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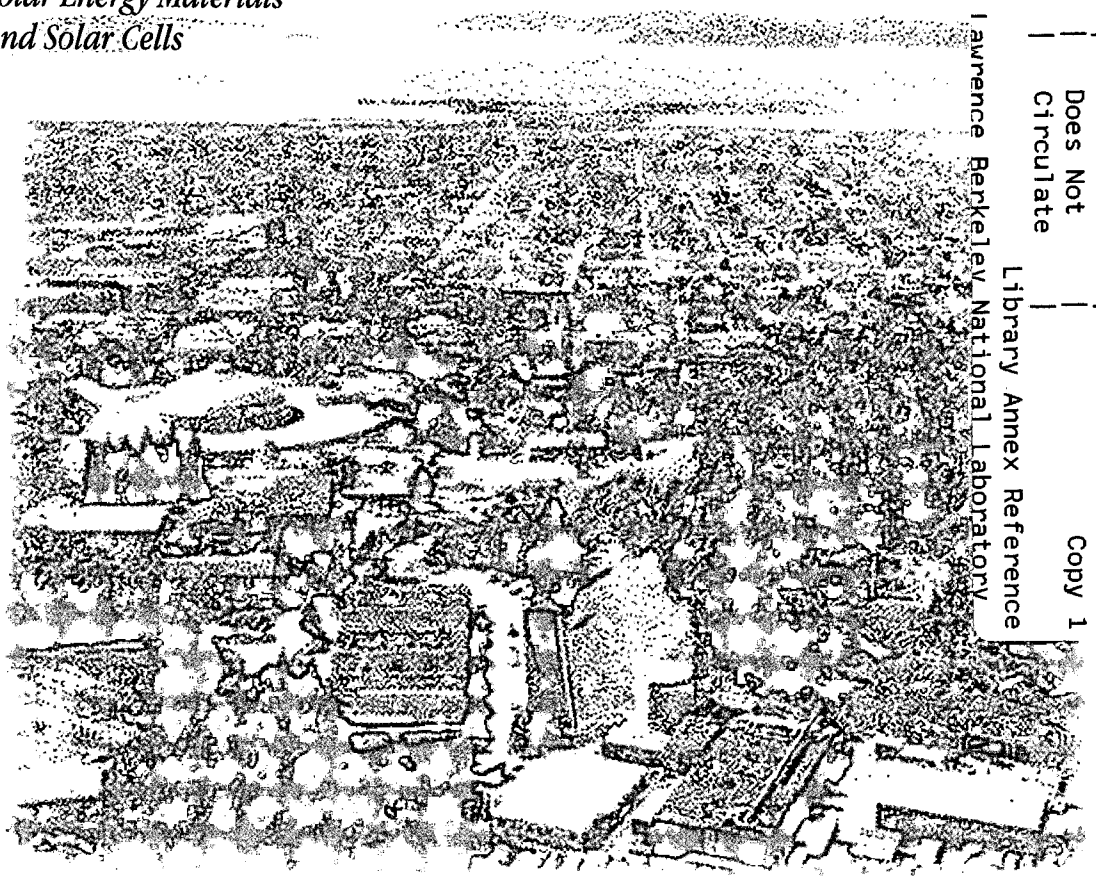

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Application issues for large-area electrochromic windows in commercial buildings

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Abstract

Projections of performance from small-area devices to large-area windows and enterprise marketing have created high expectations for electrochromic glazings. As a result, this paper seeks to precipitate an objective dialog between material scientists and building-application scientists to determine whether actual large-area electrochromic devices will result in significant performance benefits and what material improvements are needed, if any, to make electrochromics more practical for commercial building applications.

Few in-situ tests have been conducted with large-area electrochromic windows applied in buildings. This study presents monitored results from a full-scale field test of large-area electrochromic windows to illustrate how this technology will perform in commercial buildings. The visible transmittance (T_V) of the installed electrochromic ranged from 0.11 to 0.38. The data are limited to the winter period for a south-east-facing window. The effect of actual device performance on lighting energy use, direct sun control, discomfort glare, and interior illumination is discussed. No mechanical system loads were monitored. These data demonstrate the use of electrochromics in a moderate climate and focus on the most restrictive visual task: computer use in offices.

Through this small demonstration, we were able to determine that electrochromic windows can indeed provide unmitigated transparent views and a level of dynamic illumination control never before seen in architectural glazing materials. Daily lighting energy use was 6-24% less compared to the 11%-glazing, with improved interior brightness levels. Daily lighting energy use was 3% less to 13% more compared to the 38%-glazing, with improved window brightness control. The electrochromic window may not be able to fulfill both energy-efficiency and visual comfort objectives when low winter direct sun is present, particularly for computer tasks using cathode-ray tube (CRT) displays. However, window and architectural design as well as electrochromic control options are suggested as methods to broaden the applicability of electrochromics for commercial buildings. Without further modification, its applicability is expected to be limited during cold winter periods due to its slow switching speed.

Keywords: Electrochromic windows; building application; energy-efficiency

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1. Introduction

Electrochromics are a multi-layer coating on glass, about 1 micron thick, consisting of a purely ionic conductor (electrolyte) which is placed between electrochromic and counter electrode layers, which are, in turn, placed between transparent electrical conductor layers. When voltage is applied to the transparent conductors, an electrochemical reaction occurs in which ions are inserted or extracted from the electrochromic layer, resulting in a modulation of optical properties (i.e., light and heat). From the first explanation of the electrochemical effect in 1969 [1] to 31 years later, a considerable interest remains in electrochromic materials, particularly in uses for windows and skylights to reduce building energy consumption. Initially, the electrochromic community formed basic R&D objectives, then proceeded to develop small-area (7.5x7.5 cm) prototypes in laboratories. Over the past 10 years, the main objective of materials R&D has been to develop viable electrochromic devices with acceptable optical characteristics and long-term durability and to develop processes for low-cost volume production of large-area windows. Early-market, large-area window products have been nominally available in Germany since 1998 [2]. Other large-area products are expected to emerge on the market over the next two to five years.

Very little is known about the performance of electrochromic windows in buildings. Few large-area electrochromic prototypes have been produced, so very few field performance studies have been conducted [3,4]. Even less is known about how specific attributes of an electrochromic device can affect building performance. Within the electrochromic literature, there is considerable debate and speculation over many issues, such as how many cycles should be expected over the 30-year life span of a typical window or what solar-optical range is necessary for a building window, etc. Feedback from building performance studies is imperative to help direct future materials research.

In this study, we use limited building performance data to illustrate how well electrochromic materials meet lighting energy-efficiency and comfort objectives. First, a summary of general electrochromic properties is given based on a review of material science literature. Then, experimental results are given for large-area electrochromic windows installed in two side-by-side offices. The electrochromics were automatically controlled with a dimmable fluorescent lighting system to improve energy-efficiency or to control direct sun intensity. Lighting energy and visual comfort indices were monitored over a four-month winter period in Oakland, California. Material properties are related to these performance data and suggestions for improvements toward useful window products are made. These results are expected to be of greatest use to the electrochromic material science community. However, major stakeholders such as utilities, architects and engineers can also use these data to better understand how emerging electrochromic products may perform in commercial buildings.

2. Background

Essential electrochromic material performance objectives for broad building applications have been reported by [5,6] and by other material scientists as follows:

- continuous range in solar and optical transmittance, reflectance, and absorptance between bleached and colored states

- contrast ratio (CR) of at least 5:1
- coloring and bleaching times (switching speed) of a few minutes
- operating glass surface temperatures of -20°C to 80°C
- switching with applied voltages of 1-5 V
- open circuit memory of a few hours (maintains a fixed state of transmission without corrective voltage pulses)
- acceptable neutral color
- large area with excellent optical clarity
- sustained performance over 20-30 yr
- acceptable cost ($100/m^2)

Electrochemical characterizations, physical characterizations, and optical properties of individual small-area (e.g., 7.5x7.5 cm) electrochromic designs have been reported extensively in journals, but have not been summarized or methodically reported upon in a manner that can be readily grasped by the window applications community. In most cases, it is unclear or perhaps unknown how some of these properties will scale to large-area windows or whether performance observations for a specific device are broadly applicable to a class of electrochromic designs. This section attempts to summarize the characteristics of common WO_3 electrochromic devices, as can be determined by a brief review of the most recent literature and through discussions with developers and manufacturers of large-area electrochromic glazings. A complete technical summary is given in [7].

Continuous modulation of solar and optical transmittance, reflectance, and absorptance is routinely achievable. Switching occurs primarily through absorption. Reflectance modulation would yield superior energy performance for commercial buildings and some progress has been made towards this end [8]. Research to produce variable emittance is also occurring [9]. Characterization of solar-optical properties at intermediate stages of switching are not yet reported; spectral non-linearity is not expected to be significant with amorphous broad-band absorptive films [10].

The contrast ratio (T_{max}:T_{min}) and transmittance limits define the range of continuous modulation and are not expected to change with window area. Broad ranges of luminous transmittance have been reported—e.g., $7\% < T_{400\text{-}1100nm} < 81\%$ for a 100 cm^2 laminated device [11]. There may be some variation in the reporting of transmittance limits, since the full depth of saturation and bleaching is dependent on switching time. It is assumed that the transmittance limits are given for a non-destructive charge density so as to meet durability objectives. In addition, the transmittance limits may change or degrade with cycling, characteristic of "trapping of charge" in the ion injection process. Variations reported for some devices in the literature were significant, perhaps due to accelerated testing [12] or device characterization [13].

