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Improvements in Glazings: SERI Materials Research in Progress

Thomas F. Potter

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Thomas F. Potter
Solar Energy Research Institute

ABSTRACT

Progress in two areas with significant long-term potential for improving the thermal performance of apertures is summarized and evaluated.

Removing interglazing gasses may greatly reduce the conductive/convective thermal transfer through multiple pane glazings. Evacuated glazings now under investigation show the expected high resistance to thermal conductance and convection; laboratory-scale demonstration units have been produced with laser sealed edges.

Another approach, more applicable for cooling load offset, addresses the possibility of electrically controlling the transmission of solar radiation through windows. Electrochromic glazings can be operated by means of low-voltage switching to adjust the visual and infrared transmittance of the aperture.

Both concepts are discussed in relation to 1. the overall goal of greatly reducing unwanted gains and losses through windows and 2. the commercially available alternatives to these concepts. Analyses of optimal characteristics and recent technical advances at SERI are described, and future research requirements are sketched.

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BACKGROUND

Building apertures can provide perspective, visual freedom, lighting and heating for building occupants. However, the glazing system used can also produce glare, distraction, lack of privacy, and unwanted heat loss or gain. Research progress toward the control of thermal gains and losses is the primary subject of this paper.

The amount of energy lost through windows in the nation's residential buildings is not accurately known. Shurcliff (1980) has estimated that for both a typical house and a well-insulated house in the northern half of the United States, about 15% to 35% of the total heat loss during the winter is via the windows. In passively solar heated houses, which have especially large windows, the losses are estimated to be even greater--from 20% to 40%. The total losses are impressive and excessive, and are estimated to be equivalent to about 300 million barrels of oil per year, or about 3% of our total energy purchases of all kinds (Shurcliff, 1980). Perhaps half of these losses can be reduced or eliminated by properly sealing the aperture assembly against gross infiltration. The other half of the losses can be attributed to the material properties of the glazing system.

Unwanted solar gain on large expanses of residential glazing is also a problem. Large-scale monitoring of passive solar homes has shown, for example, that summer performance of glazing systems should be carefully considered to avoid overheating the space. The discomfort and higher energy costs resulting from their poor design or operation discourage the wider adoption of otherwise appropriate passive solar technologies; the misuse caused by poor design is also an avoidable energy drain.

The potential impact of resolving the technical issues now under study is thus considerable in residential applications. These and other alternatives for very-high-R and/or controllable glazings could free the energy-conscious architect from many current constraints to window sizing, shading, and orientation determined by comfort and energy-use penalties.

The optical and thermal characteristics of existing and proposed glazing configurations are of interest because they affect the overall energy performance of aperture systems. Figure 1 summarizes the thermal resistance (R-value) and solar transmittance for various glazing combinations.

Continuing efforts to improve mainly the R-value of glazings have included adding sheets of glass or polyester, providing one or more infrared reflector surfaces, and filling the space between sheets with low-conductance gasses. Figure 1 shows the improvement in R-value of typical combinations of some of these features and the usually associated decrease in transmissivity.

Effective transmissivity and R-value of the entire window system are, of course, affected as well by drapes, blinds, etc. In some applications unwanted heat gain is also avoided by constructing overhangs that block the sun's rays at higher summer angles. However, substituting improved glazing properties for manual, mechanical, or structural components would allow freer design and an increased likelihood that the overall window system would consistently operate in a more efficient manner.

