Arnold Schwarzenegger
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WINDOW SYSTEMS FOR HIGH PERFORMANCE COMMERCIAL BUILDINGS

PIER FINAL PROJECT REPORT

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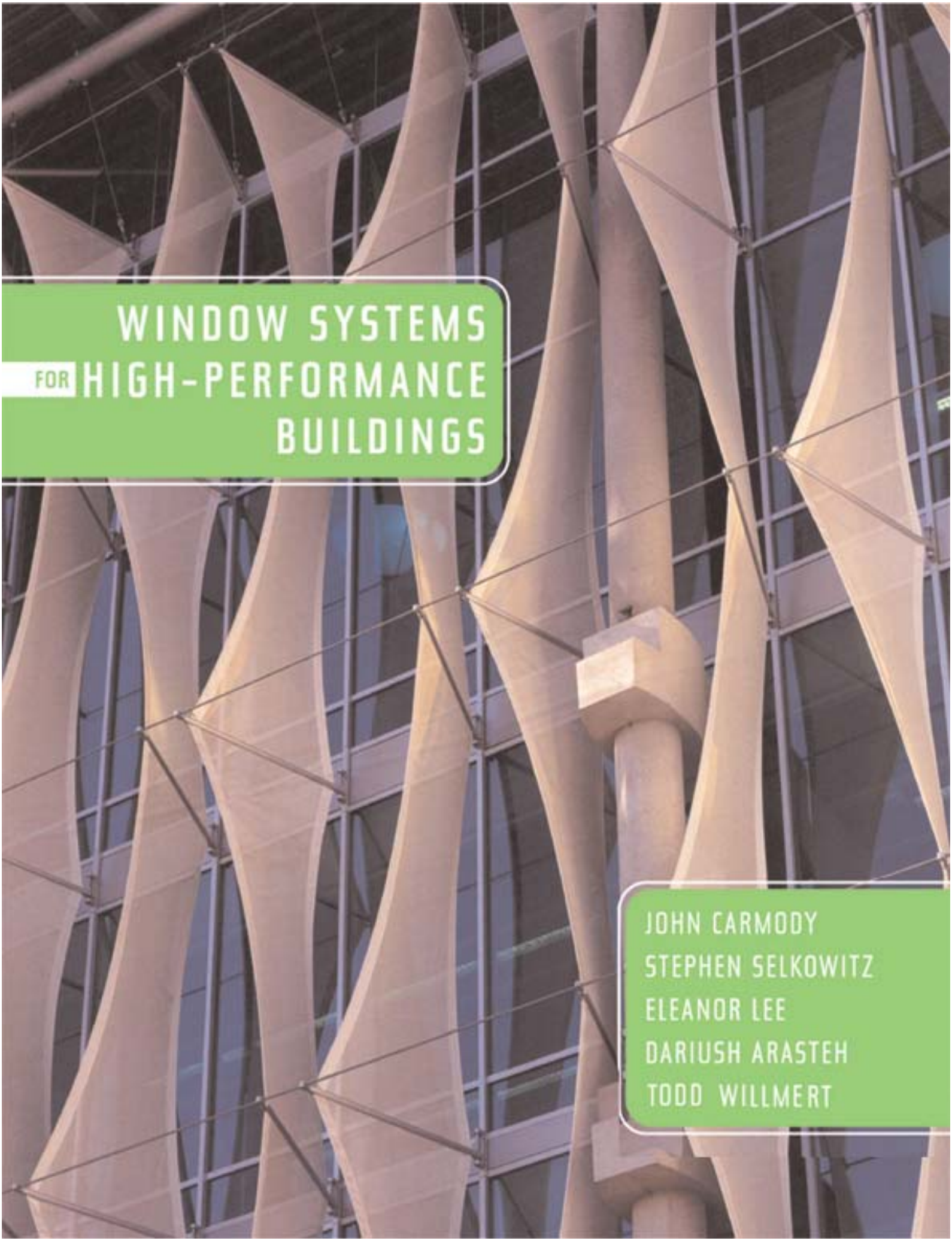

WINDOW SYSTEMS FOR HIGH-PERFORMANCE BUILDINGS

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Emerging Glazing Technologies

Most of the emerging glazing technologies presented in this section are available or nearly on the market. These include insulation-filled and evacuated glazings to improve heat transfer by lowering U-factors. Switchable glazings such as electrochromics change properties dynamically to control solar heat gain, daylight, glare, and view. Building-integrated photovoltaic solar collectors involving window systems not only generate energy but also form part of the building envelope.