Switching speed is affected by environmental conditions and glazing area. Switching speed decreases with increased glazing area [14, 15] as a function of total window resistance and the distance between bus bars. Coloring typically takes longer than bleaching. Some studies indicate that switching speed decreases exponentially with temperature for some types of devices [16]. WO_3 devices slow down below room temperature, while iridium oxide devices have a superior response (1 s) at -10°C. Liquid electrolyte devices switch faster than solid state due to increased ionic mobility [17]. Switching speed can also vary with the number of cycles [18,19]. Noticeable increases in switching time can be an indicator of degradation [20]. More costly transparent conductor (TC) materials are used in some material studies to increase speed, but

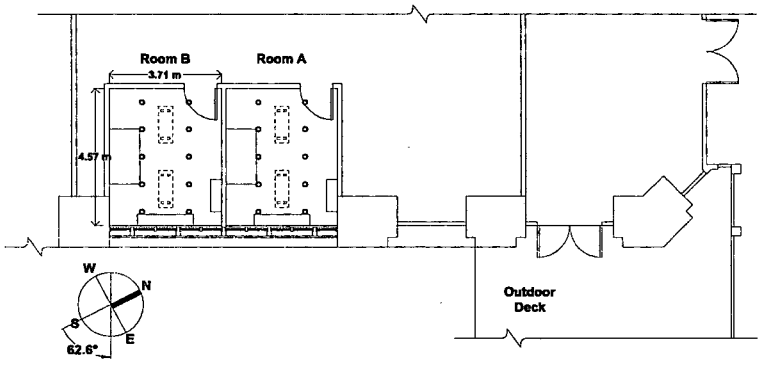

Fig. 1. Floor plan of test rooms.

most scientists realize that these devices will not be practical for building applications. In related electronic engineering fields, R&D is underway to develop cheaper TC materials [21].

Operating temperatures for long-term durability vary between devices. For some devices, switching is not permitted if the maximum design temperature is exceeded, but the device can be allowed to remain at the maximum colored state with no coating damage. Switching below 0°C may cause device degradation due to ice in WO_3 pores [22]. Thermal shock or stress can occur when there are abrupt changes in temperature within a short period (rain or hail storm), center-to-edge temperature differentials, or significant differences in insolation across the glazing (e.g., shaded versus unshaded areas of a window).

Most report switching with an applied voltage of 1-5 V. The switching profile or current (I)–voltage (V) waveform determines the rate of ion insertion, intercalation or diffusion in the electrode material. Too rapid of a transfer process can cause accelerated degradation, transient heating, and irreversible degradation of the electrodes. Research has focused on reporting I-V cycling that results in timely and adequate charge densities without coating damage. For long-term durability, pause times may be needed to allow relaxation between cycles [23].

Open circuit memory, or the ability of the electrochromic device to maintain a stable level of T without applied voltage, is determined by the type of electrochromic device. Rauh [24] defines three configurations, where battery-like configurations with polymer/gel electrolytes or all thin film coatings have extended open circuit memories, while solution and hybrid self-erasing electrochromics with liquid or gel electrolytes require continuous current to maintain the device in the colored state. For the former type, pulsed corrective voltages after several days may be required to maintain a constant transmission. For the latter type, as an example, constant power of 1 W/m^2 may be needed to maintain the window at a given state at all times.

The WO_3 device switches from a clear to deep Prussian blue. The clear state may yellow over time (e.g., due to hydrated polymers). Other colors are possible but may not be neutral.

Most developers are contending with the difficulty of creating uniform workable electrochromic coatings over large-areas without pin holes, inactive areas, or other aberrations. Transition cosmetics (during switching) are deemed to be less important than permanent non-uniformity in appearance. The degree of optical homogeneity can be dictated by the application. Some non-uniformity may be tolerated for glazings that will be viewed only from a distance (e.g., skylights).

Cycling, or repeated charging and discharging, defines the sustained performance of an electrochromic device over its expected 20-30 year life. Performance goals for typical building applications differ between scientists: from 25,000 cycles, assuming an average of three cycles per day for 20 years [25], to 50,000 cycles for durability testing [26].

Material cost projections are absent from the literature since most developers are in the prototype stage. Low-volume costs for electrochromic prototypes differ between developers: \$1,000/m^2 and up. Mature market, large-volume glazing material cost are targeted to be \$100/ m^2, not including electronic controls.

3. Experimental Method

3.1. Facility Description

The full-scale Oakland Federal Building testbed demonstration facility in California was designed to measure the electric lighting power consumption and the cooling load produced by the window and lighting system under realistic weather conditions. The facility consisted of two side-by-side rooms that were furnished with nearly identical building materials and furniture to imitate a commercial office environment. Each test room was 3.71 m wide by 4.57 m deep by 2.68 m high. The southeast-facing windows in each room were simultaneously exposed to approximately the same interior and exterior environment so that measurements between the two rooms could be compared (Figure 1).

Identical electrochromic window and lighting systems were installed in each room so that the position of the prototype and base case systems could be interchanged. Both test rooms were located in the southeast corner of a larger unconditioned, unfinished space (213 m^2) on the fifth floor of an 18-story building. The building was located at latitude 37°4' N, longitude 122°1' W. The testbed windows faced 62.6° east of true south. Both windows' view were obstructed by five to eight-story buildings one city block away and by several 24-story buildings three to six city blocks away. The average angle of obstruction was 25°. Partial direct solar shading of the test rooms occurred during the mornings of the winter test period.

The existing non-operable window consisted of 6 mm single-pane, green-tinted glass (PPG Solex, T_V=0.75, SHGC=0.46, U-Value=6.24 W/m^2-°K) and a custom aluminum frame. The window opening was 3.71 m wide and 2.29 m high with five vertically divided lights that were 0.57 m or 0.62 m wide. The window was recessed 0.43 m from the face of the building and had 0.13 m deep interior and 0.03 m deep exterior mullions.

A laminated polymer electrochromic was used for these tests [27]. The device consisted of a tungsten oxide and mixed oxide counterelectrode laminated with a Li^+ ion conducting polymer. Measured photopic transmission for a 40x40 cm sample was 29-72%. The transmission of the large windows was not measured. The manufacturer reported a visible transmission (T_V) range of T_V=0.14-0.51 and a T_V contrast ratio of 1:3.6 when the laminated electrochromic glazing is combined with an interior low-E glazing (Pilkington "Optitherm S") to form an insulating glass unit. Switching occurred with an applied voltage of 0-3 V. Design operating temperatures were between -15°C and 60°C. A 2% degradation in the maximum transmittance is expected with a constant contrast ratio (CR) after 10K-50K cycles (total cycling data were not available). The manufacturer also stated that the electrochromic could be maintained at a given

state for a week with no corrective applied voltages and with minimal change in transmission (2%). Power consumption for full switching was reported at 15 W/m^2 maximum.

The electrochromic insulating-glass units were placed 3.5 cm from the inside face of the building's existing window since changing the existing windows was not permitted. It is for this reason that no mechanical loads were monitored. The total window visible transmission range was therefore T_V=0.11-0.38. The electrochromic units formed an array of five upper (62.1x43.2 cm, 0.268 m^2) and five lower (62.1x172.6 cm, 1.072 m^2) windows to cover the full area of the window opening. The five upper windows could be controlled as a group independently from the five lower windows. Custom 3.5 cm wide frames were built to hold the units between the existing window frame. The total transparent glass area was 5.46 m^2. The window-to-exterior-wall-area-ratio was 0.40.

Two 0.61x1.22-m pendant, indirect-direct (~95%, 5%) fixtures with four fluorescent lamps (T8 or 25-mm, 32-W), continuous dimmable electronic ballasts, and a shielded photosensor were used in each room. The two fixtures were placed along the centerline of the window with the first fixture spaced 0.61 m from the window wall and the second spaced 0.86 m apart. The photosensor was placed at one end of the second light fixture and flush with the bottom of the fixture, 2.08 m from the window wall. The photosensor was tilted at a ~30° angle so that it viewed the lower to mid-height portion of the test rooms' back wall. The ballasts were rated to produce 10% light output for a minimum power input of 33%. The lighting power density was 14.53 W/m^2. The lighting controller was a prototype developed from earlier work [28] that enabled us to achieve accurate interior illuminance levels with the presence of daylight.

3.2. Tested Configurations

For the base-case system, the electrochromic windows were set to a static state all day, either fully bleached (T_V=0.38) or fully colored (T_V=0.11), to simulate "conventional" glazings. These cases will be referred to in the text as "11%-glazing" or "38%-glazing." A third static case was configured with upper bleached and lower colored windows ("11%/38%-glazing"). The electric lighting system was automatically controlled every 30 s to supplement available daylight so as to provide an average horizontal work plane illuminance of 510 lux within the rear zone of the test space.

For the prototype system, the electrochromics were automatically switched every 5-8 min to a) provide an average daylight illuminance of 540-700 lux within the same work plane area as the base case or b) to switch to the fully colored state if there was direct sun in the plane of the window. This case will be referred to in the text as "EC-glazing." The electric lighting control system was the same as the base case. Strategy (a) was designed to offset electric lighting use while minimizing solar heat gain loads on the cooling system. This strategy has been shown to yield the least annual building energy use for cooling-load-dominated commercial office buildings [29]. Strategy (b) will increase lighting energy use but improve visual comfort for some tasks. The control system was designed and tested in software using the LabView National Instrument's program and was interfaced with the manufacturer's window controller, which in turn directed switching and multipane synchronization of the electrochromics.