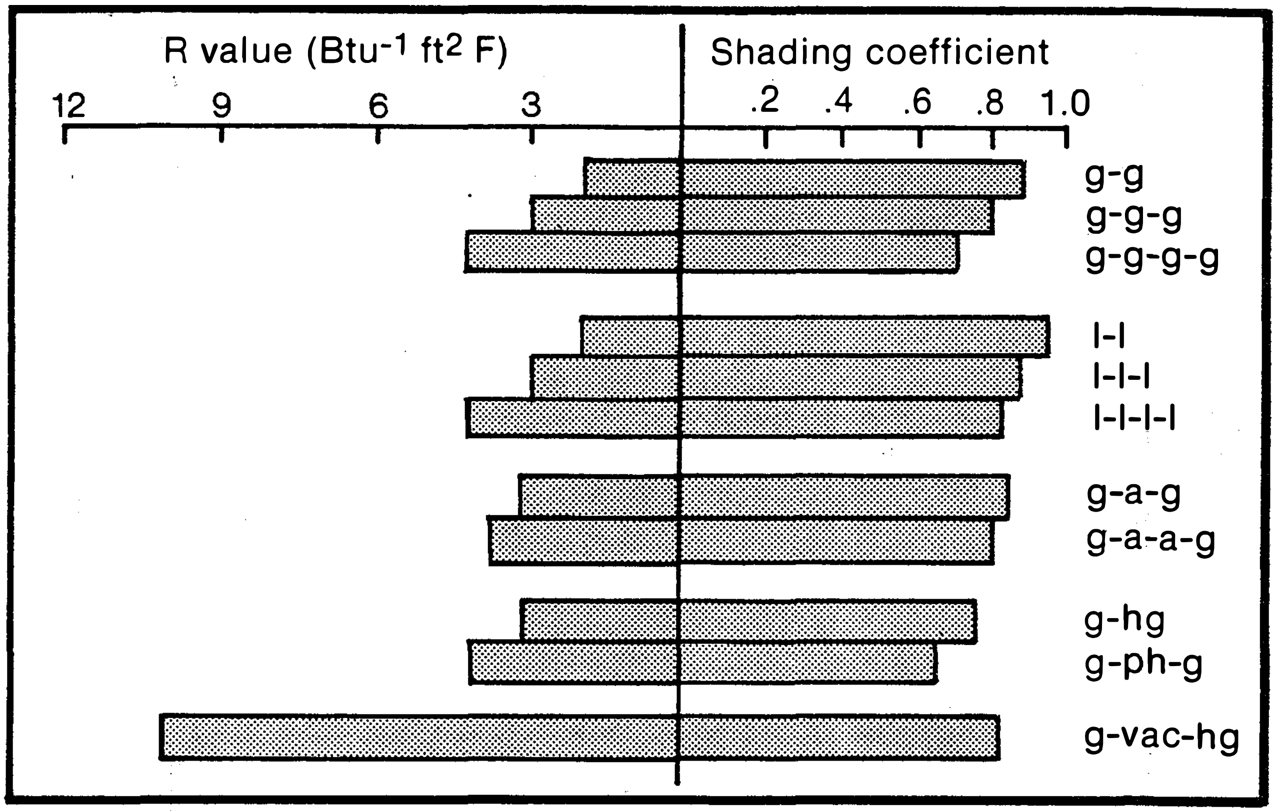

Figure 1. R-values and shading coefficients for selected glazing types. Abbreviations used for window materials are: g - 1/8-in. float glass; l- 1/8-in. low-iron sheet glass; p - 4-mil polyester film; a - 4-mil antireflective polyester film; h - heat-mirror coating with e = 0.15 (solar transmittance of coating and substrate is 0.7); vac - vacuum. Individual gap widths are 1/2-in. (12.7 mm). Calculations used ASHRAE standard summer and winter conditions. Data are from Rubin (1981), except for g-vac-hg, which were estimated by Benson et al. (1984).

The ideal window for general residential application is one with high transmittance and high R-value. For practical window applications, a balance must be struck between R-value and transmittance, and the "best" window will depend on the net energy savings (dollar savings) and the window's cost. The net energy savings depends on window location, shading, orientation, climate, and local energy costs. Several studies (Rubin, 1980; Neeper, 1982) have addressed the dependence of energy savings on the various parameters. In one study (Neeper, 1982), the balance between increasing transmittance and increasing R-values appears to favor increasing R-value. Figure 2 shows a set of curves for annual net energy savings contributed by 300 square feet of windows of various material configurations and orientations across climates (Neeper, 1982). From the figure it is evident that the savings are climate dependent, especially for south-facing windows.