INSULATION-FILLED GLAZINGS

There are several options for highly insulating windows with aerogel, honeycombs, and capillary tubes located between glazing panes. These materials provide diffuse light, not a clear view. Some of these materials are used in Europe for passive solar applications.

Aerogel is a silica-based, open-cell, foam-like material composed of about 4 percent silica and 96 percent air. The microscopic cells of the foam entrap air (or another gas if gas-filled), thereby preventing convection while still allowing light to pass. The cell sizes are smaller than the mean free path of air/gas molecules, thus reducing conduction to values below those of pure conduction for the air/gas. Long-wave thermal radiation is virtually eliminated due to the multiple cell walls through which long-wave infrared radiation must be absorbed and reradiated. The particles that make up the thin cell walls slightly diffuse the light passing through, creating a bluish haze similar to that of the sky.

Aerogel has received research attention for its ability to be both highly transparent and insulating, making it one of a number of materials that are generically referred to as transparent insulation. It should be technically possible to produce windows made of aerogel with a center-of-glass U-factor as low as 0.05. However, aerogel has only been produced in small quantities and sizes, so only tile-sized samples have been used as windows for research purposes. European manufacturers have produced double-glazed windows filled with small beads of aerogel and while the units have good insulating values, they are diffusing and do not provide a view. Aerogel might find a future application as a component of a larger window system, such as spacers between insulating panes of glass, or in skylights or glass blocks.

Figure 3-27. Exterior view of Rapson Hall at the University of Minnesota using channel glass with translucent insulation. Architect: Steven Holl Architects; Photo: Warren Bruland

Figure 3-28. Interior view of Rapson Hall using channel glass with translucent insulation. Channel glass is used as a linear glazing system, with translucent insulation sandwiched between interlocking pieces of glass. The channel glass itself has a U-factor of 0.53, SHGC of 0.69, and VT of 0.75. The insulation improves the assembly U-factor to 0.29 and SHGC to 0.36. VT falls to 0.38. Photo: Warren Bruland

EVACUATED WINDOWS

The most thermally efficient gas fill would be no gas at all—a vacuum. A number of researchers around the world have been pursuing the development of insulating window units in which the space between the panes is evacuated. If the vacuum pressure is low enough, there would be no conductive or convective heat exchange between the panes of glass, thus lowering the U-factor. A vacuum glazing must have a good low-E coating to reduce radiative heat transfer—the vacuum effect alone is not adequate. This principle has been used in the fabrication of thermos bottles for many years, with the silver coating serving as the low-emittance surface.

Evacuated window assemblies present a number of engineering problems, however. One major issue is the structural requirement to resist normal air pressure and variable pressures caused by wind and vibration. There can be large thermal stresses between large, window-sized panes of glass. A thermos bottle resists these forces easily because of its strong curved shape, but the large, flat surfaces of a window tend to bow and flex with changing pressures. In prototypes, minute glass pillars or spheres have been used to maintain the separation between the panes. The pillars are very small but are somewhat visible, reducing the window clarity.

Another issue is the maintenance of an airtight seal around the unit edge. The seal must be maintained to eliminate gaseous conduction by keeping the air density within the unit to less than one millionth of normal atmospheric pressure; an air density of only ten times this amount is sufficient to re-establish conduction to its normal value. This vacuum seal must remain intact for the life of the window, through manufacture, transportation, installation, and normal operation, wear, and weathering. Special solder glass seals have been used successfully by Australian researchers in the development of large prototypes. Center-of-glass U-factors of 0.2 have been achieved to date, with the possibility of reaching 0.12, while maintaining a high SHGC. This unit also has the advantage of being thin and thus suitable for many glazing retrofits. However, edge condition losses are larger than for conventional IGU designs, although these can be compensated for in the frame design. A major glass company now offers this technology as a commercially available product in Japan.

