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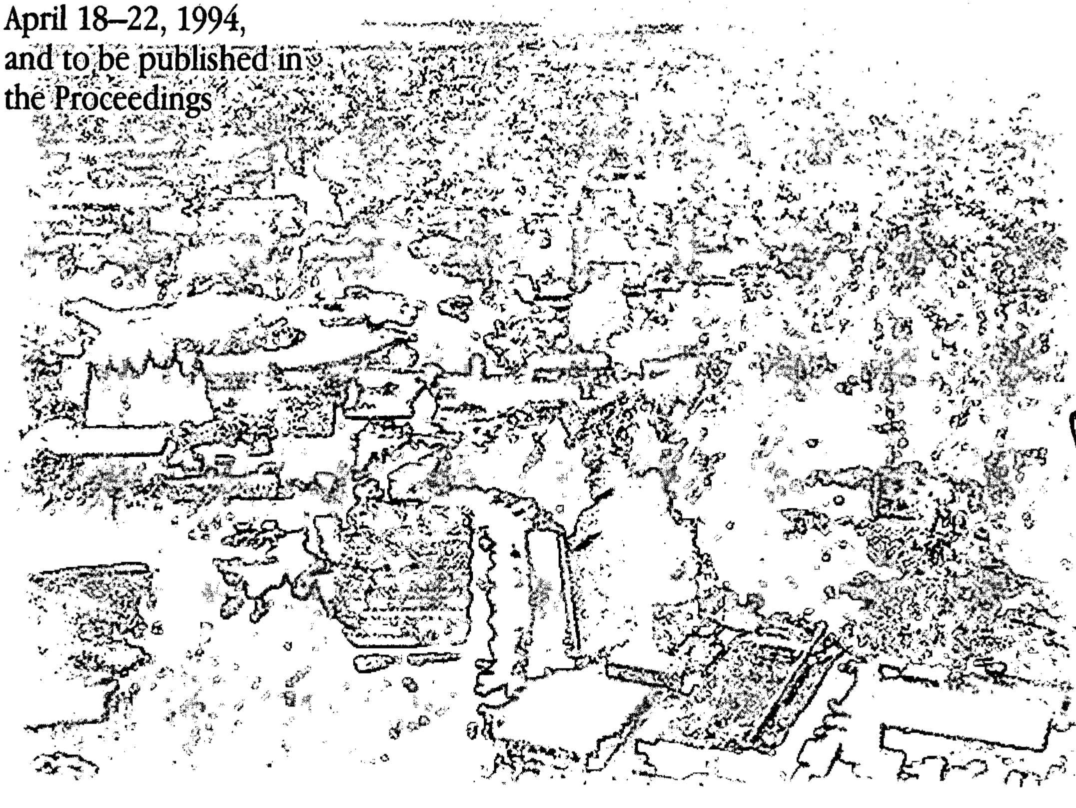

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A Review of Electrochromic Window Performance Factors

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1. ABSTRACT

The performance factors which will influence the market acceptance of electrochromic windows are reviewed. A set of data representing the optical properties of existing and foreseeable electrochromic window devices was generated. The issue of reflective versus absorbing electrochromics was explored. This data was used in the DOE 2.1 building energy model to calculate the expected energy savings compared to conventional glazings. The effects of several different control strategies were tested. Significant energy and peak electric demand benefits were obtained for some electrochromic types. Use of predictive control algorithms to optimize cooling control may result in greater energy savings. Initial economic results considering annual savings, cooling equipment cost savings, and electrochromic window costs are presented. Calculations of thermal and visual comfort show additional benefits from electrochromics but more work is needed to quantify their importance. The design freedom and aesthetic possibilities of these dynamic glazings should provide additional market benefits, but their impact is difficult to assess at this time. Ultimately, a full assessment of the market viability of electrochromics must consider the impacts of all of these issues.

2. SUMMARY

Electrochromic windows offer significant potential performance advantages in buildings. Materials science advances in the last decade now provide some optimism that workable devices with desirable performance properties can be fabricated. However, in order to make the transition from promising laboratory results to mass-produced commercial products, a very large financial investment will have to be made by manufacturers in engineering development and fabrication facilities. This investment will only be made if manufacturers can see a profitable equation linking device properties, window performance, production cost, sales price, designer/specifier interest, and owner/occupant acceptance. This equation is a complex one, including energy and peak demand costs, heating and cooling system sizing, environmental impacts, thermal and visual comfort, privacy, aesthetics, installation and maintenance costs, product distribution and marketing approaches, utility demand side management programs, and more. In the scramble to develop workable electrochromic devices, the focus of most manufacturers to date has been on refining device properties but without a detailed understanding of critical building performance issues.

This summary outlines the key arguments for the eventual market success of electrochromic windows in commercial buildings, e.g., offices. The following pages provide some of the technical backup and rationale for these conclusions. We note that there are varying degrees of confidence associated with these results and we expect that it will take significant additional study and field testing before more definitive conclusions can be reached. The problem is made more difficult in that it is not a simple "engineering optimization" problem but rather one that includes tradeoffs between energy savings and subjective human response to lighting quality.

1. Despite recent materials science advances in device performance, there is considerable room for further improvements between current devices and a marketable device.

2. Electrochromic windows will include the electrochromic (EC) coating as part of a more complex multilayer window system. Other design parameters such as substrate properties or insulating glass design, can raise or lower the apparent performance of the EC coating alone.

3. Electrochromic windows offer large energy performance benefits compared to conventional window technology. They can outperform the best currently available window systems (in most applications) and have lower annual energy performance than an opaque insulated wall. The primary energy benefits are reduced cooling loads and the ability to reduce electric lighting use by managing daylight admittance. For summer months and in hot climates year-round, the EC coatings themselves and the entire window system would normally be designed to minimize solar heat gain with admitting adequate daylight. In colder climates, admission of solar heat gain with daylight in winter may be advantageous, but this must be controlled so as not to create glare.

4. The lighting savings due to daylight utilization represent a large fraction of the EC window energy benefits. In principle any highly transmitting window will admit adequate daylight and will also save electric energy when a photocell lighting control is

used. However, experience in the US and elsewhere suggests that glazings (in particular, view windows) that admit daylight but do not have automated control of daylight transmittance, e.g., shades, blinds, often result in unacceptable glare and poor lighting quality. Under these circumstances the photocell controls may be disabled by occupants, thus eliminating the expected daylighting savings. Thus although simulations tell us that a selective glazing with a manually operated shade will save as much lighting energy as an EC window, real world shows that this potential will rarely be achieved. Blinds and shades can be motorized and automated, but this adds significant cost.

5. EC windows result in reduced peak cooling loads and should allow smaller heating, ventilating and air conditioning (mechanical system) system sizing with some first cost savings. Maximizing this benefit will require more sophisticated control systems and operating algorithms that are sensitive to occupant needs as well as energy management requirements, and may also benefit from anticipatory controls to minimize cooling loads.

6. EC windows should provide better glare control and thermal comfort management than most conventional systems. This study shows some calculated savings but more extensive modeling must be done to better understand these issues. Controlling EC devices to optimize comfort may require some tradeoffs with maximizing energy savings, although this is unlikely to reduce savings substantially.

7. Utilities with demand-side management programs to reduce energy and peak demand should be very interested in the performance of EC windows because they provide the type of flexible control the utilities need. Incentive and rebate payments to customers to promote these strategies should help reduce the actual cost to the building owner. Currently some U.S. utilities provide rebates of \$10/m^2-glazing for static, spectrally selective glazings so the rebates for EC glazings should be even higher.

8. The net added first cost of the EC window should account for the cost of the EC device and its associated wiring and controls, offset by possible mechanical system credits, the use of a lower cost shading system or elimination of the system, as well as any utility incentive credits. Some utilities might consider purchasing the entire system and providing a lease-back arrangement to the building owner.

9. Building designers have been told for years that large windows typically cause energy use penalties and many building codes recognize this effect by restricting window area. EC windows can be made in virtually any size without increasing the energy use of the facade, and often with significant reductions compared to an opaque, insulated wall. This provides a new degree of design freedom without adverse energy and environmental consequences that designers have not previously had.

10. The architectural and aesthetic appeal of a dynamic coating and controlled building facade is difficult to quantify but it will be a major factor for many buildings. Many design decisions are made not on the basis of "paybacks" but rather on the basis of style and appearance. This is likely to increase the market penetration of a technology whose appeal extends far beyond its engineering function. Electrochromic technology can be incorporated into windows in a variety of designs and patterns in addition to a one-to-one replacement for sheets of glass. They can also be incorporated into overhangs, louvers, lightshelves, and other fenestration design elements. While this study focused on vertical glazing, they also should have an important role in the sloped glazing and skylight market.

As electrochromic technology matures in the hands of materials scientists, there needs to be greater exploration of building performance issues by building scientists, designers, and marketing staff of manufacturers, and more extensive interaction and feedback between these groups. This will ensure that this new set of products has the greatest potential for a smooth and efficient transition into what promises to be a prominent role in buildings of the 21st century.

3. INTRODUCTION

Electrochromic technology is rapidly advancing towards the development of a commercial window that will allow active optical response to changing environmental conditions. Previous studies have indicated that this technology can save cooling and lighting energy and, at the same time, provide glare control and improved thermal comfort. These benefits are realized by changing the optical properties of windows to optimize heat gain, daylight, and thermal comfort in response to changing conditions. Electrochromic devices change optical properties when a low voltage is applied to the coating, allowing their control to be directly linked to the building mechanical system control system.

In this report, we survey information on electrochromic optical properties and use these properties to perform annual energy consumption and peak demand calculations. In addition, we calculate thermal and visual comfort indices. The important issue of reflecting versus absorbing electrochromic types is addressed. A first comparison was made between two principle types of control strategies: one based on simple instantaneous measurements and the other based on predictive or anticipatory calculations of the mechanical system's energy use.

4. ELECTROCHROMIC MATERIALS AND DEVICES

4.1. Idealized electrochromic materials

Reilly, Arasteh and Selkowitz[1] classified ideal electrochromics into three types whose transmittance switched over different spectral ranges: the entire solar spectrum, the visible subspectrum only or the solar infrared subspectrum only. The transmittance could vary between 0.1 and 0.8 in the particular spectral range as illustrated in Fig. 1. In addition, each of these three spectral types could change transmittance by a corresponding change in either absorption or reflection. Thus, six basic types of ideal electrochromic materials were considered.