Neeper (1982) also estimated annual net energy savings contributed in different climates by windows with different values of transmittance and thermal resistance. It is of interest to note his conclusion that an increase in transmittance saves about twice as much energy in Albuquerque, New Mexico, as in Caribou, Maine. However, an increase in R-value saves almost twice as much energy in Maine as in Albuquerque. From these data it is apparent that the optimal balance between transmittance and R-value also depends on climate.

It is reasonable to assume that the glazing of apertures will be substantially different 20 years from now. Several promising alternative approaches exist that may provide the materials basis for highly efficient window systems that will be commercially available then. Two separate areas of high-risk, preliminary research at SERI can greatly improve the control of thermal gains and losses through glazing systems. The first, which builds the technical base for developing evacuated glazings, addresses the challenge of maintaining a vacuum between glass sheets, one or more of which has an effectively infrared-reflecting film. The second evaluates the feasibility of electrically controlling solar gain using a solid state electrochromic coating.

Evacuated Glazings

Removing the interglazing gas would be an elegant solution to the problem of conductive and convective transfer across the gap. The challenge of reducing heat transfer from one glass sheet to another will be designing the assembly to accommodate the differential expansion of inner and outer sheets. Basically, the materials' issue is that flexible edge seals that will tolerate the anticipated movement over architectural lifetimes (say, 20 years or more) are not thought to be tight enough to hold a vacuum, while a rigid glass-glass edge fusion that will maintain a vacuum will be subject to the possibly destructive stresses of differential expansion.

