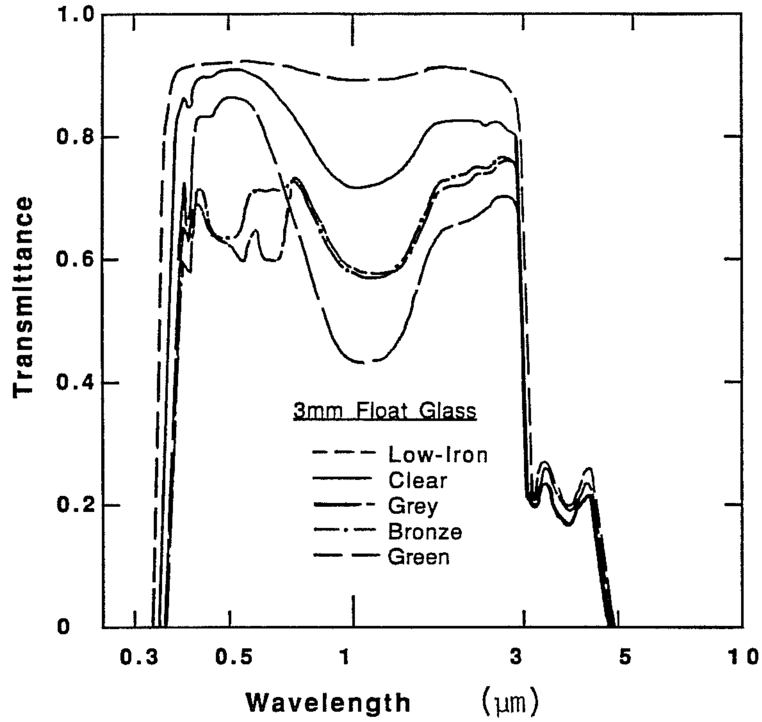


Figure 2. Spectral transmission (normal) properties of five common float glasses used in windows. (After Ref. 5)

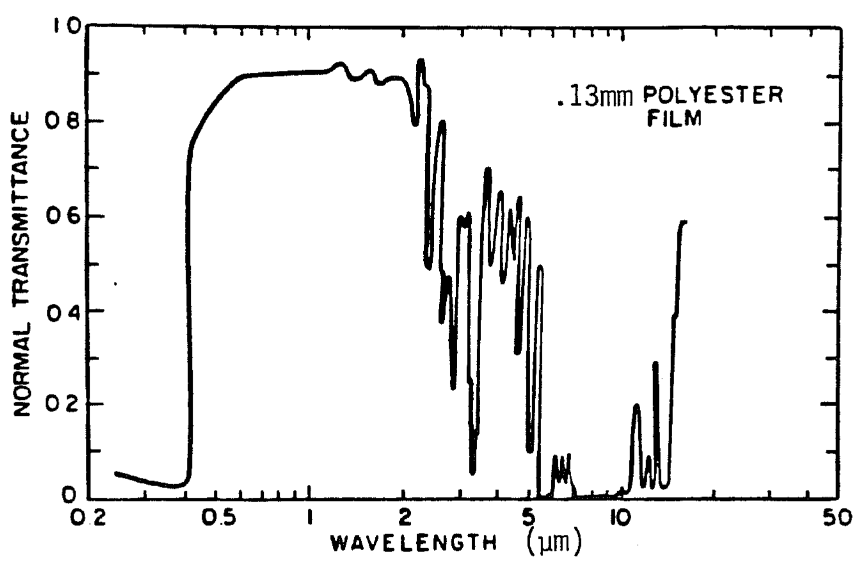


Figure 3. Spectral transmittance of a clear polyethylene terephthalate (polyester) film used in window solar control products. A 0.13 mm ($5x10^{-3}$ in) thick film is shown. (After Ref. 6)

3.3 Chromogenic Coatings and Devices

No single type of thermochromic or photochromic coating is likely to provide the full dynamic range of optical and thermal control required for windows. However, an electrochromic window with an appropriate smart controller could provide the full desired range of responses. Coatings that can be actively controlled are preferred since the glazing can then be continuously adjusted to meet the ever-changing needs of the building and its occupants. Electrochromic coatings are multilayer coatings that are more complex (3-7 layers) than the current generation of low-E coatings (1-3 layers) now on the market. A schematic example of the cross-section of an electrochromic device is shown in Figure 4.

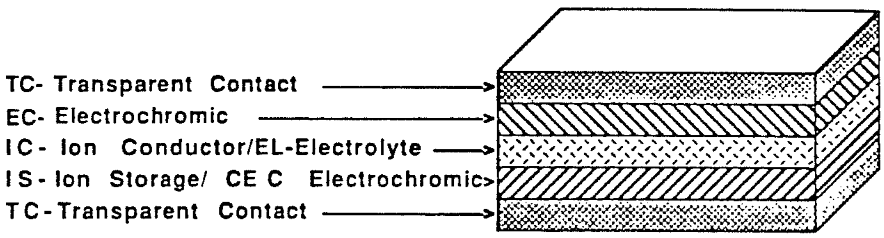


Figure 4. Schematic cross-section of a solid-state electrochromic device. The layers are (TC) transparent conductor, (EC) electrochromic layer, (IC) ion conductor or (EL) electrolyte, (IS) ion storage layer or (CEC) complimentary electrochromic layer. A five layer type is shown here; devices can be made with 3-7 or more layers.

A small current is applied through transparent conductive coatings across the multilayer film and the active electrochromic layer will change in transmittance continuously over a wide range (such as 70-20%). The coating will normally switch in a time period of seconds to less than one minute, will maintain its properties once the power is turned off, requires negligible energy consumption, and is fully reversible over thousands of cycles. Reversing the voltage returns the coating to its original state. A list of desired performance properties for a highly transmitting electrochromic device is given in Figure 5.

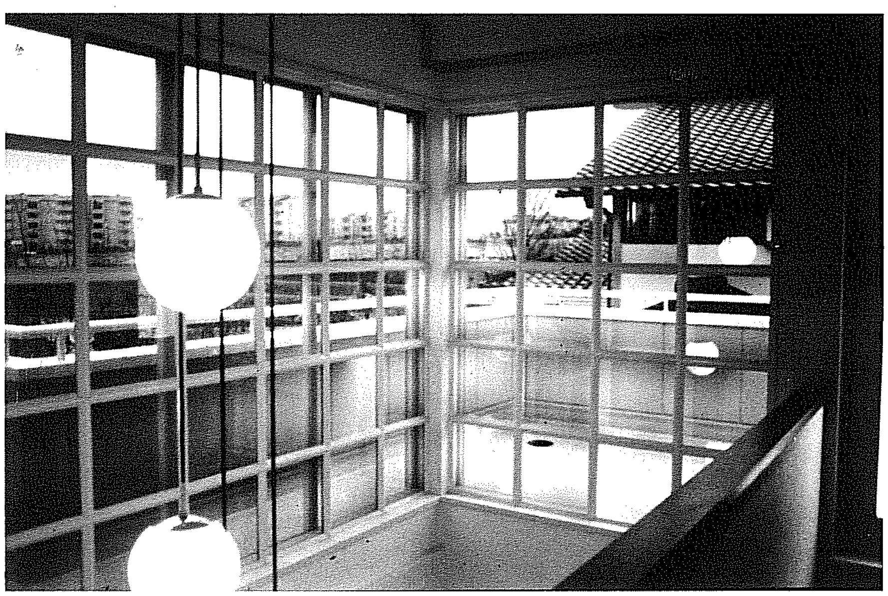
SPECTRAL RESPONSE	
Solar Transmittance, T_s	T_s (BLEACHED) = 50->70% T_s (COLORED) = <10-20%
Visible Transmittance, T_v	T_v (BLEACHED) = 50->70% T_v (COLORED) =<10-20%
Near-IR Reflectance (Only Certain Devices)	R_{nir} (BLEACHED)=10-20% R_{nir} (COLORED) =>70%
SWITCHING VOLTAGE	1-5 VOLTS
MEMORY	1-24 HOURS
SWITCHING SPEED	1-60 SECONDS
CYCLIC LIFETIME	>10K-1M CYCLES
LIFETIME	5-20 YEARS
OPERATING TEMPERATURE	-30 to 70°C and 0-70°C (If Protected)

Figure 5. Desired performance characteristics of an electrochromic glazing

Examples of prototype electrochromic windows have been demonstrated in Japan. The Asahi Glass Co. (Tokyo, Japan) has installed fifty 45 cm x 40 cm electrochromic (ECW) glass units in the Daiwa House (Mita-city, Hyogo-Pref., Japan). This house is shown in Figure 6. In another installation, 196 windows were installed in the Seto Bridge Museum (Kojima, Okayama Pref., Japan). The Central Glass Co. (Tokyo, Japan) installed two 62 cm x 39 cm prototype windows in the experimental Komatsu house in Hiratsuka City, Kanagawa Pref., Japan. Although these are just prototypes, we expect to see other demonstration installations in the near future.