The total solar heat gain includes both directly transmitted radiation as well as that fraction of the absorbed radiation which flows inward by reradiation and convection. Shading coefficient (SC), which is a standard measure of solar heat gain, was calculated for the six electrochromic types mentioned above in combinations with other glazings. The visible transmittance T_v, which is a determinant of daylight utilization, was also evaluated. These parameters were calculated using a modified version of WINDOW 3.1.[2] In cooling dominated situations, daylight, which also carries heat energy, must be weighed against solar heat gain. Fig. 2 shows that the lines of visible transmittance T_v vs. SC form a triangle for the three spectral types of ideal electrochromics as the coating is switched. For the infrared-switching electrochromic, visible transmittance is fixed so that SC increases or decreases as the coating is switched. For a given value of T_v, the solar-switching electrochromic always has a higher SC than the visible-switching electrochromic. At minimum T_v, the spectra become identical, and the solar and visible lines converge. The triangle for the three spectral types switching in the reflecting mode is shifted to lower SC than the absorbing mode triangle. In other words, all else being equal, a reflecting type coating will always reject more solar energy than an absorbing coating.

A single pane electrochromic window (with the device protected in a laminated configuration) or a double pane window with clear glass on the outside would behave as shown in Fig. 1(a). There is a significant difference between absorbing and reflecting types in these configurations, because of the large inward flowing fraction of absorbed energy. The differences between absorbing and reflecting coatings are diminished if the electrochromics are used in conjunction with a clear inner pane in a double-glazed window. Fig. 2(b) shows that, in the case of double glazing, the two triangles representing reflecting and absorbing types are much closer to coincidence. The low-T_v (high absorption) end of the absorbing triangle pivots downward, relative to single glazing, because of the increased thermal resistance between the absorbing electrochromic and the interior.

Similarly, the differences between the visible-switching and solar-switching electrochromics will diminish (the triangles will close) when the electrochromics are used in series with spectrally selective glazings. Thus, in Fig. 2(c) where the inner glazing of the insulating glass unit has spectral selectivity, the two triangles have moved together as well as closed up. The net result is to put all electrochromic glazings on a roughly equal footing except for the infrared-switching types. Infrared-switching electrochromics are not considered a useful option under the control strategies and climates used in this study.

4.2. Real electrochromic materials

4.2.1. Range limitations

We surveyed the optical properties of existing materials and devices to evaluate the best results for modeling of energy performance. The most commonly available information in the literature is transmittance over the visible spectrum only. For materials research or device development, such transmittance data often serves as a fair indicator of relative performance, especially when considering materials or devices of the same type or configuration. Performance modeling, however, requires knowledge of the solar heat gain coefficients which can only be determined from spectral data that covers the full solar band in both transmittance and reflectance. Nevertheless, we collected hundreds of these limited spectra by digitizing graphic data in published articles and converting it to common units. Some additional data and devices were obtained directly from various researchers. One of the projects being conducted by the International Energy Agency (IEA)[3] is to collect complete sets of data from the participants in many countries. As this project advances we should be able to refine our estimate of the state-of-the-art electrochromic performance. Also, the IEA is attempting to standardize the test methods used to characterize the performance of electrochromic devices.

Optical test methods are relatively well standardized. Although there is disagreement worldwide on reference mirrors, integration procedures and other details, most transmittance values are accurate to within a few percent. Comparisons among materials and devices are difficult primarily because of variations in electrochemical parameters. For example, there is no simple rule which allows the researcher to judge the maximum allowable voltage that can be placed on a device. For short periods, higher voltages can be used that will result in fast switching over a wide range of transmittance. Breakdown or irreversibility may occur, however, limiting the device lifetime. The devices used a variety of ion-storage electrodes, ion-conductors, and transparent contacts in a range of thicknesses. The electrochemical tests were not only performed under different conditions, but also in different environments with a variety of ionic species. Thicker films in general tend to have a greater dynamic range: The dark state of thick coatings is darker because of the greater path length and total charge capacity of the film while the clear state is always about the same even for thick coatings because the absorption coefficient is nearly zero.

By far the most studied electrochromic material is tungsten oxide WO_3. Although we narrowed our focus to those devices that contain tungsten oxide, no two systems were prepared or tested in the same way. One general observation was that the dynamic transmittance range of WO_3 films alone tended to represent the outer boundary of the transmittance range of complete devices made incorporating WO_3. In other words, the dynamic range of the films cycled in solution was typically greater than that of devices burdened with components with additional optical losses. Also, WO_3 has a high coloration efficiency and charge capacity. Most counter electrodes do not have the capacity to allow WO_3 to transport the maximum charge. These limits on device performance even held true in most cases where a complementary counter electrode such as IrO_2 was used in a device. In principle, such a "push-pull" device can achieve a greater dynamic range than an electrochromic/transparent conductor alone. Nevertheless, there were a few significant exceptions to this rule, especially in recent years.

The majority of devices have dynamic transmittance ranges reported between 2:1 and 4:1 in the visible with a maximum transmittance between 0.5 and 0.8. Such devices are often fabricated to serve as a temporary vehicle for a promising electrode or other device component. Devices in which each of the component layers has been chosen to be part of a balanced system and carefully tuned up are less common. For example, Cogan[4] fabricated devices from the complementary electrodes Li_xWO_3 and $Li_xCr_xO_{2+x}$. One of their latest devices of this type, using an inorganic ion conductor, has $T_v = 0.71$ to 0.09 (8:1) as shown in Fig. 3. Using a different complementary electrode pair, the same group[5] made a device for which T_v changes from 0.60 to <0.01 as shown in Fig. 4. This extreme result, however, is attained by using relatively thick electrode layers and a counter electrode of IrO_2 which is considered impractically expensive for window applications. We have recently made devices with the structure Li_xWO_3 / polymer / Li_xNiO, which is also a complementary system. For example, the device of Fig. 5 has a dynamic range of almost 7:1 when averaged over either the visible or solar spectrum..

From the range of device structures described above, it may be inferred that practical future devices may well achieve high dynamic ranges (> 10:1). In a sense we do not need to search for better devices to achieve the goals of energy efficiency. A device with a dynamic range of 10:1 already will have a very low minimum solar heat gain coefficient (SHGC). Even if a practical device with a dynamic range of 100:1 could be made, it would not have a significantly lower SHGC. On the other hand, for privacy at night, and in some cases for glare control, an electrochromic window would need to achieve $T_v << 0.1$. For a building with large windows in a sunny climate where a high maximum T is rarely needed, it might be desirable to create a device with a dynamic range of 10:1 where $T_v = 0.5\text{-}0.05$, for example.

4.2.2. Reflection vs. absorption

Thus far, for convenience, we have been referring to the transmittance range only. Reflectance is also needed to determine the SHGC, but usually reflectance does not vary significantly as transmittance changes over a broad range. It has been noted that a film that switches by reflection rather than absorption must be superior in terms of energy rejection. All else being equal, this is a true statement, as shown in Sec. 4.1. Let us examine the likely limits of reflectance modulation in real electrochromic materials.

A single-crystal of M_xWO_3, doped to progressively higher values of x, would, in principle, achieve a high value of R in the solar infrared with a sharp transition at the plasma wavelength l_p to low R at shorter wavelengths. As x increases, l_p would move into the visible region. This is in contrast to a completely amorphous film in which the absorption would increase over a broad band. These limiting behaviors for crystalline and amorphous materials can be visualized as a "vertical" versus a "horizontal" transition. Granqvist[6] calculated the expected properties for a crystalline film. The reflectance at first changes only in the near-infrared as the electron density or x increases. There are some changes in the visible due to shifts in the interference fringes for this 200 nm thick film. These shifts at first decrease the visible reflectance, even as the increasing electron density begins to increase the infrared reflectance. At the highest computed values of n, however, l_p moves into the visible range. If the electron density could be increased still further, l_p could move right through the visible resulting in complete solar and visible reflection. If infrared reflectance modulation is to become a widely useful effect, the plasma wavelength probably must sweep through the visible spectrum. Granqvist limited his study to electron density $n = 10^{22}$, which corresponds to about $x = 0.5$ for a 200 nm film with an assumed density of 7 g/cm^3. At this concentration, l_pª0.5 mm estimating from the reflectance graph. Increasing n to $2x10^{22}$ (or $x = 1$), would shift l_p down to 0.39 mm blocking all transmitted light. Whether reversible films could incorporate such high concentrations of ions is another issue. Demiryont[7] showed, for example, that for $x>0.3$ irreversible ion transport occurs in WO_3 films.

Let us consider some experimental results relating to the above theory. Owen and Teegarden[8] grew single crystals of Na_xWO_3 with x between 0.522-0.940 and measured the dielectric constants. From this data we calculate the reflectance and transmittance for the limiting values of x for a film of thickness 200 nm (see Fig. 6). The results show that high reflectance with a transition entering the visible spectrum can indeed be achieved for bulk material. Rubin[9] deposited thin films of Ag_xWO_3 and nearly matched the performance of single crystals. These results, however, do not demonstrate the ability of these materials to cycle between these states electrochemically. Berera et al.[10] were able to achieve high infrared reflectances in a c-WO_3 film by exposure to a Li plasma. Cogan et al.[11] cycled a c-Li_xWO_3 film electrochemically up to $x = 0.5$ achieving a maximum reflectance in the infrared of nearly 0.6. These results are promising even though they fall short of clearly demonstrating that a large change in reflectivity can be produced in a fast-switching long-lifetime electrochemical cell.

The high values of reflectance cited above (whether static or dynamic) require either heat treatment or ion bombardment during deposition. In many cases, even when temperatures are applied on the order of 450°C or higher, no significant changes in reflectance are produced. Typical WO_3 films have slowly rising infrared reflectance with a maximum value no higher than 0.4 in the reduced state. Most of the increased reflectance occurs at the high-wavelength end of the solar spectrum where there is not much energy. Even for single glazing the differences in shading coefficient are less than 10%. Visible transmittance always changes significantly and always by absorption, unlike the theoretical case. This means that the ideal type of electrochromic which only switches in the infrared (Fig. 1c) does not currently exist in any real approximation.