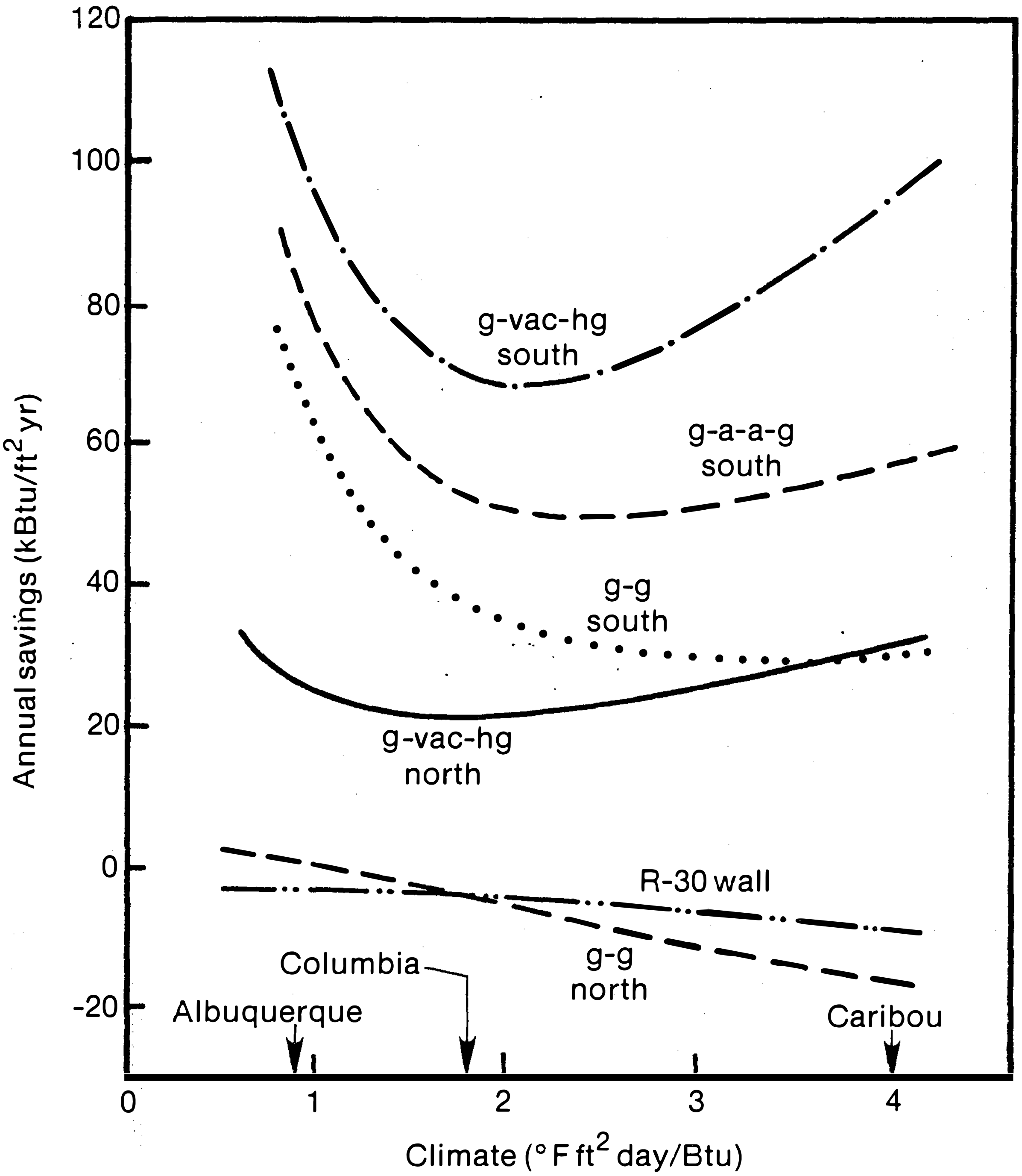

Figure 2. Computer-simulated performance of energy conserving windows and R-30 wall in different climates.

A first, and only partially alleviating, solution to the expansion problem may be to use glass with a lower coefficient of expansion. Borosilicate glass may serve, with thermal expansion of only 1/3 that of soda-lime; the work described here was performed exclusively with borosilicate glass.

Achieving the glass-glass seal is another challenge. The process that SERI has investigated uses a 350 W laser to fuse the edges, the benefits being speed, greatly reduced or eliminated vacuum contamination, and amenability to automatic control within a production vacuum oven. We believe that this fusion seal holds promise as well for extending the service life of interglazing films or fillers used in other advanced glazing systems. Borosilicate's tolerance of extreme temperature differences was key to producing earlier successfully laser-welded specimens; more ambitious, larger fabrications fractured during cooling until a regime was established for more gradual temperature reduction. Test results on the stress or thermal behavior of specimens obtained by improved procedures are not yet available.

An interglazing vacuum causes the glass sheets to deflect toward each other, which is both a technical and aesthetic (distortion) concern. Clear glass spheres ranging from 3 mm to 0.3 mm have been used in these studies to separate the sheets. The optimal size, shape, and placement of the spacers has not yet been determined, but will depend on constraints of durability, minimized conduction, stress reduction, perceptual clarity, and lack of distortion. Figure 3 shows the sensitivity of overall window assembly conductance to spacer size and spacing.

A final major technical challenge is to optimize the performance of the infrared reflector film applied to the glass, since improved infrared reflection will usually result in decreased transmissivity in the visible spectrum. A transmissivity of 0.30 is apparently tolerable in an office setting, but the lowest acceptable level for residential applications is unknown. We believe that an emissivity of 0.07 to 0.10 is achievable with a transmissivity of 0.6 to 0.8.

Evacuated Glazings Conclusions. Laboratory-scale specimens have been produced of edge-fused double glass assemblies with internal spacers and infrared reflective film. The edge seal and film layer parameters under investigation show initial promise as components of an evacuated window with greatly improved thermal performance and service life, but further study is required to resolve questions of stress tolerance and optimal configuration.

