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12th ENERGY TECHNOLOGY CONFERENCE

PATCHING THE THERMAL HOLE OF WINDOWS

Thomas F. Potter
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ABSTRACT

Materials research is being applied to the significant reduction of undesired heat gains and losses through apertures. This paper summarizes the background and recent progress supporting the development of vacuum and electrochromic windows at SERI.

Evacuated glazings now under investigation feature a thin-film, transparent infrared reflector, spherical glass spacers, and laser-welded edges. We believe that these features will result in an overall glazing R-value of 10 or more, maintainable over architectural lifetimes. Technical issues discussed include thermal and mechanical stress, optimal spacer configuration, and gaseous diffusion.

The electrochromic work has concentrated on achieving large differences in the transmissivity of window glazing by using thin, transparent films that respond to small electrical potential by becoming, reversibly, partially colored or opaque. Color memory, bleaching rates, and alternative transparent solid-state conductors are discussed.

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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 passive 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 they are estimated to be equivalent to about 300 million barrels of oil per year, or about 3% of our total energy purchases (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 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.

In residential applications, the potential impact of resolving the technical issues now being studied is considerable. The alternatives for very high R and/or controllable glazings could free the energy-conscious architect from many of the current constraints on 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-

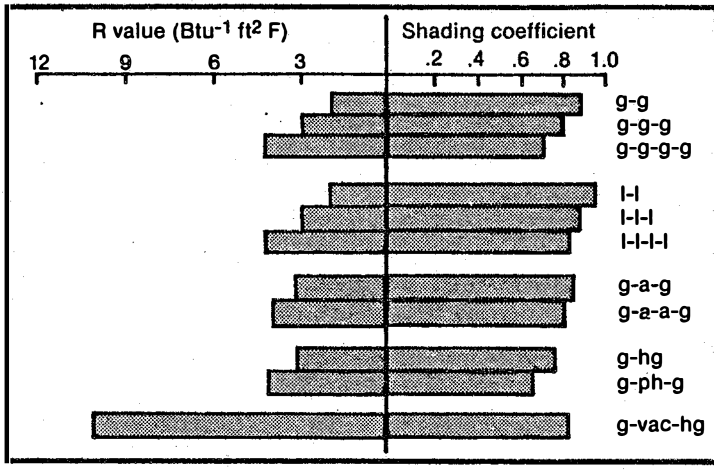

Figure 1. R-values and shading coefficients for selected glazing types. Abbreviations used for window materials are: g = 1/8-in. float glass, l = 1/8-in. low-iron sheet glass, p = 4-mil polyester film, a = 4-mil antireflective polyester film, h = heat-mirror coating with e = 0.15 (solar transmittance 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 was estimated by Benson et al. (1984).

value) and solar transmittance for various glazing combinations.

Continuing efforts to improve 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 gases. Figure 1 shows the improvement in R-value of typical combinations of these features and the associated decrease in transmissivity.

Drapes, blinds, and other window coverings also affect the effective transmissivity and R-value of the entire window system. 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.