(A)

CBB 887-7030



(B)

CBB 887-7028

Figure 6. Prototype electrochromic windows based on tungsten oxide in the Daiwa House (Mita-city, Hyogo-Pref., Japan). (A) shows the uncolored condition and (B) shows the colored condition (blue coloration) (Reproduced with permission of Asahi Glass Corp.)

Another type of active chromogenic material is the dispersed liquid crystal device. In this device liquid crystal droplets are dispersed in a polymeric medium which is laminated between two transparent conductor layers. Commercial devices made by the Taliq Corp. (Mountain View, CA, USA) have been demonstrated in a variety of applications. An example taken from a business office interior is shown in Figure 7.

CBB 896-5303

CBB 896-5305

Figure 7. Example of the Varilite ® dispersed liquid crystal panels installed as an interior privacy partition in a business office. (Reproduced with permission of Taliq Corp., Mountain View, CA, USA)

3.4 Windows Incorporating Chromogenic Glazings

From a practical perspective, the thermochromic and photochromic options might well find important specific niches in the marketplace to perform more limited functions, particularly if their cost, durability, etc., provide a good fit to the market need. The properties of the coatings alone do not completely determine the thermal performance of the glazing in the building. Total energy related performance is dependent on total solar optical and thermal properties of the complete window system, and this in turn depends in part on how the coated glazing is incorporated into the overall window system. Several possible approaches are illustrated in Figure 8. If an identical coating was used in each of these different window designs, the overall thermal performance of each window would differ significantly.

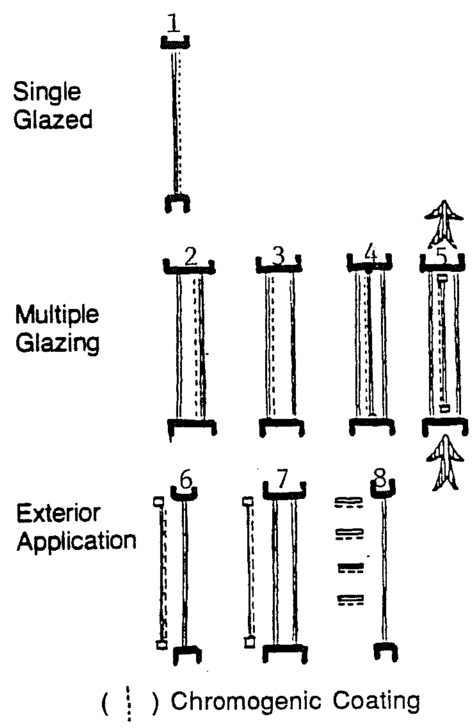


Figure 8. Chromogenic window design applications. Alternative placement of the chromogenic material is shown for single and multiple glazing types for interior and exterior applications.

We illustrate this point in Figure 9a and 9b with some quantitative results which show the dependence of total window properties on coating type and placement. Figure 9a schematically illustrates three different prototypical electrochromic responses. Type A shows a coating that switches across both the visible and near-IR wavelengths as it changes from a bleached to colored state (0.8 → 0.1). Type B switches only in the near-IR (0.8 → 0.1), maintaining a high transmittance in the visible wavelengths (0.8) for both bleached and colored states. Type C switches only in the visible (0.8 → 0.1), having a uniformly low transmittance in the near-IR (0.1) in both states.

We now show results (Figure 9b) for double glazed units consisting of two layers of clear glass with a surface having one of these coatings. We show four configurations with the electrochromic layer on the number 2 or number 3 surface (counting from the outside), and with the layer either reflective or absorptive in its non-transmitting switched state. We plot shading coefficient vs. T_v for each of the three type coatings and for the four window/coating configurations noted above. A clear, uncoated, double glazed unit is shown for reference in the upper right. For a given visible transmittance, the Type A coatings without any spectral selectivity always have a higher shading coefficient than an equivalent type C coating that rejects near-IR. A reflecting electrochromic coating always has a lower shading coefficient than its absorbing counterpart for the same configuration. Note, however, that an absorbing Type C coating on the outer pane will have a lower shading coefficient than a reflecting Type A coating on the inner pane for T_v greater than .35. The Type B coating appears as a vertical line since there is no change in T_v as the near-IR properties change.

This study reinforces our earlier conclusions that coating properties alone do not determine total window system performance and that with proper coating placement even a highly absorbing coating can provide a relatively low shading coefficient. The importance of a low shading coefficient in terms of energy and cooling impacts varies with climate, building type, and glazing area, as discussed in sections 4 and 5.

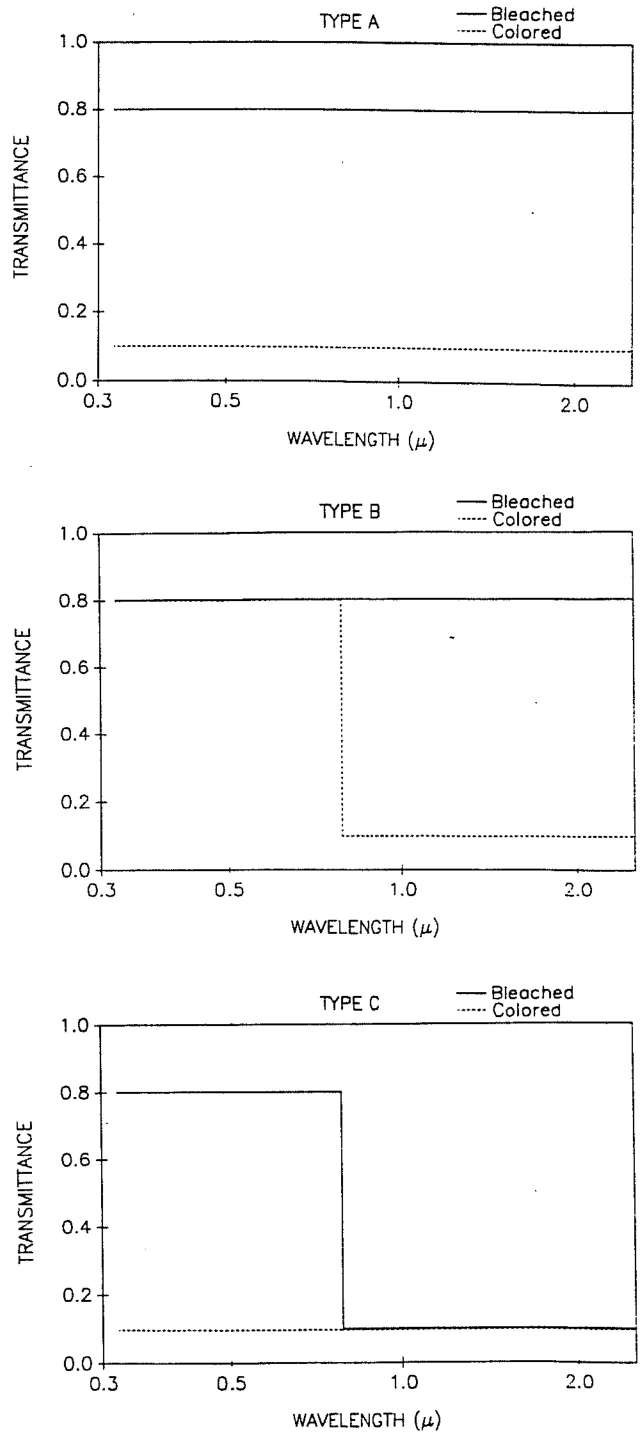


Figure 9a. Transmittance spectra of the three phototypical electrochromic devices modeled in this work. The properties of the devices switch between the bleached (solid line) and colored (dotted line) states.

