RECENT RESULTS: SERI'S DEVELOPMENT OF ADVANCED GLAZINGS

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ABSTRACT

Progress since these new window designs were presented at the 1984 ACEEE Summer Study is described.

Laboratory tests of stress failure and thermal conductance of the R-10 vacuum window are continuing. Current results are presented that confirm previous conclusions, based on simulations, that such a glazing configuration is 1) possible and 2) a significant improvement over current low-emittance (low-e) window designs. Improved economic analyses are also presented.

Further progress in developing solid-state electrochromic window coatings is described as well. Such coatings can provide automatic, electronic control over the admittance of daylight and solar heat gains through windows. In particular, the recent achievement in obtaining a neutral gray electrochromic coating, significant in the optimization of daylighting benefits, is discussed.

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BACKGROUND

Apertures are important components in architectural designs, providing view, daylighting, ventilation, and solar heating. However, existing building aperture systems have been estimated to cause as much as 3.5×10^{15} Btu/yr (3.5×10^{18} J/yr) energy loss in the United States (Selkowitz, 1985). Innovative use of existing designs or careful selection of apertures have been shown to save approximately 25% of heating and cooling loads, 50% of lighting loads, and 30% of peak electric demand (Neeper, et. al., 1984) in particular building applications.

Developing significantly advanced aperture systems could provide even greater energy conservation in a wider range of buildings. Such systems are currently becoming available, featuring multiple glazing layers, low-emittance or reflective films, and special gas fills. The challenge of greatly reducing the energy wasted in aperture systems has motivated the investigation of simpler (and therefore, hopefully, less-expensive and lighter weight) solutions based on novel designs, newly developed materials and advanced fabrication processes.

Several promising alternative approaches exist that may provide the basis for highly efficient window systems. Two separate areas of high-risk, exploratory research at SERI may greatly improve the control of thermal gains and losses through glazing systems. The first is designed to build the technical base for developing evacuated glazings and addresses the challenge of maintaining a vacuum between glass sheets, one or more of which has a transparent infrared-reflecting film. The second evaluates the feasibility of electrically controlling solar gain and daylight transmission with a solid-state electrochromic coating on the window glazing.

Vacuum Glazing

In passive-solar-heated buildings where large areas of glazed aperture are used for solar gain, heat losses during periods of limited solar radiation can be a severe problem that limits passive solar usefulness to favorably oriented sites and moderate climates. However, estimates based on annual simulations of building energy performance indicate that a highly insulating window glazing could make passive solar designs more suitable for northern climates and less dependent upon favorable building orientation. Figure 1, for example, compares the net thermal efficiency of single- and double-glazed windows; an opaque, well-insulated wall; state-of-the-art (multifilm) windows; and a highly insulating window (with an R value of 10). The standard window has a solar weighted transmittance of 80% and an R value of 2.2°F ft^2 h/Btu (k = 2.6 W/m^2 K). These predictions suggest that more highly insulating glazings could provide significant energy savings throughout the United States, even if used in north-facing windows.

The objective of our research has been to evaluate the technical feasibility of providing a more highly insulating window glazing by using a vacuum gap and infrared-reflective, low-emissivity coatings. Figure 2 shows the vacuum window design schematically. The design is similar in principle to a vacuum Dewar and has similar insulating potential. Theoretical calculations indicate that a thermal conductance as low as 0.5 W/m^2 K (R = 12°F ft^2 h/Btu) may be achieved with an optimized design. Presently available materials and techniques appear to be suitable for fabricating a vacuum window with a conductance of less than 0.74 W/m^2 ($R \geqslant 7.7$°F ft^2 h/Btu).

For an evacuated window glazing to be effective, a high quality vacuum of 1.3×10^{-3} Pa (10^{-5} torr) or better must be established and maintained over 30-year periods. This requirement precludes using any polymeric materials for sealants. The seal we chose as most promising is an all-glass seal formed by laser welding.

Previous research on this project has included

- systematic design analyses to determine the sensitivity of window performance to design parameters (Benson, Tracy, and Jorgensen, 1985),
- extensive optical measurements to identify suitable low-emissivity coatings for use in vacuum windows (Benson, Tracy, and Jorgensen, 1985; Benson, et al., 1984)
- analyses of vacuum-maintenance requirements including helium-permeation rates and the selection of a reactive metal getter to trap residual reactive gases (Benson, Tracy, and Jorgensen, 1985)
- laboratory experiments, which show that laser welding is a suitable glass sealing technique (Benson, Tracy, and Jorgensen, 1985; Benson, Tracy, and Jorgensen, 1984)
- preliminary estimates of the cost of manufacturing vacuum windows in mass-production (Benson and Tracy, 1985).