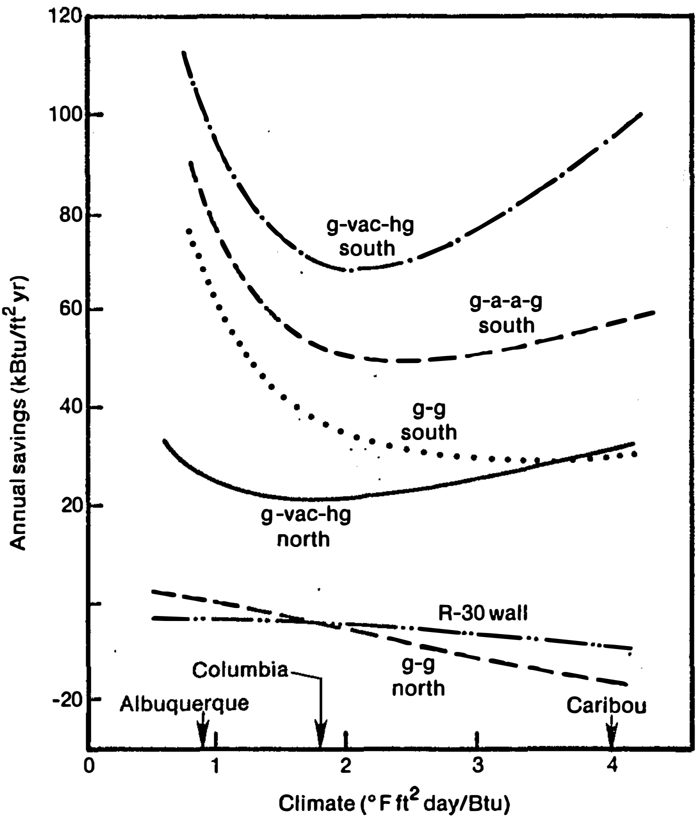

Figure 2. Computer-simulated performance of energy conserving windows and R-30 wall in different climates. (From Neeper [1982], with abbreviations used previously.)

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 that indicates the annual net energy savings contributed by 300 square feet of windows of various material configurations and orientations across climates (Neeper 1982). It is evident that the savings are climate dependent, especially for south-facing windows. Neeper concludes 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. These data indicate 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 in the future. 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 area of research, 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 area of research evaluates the feasibility of using a solid-state electrochromic coating to electrically control solar gain.

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 to design 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 (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.

A first, and only partially alleviating, solution to the expansion problem may be to use glass with a lower coefficient of expansion. Borosilicate glass, which has a thermal expansion of only one-third that of soda-lime, may serve. 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 are speed, greatly reduced or eliminated vacuum contamination, and amenability to automatic control within a production vacuum oven. We believe that this fusion seal also holds promise 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 are not yet available on the stress or thermal behavior of specimens obtained by these improved procedures.

An interglazing vacuum causes the glass sheets to deflect toward each other, which is both a technical and aesthetic (distortion) concern. We have used clear glass spheres ranging from 3 to 0.3 mm 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 0.05 to 0.08 is achievable with a transmissivity of 0.6 to 0.8.

EVACUATED GLAZINGS CONCLUSIONS

Researchers have produced laboratory-scale specimens of edge-fused, double-glass assemblies with internal spacers and infrared reflective film. The edge seal and film layer parameters under investigation show initial

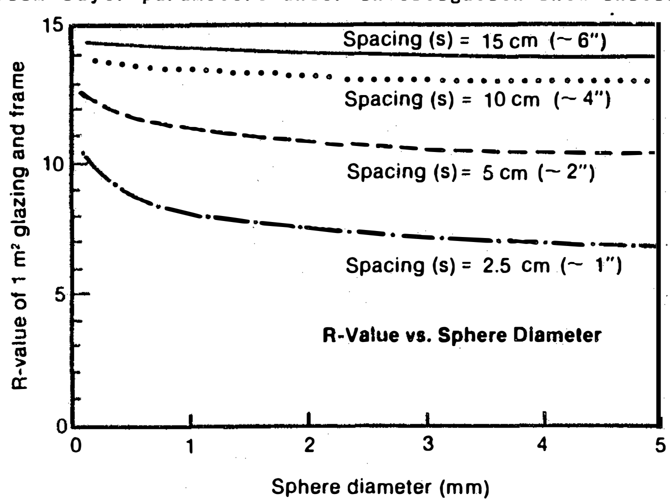

Figure 3. Effect of spacer size and spacing on window assembly conductance.

promise as components of an evacuated window with greatly improved thermal performance and service life. Further study is required to resolve questions of stress tolerance and optimal configuration.

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 the visible and infrared spectra independently, and would be easily and efficiently controllable. The basis for such control exists in commercially available electronic display devices. At SERI we are studying these thin-film, solid-state materials called electrochromics, which reversibly change their optical properties when subjected to electric current.