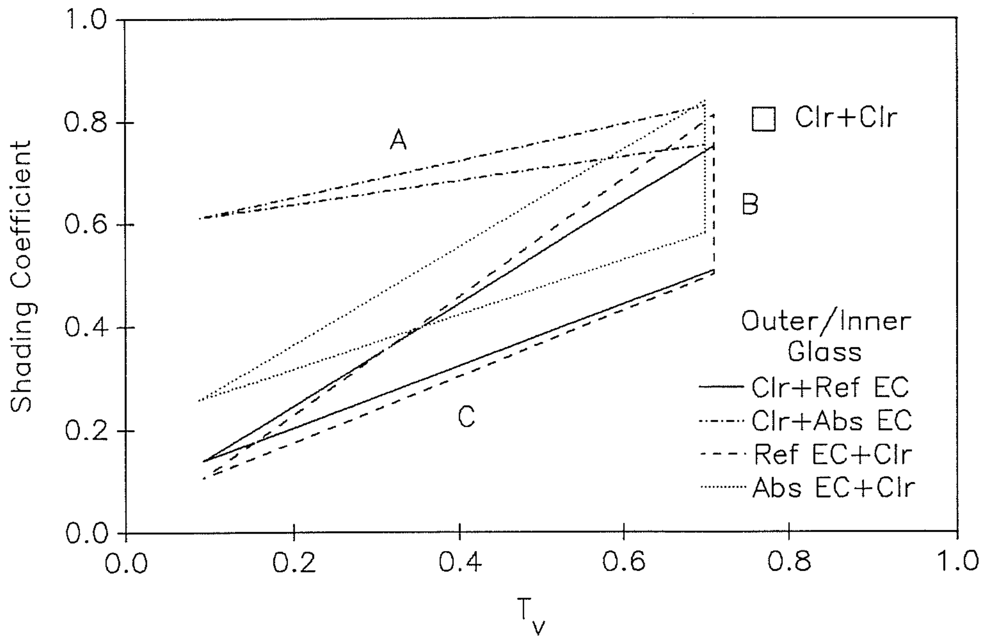


Figure 9b. Properties of reflecting (Ref) and absorbing (Abs) electrochromic coatings in a double-pane window with clear glass (Clr); the electrochromic coating has the infrared properties of clear glass (EC). The first layer listed is the outside layer. For each triangle, the results for a window with: a type A electrochromic are represented by the top line; a type B are given by the vertical line; and a type C are represented by the base. The SC and T_{vis} of a clear double glazed window without an electrochromic layer is included.(Clr + Clr).

Highly absorbing glazings also lead to thermal stresses when the glass is in direct sunlight. These stresses may approach or exceed the limits of conventional soda lime glass requiring tempered or laminated glass to meet code requirements. Thermal stress in electrochromic glazings is potentially an important issue since several of the proposed designs have a high solar absorptance, and because these absorbing layers may be incorporated into sealed units with other coatings that alter traditional heat transfer properties, e.g., low-E coatings. Results of some initial studies of stresses in highly absorbing glazings are shown in Figure 10. Here we see calculated stress patterns in a highly absorbing window which is half in shade and half in direct sunlight. Several of the highest stresses occur at the edge of the glazing which is most susceptible to initiation of cracks if the glass has imperfections due to the cutting process. Additional studies are needed to determine the importance of this issue.

Durability of any sophisticated multilayer coating is a concern to manufacturers and users. The windows industry's experience to date in this field has been generally good, although many of the more sophisticated coatings have not yet had long term field experience. The lifetime of these coatings is dependent not only on the materials systems used but in the coating deposition process, handling of the glazing during window assembly, design of the overall glazed unit (e.g., coating location within an insulated glass unit and seal properties), and operating conditions. These issues must be fully explored and understood before manufacturers will guarantee product performance for routine use on buildings.

4. ANALYSIS OF CONVENTIONAL GLAZINGS

To properly understand the performance of switchable glazings, it is useful to first examine the *comparative performance of more conventional glazings*. In the series of figures below we examine the influence of "effective aperture" in a typical office building on lighting, HVAC (Heating, Ventilating and Air Conditioning), total energy, peak demand, and chiller size. *Effective aperture* is a lumped parameter that is the product of the fractional area of the wall in glass times the visible transmittance of the glazing system. These results are taken from previous parametric simulation studies of prototype commercial buildings using the DOE-2.1C analysis model.[9,10]

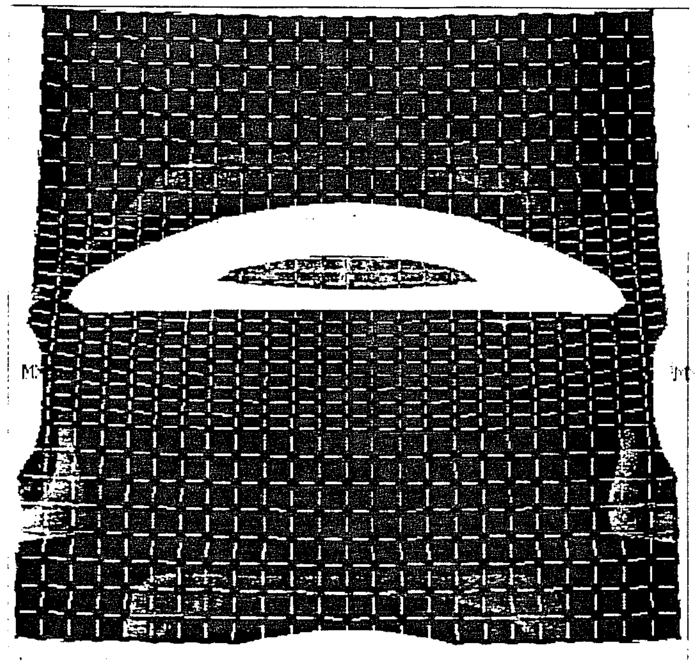


Figure 10. Calculated stress patterns seen in half shaded, highly absorbing glazings in direct sunlight. The upper half is in sunlight, the lower half in shade. Lightest tones are areas of maximum tensile stress which occurs at the edges of this .6m x .6m x .005m sheet.

In our previous studies, the influence of fenestration on net annual energy performance has been well characterized.[11-15,17] Figures 11 and 12 show some typical results from these studies. Net annual lighting energy (Figure 11) and total energy consumption (Figure 12) are shown as a function of effective aperture for a southerly-oriented facade in a representative hot, humid climate in the US (Lake Charles, LA, 30.1° N Latitude, 1051°C heating degree days at base 18°C—heating degree days are a measure of the harshness of the outdoor climate). These results illustrate typical trends and relationships between glazing properties and building energy consumption for a broad range of climates.

We compare "daylighted" and "non-daylighted" cases. "Daylighted" is used here to represent a building in which electric lighting controls dim or turn off the electric lighting in response to natural light from the sky and sun. With daylighting as a design strategy, electric lighting energy requirements drop rapidly after windows are first introduced and then level out and asymptotically approach a minimum value. This occurs as the window effective aperture increases sufficiently to provide adequate daylight for most midday operating hours. Specific savings values are a function of the lighting setpoint and lighting control strategy, as well as the climate and building parameters. These effects are illustrated in Figure 11.

In Figure 12 we examine the total energy consumption attributable to windows for the same building and climate. In the non-daylighted cases (solid lines), energy consumption increases monotonically with effective aperture. This increase is directly attributable to solar-gain-induced cooling loads. The three sets of curves reflect energy use at three different lighting power densities.

When a daylighting strategy is added (broken lines, Figure 12), electric lighting consumption is reduced and net annual energy consumption for any effective aperture is substantially reduced. A distinct energy use minimum appears in each of the daylight curves and this minimum is typically lower than the energy required for a windowless building (effective aperture = 0). At large effective apertures, energy use eventually increases at about the same rate as in the nondaylighted cases, i.e., the slopes of the dotted and solid lines are the same. Beyond a certain critical design point for minimum energy use, the constantly increasing cooling load begins to diminish daylighting's net benefits. Eventually the initial benefits are negated, as the daylighted design then requires more energy than a design having little or no glazing 100% electric lighting. These trends, repeatedly demonstrated in other climates and orientations, make apparent the need to understand in detail the impacts of glazing and daylighting on cooling loads.