These steps in the feasibility study yielded positive results and encouraged continued study to resolve remaining issues.

The status of research on the vacuum-glazing project can most easily be reported by answering technical questions posed by representatives of the glass and window industries and by other researchers and architects. The answers to their questions, which follow, relate the progress that has been made to date.

1. Will stresses caused by wind loads, atmospheric pressure and differential thermal expansion fracture the glass light?

   Stresses and strains in a vacuum window during severe weather were simulated, and are predicted to be acceptable but somewhat higher than desired. Maximum tensile stresses on the order of 2000 psi (13.9 MPa) are predicted to occur under severe wind loads (90 mph, 40 m/s) and during large temperature differences ($\Delta T=72^{o}F$, $40^{o}C$). These stresses should be reduced to ~1000 psi (6.9 MPa) and this may be possible with a better selection of edge constraints (e.g., a more compliant frame). Contact stress fracture at the "point-of-contact" between spherical supports and uncoated flat glass is unlikely as long as the distance between supports is not greater than about one inch (25 mm). Such a support separation limits the achievable thermal resistance. More measurements are required with particular attention to evaluating the strengthening effects of thin surface coatings such as the low-e coatings.

   Borosilicate glass, with a coefficient of thermal expansion only one-third that of standard soda-lime glass, has been used in experiments to date, and may be the glazing of choice for vacuum windows. The sperical spacers used have been of borosilicate glass as well. With 0.5 mm diameter and one to two inch spacing, they are not expected to substantially degrade the optical view quality.

2. Will thermal conductance through the spacers cause cold spots and a pattern of condensation over the spacer array?

   The temperature drop on the room-side surface of a vacuum window during very cold weather is a concern because it may cause unsightly condensation or frost spots to form at each of the points where spherical supports separate the two window lights. Figure 3 shows the predicted temperatures near the support spheres for a specific window design. Even at $-40^{o}F$ ($-40^{o}C$) with a 20 mph (8.9 m/s) wind increasing the rate of heat transfer from the window, the minimum surface temperature on the indoor surface of the window is predicted to be $+55^{o}F$ ($12.8^{o}C$). Condensation is unlikely to be a problem.

3. Would currently available alternatives to laser welding be more efficient?

   Laser welding technology is now established in many industries, despite its futuristic image, and appears a good choice for mass-production sealing of vacuum windows. The other most likely choice, electron-beam welding, has inherent difficulties with welding dielectric materials and is at least as costly as laser welding. The laser welding technology appears to be advancing rapidly, whereas the much older electron-beam welding technology has reached a stable state of development. Finally, most other welding techniques will contaminate the vacuum environment.

4. Will costs of such windows be prohibitive?

   A vacuum window manufacturing cost of \$2.00-\$5.00/ft^2 (\$22-\$54/m^2) appears to be achievable in mass-production. Table I compares industry figures disclosed for alternative glazings, from a confidential industry source, with estimates for manufacturing a vacuum window. Depending on the availability of low-cost view-quality borosilicate glass (not presently manufactured by the float process), vacuum windows should be the next logical step in glazings improvement.

   From another perspective, it appears that a market exists for such a performance improvement, if the manufacturing cost is nearer \$2.00 than \$5.00/ft^2. Figure 4 shows the retail price now quoted for high-performance glazings and extrapolates a retail price of \$7.00/ft^2 (\$75/m^2) over the cost of standard double glazing as the "market value" for an R-10 glazing.

Vacuum Glazing Conclusions

No "show-stopping" obstructions have been discovered that would prevent efficient manufacture of a vacuum glazing assembly. Further investigation is continuing to optimize parameters, and a vacuum welding oven will be constructed presently to fabricate meter-square vacuum window test specimens for evaluation.

Electrochromic Glazing

A different thermal transfer problem is encountered with large expanses of unshaded glass, typical in many commercial building designs. Here the unwanted solar gains create heat loads for the conditioned air system, as well as glare and thermal discomfort for building occupants. Reflective films or fixed shading devices are useful in reducing the gains, but don't allow the degree of control necessary to maximize use of the available daylighting resource.

Automatic, electronic control over the solar transmission through windows could provide a much needed load-management strategy for building heating and air conditioning systems. Research continues at SERI on one approach to achieving such optical control. A solid-state, multilayer electrochromic coating for windows is being evaluated. A momentary low voltage and low current applied to the coating reversibly changes its optical transmission over a continuous range from relatively clear to opaque. The objective of the research is to optimize the electro-optic response of an electrochromic coating for window applications and to evaluate its technical and economic practicality for use in passive-solar-heated buildings and daylighted energy-conserving buildings.