SMART WINDOWS

The emerging concept for the window of the future is more as a multifunctional "appliance-in-the-wall" rather than simply a static piece of coated glass. These facade systems include switchable windows and shading systems such as motorized shades, switchable electrochromic or gasochromic window coatings, and double-envelope window-wall systems that have variable optical and thermal properties that can be changed in response to climate, occupant preferences and building system requirements. By actively managing lighting and cooling, smart windows could reduce peak electric loads by 20–30 percent in many commercial buildings, increase daylighting benefits throughout the United States, improve comfort, and potentially enhance productivity in homes and offices. These technologies can provide maximum flexibility in aggressively managing demand and energy use in buildings in the emerging deregulated utility environment. They can also move the building community towards a goal of producing advanced buildings with minimal impact on the nation's energy resources.

The ideal window would be one with optical properties that could readily adapt in response to changing climatic conditions or occupant preferences. Researchers have been hard at work on new glazing technologies for the next generation of smart windows. After many years of development, various switchable window technologies are now in prototype testing phases and should be commercially available in the near future. As with other window

technologies, the architect will need to understand these new systems in order to specify them properly.

There are two basic types of switchable windows—passive devices that respond directly to a single environmental variable such as light level or temperature, and active devices that can be directly controlled in response to any variable such as occupant preferences or heating and cooling system requirements. The main passive devices are photochromics and thermochromics; active devices include liquid crystal, suspended particle, and electrochromics.

Photochromics

Photochromic materials change their transparency in response to light intensity. Photochromic materials have been used in eyeglasses that change from clear in the dim indoor light to dark in the bright outdoors. Photochromics may be useful in conjunction with daylighting, allowing just enough light through for lighting purposes, while cutting out excess sunlight that creates glare and overloads the cooling system. Although small units have been produced in volume as a consumer product, cost-effective, large, durable glazings for windows are not yet commercially available.

Thermochromics

Thermochromics change transparency in response to temperature. The materials currently under development are gels sandwiched between glass and plastic that switch from a clear state when cold to a more diffuse, white, reflective state when hot. In their switched-on state, the view through the glazing is lost. Such windows could, in effect, turn off the sunlight when the cooling loads become too high. Thermochromics could be very useful to control overheating for passive solar heating applications. The temperature of the glass, which is a function of solar intensity and outdoor and indoor temperature, would regulate the amount of sunlight reaching the thermal storage element. Thermochromics would be particularly appropriate for skylights because the obscured state would not interfere with views as much as with a typical vision window. Such units would come with a preset switching temperature, which would have to be selected carefully for the specific application. A thermochromic window can also be activated by a heating element in the window, making it operate like other switchable glazings, but this tends to be less energy efficient. Prototype glazings have been tested but are not yet commercially available.

Liquid Crystal Device Windows

A variant of the liquid crystal display technology used in wristwatches is now serving as privacy glazing for new windows. A very thin layer of liquid crystals is sandwiched between two transparent electrical conductors on thin plastic films and the entire emulsion or package (called a PDLC or polymer dispersed liquid crystal device) is laminated between two layers of glass. When the power is off, the liquid crystals are in a random and unaligned state. They scatter light and the glass appears as a translucent layer,

which obscures direct view and provides privacy. The material transmits most of the incident sunlight in a diffuse mode, thus its solar heat gain coefficient remains high.

When power is applied, the electric field in the device aligns the liquid crystals and the glazing becomes transparent in a fraction of a second, permitting view in both directions. Most such devices have only two states, clear and diffusing, and the power (about 0.5 W/sf, operating between 24 and 100 volts AC) must be continuously applied for the glazing to remain in the clear state. The visible transmittance range is typically 50–80 percent and the SHGC is 0.55–0.69, although dyes can be added to darken the device in the off state. Some manufacturers offer products in a variety of colors and for curved and flat-shaped glass. Glazings can be fabricated up to 3-by-7.5-foot sheets. Ultraviolet (UV)-stable formulations now permit exterior applications but UV stability and cost remain as issues.

Suspended Particle Device (SPD) Windows

This electrically controlled film utilizes a thin, liquid-like layer in which numerous microscopic particles are suspended. In its unpowered state the particles are randomly oriented and partially block sunlight transmission and view. Transparent electrical conductors allow an electric field to be applied to the dispersed particle film, aligning the particles and raising the transmittance. Typical visible transmittance (VT) and solar heat gain coefficient (SHGC) ranges for the film alone are VT=0.22–0.005 or 0.57–0.12 and SHGC=0.56–0.41 or 0.70–0.50, respectively, with near instant switching times (less than one second). The SHGC switching range is more limited than electrochromic windows (see below). The device requires about 100 volts AC to operate from the off state (colored) to the on state (near transparent) and can be modulated to any intermediate state. Power requirements are 0.5 W/sf for switching and 0.05 W/sf to maintain a constant transmission state if not off (the most colored, cobalt blue state). With research, the operating voltages could get down to about 35 volts AC. New suspensions are also under development to achieve several different colors (green, red, and purple) and to affect up to a 50 percent change in solar transmittance. Manufacturers state that these laminated glazings can be fabricated in up to 4-by-8-foot sheets and can be offered in both curved and flat shapes. Long-term durability and solar-optical properties have not been independently verified. Products are now entering the market, but cost remains an issue.