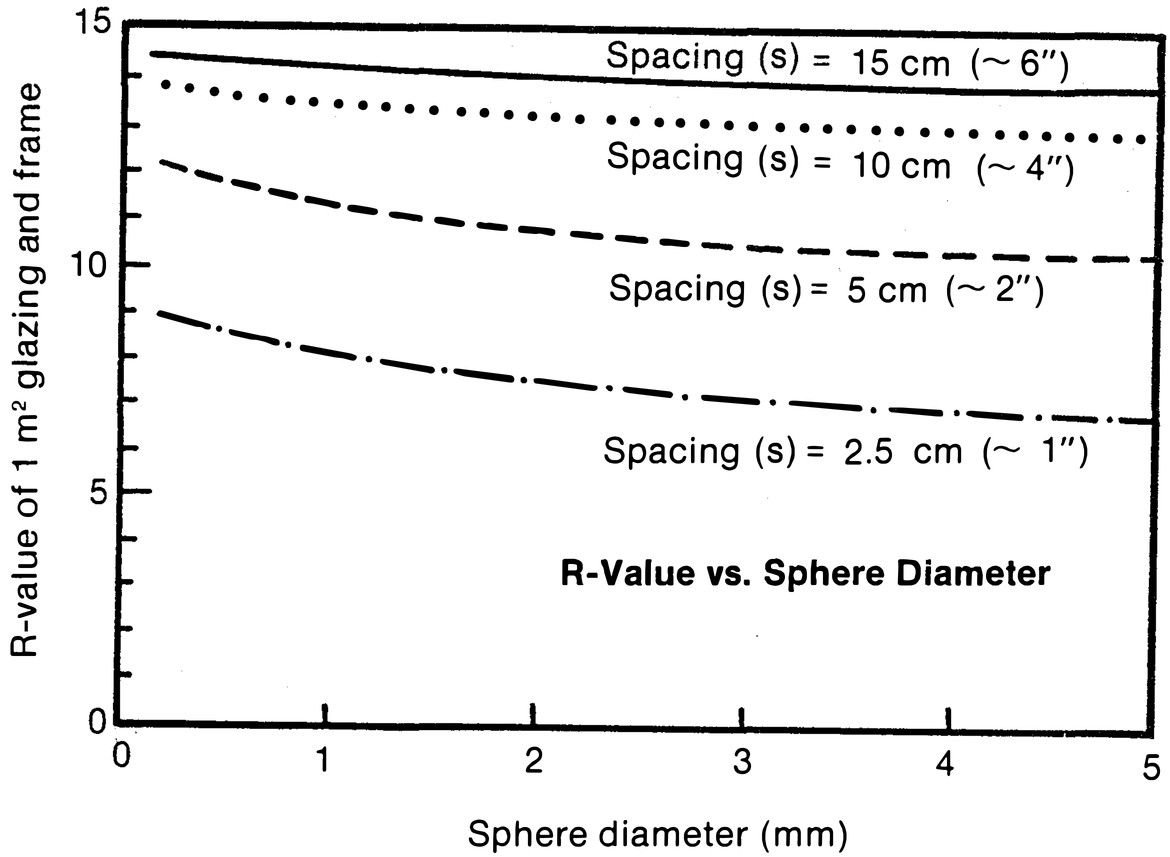

Figure 3: Effect on window assembly conductance of spacer size and spacing.

Electrochromic Coatings

It should be possible to design a glazing system that can exhibit different characteristics in reaction to differing electrical charges. An ideal system would be able to transmit, reflect, or absorb visible and infrared independently, and would be easily and efficiently controllable. The basis for such control exists in commercially available electronic display devices, and at SERI we are studying on these thin-film solid-state materials called electrochromics, which reversibly change their optical properties when subjected to electric currents.

The electrochromic process being studied depends on the fact that the oxides of tungsten, molybdenum, vanadium, niobium, and titanium exist in a crystal structure that has the unusual ability to accommodate additional positive ions without a change in basic structure. At sufficiently high concentrations of added ions, the compounds exhibit a characteristic metallic luster. The added ions increase the number of free electrons, which is thought to cause, in turn, a shift in the electron plasma absorption band and the appearance of coloration in crystalline films of the materials.