To properly model reflective films, experimental or theoretical, we must consider the issue of spectral linearity. Unlike amorphous films which have broad-band absorption, crystalline films tend to have spectral selectivity. One way to demonstrate this is to plot T_v vs. T_s as in Fig. 7. An amorphous film shows some deviation from linearity which becomes more pronounced as the film is crystallized by heat treatment. For the theoretical crystalline films discussed above the deviation is extreme. Thus, for example, controlling the illuminance level by setting T_v would result in a lower T_s or SHGC than would be expected if the variation was assumed to be linear. Conversely, controlling the transmitted solar radiation by setting T_s would give a higher value of T_v than expected. These effects will be considered in future modeling studies.

To test the annual energy performance of both existing and foreseeable electrochromic windows, we chose five materials types in accordance with the above considerations, and combined them with other glazings into eight window types for use in DOE 2.1E building energy simulations. Three of the electrochromic materials have low reflectance levels typical of most electrochromic devices. They are designated as types 80/10, 80/20, and 70/10 representing the maximum and minimum visible transmittance levels of the electrochromic layer. These materials types are intended to represent readily achievable performance. Two additional materials have reflectance levels that increase significantly in the dark state. These materials are designated G and GX to represent the theoretical calculations of Granqvist backed up by promising experimental results. Type G has a dark state corresponding to an electron density of n = 1022 (x=0.5), which is the maximum level calculated by Granqvist. Type GX has twice the number of free electrons (or x = 1) and becomes virtually opaque.

Each of the three low reflection glazings are combined with either of two idealized types of low-E glazings. The first designated E is essentially a clear glass with a low emittance. The second designated S is a spectrally selective glazing which has an identical emittance to the first, but a greatly enhanced reflectance in the solar infrared. Thus we have window types 80/10E and 80/10S, etc. The G and GX types have their own built-in selectivity and so we modeled only types GE and GXE. In retrospect, we should have also modeled GS and GXS, because this selectivity only appears in the dark state. Nevertheless, we will be able to extrapolate from the progression of results for the other glazings.

Table 1. Real Electrochromic Glazings
Solar/Optical/Thermal Properties

	T_v	SC	U-Value ($W/m^2 \cdot {}^\circ K$)
80/10E	0.65-0.08	0.67-0.20	2.40
80/10S	0.65-0.08	0.55-0.18	2.40
80/20E	0.65-0.16	0.67-0.27	2.40
80/20S	0.65-0.16	0.55-0.24	2.40
70/10E	0.57-0.08	0.60-0.20	2.40
70/10S	0.57-0.08	0.50-0.18	2.40
GE	0.65-0.06	0.67-0.15	2.40
GXE	0.65-0.00	0.67-0.06	2.40

4.2.3. Window configuration

For a double-glazed window with given gap spacing and gas fill, the primary influence on U-value is the possible presence of a low-emittance coating. One interesting aspect of a vacuum or sol-gel deposited electrochromic is that the top conducting layer might serve as a fairly good low-E coating. In the laminated configuration, however, the low-E surface would be masked by the infrared-absorbing glass or plastic layers. In a vacuum-deposited electrochromic device with an exposed low-E coating, the device would almost surely be in a protected location on one of the enclosed surfaces of the double-pane window. The U-value does not depend on which of the two enclosed surfaces has the low-E coating.

If the goal is to reject the maximum amount of solar energy, then any absorbing element should be as close to the outside surface as possible. This will minimize the inward flowing fraction of the absorbed energy by putting as much thermal resistance as possible between the absorbing element and the inside. Thus, if the electrochromic is laminated between two glazings it should be in the outside pane. An electrochromic device that is deposited on the surface of a glazing element should be on the enclosed surface of the outer pane. As discussed above, there is no advantage to be gained in either U-value or T_v by placing the electrochromic on the inner pane. Even if the electrochromic reflects some energy, placement on the inner pane will not result in any benefit in terms of solar rejection. However, this inner pane option should be explored since an early niche market might consist of adding an electrochromic glazing to an existing window and it will probably be easier and cheaper to add the electrochromic glazing at the inner window surface.

Previous modeling has shown the advantages of using an electrochromic glazing in series with a spectrally selective or "cool" glazing that permanently blocks the solar infrared. Existing electrochromics always have a strong absorbed component, so that the electrochromic device should always be in the outside pane. In the case of discrete electrochromic and spectrally selective components, the selective glazing should be on the inside pane. If that cool glazing can be integrated with the electrochromic device, then the best position would be on the outside pane.

Going beyond energy performance alone, we must consider the fact that thermal cycling may have a significant detrimental effect on the performance or lifetime of electrochromic coatings. There is very little data on this subject to date. If thermal cycling turns out to be a major problem for some types of electrochromic devices, then the only viable choice may be to position the electrochromic on the inner pane with a cool glazing on the outside for protection. This type of electrochromic may be more useful for light control than solar control. Not only may the electrochromic coating itself be affected by the thermal cycling, but also the glass substrate of insulating glazing (IG) unit may be damaged. Most electrochromics without a very big component of reflection become very absorbing in their darkest state. Conventional coatings and glasses with total absorption greater than about 50% have an increased risk of breakage or seal failure.

5. PERFORMANCE ANALYSIS

The performance of the idealized and real electrochromic systems described in Sec. 4.1 and Sec. 4.2.2, respectively, were compared to several alternative window systems for commercial building applications. We define conventional *static* envelope systems as those where the solar-optical properties are not reliably controlled, and *dynamic* envelope systems as those where the solar-optical properties are actively controlled in coordination with a dimmable electric lighting system to meet defined performance parameters such as daylight illuminance level, view, or glare. Simulation results indicate that (1) for a given control strategy, the solar-optical properties of the dynamic envelope system have a significant effect on energy and peak demand savings, (2) the performance of dynamic envelope systems with non-optimal solar-optical properties may be improved if predictive control algorithms are used, and (3) compared to conventional static glazing systems, dynamic envelope systems can be used to ensure a higher level of sustained energy-efficient performance with improved occupant comfort. These results are discussed sequentially in the sections below.

5.1 Solar-optical properties

5.1.1 Idealized electrochromic glazings

A selective IG glazing without active shading was compared to an idealized clear/ broad-band IG electrochromic, an idealized clear/ narrow-band IG electrochromic, and an automated venetian blind in the cooling-dominated climate of Los Angeles.[12] All systems were modeled with daylighting controls where the electric lighting is dimmed in response to the interior available daylight levels, for prototypical south, east, and west facing perimeter zones with a window-to-wall (exterior floor-to-floor) area ratio (WWR) of 0.50. As viewed from the outside, 50% of the building envelope would thus be glazed. The idealized broad-band electrochromic reduced annual electricity consumption by 23-30% and peak demand by 19-23%, the idealized narrow-band electrochromic reduced electricity consumption by 39-41% and peak demand by 36-39%, and the automated venetian blind reduced electricity consumption by 16-18% and peak demand by 17-24%. For the north-facing perimeter zone, all three dynamic systems reduced electricity consumption by 0-9% and peak demand by 2-7% (Tables 2 and 3). This energy performance was determined using the DOE-2.1D building energy simulation program for a prototypical commercial building module consisting of a 30.5 m (200 ft) wide, square core zone, surrounded by four 139 m^2 (1500 ft^2) perimeter zones. Each perimeter zone consists of ten 3.05 m wide, 4.57 m deep, 2.59 m high (10w x 15d x 8.5h ft) office spaces. Lighting power density was 16.1 W/m^2 (1.5 W/ft^2). The continuous dimming lighting controls reduced all electric lighting energy within the perimeter zone to 10% of full power if the daylight workplane illuminance level at a depth of 3.05 m (10 ft) from the window wall met the design illuminance level of 538 lux (50 fc).

The superior energy-efficient performance of the narrow-band electrochromic with daylighting controls was due entirely to its solar-optical range. A closer examination of how these greater savings were achieved reaffirms the importance of solar heat rejection for cooling-dominated buildings. The energy balance between the envelope and lighting system is defined by three increments in Fig. 8: (1) the solar gain increment is the incremental energy use due to cooling load from solar heat gains and, to a much lesser extent for this climate, conductive heat gains; (2) the daylighting increment is the decremental energy use due to decreased electric lighting and cooling due to lighting when daylighting controls are used; (3) the total incremental electricity use is the sum of the first two increments, where the zero line is the energy use of an insulated opaque wall (91 $kWh/m^2 \cdot yr$ (8.5 $kWh/ft^2 \cdot yr$)).[13] For WWR < ~0.30, the daylighting increment decreases abruptly to ~40 $kWh/m^2 \cdot yr$ (3.7 $kWh/ft^2 \cdot yr$) with increases in glazing area. When additional daylight is provided by larger glazing areas (WWR > ~0.30), additional reductions in energy use are attained at a greatly diminished rate. Note the differences in the daylighting increment between all systems are small since they all admit substantial light. The solar gain increment, however, increases linearly throughout the full range of glazing area for all systems, increasing to ~20 $kWh/m^2 \cdot yr$ at WWR < 0.30 and 30-70 $kWh/m^2 \cdot yr$ at WWR=0.70 except for the narrow-band electrochromic. These large differences in solar heat rejection, therefore, distinguish the energy performance between the various systems for WWR > 0.30 and diminish the large benefit achieved through the use of daylighting controls. For WWR > ~0.30 when daylight saturation has been nearly reached, a glazing with a low SC in the switched state, SC provides the best performance for cooling-dominated commercial buildings, with control of T_v being of lesser importance for energy-efficiency, although critical for other non-energy concerns such as glare control, privacy, etc.