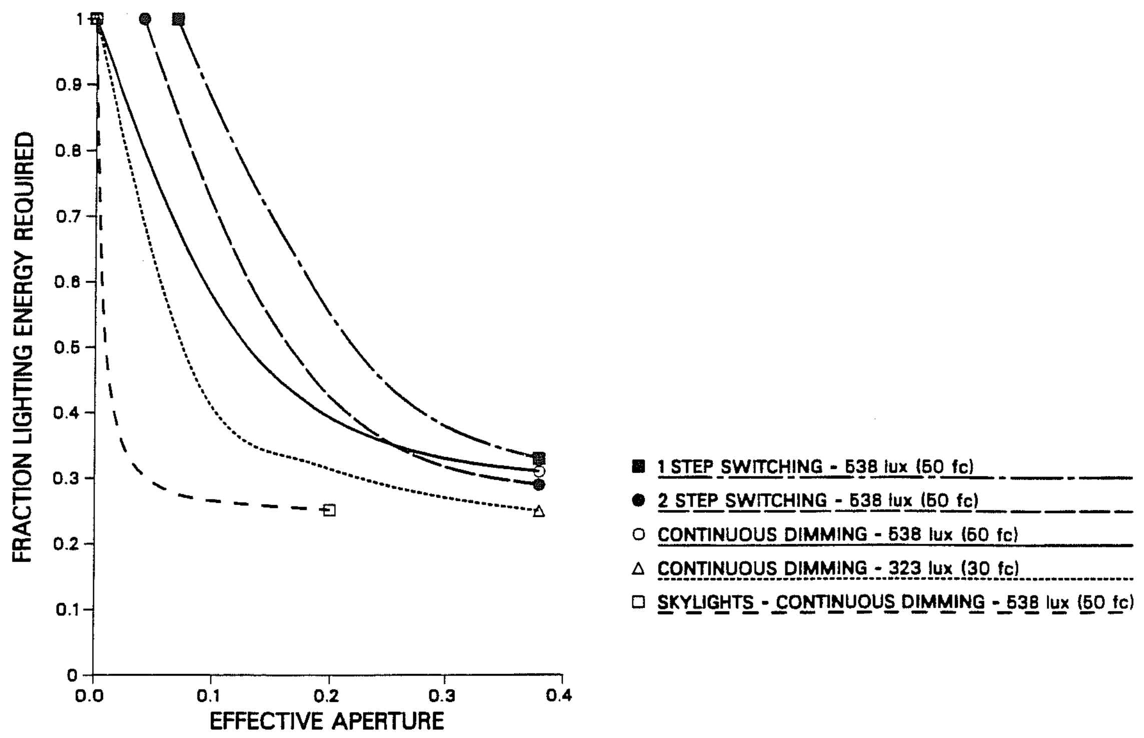


Figure 11. Lighting energy as a function of effective aperture for a south building zone showing the effect of dimming vs. switching controls and the effect of lighting setpoint. A 1 step control system is either on or off; a 2 step system is fully on, 50% on, or off; a continuous dimming system allows light output (and power input) to be continuously varied over a wide range.

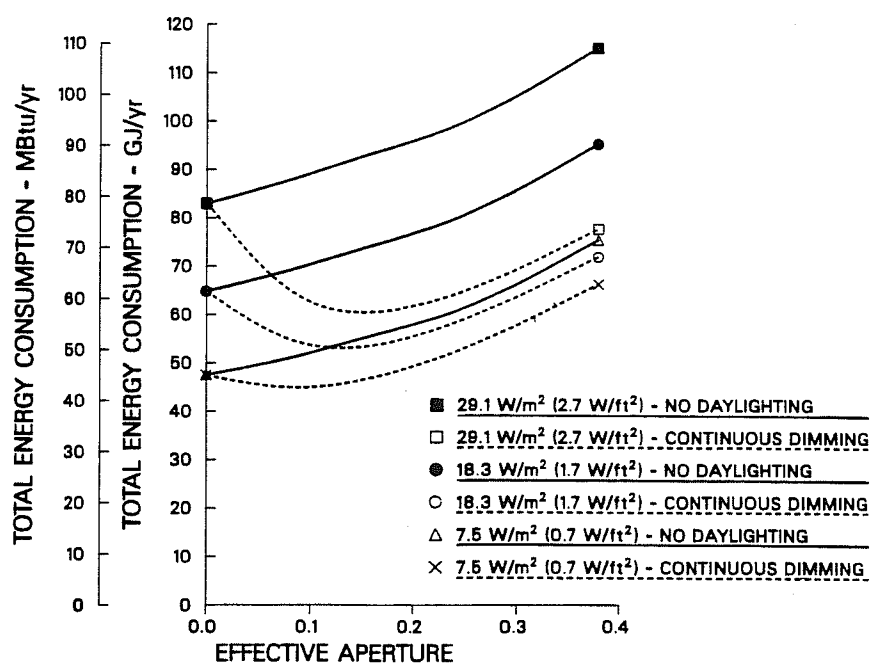


Figure 12. Total energy consumption for a typical building module as a function of lighting power density, use of daylighting controls and effective aperture. Effective aperture is dimensionless, the product of window-to-wall ratio and visible transmittance.

The key conclusions of these studies of conventional glazings are that if daylighting is used as a design strategy and electric lighting controls are provided, there is generally a moderate value of effective aperture that results in lower energy consumption than in a windowless building, and much lower consumption than in the same building without daylight use. Lighting energy use falls off rapidly as window size first increases, and then reaches an asymptotic limit at the point where interior daylight levels exceed the desired setpoint. As the window size increases further beyond the optimum, cooling loads increase monotonically causing the total energy use to rise at about the same rate, thus offsetting daylighting savings.

Energy costs in a commercial building include charges for peak electric demand as well as energy. Figure 13 shows how effective aperture influences peak electric demand for the same base case building with various combinations of interior and exterior shades. In each case the daylighted building always has significantly lower peak demand than the equivalent non-daylighted case and over a broad range of aperture values the demand is lower than that of a building without windows.

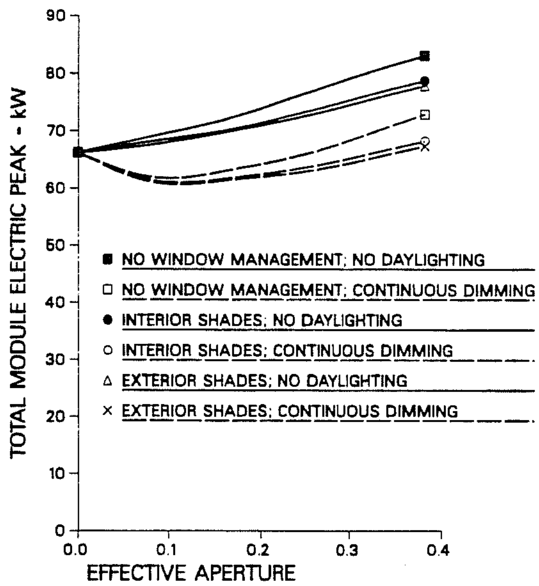


Figure 13. Peak electric demand for a typical building module as a function of effective aperture. Lighting power density is 18.3 W/m^2 (1.7 W/ft^2)

Proper selection of glazing in a daylighted building can not only save annual operating costs but can reduce first cost of some major building components as well. The chillers that provide cooling in most commercial buildings are a major cost and chiller size is directly related to cooling loads from windows. Figure 14 shows the relationship between chiller size and effective aperture in our base case building. For a given effective aperture, the cost savings between the larger chillers required for a non-daylighted building and the smaller chiller needed in a daylighted building can help offset the cost of higher performance glazings and daylighting controls.

These results suggest that properly managed commercial building windows can provide large savings relative to the typical glazing used in offices today. The key to achieving these savings is to capture the benefits of daylighting without incurring the penalties due to solar gain. In most cases (except perhaps north facing windows) this requires some form of window management, e.g., a simple shade or blind. However, experience tells us that these systems are rarely used in an optimal manner. In fact they are only infrequently used by occupants at all, and often in an improper manner. More sophisticated devices might work but practical problems with cost and maintenance for automated mechanical devices limit their market penetration.

Based on this analysis, properly designed and managed windows have the technical potential to save 50-70% of the lighting energy and perhaps 30-40% of total perimeter zone energy use with daylighting. But actual use of daylight design to save energy occurs in much less than 1% of U.S. buildings today so the total realized savings are much less than 1% of technical potentials. This is due in part to the fact that a reliable and simple-to-specify technology, with appropriate design tools, is not yet available to the building design community.

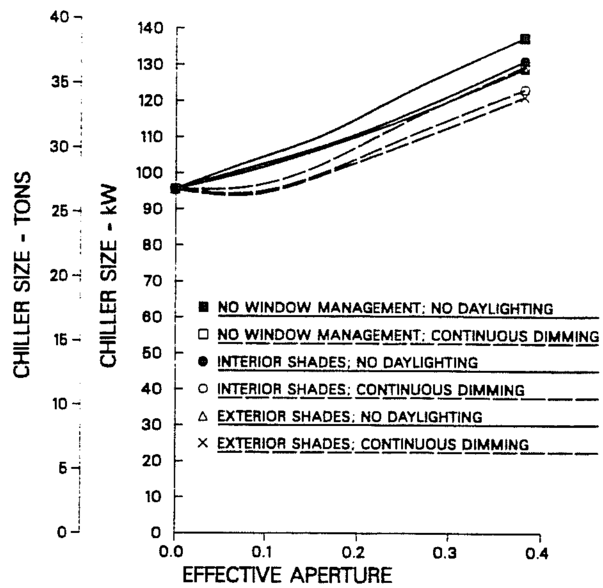


Figure 14. Chiller size for a typical building module as a function of effective aperture. Lighting power density is 18.3 W/m^2 (1.7 W/ft^2)

Smart windows have the technical potential to save 70-80% of electric lighting use and 50-60% of total perimeter zone energy use, a modest but important increase over conventional technology. But if these windows can be developed and marketed, they will provide enormous new savings because they will make the "potential" savings noted above much more realizable. It is possible that they could capture 25-50% of the potential, or 10-30% of the net energy used in perimeter zones of buildings in the commercial sector.