Electrochromic Windows

The most promising switchable window technology today is electrochromic (EC) windows. An electrochromic coating is typically five layers, about one micron thick, and is deposited on a glass substrate. The electrochromic stack consists of thin metallic coatings of nickel or tungsten oxide sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. This field moves various coloration ions (most commonly lithium or hydrogen) reversibly between the ion storage film

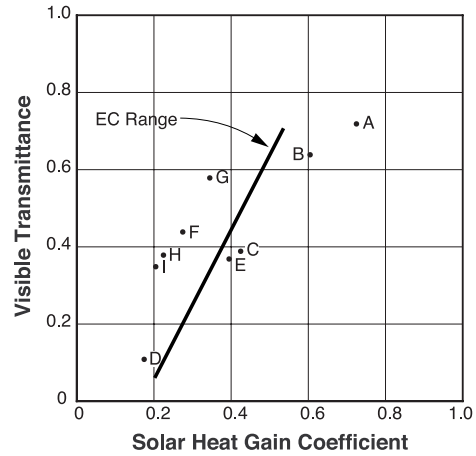
through the ion conductor (electrolyte) and into the electrochromic film. The effect is that the glazing switches between a clear and transparent prussian blue-tinted state with no degradation in view, similar in appearance to photochromic sunglasses.

The main advantages of EC windows is that they typically only require low-voltage power (0–10 volts DC), remain transparent across its switching range, and can be modulated to any intermediate state between clear and fully colored. Switching occurs through absorption (similar to tinted glass), although some switchable reflective devices are now in research and development. Low-emittance coatings and an insulating glass unit configuration can be used to reduce heat transfer from this absorptive glazing layer to the interior. Typical EC windows have an upper visible transmittance range of 0.50–0.70 and a lower range of 0.02–0.25. The SHGC ranges from 0.10–0.50. A low transmission is desirable for privacy and for control of direct sun and glare, potentially eliminating the need for interior shading. A high transmission is desirable for admitting daylight during overcast periods. Therefore, the greater the range in transmission, the more able the window is to satisfy a wide range of environmental requirements.

For some EC types (polymer laminate), the device is switched to its desired state and then no power is needed to maintain this desired state. This type of device has a long memory once switched (power is not required for three to five days to maintain a given switched state). Another EC type (all-solid-state) requires minimal low-voltage power to both change and maintain a given state (0.02 W/sf). When powered off, the EC goes to clear. The advantage of this type of EC is that it can switch faster than its long-memory counterpart. This second type has also been shown through independent tests to be extremely durable under hot and

Figure 3-29. SHGC and VT range for electrochromic glazing

See Figure 3-32 for glazing properties of A–H.