The present understanding of the electrochromic process in these metal oxides is not well developed for glazings application, since most research to date has been carried out for application to electronic displays; very fast switching times (milliseconds) and high contrast have been primary research objectives. For glazing applications much slower switching times (perhaps minutes) are tolerable. The primary objectives are to obtain large changes in solar transmittance and a fairly broad spectral response in order to achieve a visually acceptable neutral color density.

Since Deb's (1969) discovery of electrochromic behavior in tungsten oxide and molybdenum oxide thin films, a great deal of research has been conducted on these and other metal oxides, including those of vanadium, niobium, and titanium. The majority of research, however, has focused on tungsten oxide, which may be considered a model electrochromic metal oxide.

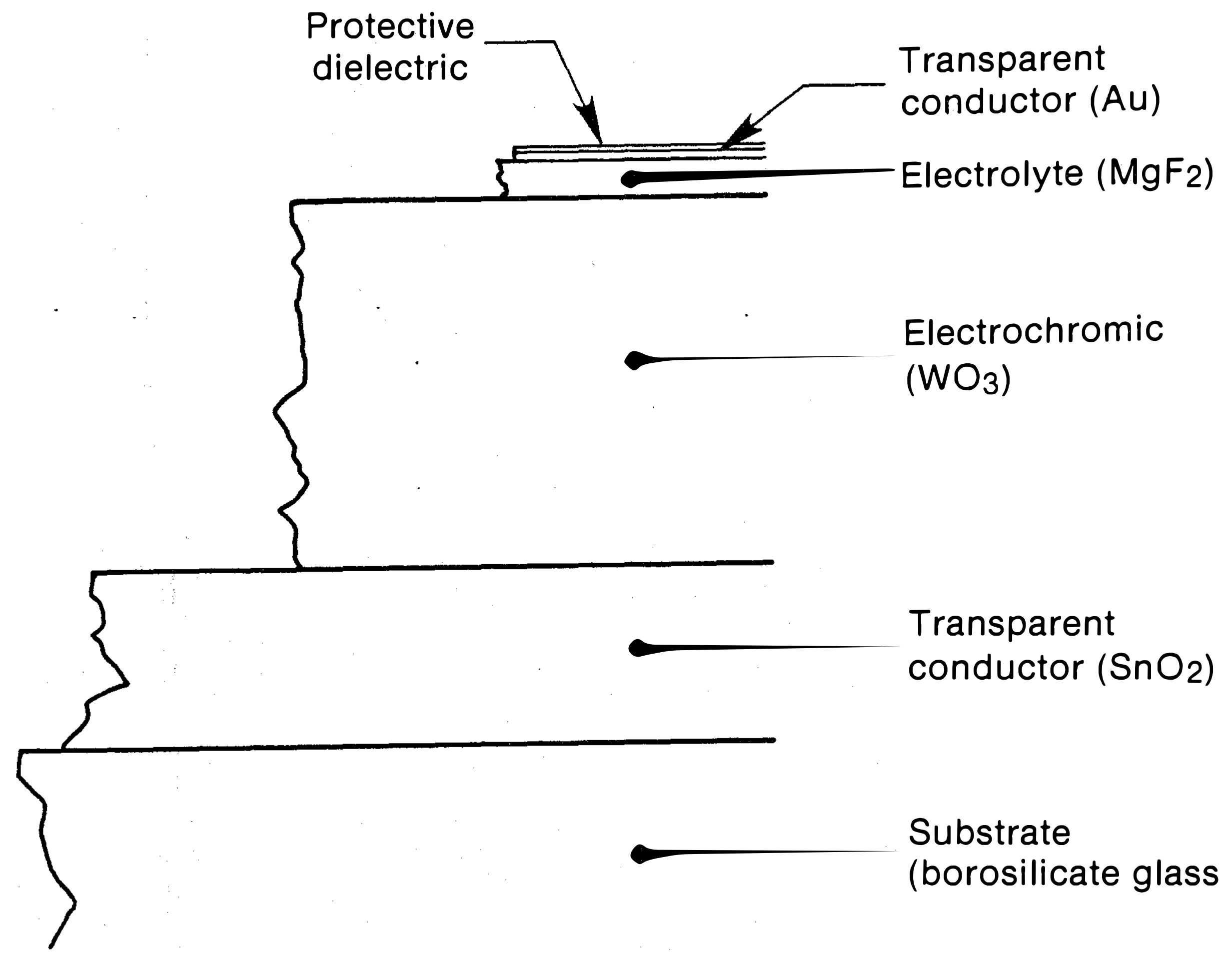

Figure 4. Schematic diagram of basic solid state electrochromic cell, with materials configuration of SERI test device.

Solid-state, thin-film electrochromic coatings based on tungsten oxide with configurations similar to that shown in Figure 4 have been reported in the literature by Deb and others. The electrochromic material together with a solid electrolyte material is deposited between transparent conductor layers. A surface protective layer is normally added to provide abrasion resistance, electrical isolation, and protection from outside contaminants. We used this basic configuration in our studies, with the materials indicated, except for the absence of the top protective layer.

Initial experiments at SERI were designed to reproduce results obtained on multilayer, solid-state electrochromic devices (Deb 1969, 1973). Coatings of this configuration, fabricated 10 years ago, are still operational and provide valuable comparisons to devices fabricated in our own laboratory. We repeatedly colored and bleached the test devices before