Table 2. Description of Envelope and Lighting Systems

	T_v	SC	U-value (W/m^2·°K)
DOE-2.1D Glazings:			
Selective IG	0.61	0.41	1.87
Selective IG, Shade[a]	0.61/0.21	0.41/0.25	1.87
Venetian Blind[b]	IDC[c]	[d]0.59–0.00	1.87
Idealized Broad-band[e]	0.70–0.09	0.84–0.26	1.99
Idealized Narrow-band[e]	0.71–0.09	0.50–0.11	1.99
DOE-2.1E Conventional Glazings:[f]			
Tinted Grey	0.38	0.54	2.88
Reflective Clear	0.13	0.20	2.45
Low-E Tint	0.41	0.35	2.37

a) The shade was modeled as manually operated where the shade is fully drawn down by the occupant during daylight hours if direct sun or glare is present. The shade was triggered if the transmitted direct solar radiation exceeded 94.5 W/m^2 (30 Btu/h·ft^2) or glare computed using the Hopkinson Cornell-BRS formula exceeded 20. The shade was modeled as an ideal diffuser, and reduces daylight transmission by 65% and solar heat transmission by 40%. Although the shade optical properties are realistic, the assumed manual operation of the shade is unlikely to be achieved in a real building unless it is automated.

b) The venetian blind was controlled to maximize the workplane illuminance level without exceeding the design illuminance level of 538 lux (50 fc) at a distance of 3.92 m (12.86 ft) from the window wall and a height of 0.76 m (2.5 ft) using discrete 15° tilt angles.

c) The daylight performance of the optically complex venetian blind system was accomplished using the IDC (Integration of Directional Coefficients) method, which combines scale model photometric measurements with analytical computer-based routines to determine daylight factors and daylight illuminance under any sun, sky, and ground condition.[14] Photometric measurements were taken for eleven discrete tilt angles for a WWR=0.50.

d) The thermal performance was characterized using a mathematical model derived for a between-pane louver system with a diffuse surface reflectance.[15] The SC data are given for the full 180° tilt angle range for an average summer and winter solar position.

e) The electrochromic glazings were controlled to meet the design workplane illuminance level of 538 lux (50 fc) at a distance of 3.05 m (10 ft) from the window wall, and a height of 0.76 m (2.5 ft), where SC was defined as a linearly dependent variable of T_v between clear and colored states.

f) These glazings were defined using the WINDOW 4.0 library option in the DOE-2.1E building energy simulation program.

Table 3. Total Perimeter Zone Energy and Peak Demand Performance Data (WWR=0.50, Los Angeles)

	North	East	South	West
Electricity Consumption (kWh/m^2·yr)				
Selective IG, NS NDLC	106.2	194.2	226.3	206.9
Selective IG, S NDLC	106.6	147.4	161.3	156.1
Selective IG, S DLC	57.4	69.2	75.9	70.7
Blinds, DLC	59.4	71.7	76.2	77.0
Broad-band EC, DLC	56.5	67.2	72.2	70.7
Narrow-band EC, DLC	52.0	54.0	54.5	54.0
Optimum	46.5	46.4	47.1	46.0
Peak Demand (W/m^2)				
Selective IG, NS NDLC	58.1	119.2	134.1	119.3
Selective IG, S NDLC	48.1	59.2	61.3	61.4
Selective IG, S DLC	43.8	54.4	55.6	42.0
Blinds, DLC	40.7	53.5	54.0	56.4
Broad-band EC, DLC	44.7	52.6	54.4	55.2
Narrow-band EC, DLC	40.6	42.5	43.1	43.5

N: No, S: Shades, DLC: Daylighting Controls

5.1.2 Realistic electrochromic glazings

In a separate analysis, the energy and peak demand performance of the eight realistic electrochromics described in Sec. 4.2.2 and Table 1 were compared for a west-facing perimeter zone in Blythe, California (Cooling Degree Days (CDD) = 2280 (23.9°C (75°F)) using the DOE-2.1E building energy simulation program (Figs. 9 and 10 and Table 4). All electrochromic glazings were controlled to maintain the design workplane illuminance level (538 lux (50 fc)) and were used with a daylighting-controlled electric lighting system. As with the idealized electrochromic glazings analyzed above, we find the solar heat rejection properties of the glazings to be the principle factor that differentiates the performance between real electrochromic glazings: (1) All S-type selective electrochromic glazings produced a maximum electricity consumption savings of 5-6% (WWR=0.60) over their E-type electrochromic counterpart; e.g., 80/10S and 80/10E. These savings were due to the higher solar heat rejection provided by the static selective glazing. (2) A variation in the upper range of transmission for the same lower range of transmission had no significant effect on energy savings since the windows were large; e.g., the **80**/10S and the **70**/10S produced the same energy performance for this control strategy. A reduction in the lower range of transmission, however, yielded higher energy savings; e.g., the 80/**10**S produced 8% greater electricity consumption savings over the 80/**20**S. (3) The GXE produced the highest energy savings between all eight real electrochromic glazings due to its large transmittance range. However, roughly compared to the idealized narrow-band electrochromic (NBEC) glazing, the GXE produced slightly less energy and demand savings for WWR > ~0.30. This is due to the lower SC of the narrow-band electrochromic for the same level of visible transmittance between $0.09 \leq T_v \leq 0.71$ (note the narrow-band electrochromic performance was computed using the DOE-2.1D program, and hence may not be directly comparable). The GXE performance may be improved in this case if coupled with a selective glazing.

We present the solar-optical properties of the idealized and real electrochromic glazings relative to other static conventional systems in Fig. 11 to facilitate comparison of the solar-optical properties relative to energy performance. Given the results of our analysis, we conclude that additional materials research should be directed towards achieving a large dynamic range within the lower edge of the graph to achieve maximum energy and peak demand savings for cooling-dominated commercial buildings with daylighting controls. This is particularly true in cases where the use of large windows means that the glazing will frequently be in a low transmission state.

Table 4. West Perimeter Zone Energy and Peak Demand Performance Data vs. Window to Wall Ratio (Blythe, CA)

	Window-to-Wall Ratio (WWR)				
	0.00	0.1	0.3	0.4	1.6
Cooling + Fan + Lighting (kWh/m^2-yr)					
GE	90.4	71.8	71.7	76.5	81.4
GXE	90.4	71.1	69.0	71.0	73.6
80/10E	90.4	73.7	79.6	90.2	100.7
80/10S	90.4	69.5	74.8	85.0	95.6
80/20E	90.4	74.1	80.7	95.0	110.2
80/20S	90.4	70.0	76.0	89.1	103.3
70/10E	90.4	75.1	80.3	90.4	100.9
70/10S	90.4	71.3	75.6	85.5	95.8
Low-E Tint	91.5	76.4	88.7	106.2	126.4
Low-E Tint, Shades	91.5	76.0	81.4	95.6	112.3
Idealized narrow-band	97.1	70.3	64.1	62.0	60.5
Peak Demand (W/m^2)					
GE	47.5	51.0	54.6	58.6	62.3
GXE	47.5	5.8	53.2	55.5	58.2
80/10E	47.5	52.1	60.0	68.1	75.9
80/10S	47.5	50.2	58.1	66.4	74.4
80/20E	47.5	52.1	60.2	71.7	81.4
80/20S	47.5	50.3	58.4	68.7	78.8
70/10E	47.5	52.1	60.1	68.1	75.9
70/10S	47.5	50.3	58.1	66.4	74.4
Low-E Tint	47.8	50.9	65.0	78.5	91.6
Low-E Tint, Shades	47.8	50.2	59.4	70.3	80.8
Idealized narrow-band	58.5	55.2	53.4	52.9	52.5

Note: Values for low-E and idealized narrow-band are not directly comparable since they were calculated with DOE 2.1D. See also captions for Fig. 9 and Fig. 10.

5.2 Predictive control algorithms

In the previous section, the control strategy continuously adjusted the electrochromic transmission to always meet the instantaneous design illuminance levels if possible. To improve the performance of near-term technologies independent of material improvements, a more sophisticated control strategy can be designed to determine the optimum energy balance between the envelope and lighting system on a real-time basis. This energy balance varies significantly with diurnal and seasonal variations in meteorological conditions throughout the year, and on the efficiency of the electric lighting system. For example, the clear sky horizontal exterior illuminance levels range from 15,000 to 90,000 lux (1400 to 8900 fc) from morning to noon hours at the equinox, and 105,000 to 55,000 lux (9800 to 5100 fc) from summer to winter in Los Angeles, with only moderate changes in outdoor average air temperature from 19.9° to 12.4°C (67.8° to 54.3°F) throughout the year.[16] During the winter with low daylight availability, the optimum energy-efficient control algorithm may result in increased daylight admission (up to and even exceeding the design illuminance level) to offset electric lighting requirements, since cooling energy use is low. During peak summer load conditions, however, heat gains from solar radiation can far exceed heat gains from electric lighting. Therefore, a decrease in daylight admission below the design illuminance level while slightly increasing electric lighting requirements, may result in a lower total energy use. The balance depends upon the effective efficacy of the two competing sources—daylight and electric lighting.

This type of control algorithm involves the prediction of cooling energy use from measured instantaneous heat gains, and are thus categorized as anticipatory or predictive control algorithms. Although the control objective is different from that of envelope/ lighting systems, predictive control algorithms have been used for space conditioning/ mechanical equipment control over the past ten years.[17] Predictive control algorithms are made complicated by several factors: (1) The total load on the cooling system is the sum of the instantaneous heat gains and the heat gains absorbed and reradiated by the thermal capacitance of the building from previous hours. Prediction of cooling energy use must therefore account for this time lag in heat gains. (2) Mechanical system parameters, such as the part-load characteristics of the cooling system or time delays introduced by the air distribution system, can significantly affect the accuracy of building energy control. (3) Non-steady state conditions due to unanticipated changes in building use, weather, and occupancy can lead to inaccurate control and unrealized energy savings. To maintain accurate response to these changes, feedback or closed-loop control may be required during the operation of the building to ensure sustained performance.