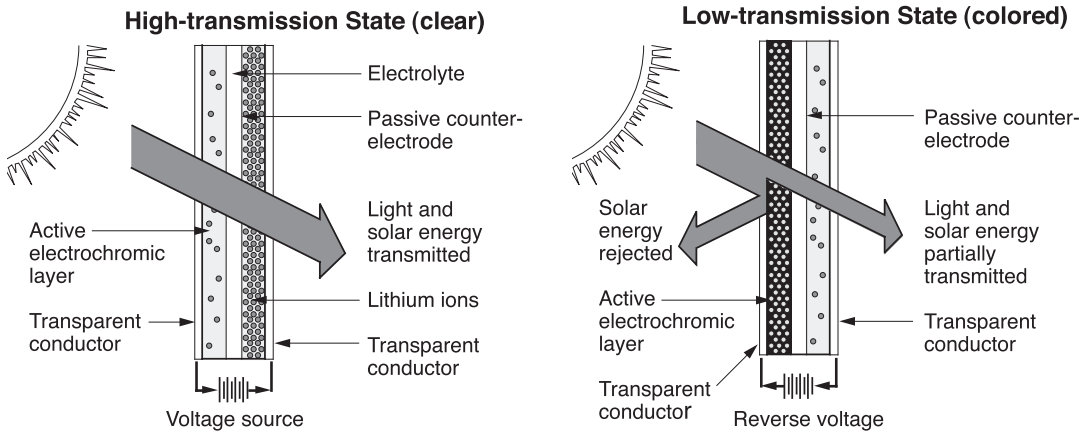


Figure 3-30. Schematic diagram of a five-layer electrochromic coating (not to scale—the actual thickness is 4 microns or 1/50th of a human hair). A reversible low-voltage source moves ions back and forth between an active electrochromic layer and a passive counterelectrode. When the lithium ions migrate into the active electrochromic layer, an electrochemical reaction causes that layer to darken. When the voltage is reversed and the ions are removed, the electrochromic layer returns to its clear state.

cold conditions and under intense sun. These devices have been cycled (from clear to colored and then back again) numerous times under realistic conditions so that one can expect long-term sustained performance over the typical 20–30 year life of the installation.

Switching speed is tied to the size and temperature of the window. Coloring typically takes longer than bleaching. A 3-by-6-foot window can take 10–15 minutes to switch across its full range if warm and up to 25 minutes if cold. If the conditions are adverse (too hot, too cold, ice, thermal shock), the window may be prevented from switching. Typical operating temperatures are between –20 and 190 degrees Fahrenheit.

Electrochromic glazings are fabricated as insulated glass units using standard or laminated glazing. Wire leads extending from one edge are tied into the building's electrical system. The window can also be powered using photovoltaic cells to avoid the cost of wiring to the building. Once installed, the window or skylight can be operated by a manual switch or remote controller, a simple stand-alone automatic system, or a sophisticated central energy management system that integrates its operation with other building systems, such as the electric lighting and mechanical system.

Controlling and modulating incoming light and solar heat gains leads to lower energy bills and increased occupant comfort. The higher initial price of electrochromic glazing can be partially offset by these and other factors, such as reduction in HVAC equipment size and window treatment. Electrochromic windows give building owners the ability to modulate heat gain through the window, reducing cycling stress on HVAC motors and other equipment. Additional operating costs for the static glazings—shade replacement and cleaning, UV fading of textiles and fabrics, increased HVAC maintenance, and reduced life of the HVAC system—can also buy down electrochromic glazing's higher initial cost. Electrochromic glazing provides functionality that other types of shading do not—for example, in darker states, it is still possible to provide view rather than blocking it completely with drawn shades or blinds.

Electrochromic technology has been actively researched throughout the world for over thirty years, and promising laboratory results have led to prototype window development and demonstration. Examples of electrochromic window prototypes have been demonstrated in a number of buildings in Japan and more recently in Europe and the United States. Millions of small electrochromic mirrors have been sold for use as rearview mirrors in automobiles and trucks. Electrochromic glazings have also been installed as prototype sunroofs in cars.

Electrochromic glazings are nearing commercial readiness. Currently, flat durable window and skylight products are emerging on the market in sizes of 18-by-36 inches, although larger sizes are expected in the next three to five years. A full-scale field test is now underway at the Lawrence Berkeley National Laboratory (LBNL). An additional field test in a home in Houston, conducted by the National Renewable Energy Laboratory, is scheduled to begin in winter 2003. For the LBNL test, 10-by-15-foot-deep private offices have been fitted with a large 10-by-9-foot window wall of EC glass. Each EC window can be switched independently to control local