3.3. Experimental Procedure and Data Analysis

Data were collected for four months from November 1, 1999 to February 28, 2000, then the

facility was dismantled. The system was tested and developed iteratively over this period to refine control system algorithms and hardware operations according to observations in the field. During this period, time delays before activation were introduced to improve electrochromic control performance, but these delays varied by no more than 3-5 min. For energy monitoring, data were sampled every 6 s then averaged and recorded every 6 min from 6:00-19:00 and every 20 min from 19:00 to 6:00 (standard time) by Campbell Scientific CR10 dataloggers. Weather data, collected on the roof of a five-story adjacent building wing, were sampled and recorded every 1 min by a CR10 datalogger. Interior illuminance measurements and electrochromics data were sampled and recorded every 1 min from 5:00 to 19:00 by a National Instruments LabView data-acquisition system. Performance parameters were defined as follows:

- Visible transmittance, T_v. The electrochromic transmission was reported by the manufacturer's control system: the transmission of each electrochromic window unit was given as a scaled value (±0.01) between maximum (0.51) and minimum (0.14) values and was designed to be proportional to T_v. T_v data reported in this study includes the electrochromic glazing unit and the existing glazing (T_v=0.11-0.38), and is given as the average T_v of the 5 or 10 active electrochromic windows.
- Surface temperature of each electrochromic window was monitored to within ±1°C by the manufacturer's control system and is reported for an individual window.
- Day, n, is defined as the 12 h period from 6:00 to 18:00 standard time. All 1-min monitored visual comfort parameters were averaged over a day.
- Global exterior horizontal illuminance, E_{vgh}, was monitored with an unshielded Li-Cor sensor. Li-Cors have an accuracy of 1% of reading for the range of 500-100,000 lux and 3% at ~100 lux. Horizon obstructions at the roof weather station differ from the vertical windows, so E_{vgh} may be a poor indicator of daylight availability to the test rooms.
- Daily lighting energy use. Electric lighting power consumption was measured in each test room with watt transducers (Ohio Semitronics GW5) that were accurate to 0.2% of reading. Daily lighting energy use was defined as the sum of 6 min data over a day.
- Average total workplane illuminance, E_h, and maximum work plane illuminance, $E_{h\,max}$. Horizontal illuminance due to daylight and electric light was measured at a work plane height of 0.76 m in a two by five array of Li-Cor sensors. E_h was determined using data from the four sensors located towards the rear of the test cell: 2.44 m and 3.35 m from the window wall and 0.74 m on either side of the centerline of the test room. $E_{h\,max}$ was defined as the maximum reading of the 10 sensors across the entire room.
- Average fluorescent illuminance, E_{hf}, is the horizontal illuminance due to electric light and was determined using correlations to input power (r^2=0.97).
- Window luminance, L_v. A shielded Li-Cor sensor was placed in the center of the rear wall at seated eye level (1.22 m) to monitor average window luminance. Average window luminance, L_v, was derived from an equation that summed the luminance contributions from the mullions or window weighted by the solid angle of these elements. Luminance was determined using correlations to sensor data and diffuse surface reflectance measured with a Colortron spectral reflectometer.
- Side wall luminance, L_{wall}. An unshielded Li-Cor sensor was placed 2.32 m from the window at seated eye level (1.22 m) and on each side wall (r=0.88) to monitor illuminance. This was converted to luminance, assuming a lambertian diffusing surface. The greater of

Table 1
Between-room daily measurement error (n days)

	n	A-B avg±sd	%Δ
Lighting energy (Wh)	2	-103 ± 6	4 ± 0.5 %
$E_{h\ rear\ avg}$ (lux)	5	-4 ± 2	-1 ± 1 %
$L_{v\ avg}$ (cd/m^2)	5	10 ± 18	4 ± 8 %
SR_{avg}	5	0.02 ± 0.02	1 ± 2 %

the two sidewall luminance levels per minute was used to determine the percentage of the day when L_{wall} exceeded 300 cd/m^2.

- Glare subjective rating, SR. Vertical illuminance, E_v, facing the window (worst case) was measured in the center of the room, 2.3 m from the window, and at seated eye level (1.22 m) with an unshielded Li-Cor sensor. The glare subjective rating, $SR=0.1909E_v^{0.31}$, was computed from these data and is a measure of discomfort glare caused by viewing high or non-uniform luminance for computer visual-display terminal (VDT) tasks [30]. A value of 0.5 defines the borderline between "just imperceptible" and "just noticeable," 1.5 defines the borderline between "just noticeable" and "just disturbing," and 2.5 the borderline between "just disturbing" and "just intolerable."

For VDT tasks, the luminance of interior surfaces should be kept below 300 cd/m^2 to minimize veiling reflections and luminance contrasts between background and task surfaces and below 850 cd/m^2 to minimize contrasts between task and remote surfaces [31]. Luminance ratios should be kept to within 3:1 at the task and to within 10:1 for remote surfaces. Spot luminance measurements were taken periodically during stable sky conditions using a handheld Minolta Chroma Meter (CS-100) with a 3° spot.

A time-series error analysis was performed for days when the electrochromics were both static or operating in the same manner in both rooms and with operable fluorescent lighting. The average daily measurement error between rooms is summarized in Table 1. Between-room errors that occurred on a per minute basis were due primarily to positional effects. Room A was located to the east of Room B and was subject to slightly more early morning shading from an adjacent east building wing. Horizon obstructions from opposing buildings also differed slightly between rooms. The differences in E_h and SR data between rooms, for example, were largest when low-angle winter sun was present in the rooms. Shifting Room A's data later (~5 min) would minimize these differences. There were also slight differences in the set-up and/or operation of the lighting control system between rooms. Room B's lighting system tended to consume on average 8±4 W more power than Room A within the power range of 160-250 W (full power). There was an insufficient range of datapoints to characterize this error, so energy data were not corrected.

4. Test results

Energy, visual comfort, and electrochromic operations data are presented for three typical winter sky conditions in Figures 2-4. For some graphs which clip the data, the maximum value

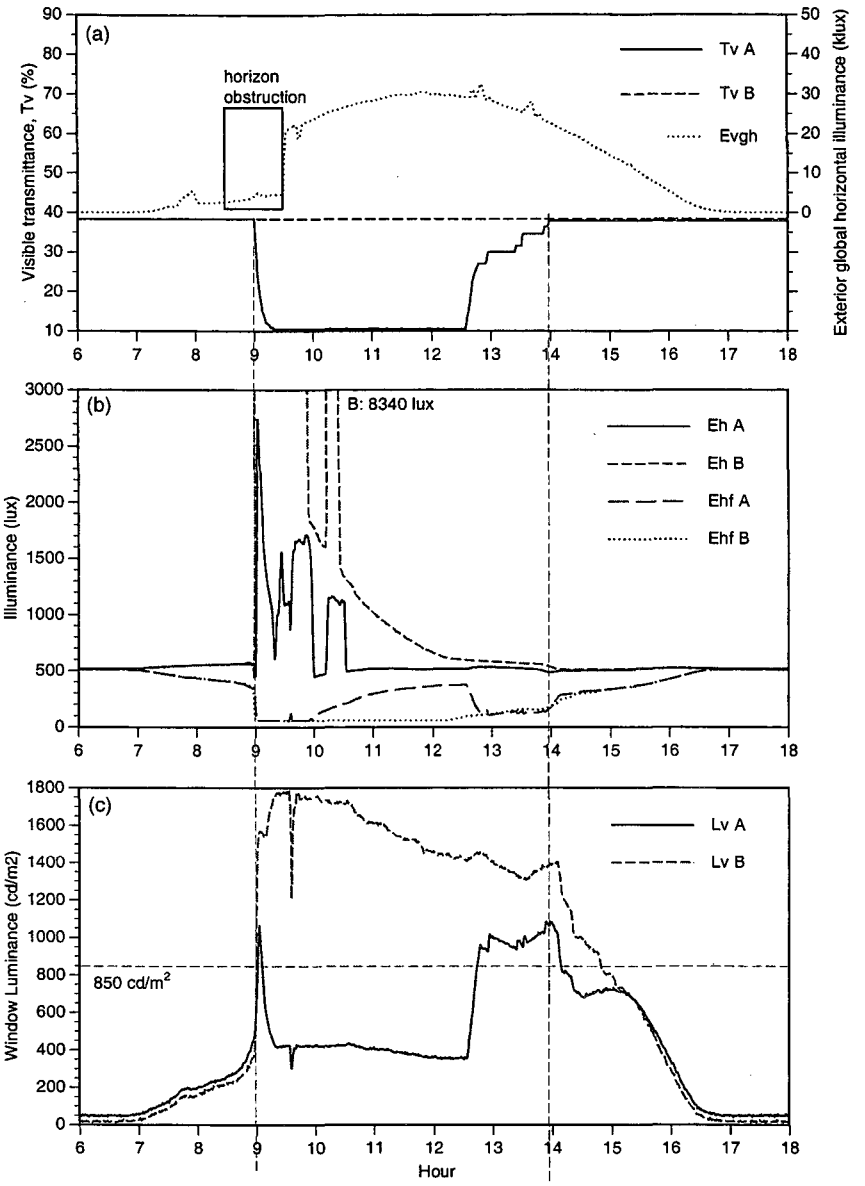

Fig. 2. Clear day, 38%-glazing. Monitored electrochromic transmission (T_v), global exterior horizontal illuminance (E_{vgh}), average total work plane illuminance (E_h), average fluorescent work plane illuminance (E_{hf}), and average window luminance (L_v) for the static (B: 38%-glazing) and dynamic (A) electrochromic-lighting system. Daily lighting energy savings were -223 Wh (-11%). Data are shown for southeast-facing offices in Oakland, California on a clear day, December 11, 1999.