The energy savings benefit of using predictive control algorithms is difficult to assess due to the separation of heat gain and load calculations from cooling energy use calculations in the DOE-2 building energy simulation program. Instead, the performance of the dynamic systems controlled by instantaneous measurements of workplane illuminance was compared to a hypothetical optimal dynamic system to provide a rough assessment of the potential energy-savings resulting from this more complex method of control (Fig. 8). The hypothetical system was defined as a system that enables the lighting system to dim to minimum power during all daylight hours with complete solar heat rejection. For all orientations and glazing areas, the minimum annual electricity consumption was found to be 46-47 kWh/m^2·yr (4.27-4.34 kWh/ft^2·yr) for the hypothetical system. For a WWR=0.70 the idealized broad-band electrochromic with conventional controls uses 71-75 kWh/m^2·yr (6.59-7.01 kWh/ft^2·yr). Predictive controls can potentially provide an additional 35-39% energy savings for east, south, and west-facing perimeter zones of a prototypical commercial building in Los Angeles. The automated venetian blind can similarly attain an additional 35-40% maximum energy savings for a WWR=0.50. These savings may be partially attained if the between-pane venetian blind, for example, is controlled to reduce solar radiation heat gains during peak cooling conditions (up to full closure of its louvers). This large margin of potential energy savings suggests that if predictive control algorithms can be implemented with relatively low cost, the complexities of pursuing this type of control may be worth the effort.

Implementation of predictive control would entail more sophisticated software/ hardware to precalculate building energy use and possibly a more involved commissioning process when installed in the building. Multiple local (office-by-office) or global (building wide) sensors may be required to control and monitor the building envelope, lighting, and mechanical system. Recent technological advances have brought this level of complex control to the commercial market. New lighting technologies include controllers that can accept inputs from multiple sensors (e.g., daylight, occupancy, ambient light, and manual wall dimmers), then reconcile possible conflicting inputs so that only one control signal is sent to the ballasts. New "low-cost" microprocessor chips with open protocol communications hardware (via twisted pair, radio frequency, etc.) facilitate distributed point-to-point control—allowing flexible and low cost reconfiguring of the lighting system without requiring direct physical access. Recent developments in user-friendly energy management control systems facilitate reconfiguration by untrained building managers of electric light scheduling, mechanical system control, fire protection, and security. Additional research and development is required to develop a practical, cost-effective solution to sophisticated envelope/ lighting control.[18]

By the year 2000, "smart" electrochromic glazings should begin to capture the market for dynamic envelope systems. However, building simulations indicate that the automated venetian blind system is a viable short-term alternative to the initial idealized broad-band electrochromics that should be available in limited commercial production within three to five years. If the venetian blind system is operated or redesigned to improve its solar-optical properties (e.g., increased blind surface reflectance, improved blind geometry, retraction of the blind to a fully open position during periods of low daylight availability, or the use of predictive control algorithms), this system may provide many of the benefits of the broad-band electrochromics. However, automated blinds will likely still be slow to capture market share due to their cost and uncertainty regarding long-term performance.

5.3 Sustained performance

5.3.1 Manual versus automated envelope systems

A comparison between the conventional selective IG glazing with manually controlled shades, the idealized broad-band electrochromic, and the automated venetian blind reveal little difference in performance between manually-operated and automated systems (±5%) for WWR < 0.50 (Fig. 8). The DOE-2 manually controlled diffusing shade was designed to operate to the fully closed position on an hourly basis when thresholds for direct sun and glare were exceeded. Experience in occupied buildings tells us that this reliable performance from occupants is not achievable. In a study investigating the frequency and nature of venetian blind operation by the occupant, it was found that about 60% of the blinds in several high-rise Tokyo office buildings (690 out of 1154 windows) were never used during the day.[19] In a separate internal survey of ten offices, occupants typically spent 3.5 hours away from the office on excursions lasting 30 minutes or longer.[20] This non-optimal operation can result in an inadvertently excessive admission of direct sun that can contribute substantially to the peak cooling load during mid-day. To ensure sustained and guaranteed energy-efficient performance, reliable automated systems provide a distinct advantage over manually operated systems.

5.3.2 Occupant comfort

While there are no conclusive studies correlating dynamic envelope/ lighting systems, occupant environmental satisfaction, and worker productivity, there is a growing interest in the commercial buildings industry to provide both an energy-efficient and high quality work environment. Occupant surveys reveal some of the shortcomings of conventional design practice and broaden the definition of an acceptable office environment. In a study of office workers in the Pacific Northwest region (generally an overcast and cool climate), slightly over 40% of the occupants said they experienced the sun as too bright at least sometimes, and 60% of the occupants said that the window was a primary source of glare and interfered with their work. In addition, 55-60% of occupants along the east, west, and south walls said it was too warm at least sometimes, especially in the late afternoon and in the summer—*despite* the provision of space conditioning.[21] Yet while visual and thermal discomfort frequently occur at the perimeter office zones, over 50% of the occupants in several high-rise office buildings in Tokyo preferred to have seats nearer the window citing advantages of brightness, outside view, wide visual range, and open feeling, with only 6-8% preferring seats further away.[19]

Since dynamic envelope systems can be designed to reduce the large variability of daylight and solar radiation within the workspace, the visual and thermal comfort of the occupant may be improved. By achieving a more uniform daylight level throughout the day which does not greatly exceed desirable illuminance and luminance levels, eye fatigue and discomfort glare caused by excessive daylight levels or the brightness of the window plane can be decreased. By decreasing the peak levels and the large variation in perimeter solar heat gains, thermal discomfort arising from either central mechanical system control of the environment or inadequate mechanical system control of individual building zones may be decreased. Note that some variation of daylight levels is desirable as long as the limits are not greatly exceeded; the variability of natural light can have a stimulating effect and may even be vital to human biological functions.

5.3.2.1 Thermal comfort

The thermal comfort performance of realistic electrochromic glazings were compared to conventional static glazings to illustrate how a reduction in the variability of solar radiation can improve comfort. Previous studies with experimental testing on thermal comfort, resulting from high intensity sources, have been largely concerned with a subject's response to infrared heating devices, not the high intensity radiation of the sun. Therefore, Fanger's comfort equations were used to derive a correlation between transmitted direct solar radiation, the primary source of thermal discomfort from windows, and the percentage of people dissatisfied (PPD) with the thermal environment.[22, 23,24] Under typical office design conditions when the occupant is not seated directly adjacent to the window, glass surface temperature was found to have a small effect on the mean radiant temperature, and hence on thermal dissatisfaction. The electrochromic glazings and a reflective glazing (SC=0.20, T_v=0.13) with no shade control produced between 5-10% PPD under peak cooling conditions for a west-facing office module in Blythe, California (33.6° latitude). A tinted grey glazing (SC=0.54, T_v=0.38) produced 20% PPD between 2-6 PM. For reference, a window aperture with no glazing produced over 50% PPD between 1-6 PM, reaching a level of 100% PPD between 3-5 PM (Fig. 12). Five percent of the people are always dissatisfied in Fanger's model.

Two conclusions may be cautiously drawn from this limited example: (1) The electrochromic glazings, controlled to meet the design workplane illuminance of 538 lux (50 fc), may be controlled instead to minimize direct solar radiation levels and, consequently, thermal discomfort. For example, the GXE electrochromic glazing (SC=0.06-0.65) can be modulated to reduce direct solar radiation to near zero, thus further decreasing the percentage of people dissatisfied with the thermal environment from ~10% maximum to possibly 5%. (2) While differences from 20% PPD to 10% PPD might seem inconsequential, thermal discomfort can lead to reductions in worker productivity. By far, the largest economic factor in commercial buildings is the cost of peoples' time. All other first costs and operating costs are but a tiny fraction of the salaries of people. A person occupying an 11 m^2 (120 $ft^{2)}$ office, whose salary and benefits cost $60,000US is equivalent to paying $5454US per square meter per year

($500US/ft^2·yr). Design solutions that improve productivity by even a small margin are thus highly cost-effective. While there is little hard data that show a direct relationship between energy-efficient designs and productivity, there is anecdotal evidence that views of the outdoors, connections with the outside, a glare-free and thermally comfortable environment all contribute to a more satisfied worker, who is likely to be more productive. Further work is needed to explore alternative control strategies and to better understand the relationship of high intensity solar irradiance to thermal comfort.

5.3.2.2 Visual comfort

An assessment of visual comfort was also made for the same systems and under the same peak load conditions in Blythe, California. The glare index was calculated using the Hopkinson Cornell-BRS formula[25] in the DOE-2.1E program for a person with a view of the north interior sidewall in a 3.05 m wide by 4.57 m deep (10 x 15 ft) office with a west-facing window. This formula is acknowledged to need improvement but, in the absence of better models, we use it to begin to understand visual comfort issues. From early morning to ~2 PM when the sun is out of view from the west-facing window and only skylight enters the space, the glare discomfort is "just perceptible" for all systems at a distance of 1.52 m (5 ft) and below "just perceptible" at a distance of 3.05 m (10 ft) from the window wall. The glare index defines thresholds of just achieving a level of visual discomfort; e.g., at a glare index of 10, visual discomfort is "just perceptible." For late afternoon hours when the sun is within the window-facing hemisphere, the glare discomfort rises in proportion to direct sun penetration. All systems approach a level of "just uncomfortable" between 3-6 PM at 1.52 m (5 ft) from the window wall, and a level slightly below "just acceptable" between 4-6 PM at 3.05 m (10 ft) from the window wall (Fig. 13). The GXE electrochromic glazing (T_v=0-0.65) produced a slightly higher glare index than the static reflective (T_v=0.13) and low-E tinted (T_v=0.41) glazings for morning hours because it was controlled to admit daylight to maintain the design workplane illuminance level of 538 lux (50 fc). The GXE transmission may be further reduced (down to T_v=0) to limit direct source glare from the window itself and the luminance contrast of surrounding room surfaces, with some increase to lighting energy use.

5.3.3 Cost savings

Total electricity cost was computed for the whole building module in Los Angeles using a time-of-use rate schedule (Table 5).[26] A time-of-use rate schedule adjusts the electricity energy and demand cost according to the season and time of day; e.g., between 12:00-6:00 PM in the summer, the energy cost is 3.4 times higher at $0.147US/kWh and the demand cost is 5.3 times higher at $19.45US/kW than the rates charged between 1:00-8:00 AM. To derive average perimeter zone operating costs we subtracted estimated core zone operating costs from the whole building module costs.[27] We used a fixed cost of $14.42US/m^2 per year for the core zone. Demand cost is typically 40% of the total electricity cost where approximately 70-75% of the total annual demand cost is accumulated during the summer period from April through October when demand rates are significantly higher. These calculations were performed using DOE-2.1D for the same conditions described in Sec. 5.1.1 in Los Angeles for a WWR=0.50.