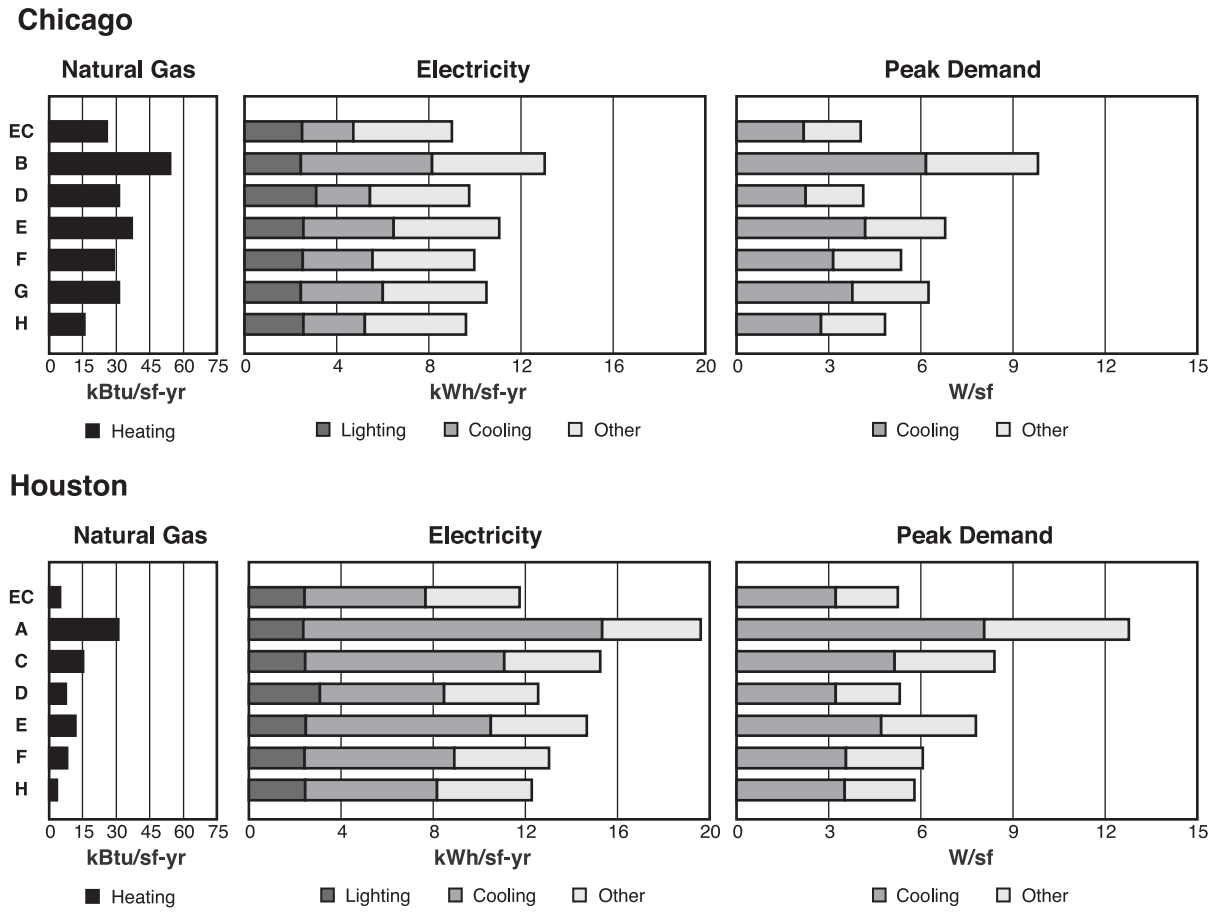
sources of glare and to admit daylight. The windows are linked electronically to light sensors and dimmable fluorescent office lighting. The glazings are operated so that they admit maximum daylight under dark, overcast conditions and minimum solar heat when sunny skies prevail. Occupants in the offices can override the automated controls if they desire. Overall, this building-scale field test reinforces the capability of switchable windows to provide energy savings while improving comfort and amenity in an office environment.

Figure 3-32 illustrates the simulated energy and peak demand performance for electrochromic glazing (EC) in south-facing offices located in Chicago and Houston. In both climates, the electrochromic glazing results in the lowest energy use and peak demand if the windows are controlled to maintain a daylight workplane illuminance of 50 fc and the lights are dimmed.

Figure 3-31. Field test of electrochromic windows at LBNL. (Left) *Interior view of EC window with the lefthand window column set to fully bleached or clear and the righthand window column set to fully colored. The middle window column is set to a transmission level halfway between the two extreme states.* (Right) *Exterior view of EC window. Photo: Courtesy of LBNL; Photo: Roy Kaltschmidt*

Figure 3-32. Energy use and peak demand comparison of electrochromic (EC) and other windows

All cases are south-facing with a 0.60 window-to-wall ratio and no shading. Numbers are expressed per square foot within a 15-foot-deep perimeter zone. Results were computed using DOE-2.1E for typical office buildings in Chicago, Illinois and Houston, Texas (see Appendix A).