is noted on the graph with text. These results demonstrate that the electrochromic-lighting system operates according to design. Daily lighting energy use for the four-month test period is given in Figure 5 and is summarized in Table 2. Daily lighting energy use is 6-24% less compared to the 11%-glazing and 3% less to 13% more compared to the 38%-glazing during this winter period. The benefits are not as large as expected due to direct sun control. Summer results are expected to be better since solar altitudes are higher and daylight availability is greater. Note that for this large window-to-wall area ratio, incremental differences in cooling and lighting energy use between glazing systems may be derived principally from cooling en-

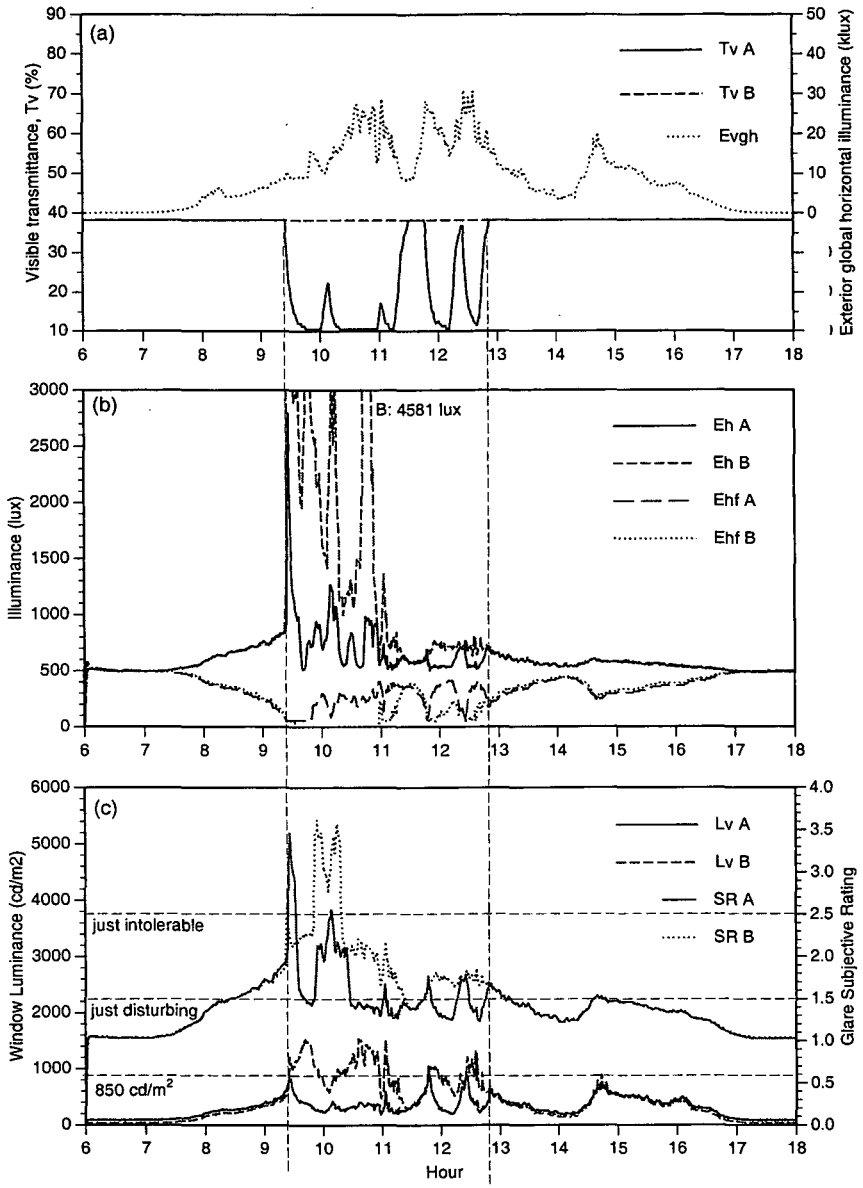

Fig. 3. Partly-cloudy, 38%-glazing. Monitored electrochromic transmission (T_v), global exterior horizontal illuminance (E_{vgh}), average total work plane illuminance (E_h), average fluorescent work plane illuminance (E_{hf}), average window luminance (L_v), and discomfort glare subjective rating (SR) facing the window for the static (B: 38%-glazing) and dynamic (A) electrochromic-lighting system. Daily lighting energy savings were -210 Wh (-9%). Data are shown for southeast-facing offices in Oakland, California on a partly cloudy day, January 13, 2000.

ergy reductions [32]. Additional cooling load reductions can be expected when compared to the 38%-glazing. Visual comfort parameters for window brightness, glare, and interior illuminance were averaged over the day or given as meeting a specific criteria for a percentage of a day. These data are given in Figures 6 and 7.

An example interpretation of the data for the clear sunny winter day is provided (Figure 2, December 11, 1999). The electrochromic is switched from full bleached to full colored ("T_v A") when direct sun enters the window in the morning. It remains in this state for 3 h until midday, after which it is gradually switched to the full bleached state as the sun moves out of the

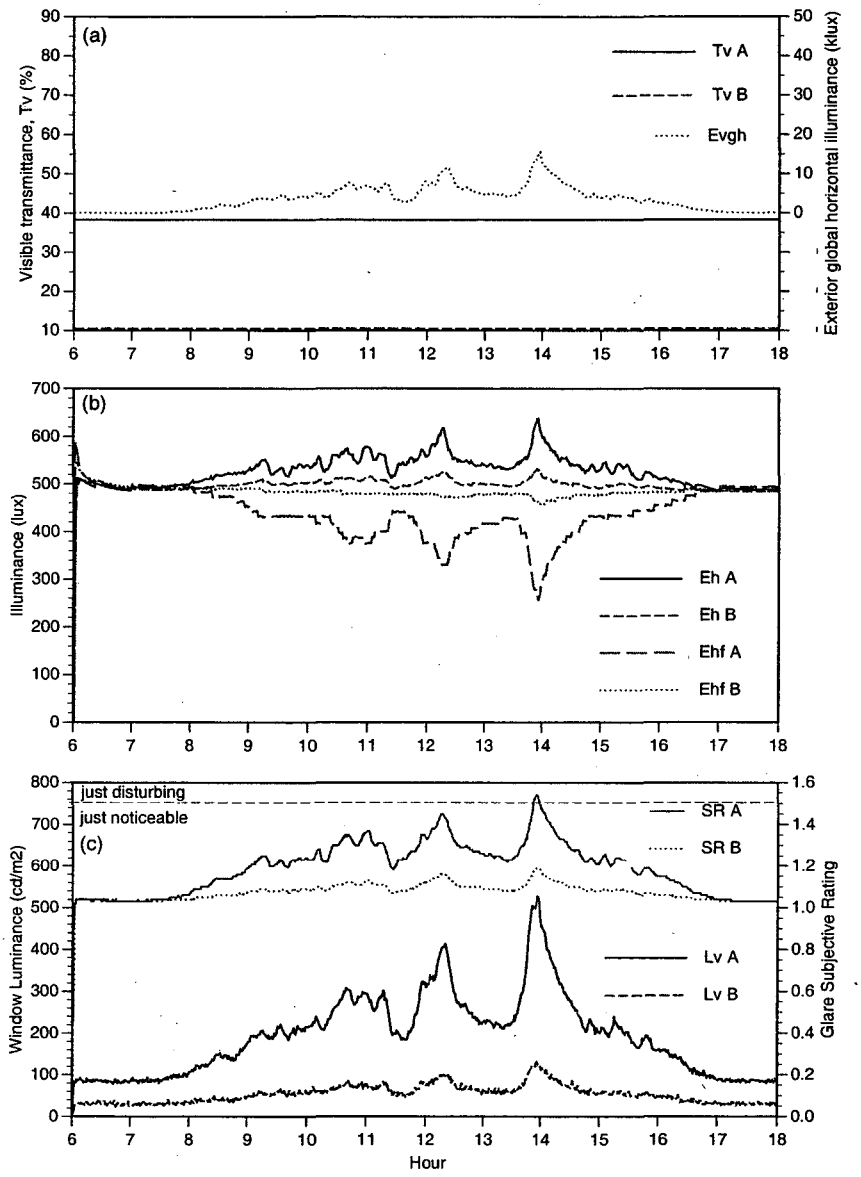

Fig. 4. Overcast, 11%-glazing. Monitored electrochromic transmission (T_v), global exterior horizontal illuminance (E_{vgh}), average total work plane illuminance (E_h), average fluorescent work plane illuminance (E_{hf}), average window luminance (L_v), and discomfort glare subjective rating (SR) facing the window for the static (B: 11%-glazing) and dynamic (A) electrochromic-lighting system. Daily lighting energy savings were 251 Wh (8.6%). Data are shown for southeast-facing offices in Oakland, California on an overcast day, January 15, 2000.