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 in turn is thought to cause 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 glazing 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 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.

Deb and others have reported solid-state, thin-film electrochromic coatings based on tungsten oxide with configurations similar to that shown in Figure 4. The electrochromic materials and a solid electrolyte material are deposited between transparent conductor layers. A surface protective layer is normally added to provide abrasion resistance, electrical isolation, and protection

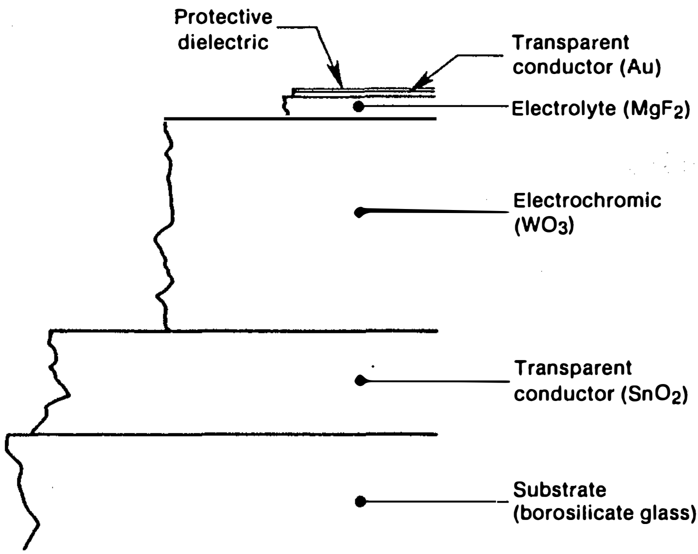

Figure 4. Schematic diagram of a basic solid-state electrochromic cell (Scale: 1 in. = 4×10^{-7} in.)

from outside contaminants. We used this basic configuration with the materials indicated in our studies, 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 V) was applied. The tin oxide layer was the negative electrode and the gold layer was the positive electrode. The device was bleached by reversing the polarity of the electrodes. Bleaching required less voltage and much less time than coloring.

Figure 5 shows spectral recordings of a typical device in the bleached, intermediately colored, and fully colored states. The intermediately colored state was achieved by applying 10 V for 3 minutes to the device, and the darkly colored state by applying 7.7 V for 60 minutes. The first visible signs of coloring appeared 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 a meter) 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 of 10 V for 3 minutes resulted in a 29% reduction in spectral transmittance. Application of 7.7 V 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.

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 more than 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

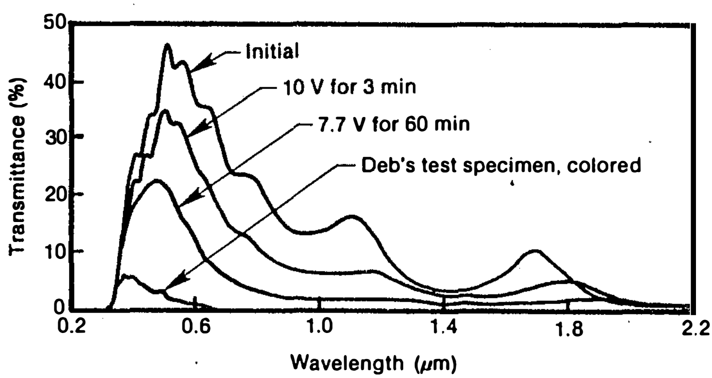

Figure 5. Spectral and solar transmittance measured for the Deb and SERI solid-state electrochromic devices.

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 V. 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 similarly 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 the substitution of a tin oxide or indium tin oxide top contact could considerably improve these low values. 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 glazing 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 promise to provide a greatly changed perspective on building apertures, and the "smart" window of the future will probably exhibit both the heat retention and controllable admittance features described. If the preliminary technical work proceeds as planned, the building industry will be able to develop products that considerably alter the way homes and offices are built and operated, substantially decreasing energy use.

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