Window A single glazing clear U=1.07 SHGC=0.69 VT=0.71	**Window E** double glazing low-E, bronze tint U=0.49 SHGC=0.39 VT=0.36
Window B double glazing clear U=0.60 SHGC=0.62 VT=0.63	**Window F** double glazing spectrally selective low-E tint U=0.46 SHGC=0.27 VT=0.43
Window C double glazing bronze tint U=0.60 SHGC=0.42 VT=0.38	**Window G** double glazing spectrally selective low-E clear U=0.46 SHGC=0.34 VT=0.57
Window D double glazing reflective coating U=0.54 SHGC=0.17 VT=0.10	**Window H** triple glazing 1 low-E layer, clear U=0.20 SHGC=0.23 VT=0.37

Gasochromic Windows

Gasochromic windows produce a similar effect to electrochromic windows, but in order to color the window, diluted hydrogen (below the combustion limit of 3 percent) is introduced into the cavity in an insulated glass unit. Exposure to oxygen returns the window to its original transparent state. To maintain a particular state, the gap is simply isolated from further changes in gas content. The optically active component is a porous, columnar film of tungsten oxide, less than 1 micron thick. This eliminates the need for transparent electrodes or an ion-conducting layer. Variations in film thickness and hydrogen concentration can affect the depth and rate of coloration.

Visible transmittance can vary between 0.10–0.59 with a SHGC range of 0.12–0.46. Transmittance levels of less than 0.01 for privacy or glare control are possible. An improved U-value can be obtained with a triple-pane, low-E system (since one gap is used to activate the gasochromic). Switching speeds are 20 seconds to color and less than a minute to bleach. The gas can be generated at the window wall with an electrolyser and a distribution system integrated into

the facade. Gasochromic windows with an area of 2-by-3.5 feet are now undergoing accelerated durability tests and full-scale field tests and are expected to reach the market in the near future.

Motorized Shading

Motorized roller shades, drapes, blinds, exterior awnings and louvers are commercially available systems analogous to switchable windows. These systems have been used over the past thirty years in numerous buildings and so do not fall into the category of emerging technologies—they are discussed in the following section on sun-control devices.

Figure 3-33. Photovoltaics integrated with glazing. In this type of application, the solar cells provide shading and generate electricity. Photo courtesy of DOE/NREL; Photo: Paul Maycock

BUILDING INTEGRATED PHOTOVOLTAICS (BIPV)

Photovoltaics (PV) are solid-state, semiconductor type devices that produce electricity when exposed to light. Electrons in the photovoltaic material are knocked free by light to flow out of the device as an electric current. The more intense the sunlight, the stronger the electric current.

This phenomenon was discovered in the mid-1800s, yet important applications followed much later—for satellites and applications where extending the electric grid is cost prohibitive. Architectural applications have only recently become prominent. With Building Integrated Photovoltaics (BIPV), for instance, photovoltaics are integral to the building skin: the walls, roof, and vision glass. The envelope produces electricity, which flows through power conversion equipment and into the building's electrical system.

Photovoltaic vision glass integrates a thin-film, semitransparent photovoltaic panel with an exterior glass panel in an otherwise traditional double-pane window or skylight. All the PV types can be integrated and/or laminated in glass, but only thin-film photovoltaics will be translucent. Electric wires extend from the sides of each glass unit and are connected to wires from other windows, linking up the entire system. If the PV cells are part of the vision glass, various degrees of transparency are possible—as in frit glass—since the PV cells offer shade and produce electricity (Figure 3-33). In some cases, the PV panels are placed in spandrel panels, rather than the vision glass. Smaller PV systems can be used to power facade equipment directly instead of being connected to the electrical grid in the building. Vertically oriented PV panels are optimally not positioned toward the sun. One approach to position the PV panels more perpendicular to the sun is to place them into fixed shading devices on the facade or on movable shading panels, using the generated power to track the shades to the optimal solar angle (Figure 3-34).

Figure 3-34. Photo of PV panels integrated into sun-shading system. Photo courtesy of Kawneer Company; Photo: Gordon Schenck, Jr.

Current PV production technologies, pricing structure, and energy rates limit BIPV use to prominent, prestige buildings (although PV-integrated cladding costs are comparable to marble). Of course, as these factors are in constant flux, BIPVs are receiving increased attention that is justified by the promise of a building envelope that can generate energy in addition to providing shelter.