Table 5. Annual DOE-2.1D Electricity Costs ($/m^2·glazing·year) (WWR=0.50, Los Angeles)

Window System	Manual Shades Used?	Daylight Control Used?	Perimeter Zone Annual Cost	
			($U.S./m^2-yr)	($U.S./ft^2-yr)
WWR=0			$29.33	$2.73
Clear IG*	No	No	$59.24	$5.50
Selective IG**	No	No	$40.65	$3.78
Clear IG*	No	Yes	$45.72	$4.25
Selective IG**	No	Yes	$27.90	$2.59
Selective IG**	Yes	Yes	$22.97	$2.13
Venetian Blinds		Yes	$23.57	$2.19
Broad-band EC		Yes	$22.47	$2.09
Narrow-band EC		Yes	$18.36	$1.71

Cost is given per square meter (square foot) of glazing area.
*Clear IG T_v=0.88, SC=0.95
**Selective IG T_v=0.61, SC=0.41

The electrochromic windows all have lower operating costs than an opaque wall and will provide good paybacks compared to some conventional technologies. But these energy savings alone may not result in rapid paybacks compared to the best selective IG with manually operated blinds and daylighting controls. This should be interpreted with caution, however, since we do not believe that the manually operated system is a viable real-world choice for guaranteeing daylighting savings for most buildings. There are also other cost benefits, as noted below, which can further reduce the apparent payback periods of the automated electrochromic systems.

To obtain a complete estimation of cost-effectiveness, capital cost savings due to cooling capacity reductions of the mechanical chiller and utility financial incentive credits for the use of energy-efficient technologies can be included with energy cost savings. The size of the mechanical chiller is typically based on the peak load, so reductions in peak cooling load can result in decreased cooling equipment capacity. Financial incentives are offered to building owners by some U.S. utilities in order to increase the market penetration of advanced technologies that significantly reduce electric demand, and thus to avoid expensive supply costs for added demand capacity (power plants). In an earlier study of cost-effectiveness, these factors were combined to determine a simple payback period for electrochromic glazings.[28] At an added first cost of $161US/m^2·glazing for installed, mass manufactured electrochromic glazing, the simple payback period was found to be as low as 3.2 years. If the added cost of the glazings is higher, i.e., $269US/m^2·glazing , the simple payback period then rises to 6.6-7.6 years which should still be acceptable for many owners.

These savings were estimated for the idealized narrow band electrochromic with daylighting controls compared to standard tinted glazing (T_v=0.38, SC=0.54) with daylighting controls and no shading for four perimeter zones with windows (WWR=0.60) facing each cardinal orientation in Blythe, California. Energy cost was set at $0.10US/kWh and demand cost was set for four months at $17.00/kW, resulting in a energy savings of $27.13US/m^2·glazing and an added demand savings of $27.13US/m^2·glazing . Installed chiller cost was estimated at $1000US/ton, resulting in a first cost savings of $27.13US/m^2·glazing. Incentives for glazing and lighting controls were assumed to be $0.05US/kWh, resulting in a first cost savings of $27.13US/m^2·glazing. These results are optimistic in the sense that electricity costs are high and the climate is severe. However, these are exactly the types of niche markets that one would expect to be the first targets for new electrochromic products.

The additional complexity and cost of a dynamic system can be more readily justified if it achieves energy savings with *enhanced* occupant comfort for a larger percentage of the year. Additional possible benefits include increased rentability of the building due to a technological state-of the-art design image, and the reduced need for interior blinds or drapes. We believe that enlightened building owners will pay a premium for a proven high performance, high visibility technology that enhances comfort and productivity in the work environment, and that coupled with the energy and cost savings potentials, these dynamic systems have a promising future in commercial buildings.

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27. Accurate costs for individual perimeter zones are difficult to determine in DOE-2.1D since all costs are determined at the central plant not zone level. Zone costs can be approximately determined specifying separate plant units for each zone, but this results in an annual 8-15% overestimation of cost due to simulated plant inefficiency. In addition, between different envelope and lighting systems, the mechanical system size and overall coefficient of performance (COP) will change at the central plant level since the mechanical system sizing is dependent on peak load conditions. Separate simulation runs must be performed, in the future, with a fixed mechanical system size or with a packaged system-level mechanical system to allow more detailed comparability between costs.
28. J. L. Warner, M. S. Reilly, S. E. Selkowitz, D. K. Arasteh, and G. D. Ander, "Utility and economic benefits of electrochromic smart windows," Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency, August 30-September 5, 1992, Pacific Grove, CA. LBL Report 32638, Lawrence Berkeley Laboratory, Berkeley, CA.

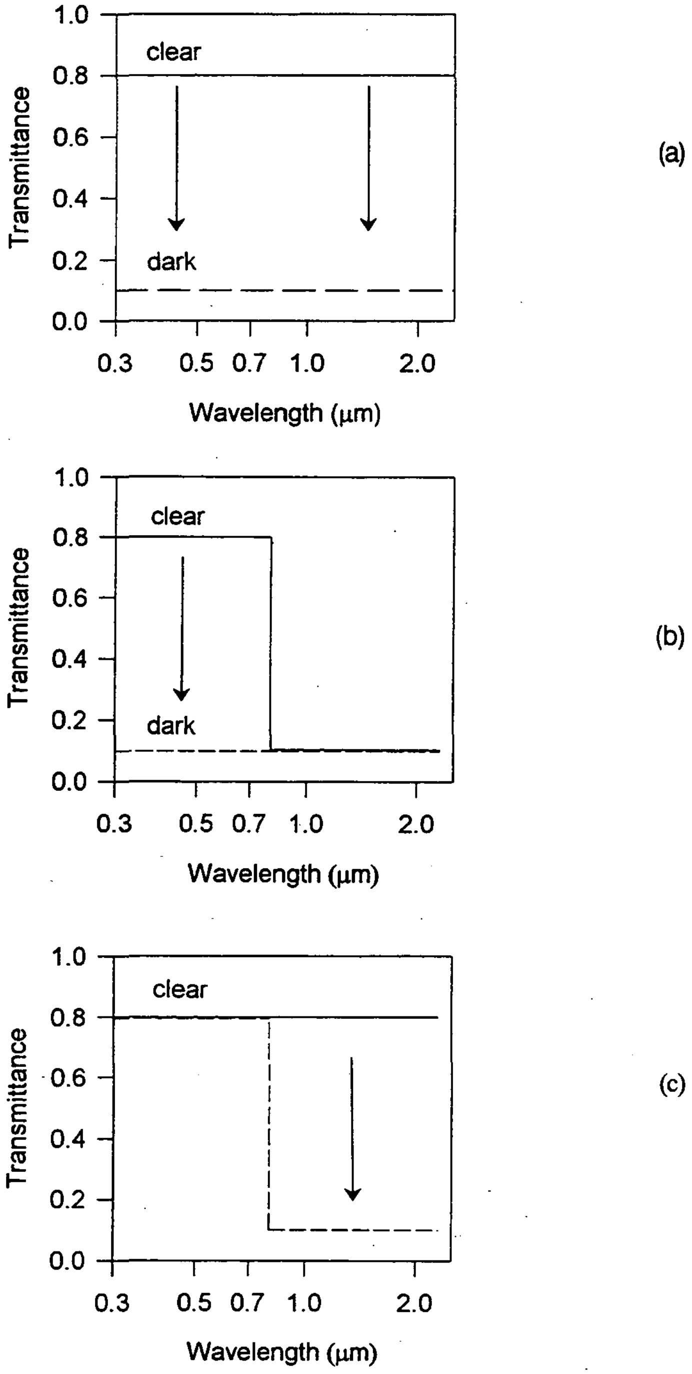

Fig. 1. Idealized electrochromic spectra in the "clear" and "darkened" state: (a) uniform switching occurs over the entire solar spectrum; (b) switching occurs over the visible spectrum only with constant low transmission in the near infrared in both "clear" and "dark" states; and (c) switching occurs over the infrared spectrum only with constant high transmission in the visible spectrum in both "clear" and "dark" states.