5. ANALYSIS OF CHROMOGENIC GLAZING EFFECTS

5.0 Background

Smart glazings can be expected to perform many different useful functions in both residential and commercial buildings. A list of major energy-related and non-energy-related functions for smart glazings, with relative priorities, is shown in Figure 15.

KEY ■ = Primary; □ = Secondary

CAPABILITY OR CONTROL FUNCTION	RESIDENTIAL			NON-RESIDENTIAL					
	WINDOWS	SKYLIGHTS	SUNSPACES	VIEW WINDOWS	DAYLIGHT WINDOWS	ENVELOPE SYSTEMS	SKYLIGHTS	ATRIA	INTERIORS
GLARE (VISUAL PERFORMANCE)				□	■	■	■	■	□
GLARE (VISUAL COMFORT)	□	□	■	□	■	■	□	■	□
PRIVACY	■		■	□					■
CONTROL OF INTERIOR FADING	■		■	□	□	□			□
DAYLIGHT CONTROL				□	■	■	■	■	□
THERMAL COMFORT	■	□	■	□	□	■	□	□	
SOLAR GAIN CONTROL (COOLING)	■	■	■	■	■	■	■	■	
CHILLER/HVAC SIZE				□	■	■	■	■	
PEAK DEMANDS CONTROL					■	■	■	□	
WINTER SOLAR GAIN CONTROL	□		□			□		□	
CONTROL RESPONSIVENESS					■	■	■	■	
CONTROL RELIABILITY					■	■	■	■	

Figure 15. Matrix for residential and non-residential applications and control functions for chromogenic glazings.

First generation smart glazings will probably be expensive, so they are more likely to be used first in commercial buildings, although eventually there will be a large residential market as well for the high end of the housing market where performance and even novelty are more important than cost. This chapter focuses primarily on commercial building applications where the energy benefits are likely to be larger and the decision-making approaches for investment in building technology are more likely to accommodate first use of a powerful new building technology.

As noted in the introduction, cooling and daylighting are the key energy-related issues for new commercial buildings in most climates. Windows generally provide a desired amenity in the form of view and contact with the out-of-doors. But this is obtained at a cost: lack of privacy, potential problems with thermal and visual discomfort, and potential increases in energy consumption, peak electric demand, and chiller size.

We can now define the ideal window from a semi-quantitative energy performance perspective. In the summer it would let in adequate daylight to eliminate or reduce the use of electric lighting, while maintaining cooling at a level less than or equal to the cooling level associated with the electric lighting alone. In the winter it would let in adequate daylight to satisfy illumination requirements, without creating glare, and the solar gain associated with daylight admittance would offset heating to the extent that it was useful, without producing overheating or thermal discomfort.

The building envelope acts as an intermediary between the external climate and the interior building environmental needs. The external climate changes continuously in both predictable and unpredictable ways. The impact on the envelope is, of course, highly orientation dependent. The interior environmental needs, particularly lighting, also change with time and task over daily, seasonal, and annual cycles. As noted above, it is thus impossible to find a single static solution for the envelope that provides satisfactory performance at all times. The static solution that comes closest to eliminating the possibility of large new energy loads is the use of highly reflective glass. Although cooling loads from the glazing and glare are thereby controlled, electric lighting is a necessity and the glazing will still have poor thermal transmittance properties relative to an insulating wall.

Heat loss is readily controlled using glazing materials with thermal resistance of at least R 0.7 m^2-°C/W (4 hr-ft^2-°F/BTU.). This technology is commercially available today, although not widely used in commercial buildings. In addition, the first cost penalty for higher heating load is not too great since in most climates peak cooling dictates system sizing. (There are other significant benefits to using very high R glazings but these are not considered further here.)

5.1 Analysis Methodology

The impacts of switchable glazings were assessed in the context of whole-building energy use using a modified version of the same building energy simulation models, DOE-2.1B and DOE-2.1C, used in the study of conventional glazings.[9,10,16] This detailed hour-by-hour building energy simulation tool allows us to examine in some detail how switchable glazings influence energy use in buildings.

In the previous section we found that optimizing glazing energy performance involves balancing the daylighting benefits against the cooling costs. (There are other related tradeoffs between view and privacy, light and glare, etc.). From the standpoint of effective energy utilization, a lighting system should ideally provide no more light flux than is necessary to meet the required illumination level at the task. This is true of electric lighting systems as well as daylighting systems. However, in many designs, especially in typical perimeter offices with windows in one wall, daylighting provides highly nonuniform flux distribution. Electric lighting is typically controlled uniformly over a large daylighted zone in response to the daylight level at a single point in the zone. Daylighting can be designed to provide much, or even all, of the required lighting, but because of nonuniform flux distribution and imperfect controls for electric lighting, illumination levels in some parts of the room sometimes exceed requirements. The excess illumination imposes a cooling load with no additional lighting benefit.

In order to better understand the impact of chromogenic glazings on the relationship between daylighting and cooling load, we compared the performance of several different conventional and smart glazing options. We examined daylighting and solar control impacts by varying both types of control mechanism and control logic. These included varying the spectral selectivity of the glazing, using simple window shades with on-off control, and using sophisticated optical switching materials having continuously variable transmission that is responsive to light levels.

We studied glazing performance in two extreme climates: heating-dominated Madison, WI, USA (43.1° N Latitude, with 4176°C heating degree days at base 18°C) and cooling-dominated Lake Charles, LA, USA. In both climates the trends and the magnitude of daily cooling load effects are similar, but because of Madison's shorter cooling season, its annual values are much lower. For this discussion we will use examples from Lake Charles.

5.2 Description of Glazings and Control Algorithms

The fenestration systems modeled, all with Window-to-Wall-Ratio (WWR) = 0.3, include three conventional types and two that have advanced glazing materials with chromogenic properties. The term K_e, the ratio T_v/SC, is useful in discussing the daylighting transmittance of the glazing material in relation to the cooling impact of the material. SC is the shading coefficient of a glazing, a dimensionless value that indicates the total solar heat gain of the glazing relative to clear single glass (which has SC = 1.0). SC includes directly transmitted radiation as well as energy that is absorbed by the glazing and then reradiated or convected into the room. The glazings are identified as follows:

PR - Passive Response Chromogenic
Photochromic glass, responsive to solar radiation. Shading coefficient (SC) varies linearly from 0.8 to 0.2 as total solar radiation incident on the glass varies from 31.5-315 W/m^2 (10-100 Btu/ft^2 h). Visible transmittance is equal to shading coefficient (K_e = 1.0). There are no separate operable shades with the photochromic glass.

AC - Actively Controlled Chromogenic
Electrochromic glass with T_v controlled to hold daylight levels to a maximum of 538 lx (50 fc) at the control point in the room. Maximum T_v = 0.8 and K_e = 1.0. There are no separate operable shades.

HT - High Transmission Glazing
Conventional high-transmission glazing system with SC = 0.8 and T_v = 0.78. No operable shades.

HTS - High Transmission Glazing with Shade
Conventional high-transmission glazing with SC = 0.8 and T_v = 0.78. A window shade is deployed when transmitted direct-beam solar exceeds 63 W/m^2 (20 Btu/ft^2 h). The window shade reduces solar gain by 40% and reduces visible light transmittance by 65%.

LT - Low Transmission Glazing
Conventional low-transmission glass with SC = 0.18 and T_v = 0.07. No operable shades.

The driving environmental force that makes switchable glazings so desirable is the tremendous variability of daylight. Daylight flux levels vary widely over time, from sunrise to sunset, from cloudy day to clear day, and from season to season. With a single fixed daylight aperture, and without variable solar control, interior daylight levels will be either too high or too low much of the time. High levels will add cooling load; low levels will add electric lighting load.