performing optical measurements. To color the device, a small voltage (typically 2-10 volts) was applied. The tin oxide layer was the negative electrode and the gold layer was the positive electrode. By reversing the polarity of the electrodes, the device was bleached. Bleaching required less voltage and much less time than coloring.

Figure 5 shows spectral recordings of a typical device in the bleached, intermediate colored, and fully colored states. The intermediate colored state was achieved by applying 10 volts for 3 minutes to the device and the darkly colored state by applying 7.7 volts for 60 minutes. However, almost all of the coloration occurred within the first 6 minutes, with the first visible signs of coloring appearing within 10 seconds. Bleach times were typically 10-30 seconds.

Experiments were necessary to optimize many variables before a functionally reversible solid-state device could be constructed. A partial list of these variables includes purity of evaporation materials, compatibility of evaporant with its boat source, residual total and partial pressures in the vacuum chamber, substrate temperature, deposition rate, substrate cleaning procedure, and film thicknesses. To date, the best electrochromic performance has been achieved using a 380-nanometer (nm, billionth of an inch) coating of fluorine-doped tin oxide on a borosilicate glass substrate with the following multilayer thin-film configuration: 800 nm of tungsten oxide, 90 nm of magnesium fluoride, and 20 nm of gold. For this configuration, cathodic coloration for 3 minutes at 10 volts resulted in a 29% reduction in spectral transmittance. Application of 7.7 volts for an additional 60 minutes resulted in a total 68% reduction in transmittance (see Figure 5). Similar applied potentials resulted in anodic decoloration to initial transmittance values within 10 seconds. In practice, lower potentials (50% lower) are usually applied during anodic decoloration to reduce the current density and prevent heating the cell.