window plane for the rest of the day. Fluorescent lighting ("E_{hf} A") is used in the early morning, mid-morning, and late afternoon; mid-morning lighting use compensates for direct sun control even though more than sufficient daylight is available. Daily lighting energy use is 11% greater than the 38%-glazing base case. Work plane illuminance throughout the entire room peaks at 8,110 lux under direct sun, and the average rear-area illuminance ("E_h A") peaks at 2,741 lux. Average window luminance ("L_v A") is controlled in the morning to within ~400 cd/m^2 after the electrochromic windows first switch from bleached to colored (20-min delay due to switching speed), then rises to less acceptable brightness levels in the early afternoon—850-

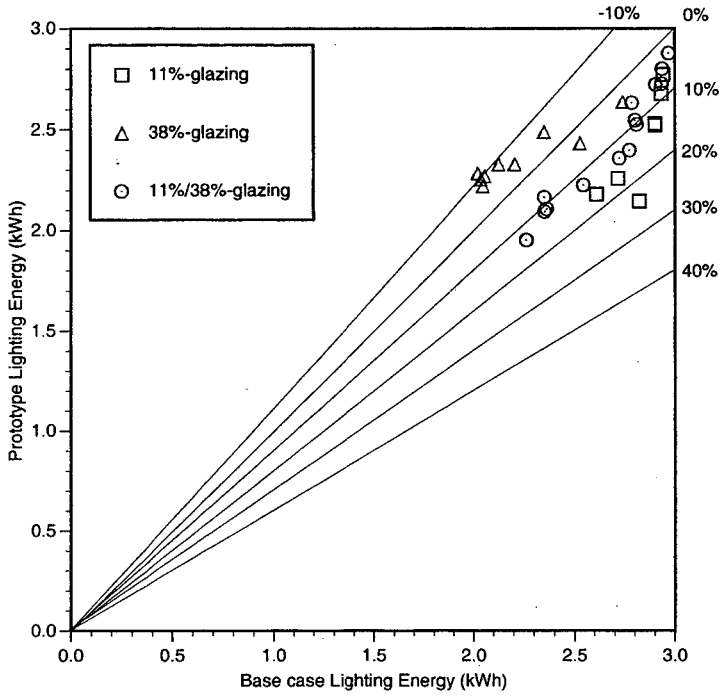

Fig. 5. Daily lighting energy use (kWh) of the base case and prototype window-lighting system, where the base case was defined by three static glazing configurations: T_v=0.11, T_v=0.38, or Tv=0.11 for lower windows and T_v=0.38 for upper windows. The prototype system was defined by an electrochromics-lighting system that was automatically controlled to produce 540-700 lux at the work plane or to switch to fully colored when direct sun is present. Diagonal lines show percentage differences between the base case and prototype. Both cases were defined by the continuous dimming lighting control system. Lighting power density was 14.53 W/m^2, glazing area was 5.46 m^2, and floor area was 16.96 m^2. Data were collected from November 1999 to February 2000. Measurement error between test rooms was -103±6 Wh (-3.96±0.53%).

1,080 cd/m^2 from 12:44 to 14:08—as direct sun control restrictions are relaxed. The window luminance exceeds the IES RP-1 limit of 850 cd/m^2 for 89 min or 12% of the day.

5. Discussion

The performance of large-area electrochromic devices for window applications is evaluated within the context of this full-scale demonstration using test data, on-site spot measurements, and other supporting calculations. This discussion focuses on whether large-area electrochromics are practical for commercial building applications and whether near term material developments or other design features can be used to overcome any technological shortcomings. Material attributes are discussed in the order of the performance objectives given in the Background section.

5.1. Fully-colored transmission ($T_{v\text{-}c}$)

The benefit of a very low visible transmittance (~0.01) in the colored state, $T_{v\text{-}c}$, has been argued for the following reasons: a) visual comfort may be improved [33], and b) the added cost for shades (for both privacy and direct sun control) may be avoided. A very low $T_{v\text{-}c}$ may

Table 2
Average daily lighting energy use (Wh) of the dynamic versus static electrochromic window system with dimmable daylighting controls

	11%-glazing	38%-glazing	11%/38%-glazing
n (days)	7	9	14
E_{vgh} (klux)	7 ± 4	10 ± 3	9 ± 6
Dynamic	2,443 ± 248	2,363 ± 135	2,440 ± 296
Static	2,829 ± 126	2,231 ± 255	2,679 ± 253
Δ (Wh)	387 ± 161	132 ± 134	-239 ± 85
%Δ	14% ± 6%	-7% ± 6%	9% ± 3%

Values are expressed in average ± standard deviation.
Average error of measurement between test rooms is -103±6 Wh (-3.96±0.53%), n=2.
E_{vgh}=average daily horizontal global illuminance (klux).

indeed be advantageous in that it broadens the applicability of electrochromics and decreases the percentage of time that discomfort glare due to window brightness is experienced. Interior shades may still be required for most buildings, although the frequency of their use will be substantially reduced. This summary assessment is explained below in the following order: a) daylighting, b) brightness control of the window, c) direct sun control, and d) view and privacy.

a) *Daylighting.* In all practicality, electrochromics alone cannot simultaneously control direct sun *and* provide daylight for some tasks, view positions, and solar angles. With the electrochromic window acting as both the shade and admissor of daylight, there is no optimal balance between daylighting for energy-efficiency and direct sun control since satisfying one criteria would be to the detriment of the other. Under worst case winter conditions and for near-south-facing windows, this effect is made evident in Figure 2 (clear sky) where the EC-glazing, controlled for glare, requires supplemental fluorescent lighting from 10:00-12:40 despite sufficient daylight availability. Opaque shading systems (e.g., venetian blinds at a cut-off angle) can satisfy both of these requirements, while compromising view. Figure 8 shows winter sun patterns in the room; in the summer, when the depth of sun penetration is less due to higher sun angles, alternate control strategies or the use of overhangs and/or fins can be used to increase daylight admission. As discussed in (c) below, the impact on lighting energy-efficiency is dependent on the task.

To improve lighting efficiency during periods of direct sun, control of individual electrochromic windows (and/or interior shades) within a room is preferable to a single, grouped window system all controlled to the same low transmittance. This gives the flexibility to control specific glare sources (e.g., bright sky, reflections off water) within the horizontal and vertical view while improving daylighting. For example, lighting energy use for the 11%/38%-glazing is 7% less than the EC-glazing during the periods of a nearly clear day when the EC-glazing is controlled to T_V=0.11 for direct sun.

One might argue that by decreasing daylight as one controls for direct sun, one also decreases solar gains and cooling energy use. However, DOE-2.1E energy simulations of monthly peak clear days in a temperate climate (Los Angeles) indicated that hourly cooling energy reductions were outweighed by significant increases in lighting energy use given absorptive EC windows in a south-facing perimeter office zone.