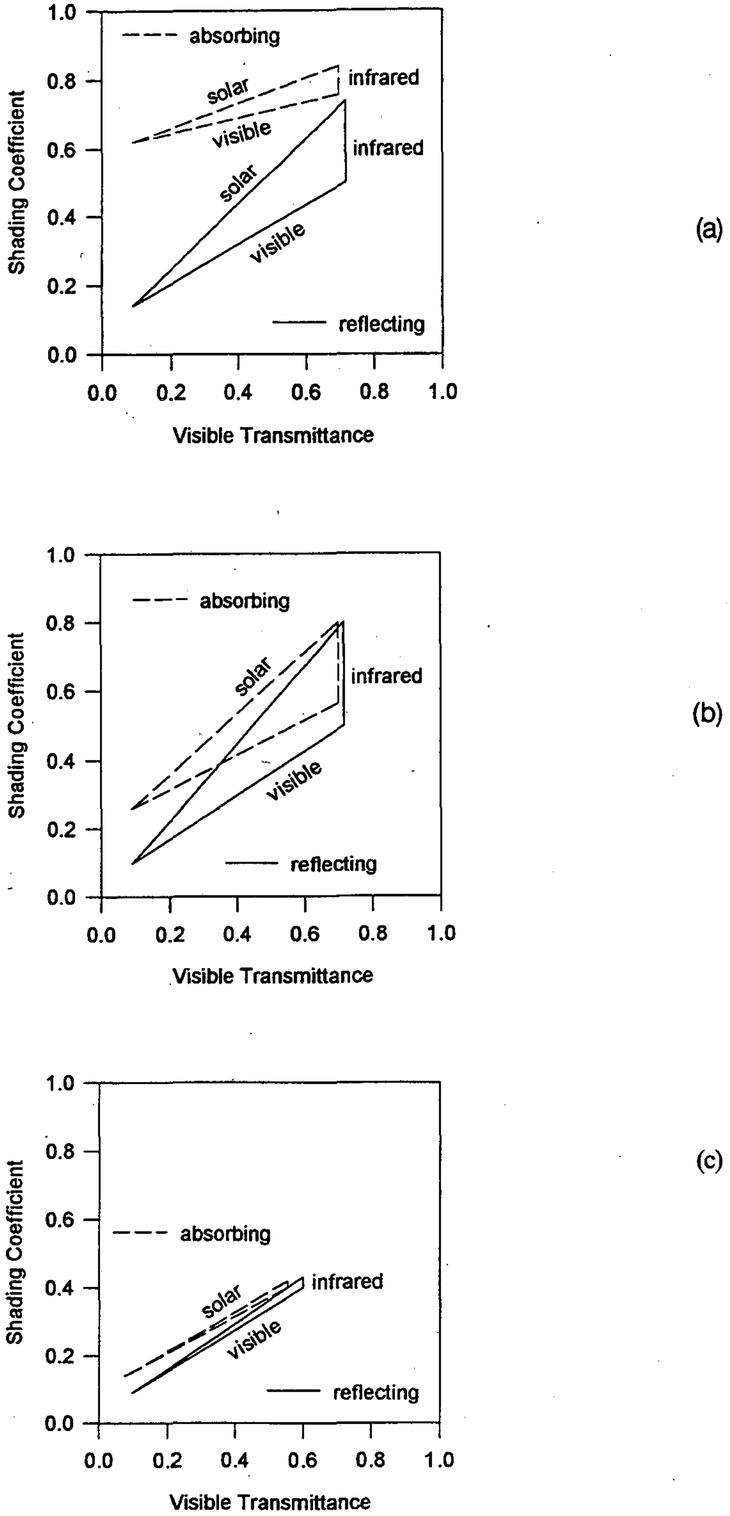

Fig. 2. In a window with an electrochromic (EC) glass, the relationship between light transmittance and solar control (i.e., shading coefficient) in both "clear" and "dark" states varies with glazing configuration: (a) single or double pane with EC glass inside; (b) double pane with EC glass outside; and (c) double pane with spectrally selective glazing inside and with the type of EC coating-absorbing vs. reflecting..

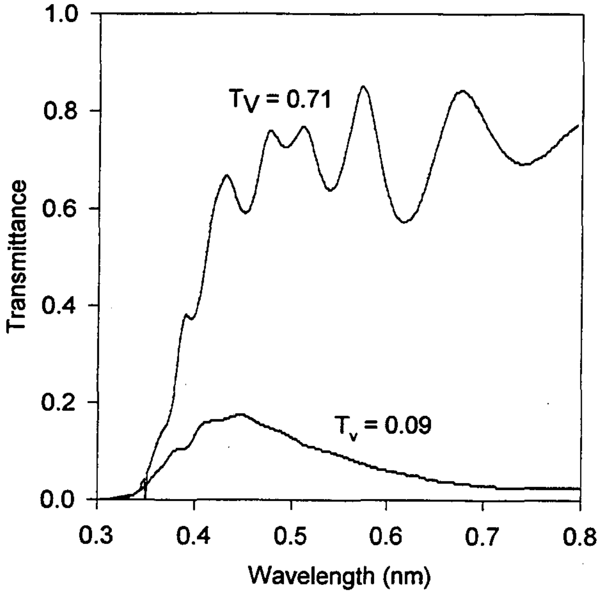

Fig. 3. Spectral transmittance for a completely inorganic complementary electrochromic device with transmittance range 8:1. The device electrodes are Li_xWO_3 and Li_yCrO_{2+x}.

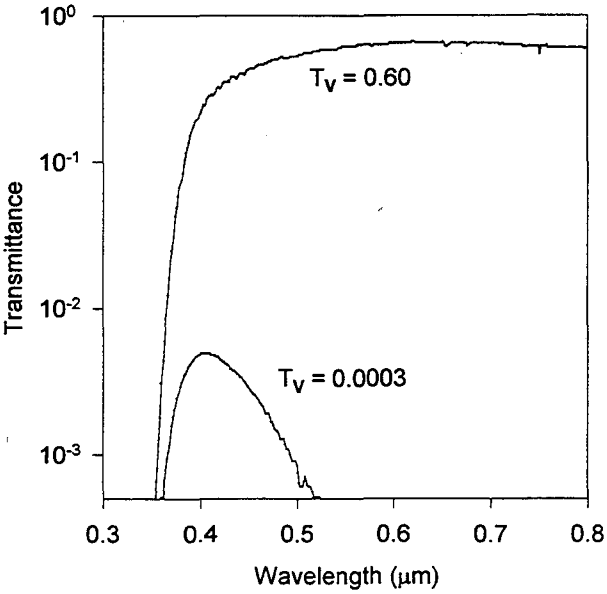

Fig. 4. Spectral transmittance for a WO_3 / IrO_2 complementary device using a polymer electrolyte with transmittance range >60:1.

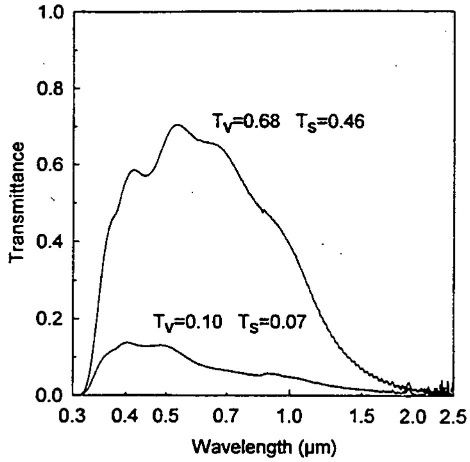

Fig. 5. Spectral transmittance for a Li_xWO_3 / Li_xNiO complementary device using a polymer electrolyte with visible transmittance range 8:1.

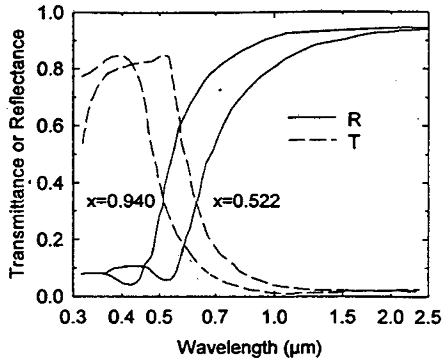

Fig. 6. Spectral reflectance and transmittance for thin films of Na_xWO_3. Calculated from extrapolated optical constants (ref. 8).

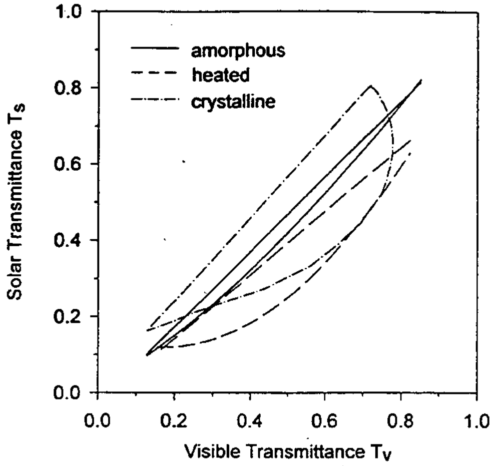

Fig. 7. Nonlinearity of the response of T_S (or SC) to change in T_V.

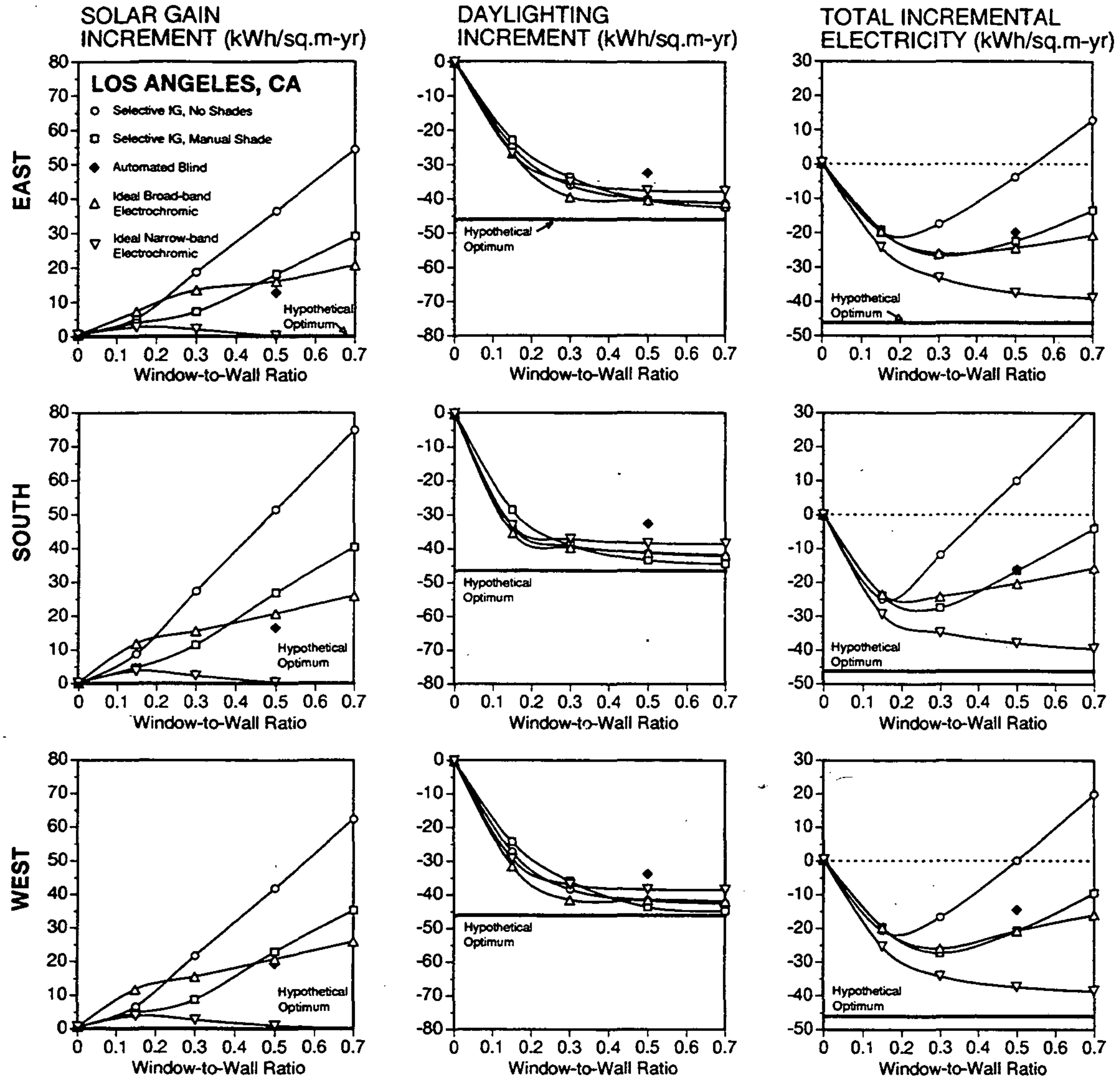

Fig. 8. Incremental electricity consumption for a prototypical commercial office building zone in Los Angeles (DOE-2.1D). The data show the performance of a selective IG glazing with and without shade, an automated venetian blind, and idealized narrow-band and broad-band electrochromics. The hypothetical optimum is an imaginary system that always meets lighting requirements and never has a cooling load due to solar gain.