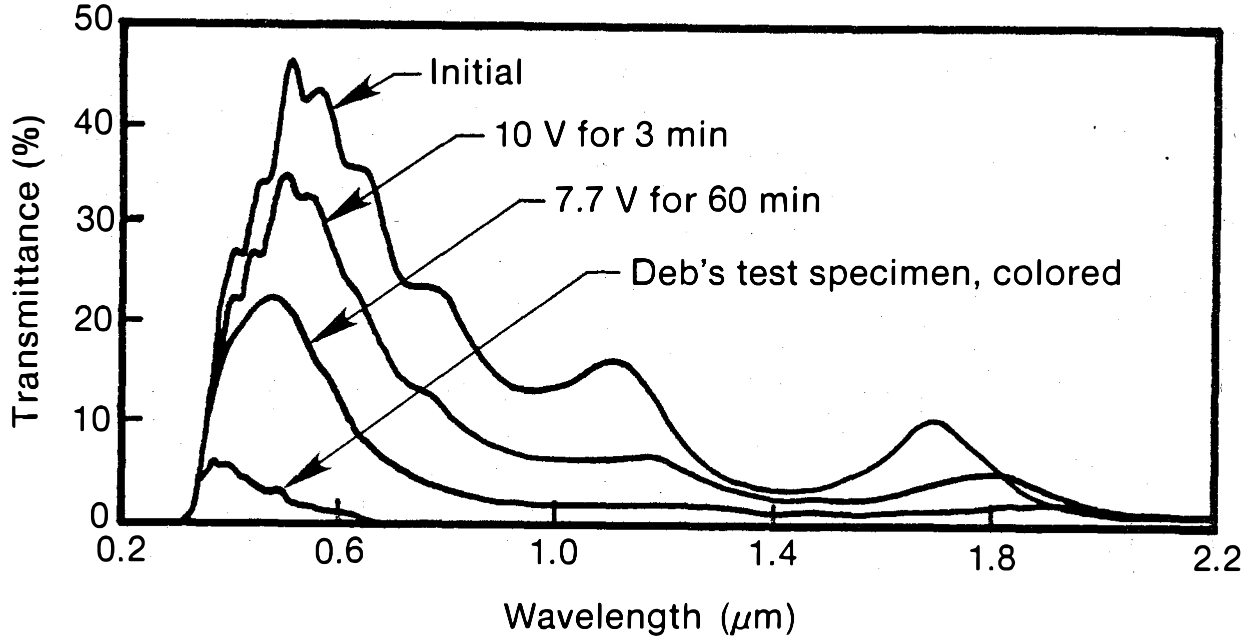

Figure 5. Spectral and solar transmittance measured for the Deb and SERI solid-state electrochromic devices.

For comparison, we also measured an electrochromic device fabricated by Deb in 1973. The bleached states of Deb's device and our device were nearly identical, but Deb's device colored to a darker navy blue, almost black color (see Figure 5). Another major difference concerns color memory. When we removed the potential across Deb's device, the color faded visibly and the device returned to its bleached state within several hours. We measured the transmittance on one of our devices over 20 hours after the electrical potential had been disconnected and detected no change in transmittance in either the spectral scans or in the solar weighted transmittance calculations. This "memory" capacity shows that at least a daily cycle would be possible in building applications without reimposition of an electric charge. For longer periods, the brief application of potential at daily or longer intervals could serve to recharge the system.

Deb's solid-state device of similar configuration colors more efficiently, becoming virtually opaque after 3 minutes of cathodic coloration at 6 volts. Its transmittance is reduced to 1% of the initial transmittance at the 600 nm wavelength (see Figure 5). Anodic decoloration of this 10 year old device can be accomplished within approximately one minute with similar applied potential and slightly higher current densities.

In the bleached state, none of the specimens prepared to date has had a solar weighted transmittance higher than 25%. This low transmittance is largely due to reflectance and absorptance losses attributable to the gold electrode. If a more transparent electrode were used instead of gold, the change in transmittance of the colored and bleached states would become much more significant. Other research indicates that these low values could be considerably improved with substitution of a tin oxide or indium tin oxide top contact. Future research will include testing of alternative transparent conductor films as the top contact.

Electrochromic Coatings Conclusions Thin-film multilayer coatings based on the electrochromic material tungsten oxide have been reproducibly fabricated by thermal vapor deposition. By adjusting fabrication parameters, coatings with stable, reversible coloration, and long-term open circuit memory have been made. These characteristics suggest significant potential for such coatings in glazings applications, but more work is required to optimize the design and performance before a definitive evaluation of practicality can be made.

CONCLUSIONS

These two advanced window concepts show promise for providing a greatly changed perspective on building apertures. If the preliminary technical work proceeds as planned, the building industry can develop products that will alter the way homes and offices are built and operated, substantially decreasing energy use.

ACKNOWLEDGMENTS

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