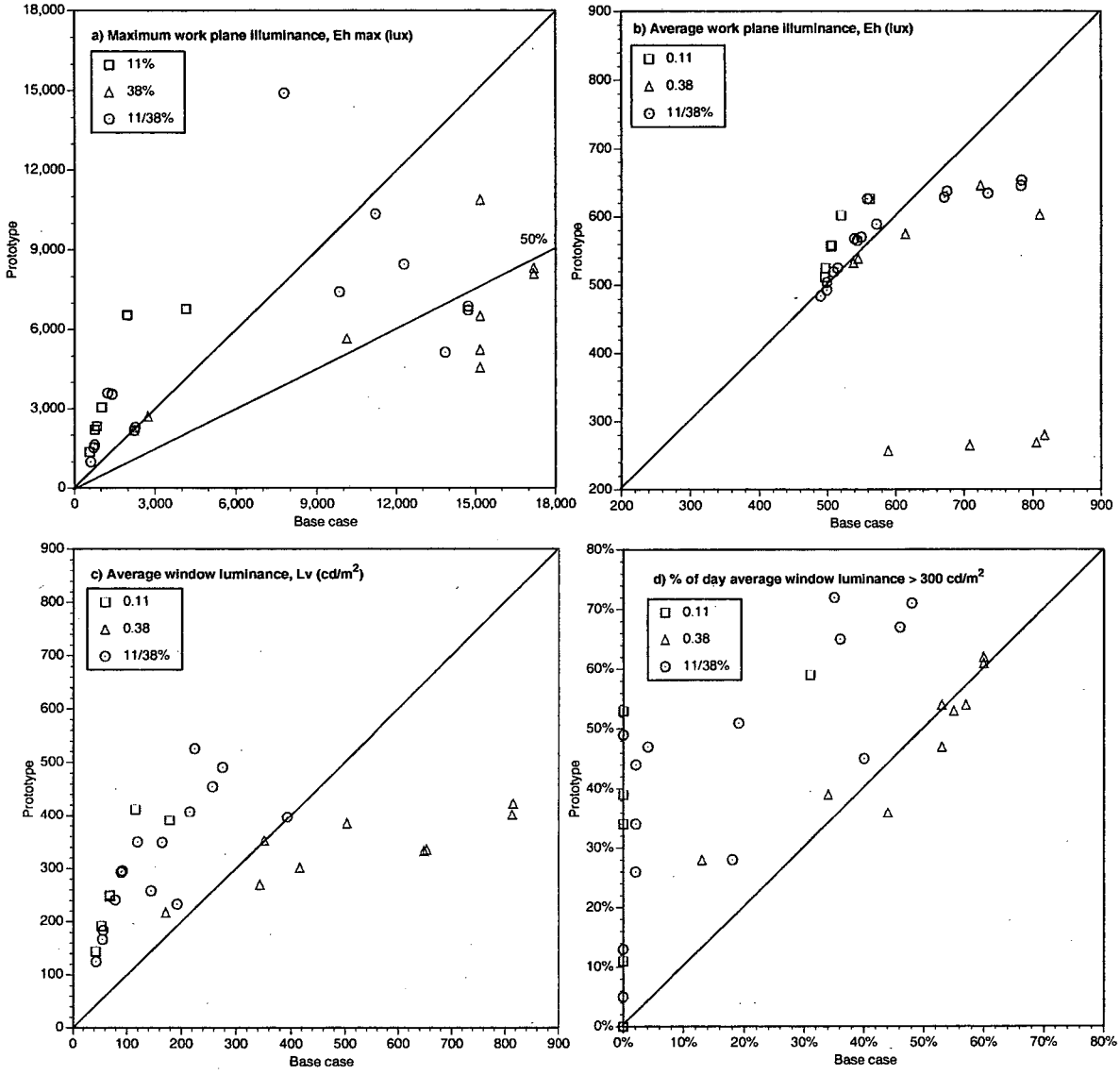

Fig. 6. Visual comfort parameters for a south-east facing window: a) maximum work plane illuminance, $E_{h\,max}$, b) average total workplane illuminance, E_h, c) average window luminance, L_v, (cd/m^2), d) percent of the day when L_v exceeded 300 cd/m^2.

b) *Brightness control.* The monitored data indicate that electrochromics can decrease the frequency of discomfort glare due to window brightness compared to static glazings (Figure 7a). On a clear winter day, the average window luminance exceeded 850 cd/m^2 for 47% of the day for the 38%-glazing and 12% of the day for the EC-glazing. Discomfort glare (SR) facing the window (worst case) was within "just disturbing" levels 42% versus 27% of the day between the 38%-glazing and EC-glazing, respectively (Figure 7d). For all four glazing cases, SR values exceeded "just intolerable" levels for no more than 6% of the day or ~40 min. Through inference, one can assume that with a $T_{v\text{-}c}$ lower than 0.11, these percentages will decrease further.

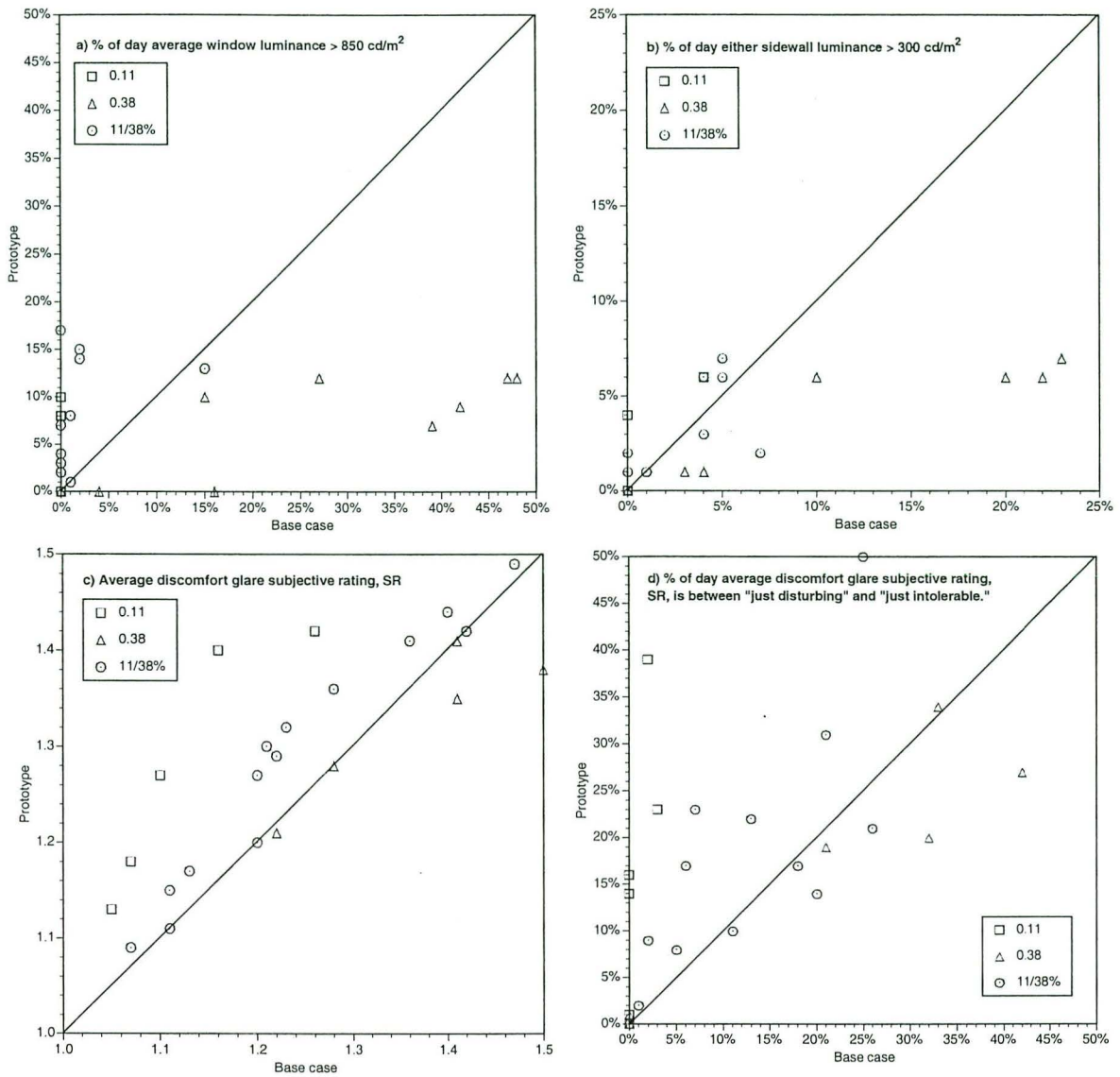

Fig. 7. Visual comfort parameters for a south-east facing window: a) percent of the day when L_v exceeded 850 cd/m^2, b) percent of the day when the luminance of either sidewall, L_{wall}, exceeded 300 cd/m^2, c) average glare subjective rating, SR, facing the window, d) and percent of the day when SR was between 1.5 (just disturbing) and 2.5 (just intolerable).

c) *Direct sun.* Controlled-intensity direct sun poses a rather unique situation for visibility and visual comfort models due to its large area, non-uniform luminance distribution on the task and surrounding surfaces. Visual comfort assessments are dependent on many variables: size and position of luminous source(s) relative to the field of view, uniformity and intensity of the luminous source, type of visual task, etc. Low winter solar altitudes pronounce direct sun effects for south-facing window orientations. North-facing windows see low direct sun infrequently during mostly unoccupied hours.

If the sun (or specular reflections of the sun) is in the field-of-view, the 11%-glazing cannot control its intensity to permit comfortable viewing of the sun or areas of the sky in which the sun is visible. Disability glare will impair the visibility of secondary objects (similar to night

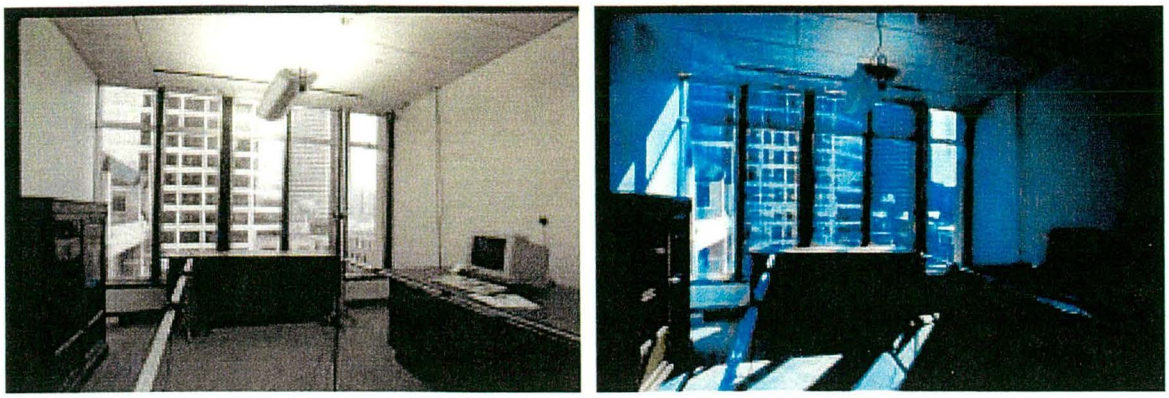

Fig. 8. Interior view of test room B on a partly cloudy day, February 23, 2000. The electrochromic windows are in the clear state at 10:30 under diffuse light conditions (left). When sun enters the window, the electrochromic switches to its fully colored state by 10:50 (right).

roadway visibility with oncoming headlights). The luminance of the sun ranges from several million cd/m^2 when it is near the horizon, to over a billion cd/m^2 as it approaches the meridian [34]. Glare calculations suggest that transmittances of less than 0.001 are needed to reduce these luminances to comfortable levels. For these conditions, blocking direct sun with an interior shading device will yield better lighting energy-efficiency. Under partly cloudy conditions and with slow switching speeds, instantly deployed shading devices also have advantages for controlling direct sun.