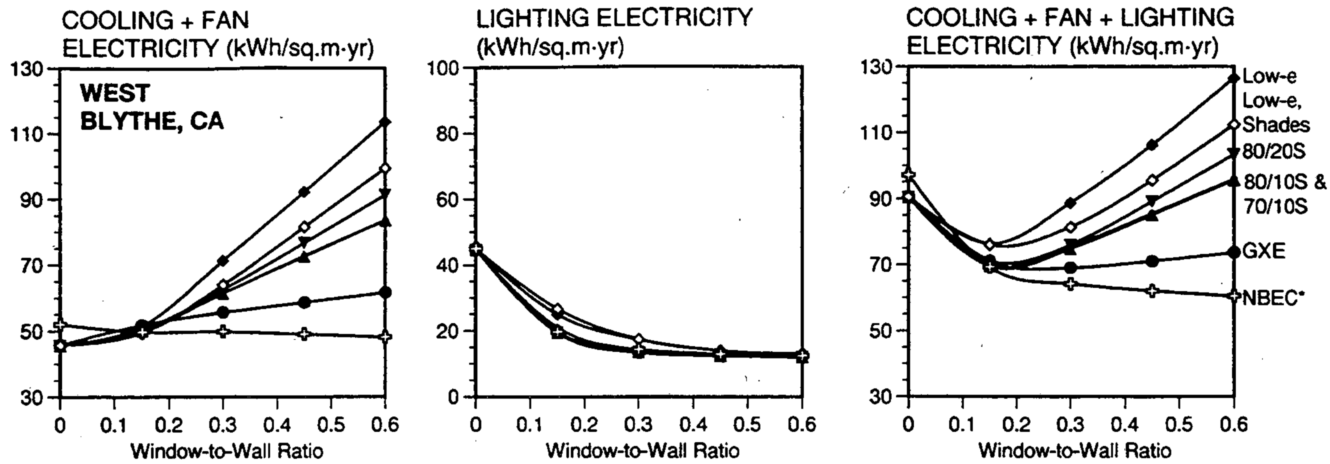

Fig. 9. Annual cooling, fan, and lighting electricity consumption (kWh/m^2·yr) for a west-facing perimeter zone in a prototypical commercial office building module located in Blythe, California calculated using DOE-2.1E. The idealized narrow-band electrochromic (NBEC) performance, calculated with DOE-2.1D, is shown for reference but is not directly comparable due to differences in the 2.1D vs. 2.1E programs. All electrochromic glazings are controlled to maintain a workplane illuminance level of 538 lux (50 fc). The performance of a static conventional low-e glazing (T_V=0.41, SC=0.35) with and without manually operated shades is also given.

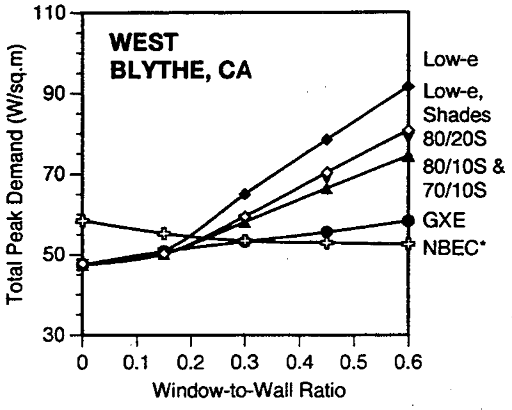

Fig. 10. Total electricity peak demand for a west-facing perimeter zone in a prototypical commercial office building module located in Blythe, California (DOE-2.1E). As in Figure 9, the NBEC results are not directly comparable since they were calculated with DOE 2.1D.

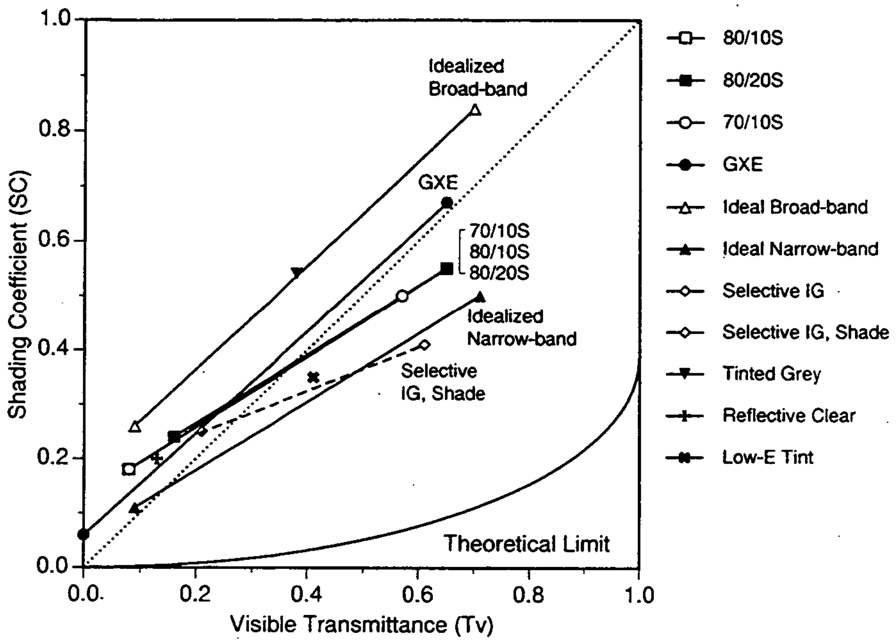

Fig. 11. Diagram of the solar-optical properties of existing and idealized electrochromics and static conventional glazings.

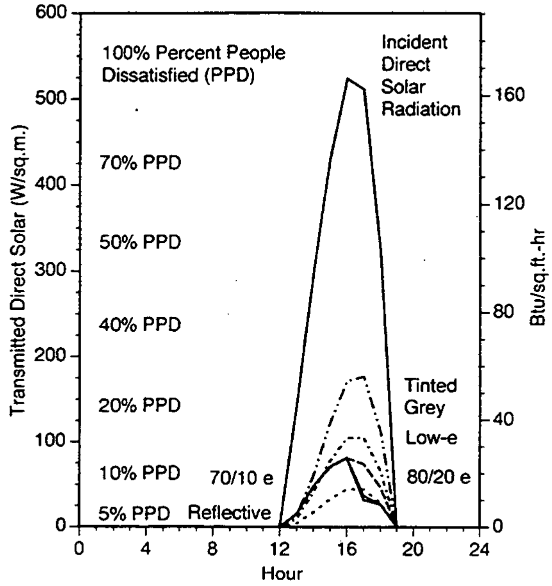

Fig. 12. Thermal comfort performance during peak cooling conditions in Blythe, California for a west-facing perimeter zone in a prototypical commercial office building module. Results are shown for several electrochromic glazings and static glazings for a window-to-wall area ratio of 0.30. The electrochromic windows were controlled to maintain an illuminance level of 538 lux (50 fc). All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m^2 (1.5 W/ft^2).

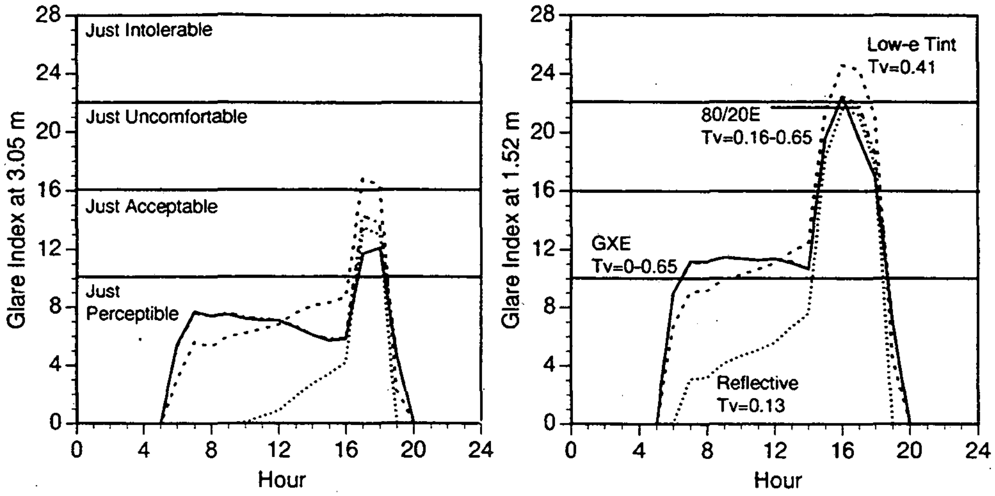

Fig. 13. Visual comfort performance at two room locations during peak cooling conditions in Blythe, California for a west-facing perimeter zone in a prototypical commercial office building module. Results are shown for several electrochromic glazings and static glazings for a window-to-wall area ratio of 0.30. The electrochromic windows were controlled to maintain an illuminance level of 538 lux (50 fc). All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m^2 (1.5 W/ft^2).

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