An example of the variability of the solar heat gain through several fenestration options over a day in a west zone is shown in Figure 16. The concurrent daylight levels at the control point are shown in Figure 17. For both figures we show results for a clear July day, showing the variability from diffuse early morning sky to direct afternoon sun. A similar range would occur in a south zone, but with seasonal variation.

With high-transmission glass (HT), daylight from a diffuse sky provides design lighting requirements most of the morning hours. During afternoon hours, with direct-beam solar as a source, even with shades pulled (HTS) the daylighting level is about twice the required level, imposing additional cooling load with no additional lighting benefits. If afternoon solar control were to govern the daylighting level, morning daylighting levels would be too low and electric lighting would be required. Low-transmission glass (LT) illustrates this approach as it minimizes solar heat gain but provides insufficient daylight to meet the design criteria.

A fenestration control option that continuously modulates the daylighting aperture so that the daylight level at the control point never exceeds the design level is represented by AC. In this case, the chromogenic glazing was modeled with K_e = 1.0. An automatically controlled mechanical device, such as exterior venetian blinds, might be expected to perform similarly. This level of control is required to mitigate the afternoon peak solar gain while retaining required daylight levels in the morning. Figure 16 confirms that the active chromogenic material has the lowest overall daily peak cooling load.

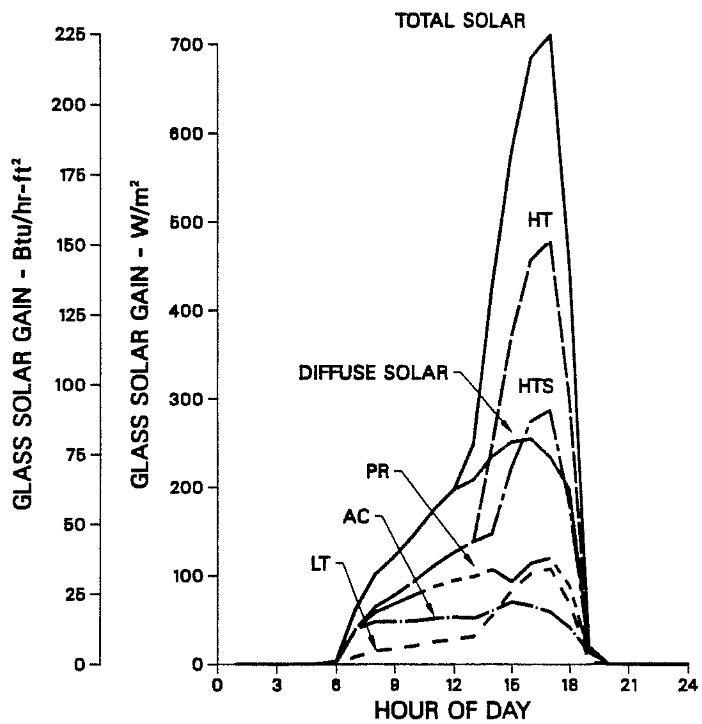


Figure 16. Hourly solar heat gain through several conventional and chromogenic glazing options for a West-facing zone on a clear July day. "Diffuse Solar" or "Total Solar" show the magnitude of solar radiation incident upon the west-facing glazing.

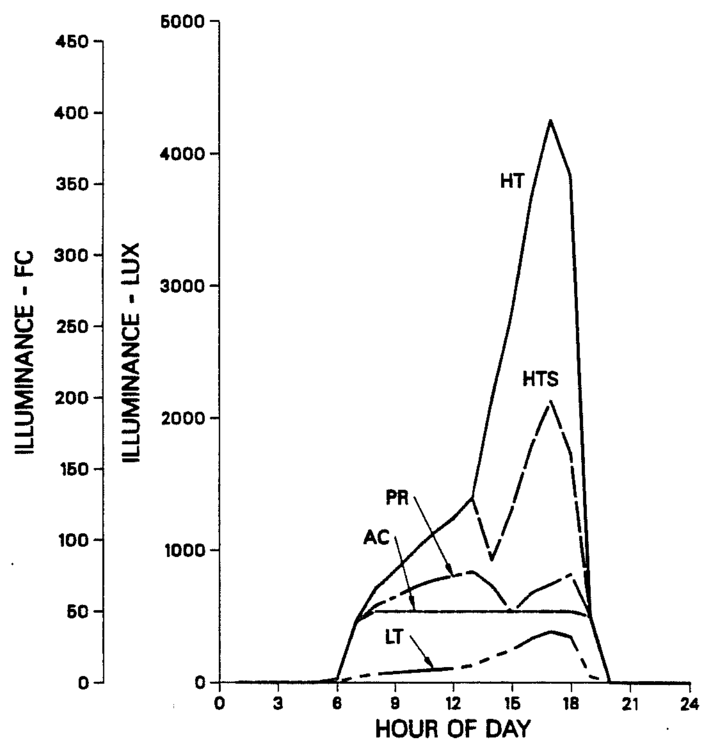


Figure 17. Hourly interior daylight illuminance through several conventional and chromogenic glazing options for a West-facing zone on a clear July day. Desired level is 538 lux.

Figure 18 shows the effect of the five glazing options on monthly cooling load. As expected, the high transmission glazing (HT) has the highest cooling loads and the addition of a simple shade only provides a small improvement. The "electrochromic" glazing consistently outperforms the "photochromic" glazing for all months and has the lowest annual cooling consumption of all five options. The low transmission glazing (LT) is generally better than the photochromic but not as good as the electrochromic glazing. If our analysis stopped at this point, one would be inclined to select low transmission glazing as the most cost effective glazing in reducing cooling load.

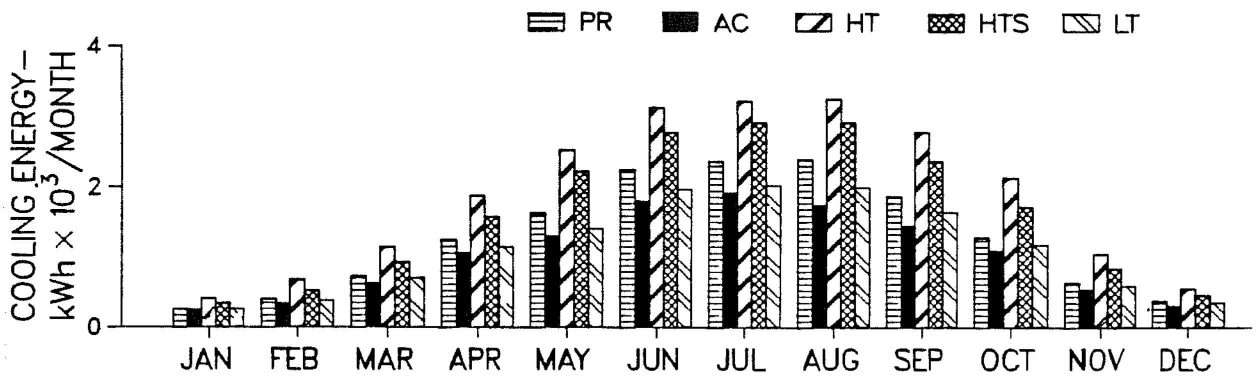


Figure 18. Monthly cooling energy consumption for five glazing options in the building module in Lake Charles.

However, the complete energy consumption picture for this $558m^2$ module (6000 ft^2) is shown in Figure 19. This plot of monthly total energy consumption includes lighting, heating, cooling, fans, and miscellaneous internal electrical use. The two smart glazings are clearly the best performers year round, with the electrochromic glazing having an advantage in the summer months as noted above. The low transmittance glazing is the poorest performer in the winter months because there is little or no daylighting benefit. During the summer months the low transmission glass performs about the same as the clear glass with shading. This occurs because even though the low transmission glass has lower cooling loads (refer to Figure 18) it also has higher lighting loads than the clear glass with shading.