Discomfort glare, or the sensation of pain or annoyance that is created by high or non-uniform brightness, will also occur if $T_{v\text{-}c}$ is not sufficiently low to control bright sky luminances. The average luminance of the sky ranges from 2,000 cd/m^2 for overcast skies to 8,000 cd/m^2 for clear skies. Cloud luminances can reach 30,000 cd/m^2. At the test site, spot luminance measurements through the 11%-glazing of the clear and cloudy portions of the sky were within 1,000-7,700 cd/m^2 (E_{vgh}=38 klux).

Direct sun can decrease the visibility of VDT tasks by reducing contrast or washing out the screen image. Bright or specular surfaces can be direct sources of glare or can cause veiling reflections in VDT screens. Spot luminance measurements of surfaces in direct sun indicated bright levels with the 11%-glazing: white paper 870-1,240 cd/m^2; desk (r=0.05) 245-436 cd/m^2; interior painted matte walls (r=0.88) 660-1,300 cd/m^2 (E_{vgh}=10.5 klux). Luminance ratios between task areas that were in or out of direct sun approached 12:1.

The type of VDT can affect the significance of this problem (Figure 9). Older CRT screens are more susceptible to veiling reflections and direct sun washout. Newer display technologies, such as liquid-crystal display (LCD) screens with anti-reflection coatings, can be viewed under some direct sun conditions.

Visual comfort may be greater if the occupant has options to change viewing and task positions. With computer-based tasks, the occupant is often forced to face the window or cannot reposition computer hardware due to the fixed layout of systems furniture, small offices, or other factors. For reading and writing tasks, the occupant is typically more free to move both task and viewpoint. The threshold for discomfort glare is also much greater (~10,000 cd/m^2).

d) *View and privacy.* If a low-transmittance electrochromic (T_v<0.001) is used to control direct sun, the view, as indicated by the visibility of exterior objects viewed through the electrochromic, will be seriously compromised since contrast sensitivity (the ability to see dif-

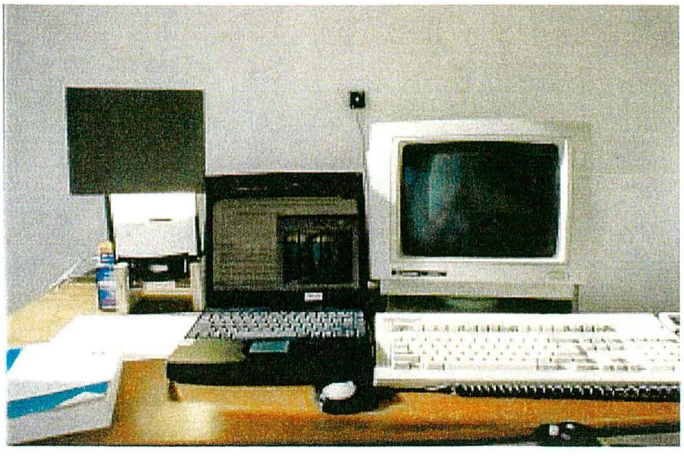

Fig. 9. Veiling reflections and direct sun on a CRT versus an LCD computer screen.

ferences in luminances) would be reduced. For privacy during the day, a low transmission of 6-11% is sufficient to provide visual privacy for most subjects and tasks in commercial buildings. At night or when the subject is directly illuminated by direct sun, a lower transmission may be required. Low transmission glazing again reduces the contrast of objects viewed through it and therefore one's acuity (the ability to resolve small details). The *perception* of privacy by the occupant is perhaps more important. Occupants may not experience privacy if they feel themselves being watched [35]. For example, reflective glazings provide complete privacy when the interior luminance is less than the exterior luminance, but many people would be hesitant to assume complete privacy behind a street-level reflective window. For a sense of complete privacy, very low transmission electrochromic glazings may not be the panacea. Opaque shades or other architectural measures may be required for commercial spaces where privacy is a primary concern.

5.2. *Fully-bleached transmission ($T_{v\text{-}b}$)*

The greatest advantage to using an electrochromic glazing compared to conventional window systems is the provision of unmitigated view throughout the day, which is the primary function of most commercial windows. A greater T_v in the bleached state ($T_{v\text{-}b}$) will decrease lighting energy use, increase interior illuminance levels and room brightness, improve contact with the outdoors, and broaden the applicability of electrochromics to buildings where daylight availability is low. The consequences on lighting energy use may be small. On an overcast winter day, when an increased $T_{v\text{-}b}$ is likely to have the largest effect on lighting energy, the EC-glazing remained bleached (T_v=0.38) throughout the day resulting in an 6-9% reduction in daily lighting energy use compared to the 11%-glazing.

The perceived brightness of the room is perhaps of greater significance, although difficult to evaluate without subjective data. With the 38%-glazing and a large window area, interior rear daylight illuminance levels were on average 104±74 lux on an overcast winter day and 242±155 lux throughout a clear sky winter afternoon. Mid-depth side wall luminance levels exceeded 300 cd/m^2 for no more than 7% of the day during this winter period for the EC-glazing and for no more than 23% of the day with the 38%-glazing (Figure 7b). Generally, the apparent brightness of a room is reduced with lower lighting levels such as these. However, the

perception of brightness can be quite independent of the physical value of illuminance. For example, Hopkinson and Kay [36] suggested that a gloomy appearance is more likely to be due to unfavorable adaptation of the eye than to the lack of light. Visitors to the test site remarked on the gloominess of the test rooms since immediate visual comparisons could be made between the 11%-glazing (deep blue), 38%-glazing (neutral tint), and 75%-glazing (slightly green tinted windows outside the test rooms). The blue coloration of switched electrochromic windows will also affect brightness perception [37].

5.3. Thermal properties

Thermal discomfort due to direct solar irradiation may occur. Again, alternate control strategies and/or shades may be required. This area of research is fairly undeveloped since most thermal comfort models assume there is no direct sun striking the subject [38]. Subjective comfort studies with a partially-irradiated subject (hand, foot) have also not been conducted, although such research is being planned for the automobile industry [39].

Thermal discomfort can also occur through radiative exchange between a hot window surface and the occupant. The electrochromic layer rejects heat by absorption, rather than reflection, and so can get quite hot when irradiated. Surface temperature calculations using WINDOW4 [40] under ASHRAE Summer Conditions (T_{out}=31.7°C, T_{in}=23.9°C, and Solar=783 W/m^2) of the fully-colored dual-pane electrochromic window used in this test (without the existing third pane) indicate that the inside glass surface temperature (T_{surf}=23.9°C) may not significantly contribute to thermal discomfort. Other electrochromic glazings with greater absorptivity in the fully colored state should be studied further. Low-emissivity coatings on glazing surface 2 or 3 will further reduce this effect. Single-pane, laminated electrochromics, if such a product is considered viable, would cause thermal discomfort since surface temperatures of absorptive electrochromics reach 60-80°C. Separately, glass breakage with highly absorptive devices may be a significant design issue.

5.4. Switching speed

Achieving fast switching speeds is very important to ensure visual comfort in buildings particularly if electrochromic windows are to be marketed without the use of exterior or interior shades (Figure 8). Direct sun control should be fairly immediate, if no other options for its management are available (e.g., reposition task or eye, or draw the shade). User annoyance, discomfort, and loss of personal autonomy due to lack of control options will reduce task performance.

At the test site, both the large and small electrochromic windows exhibited a slow response (9-26 min) to unstable sun and sky conditions that fluctuated by 20-40 klux within 1-2 s. Switching profiles from bleached to colored for the 1.07 m^2 window are given in Figure 10 for glass surface temperatures of 12-43°C. For these data, the glass may or may not be directly irradiated. Note that the switching profile is exponential so that a ~35% reduction in transmission is achieved within the first 5 min. For many situations, the T_v and solar threshold for visual and thermal acceptability may be attained within this time frame. Data also indicated that switching from colored to bleached states is 25-40% faster than from bleached to colored. With the electrochromic protected by the existing glazing, switching speeds were faster than what would normally be seen for an electrochromic exposed to low outdoor temperatures. Generally, devices take about

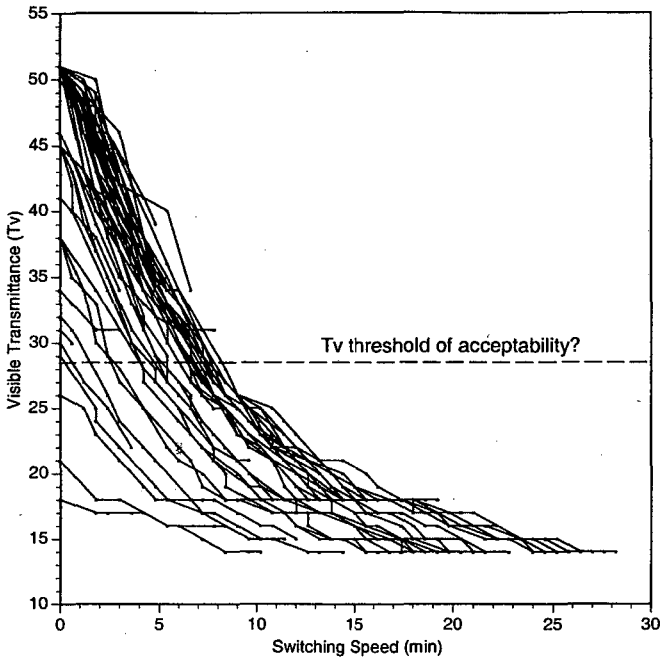

Fig. 10. Bleach-to-color switching speed profiles for a 62.1x172.6 cm electrochromic window at surface temperatures of 12-43°C with varying incident solar radiation.

five times longer to switch at surface temperatures of -10°C than at room temperatures of 21°C. Direct irradiation will improve speeds.