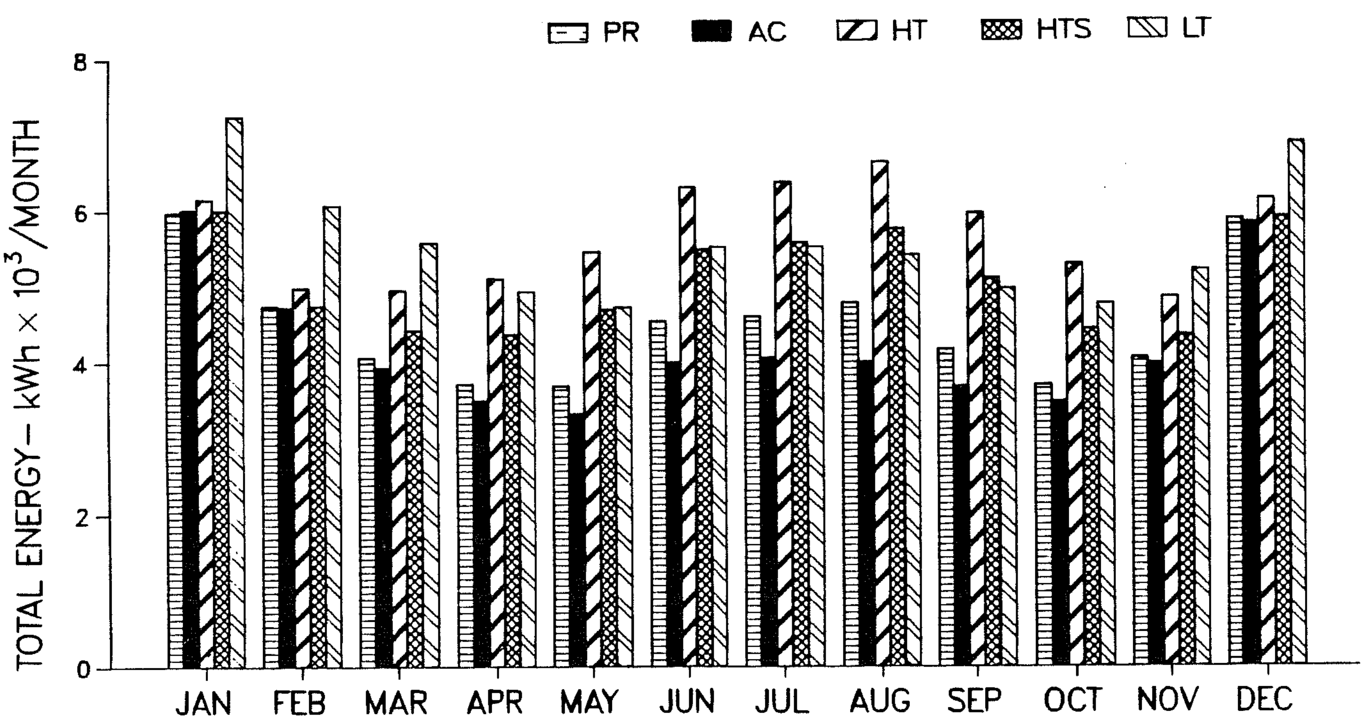


Figure 19. Monthly total energy consumption for all end uses for five glazing options in the building module in Lake Charles.

An additional perspective is provided in Figure 20, where monthly peak electric demand is plotted over the year. Once again the electrochromic glazing has the best performance with the photochromic glazing following closely behind. Lighting and cooling are the key contributors to the peak demand. The smart glazings provide adequate daylight to reduce electric lighting demand while minimizing cooling. If the lighting power density was higher than the efficient system modeled in this study, 18.3 W/m^2 (1.7 W/ft^2), the savings would be even greater.

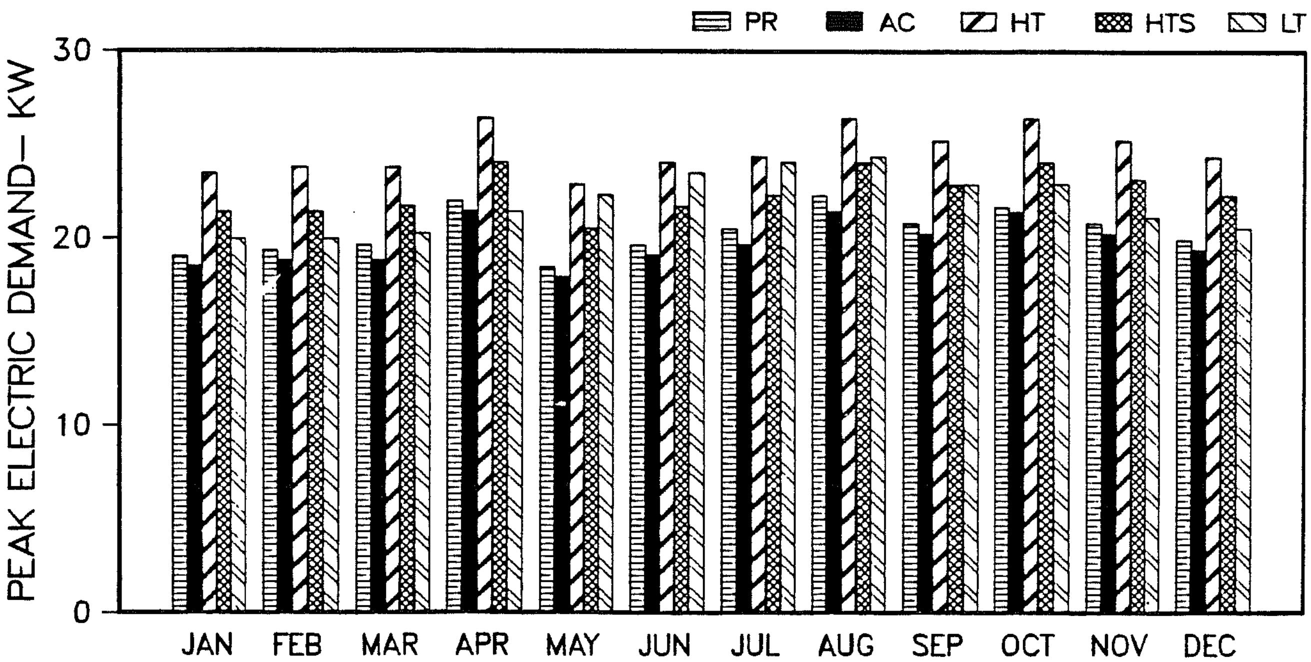


Figure 20. Monthly peak electric demand for five glazing options in the building module in Lake Charles.

A final perspective is provided by examining the impact of these five glazing options on chiller size which represents a significant first cost in most buildings. Since chiller size is determined by the peak cooling load, we find the ranking follows that shown for cooling loads in Figure 18. The electrochromic has the smallest chiller size followed by the low transmittance glass and then the photochromic glazing. The chiller required for the electrochromic glazing is 12% smaller than that of the low transmittance glazing and 36% smaller than the system needed for the unshaded clear glass.

5.3 Cost Implications

With proper design, smart glazings will reduce peak cooling loads, peak electrical demand, and building energy requirements, which in turn will affect both first cost and operating cost. Advanced glazings would generally be more expensive than a conventional coated glass alternative and may require additional expense for costs. However, reductions in chiller size may provide first-cost savings that can offset some of the costs of electric lighting controls, solar-control devices, and improved glazing products. If we substitute the electrochromic glazing for the high transmission glazing with conventional shading the first cost savings resulting from chiller size reductions amounts to \$72.00/m^2 glass (\$6.67/ft^2) glass, a very significant, figure that should offset a large fraction of the incremental cost of the new glazings.

Annual operating costs are influenced by the effectiveness of the daylighting design in relationship to the electric lighting system, the climate, and local utility rates, which vary widely. Annual electricity costs per unit area of daylighted space are shown in Figure 21. Using a typical utility rate structure in the US today, (peak demand charges of \$17/kW and consumption charges of \$0.07/kWh), we calculate annual costs (in US \$) for the conventional glazing with and without daylighting controls and for the smart glazings described above.