The ramifications of slow switching speeds on visual comfort can be understood by examining a case study example where the sun is intermittently obscured and revealed by transient clouds or intervening buildings. In Figure 3, discomfort glare exceeds the "just intolerable" borderline (SR>2.5) for 9 min as the windows color from 38% to 19%/14% transmission (lower/upper windows, respectively) when direct sun first comes into the plane of the window. Discomfort glare is then within the "just disturbing" range for 9 min as the electrochromics continue to color to 11%. At 10:00, direct sun is temporarily obscured and the electrochromic makes excursions back towards the bleached state. At 10:09, direct sun is again present, causing intolerable discomfort glare for another 2 min. All told, discomfort glare is above "just intolerable" levels for 11 min due to slow switching speeds.

On the other hand, instantaneous switching can also have undesirable side effects. Windows provide a diurnal connection to the outdoors. Variations in lighting intensity provide information about weather and time of day and are known to have positive health effects. An electrochromic can dampen interior light level variations, resulting in a monotonous interior environment if always controlled to maintain the same interior illuminance.

The effects of switching speed on energy-efficiency may be significant, but were not quantified in this test. In a separate study of automated venetian blinds in the same test rooms, the activation time was varied from 30-s to 5-min and 10-min. Daily lighting energy use increased by 31-43% and 72-86%, respectively, while daily cooling load and peak cooling loads remained unchanged on clear summer days [41]. Separately, some manufacturers may impose surface temperature limits on the electrochromic itself and force "relaxation" or no switching activity to prevent coating damage if these limits are exceeded. For the electrochromic device studied here, the electrochromic was prevented from switching at temperatures above 60°C, but the

device was allowed to stay at the fully colored state. Control options for peak cooling load management may be restrained by these operational limits.

During cold winter periods, switching speeds of 1 h and greater will have a significant effect on comfort. Direct sun can provide passive solar heating, but visual comfort will be compromised for some tasks. Exterior or interior shades will be required for these applications.

Slow switching speeds will influence the design of the control system. Controller user feedback will be required so that occupants can determine if the electrochromic is in the process of switching or is at rest. Since switching speed varies with window size, multi-pane tracking control between windows of various sizes will be slightly asynchronous; e.g., at the test site, the smaller upper windows switched faster than the larger lower windows. Uniform time delays can be used to decrease controller hysteresis. Smarter algorithms that have a memory of site conditions can also be used to improve comfort.

Increased switching speed can be accomplished by decreasing the distance between the bus bars or by material improvements to increase the conductivity of the transparent conductors. Secondary measures such as exterior overhangs and fins will decrease dependence on the electrochromic for full sun control, but may increase thermal stress on the electrochromic. For cold climates, the electrochromic may be used as an interior layer in a multi-layer system to improve speed but this position will compromise its heat rejection properties.

5.5. Stability

Transmission of the windows at the test site was not independently monitored, so degradation rates or variability of T_v and CR with the number of cycles or leakage current could not be verified. Lack of closed-loop feedback control poses several problems. If there is significant degradation in T with cycling over 20-30 years and all windows in the room are not cycled at the same rate (e.g., as suggested for glare control), eventually a non-uniform checkerboard appearance will occur across the facade. Feedback sensors can be designed for the electrochromic window to provide independent measures, but may increase cost. A gradual decrease in CR over the life expectancy of the product will also result in the loss in ability to meet the initial design conditions: energy-efficiency and comfort may degrade as well over time. Glass replacement may also result in a non-uniform appearance between new and old panes, since the absolute transmission levels cannot be calibrated between windows.

5.6. Appearance

The electrochromic window systems tested had excellent optical clarity, no coating aberrations (holes, dark spots, etc.), uniform density of color across the entire surface during and after switching, smooth gradual transitions when switched, and excellent synchronization or color-matching between a group of windows during and after switching. The windows had a very slight yellowish tint when fully bleached and a deep blue tint when fully colored. The glazings were not reflective.

5.7. Cycling

Several examples of the patterns for electrochromic cycling have been given above in Figures 2-5. These data show that one can expect no cycling on overcast winter days, two or more

cycles on partly cloudy days, and one full cycle on clear winter days if the electrochromic is controlled for energy-efficiency and direct sun. For durability tests, however, the number and depth of cycles to be expected over the life of the window (20-30 years) will vary with building and site parameters such as glazing area, illuminance setpoint, weather, window orientation, etc. The number of cycles per day may also increase if the occupant is permitted to override the automatic controller (e.g., for view or privacy). Given the range of user activities that can occur in a space, a user-override option is advised.

6. Conclusions

The objective of this work was to determine whether actual large-area electrochromic devices will indeed provide significant performance benefits and to suggest possible material improvements that would make electrochromics more practical for commercial building applications. A literature search was made to determine common properties of actual small and large-area electrochromic devices. Monitored lighting performance data from a full-scale, 4-month winter test of specific large-area electrochromic devices were used primarily for this evaluation. No thermal evaluation was performed. Supporting calculations and projected performance from common device properties were also used. The relative lighting and visual comfort performance is summarized as follows:

Daily lighting energy use of the EC-glazing was 6-24% less compared to the 11%-glazing, 3% less to 13% more compared to the 38%-glazing, and 3-14% less than the 11%/38%-glazing. The benefits were not as large as expected due to direct sun control. Summer results are expected to be better due to higher solar altitudes and greater daylight availability. For this large window-to-wall area ratio, incremental differences in energy use between glazing systems may be derived principally from cooling energy reductions.

Interior total illuminance levels of the EC-glazing were greater than the 11%-glazing. With the EC-glazing, window brightness was uncontrolled (>850 cd/m^2) for no more than 10% of the day, while the 11%-glazing had no uncontrolled window brightness. The discomfort glare subjective rating exceeded "just intolerable" levels for 4-5% of the day in both cases.

Interior total illuminance levels of the EC-glazing were on average less than the 38%-glazing. With the EC-glazing, window brightness was uncontrolled (>850 cd/m^2) for no more than 12% of the day, while the 38%-glazing had uncontrolled window brightness for no more than 48% of the day. The glare subjective rating exceeded "just intolerable" levels for 2-4% of the day in both cases.

Large-area electrochromics will be broadly applicable to vertical windows in commercial buildings with occupants performing VDT tasks if they are designed or operated as follows:

- A continuous luminous transmission range of ~0.08-0.80 (or broader if possible) and CR of 1:10 or greater is preferred for some direct sun intensity control, privacy, and increased daylight during overcast sky conditions. This is achievable with some reported electrochromic devices noted in the literature. The strategy of blocking direct sun with a heavily darkened electrochromic window compromises daylight admission and potential lighting energy reductions, and will not necessarily ensure visual comfort for VDT tasks. To block direct sun for south-, east-, and west-facing windows, separate provisions—such as enabling control of portions of the entire window plane or use of interior or exterior shades—will be needed

to achieve significant total energy reductions.

- Faster switching speeds are required to increase visual comfort. This is not currently achievable for large-area glazings (>0.1 m^2) across the lower range of possible outdoor temperatures (-20-80°C). Achieving a partially-switched T_v "threshold" within 5 minutes may be acceptable for most visual tasks. Increasing switching speeds without affecting window longevity poses perhaps the next greatest technical challenge for large-area devices, particularly if use during cold winter months is desired. Scientific breakthroughs in transparent conducting materials may occur, but are expected from a separate industry. Electrical wires through transparent areas of the window (similar to a car window defogger) may be a solution. If interior or exterior shades are used to block direct sun or if non-VDT tasks are being performed, switching speed becomes less critical. Replacement of CRT screens with newer LCD screens or improved anti-reflection coatings will also partially mitigate this problem.
- A minimum change (2-5%) in transmission limits over the life of the device (30-50K cycles) and/or closed-loop feedback control is needed to ensure sustained performance over the life of the window. Some manufacturers have reported that this is currently achievable for large-area glazings, but independent verification has yet to be done. The electrochromic tested in this work appeared to have excellent open circuit memory, but independent verification was not done.
- Durability over 30-50K cycles is required, particularly for applications in climates with partly-cloudy skies. This is reported to be achievable for some devices, but the rate and depth of cycling for these durability tests may not be the same as would be expected with practical device use.
- The tested WO_3 device exhibited a strong blue color when fully switched, which may affect brightness perception and accurate color rendition. Windows that were switched to different transmission levels within the same window wall made these effects more apparent. A more neutral color is achievable with slightly yellow and brown counterelectrodes.

Subjective human factors studies are required to determine the likely preferences for the electrochromic transmission range, direct sun control, and switching speeds for different tasks. A detailed, accurate thermal evaluation is needed to determine heating and cooling load benefits. An evaluation of thermal comfort for an irradiated subject requires more research. Alternate window designs and control strategies should be considered to improve the performance of electrochromics in buildings. Further research may occur under the auspices of the International Energy Agency Task 27. A new demonstration project called Switchable Facades Technologies (SWIFT) will evaluate energy use, control strategies and human factors in both commercial and residential buildings in Europe [42].

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