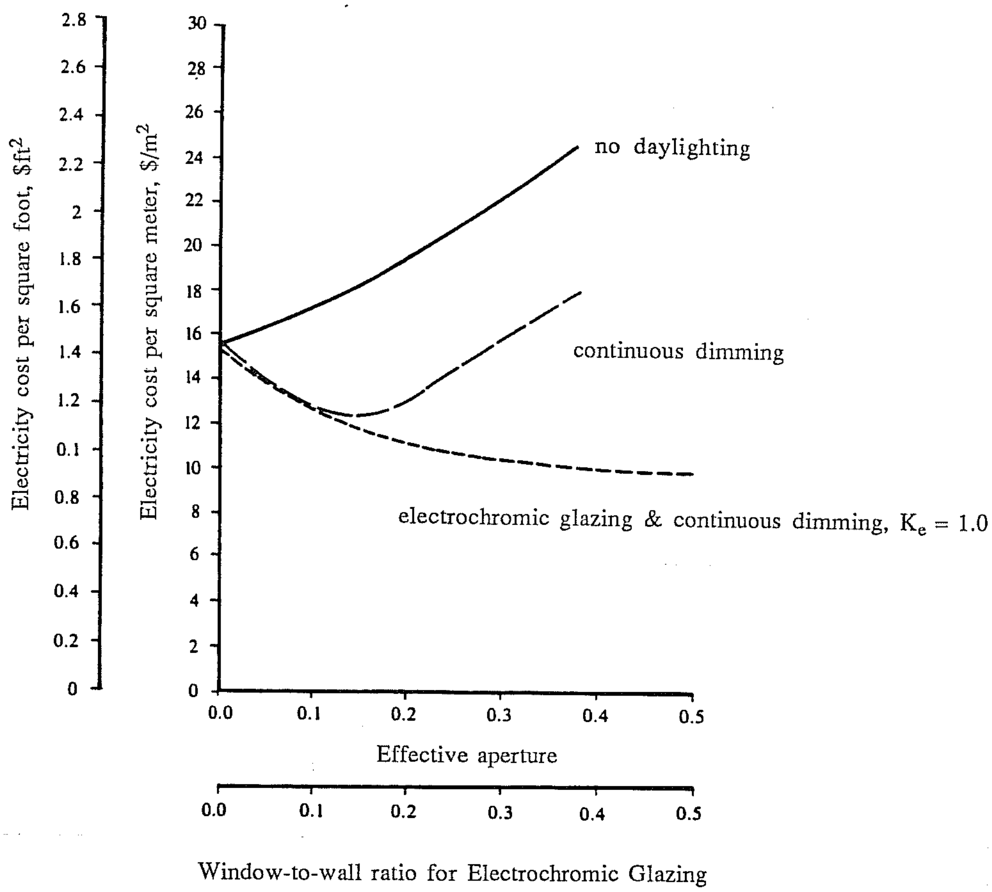


Figure 21. Annual electricity costs (in US$) per unit area of daylighted floor space. All three curves are for lighting power density of 18.3 W/m^2 (1.7 W/ft^2).

The upper two curves are similar in shape to results shown in Figure 13 for total energy consumption of daylighted and non-daylighted cases for conventional glazings. The benefits of daylighting controls are apparent, but both curves show rapidly rising energy use when the effective aperture increases above .2. The lower curve in Figure 21 representing the electrochromic glazing, however, shows continuously decreasing energy costs out to the largest effective aperture, which would represent a wall with an almost entirely glass facade. Thus smart glazings appear to provide significant cost savings as well as the architectural freedom to size windows to accomodate view, aesthetics, etc., without an energy or comfort penalty. (Note that additional factors not relevant to this warm climate example might further constrain glazing selection and area.)

6. SUMMARY AND CONCLUSIONS

Chromogenic coatings are an important emerging technology for the window and building industry. They enhance building performance by improving the energy performance of buildings as well as by addressing all of the related energy/productivity issues that will influence future building design and operation. In principle, most of the benefits we see for smart glazings might be captured by intelligent and consistent use of existing window control technology. But people are paid to be productive and experience tells us that only a minority will be willing to take an active involvement in window management activities.

Smart window technology offers the potential to capture the large savings that can theoretically be obtained by existing technology but will otherwise never be achieved. Benefits include energy savings, electric load shaping, and peak demand reductions, as well as downsizing of HVAC systems. These can be achieved while also providing improved levels of thermal and visual comfort, privacy, view, and other benefits associated with window use.

The energy savings potential for switchable glazings has been one of the major forces motivating R&D on the subject. These same forces were critical to the initial market success of low-E glazings. However, it would be a serious mistake to believe that "energy cost paybacks" alone will drive market development. There are numerous market-context issues, still unresolved, that influence the cost, performance, and acceptance of a chromogenic window. Several of these issues (benefits, obstacles, and uncertainties) are summarized below:

1. <u>Window Design</u>

   The specific optical and thermal properties of the chromogenic glazing, such as its absorptance and reflectance over the solar and thermal spectra, influence thermal stress which in turn influences the probability of breakage. The glazing surface on which the chromogenic layer is placed can influence the thermal properties of the total window unit. The use of other types of coatings and treatments, e.g. UV filters, low-E coatings, gas fills, all influence the properties and cost of the finished product. Smart windows can have either a diffuse or specular transmittance response. In some applications a diffuse low transmission state is important for privacy, although in most applications the diffusing properties are not desired because view is obstructed.

2. <u>Control Systems</u>

   Issues of passive-response chromogenic devices (photochromic and thermochromic) versus active-response devices (electrochromic and liquid crystals) are important. The active response materials have complete user or automatic control potential. The passive devices are limited in their capability to respond "intelligently" to all ambient environmental influences. The passive control device has the advantage of being self-contained. The active device will probably require an electrical supply and a control circuit. Either a central or local control system might be used and power could even be provided on a decentralized basis with the use of solar cells. Most building systems in the future are likely to be automated but there is not yet a complete understanding of whether manual control at each window should be provided. Of the passive devices, there are differences between control with temperature or light intensity. The trigger points for these materials can often be adjusted when the material is fabricated but not thereafter, so there is little ability to cope with newly encountered conditions at the building site.

3. <u>Cost</u>

   The probable cost of a chromogenic glazing can be analyzed on several different bases. First, a production cost perspective would include: the influence of the materials cost, the deposition method, the device design, and the ease of assembly into a window unit. For electrochromics there are a range of potential deposition methods and device designs which can influence both cost and device characteristics. Second, the costs can be looked at from a market viewpoint. This perspective examines the equivalent products now on the market, their cost, and how easily they might be displaced by a chromogenic product with its price level. The preliminary opinion is that chromogenic glazings will fit well into niche markets at first and expand into the major markets later, similar to the development of Low-E glass. The many benefits (e.g., comfort, reduced fading) of chromogenic glazings will help make a marketing case that will far outweigh the energy payback arguments alone. First cost savings from reduced chiller size, as well as incentives from electric utilities to reduce peak power requirements, are all likely to also favorably influence the market potential of smart glazings in the future.

4. <u>Marketability</u>

   An important initial market will be those applications where expensive mechanical shading systems are now used. As noted above, chromogenic glazings can be marketed stressing a wide range of advantages to overcome the cost obstacles. In addition to the energy payback viewpoint, it seems likely that the glazings will be marketed from several other points of view: their role as a dynamic novelty item, privacy, comfort, health, and office productivity. In the future, other novel financial arrangements are possible: a curtain wall system incorporating electrochromics might be purchased by an electric utility and leased back to the building owner.

5. <u>Non-architectural Applications</u>

   A range of additional building applications for interiors, privacy use, and aesthetics will help introduce chromogenic products throughout the building sector. Applications in other fields, such as automotive, aircraft, etc., will aid in the introduction of chromogenic glazing into the buildings market. First use of electrochromic devices as rear view mirrors and sunroofs in cars, and as sunglasses, will help speed public understanding of the benefits of these devices for future building applications.

6. Glazing and Building Industry Trends

The glazing and window industry is tending toward higher value-added products under the pressure of more highly competitive global markets. Smart glazings will provide a product worth many times the value of the basic glass component. There is a tendency towards "smarter" buildings in the future using more sophisticated automation and control systems and enhanced communications between building components. There is probably a large niche in this market for building system suppliers who provide integrated curtain wall systems to building owners, suggesting the need for further explorations of the links between the smart glazings elements and the remainder of the building to which the glazings will be linked.

7. Environmental Trends

There is growing evidence that current international attention to major global environmental threats (e.g. global warming, CFCs and the ozone layer, acid rain) will result in a coordinated world-wide response. Most studies suggest that in the short term (the next 20-30 years) the most cost effective societal option to slow environmental degradation is an aggressive energy efficiency program that substantially reduces energy use and related emissions while permitting real growth in needed energy services. Smart glazings, along with many other advanced building technologies, would become an important element in such a future scenario.

Within this broad perspective we are confident that smart glazings will be successfully developed and marketed for architectural applications. Since there are many different building applications and needs, several different smart glazing technologies may all find market niches. In the near term, the versatility of active response chromogenics (probably electrochromics) suggest that they are clearly the switchable glazing type most likely to find widespread applicability in buildings. While there are many difficult technical challenges to be solved before electrochromic glazings become commercially available, there are no obvious insurmountable technical or production problems at this time.

Chromogenic glazing technology also fits well with the trend toward more sophisticated building management control devices and systems, and the trend to integrate electronics and sensors into the products and machines on which we depend at home and at work to make them more responsive to human needs. The specific successful coating technology and the timing of market introduction depend upon accomplishments in the laboratory and on market forces. With continued R&D, viable commercial products for buildings should be developed and reach the market in 4-8 years. These smart windows will become an important feature in the home and office of the future, where health, comfort, productivity, and control of energy costs will continue to be important concerns.

7. ACKNOWLEDGEMENTS

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