Details of the concept and early research and development results have been reported previously (Potter, 1984) and will not be repeated here except as they relate to the major research questions. These are listed below, with a summary of progress to date.

1. Given the cost of single-layer film deposition, won't the cost of a stack of such films be very high?

   Transparent and reflective coatings are now commonly applied to architectural glass to achieve particular aesthetic or performance objectives. A typical coating process involves exposing the glass in a vacuum chamber to free metal atoms. These are driven from an ingot by electrical charge (sputtering) or evaporation; they are then deposited on the glass in a thickness determined mainly by exposure time. The resulting film is either an oxide or a metal, depending on whether oxygen is allowed into the deposition chamber during the process. A typical low-e coating consists of three layers--metal oxide/metal/metal oxide.

   The cost of applying such coatings is largely determined by the ratio of annualized capital costs to annual production rates. Large vacuum-sputter coating plants costing on the order of $\$10^6$ and having annual production rates on the order of 3×10^5 m^2 (3.2×10^6 ft^2) are used to produce solar gain control coatings and low emissivity (so-called "heat mirror") coatings for window glass at costs on the order of $\$3.50/m^2$ ($\$0.33/ft^2$). However, these coatings are only a few hundred nanometers thick, whereas the total thickness of an electrochromic, four-layer stack (transparent conductor-electrochromic-ionic conductor-transparent conductor) would be on the order of 1200 nm. Therefore, a higher-speed process and/or a lower-cost coating process may be needed to produce economically practical coatings.

A new, plasma-enhanced, chemical-vapor process for depositing amorphous electrochromic coatings has been invented at SERI. The process is potentially more economical than thermal evaporation or ion sputtering. It requires less costly equipment, is capable of a higher deposition rate, and uses potentially lower-cost materials. A patent application has been filed.

2. What color is the light transmitted by an electrochromic glazing?

   The electrochromic response of tungsten oxide is an optical absorption in the red portion of the visible spectrum; this causes a deep blue color, which is not ideal for daylighting application. An amorphous, molybdenum oxide electrochromic coating (a-H_xMoO_y) was deposited by the new plasma-enhanced chemical-vapor-deposition process. Its electrochromic response is almost a neutral color (see Figure 5) and much superior to the blue transmittance characteristic of a-H_xWO_y or c-Li_xWO_y. This neutral response greatly improves the aesthetics, visual acceptability, and daylighting utility of the coating in a window application.

3. What is known about the service life of the electrochromic cell?

   Cyclic durability testing, while still preliminary (i.e., in the 50,000 cycle range), suggests that the lifetime and operating temperature range of the solid-state coatings based on H_xWO_y may be acceptable. More testing is required to establish the bounds of useful operating conditions for both the H_xWO_y and the new H_xMoO_y coatings.

Electrochromic Glazing Conclusions

Significant progress has been made in the understanding and application of solid-state electrochromic film behavior in a window glazing. Several improvements in optical response and reductions in the cost of production appear to be possible with plasma-enhanced chemical-vapor deposition.

ACKNOWLEGEMENTS

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Table I. Cost/Rating Comparison of Alternative Glazings ($\$/ft^2$)

Element	2-Pane Standard R-2	3-Pane Standard R-3	2-Pane Low-e R-3.3	2-Pane Low-e Gas-Filled R-4.5	2-Pane Low-e Vacuum R-10	2-Pane Low-e Vacuum R-10
Glass	0.45	0.67	0.45	0.45	1.20	0.60[a]
Low-e coating	—	—	0.63	0.63	0.63	0.63
Edge materials	0.25	0.35	0.25	0.25	—	—
Gas fill	—	—	—	0.20	—	—
Labor (wash, assemble)	0.25	0.35	0.35	0.35	0.25	0.25
Laser weld	—	—	—	—	0.38	0.38
Manufacturing cost	0.95	1.37	1.68	1.88	2.46	1.86
Office, freight, profit multiplier	× 1.40	× 1.40	× 1.40	× 1.40	× 1.40	× 1.40
Cost to window manufacturer	1.33	1.92	2.35	2.63	3.44	2.60
Cost-to-list multiplier	× 3.00	× 3.00	× 3.00	× 3.00	× 3.00	× 3.00
Retail cost	3.99	5.76	7.05	7.89	10.32	7.80

[a] Assumes a 33% cost penalty for manufacture of borosilicate glass over costs for soda-lime glass.

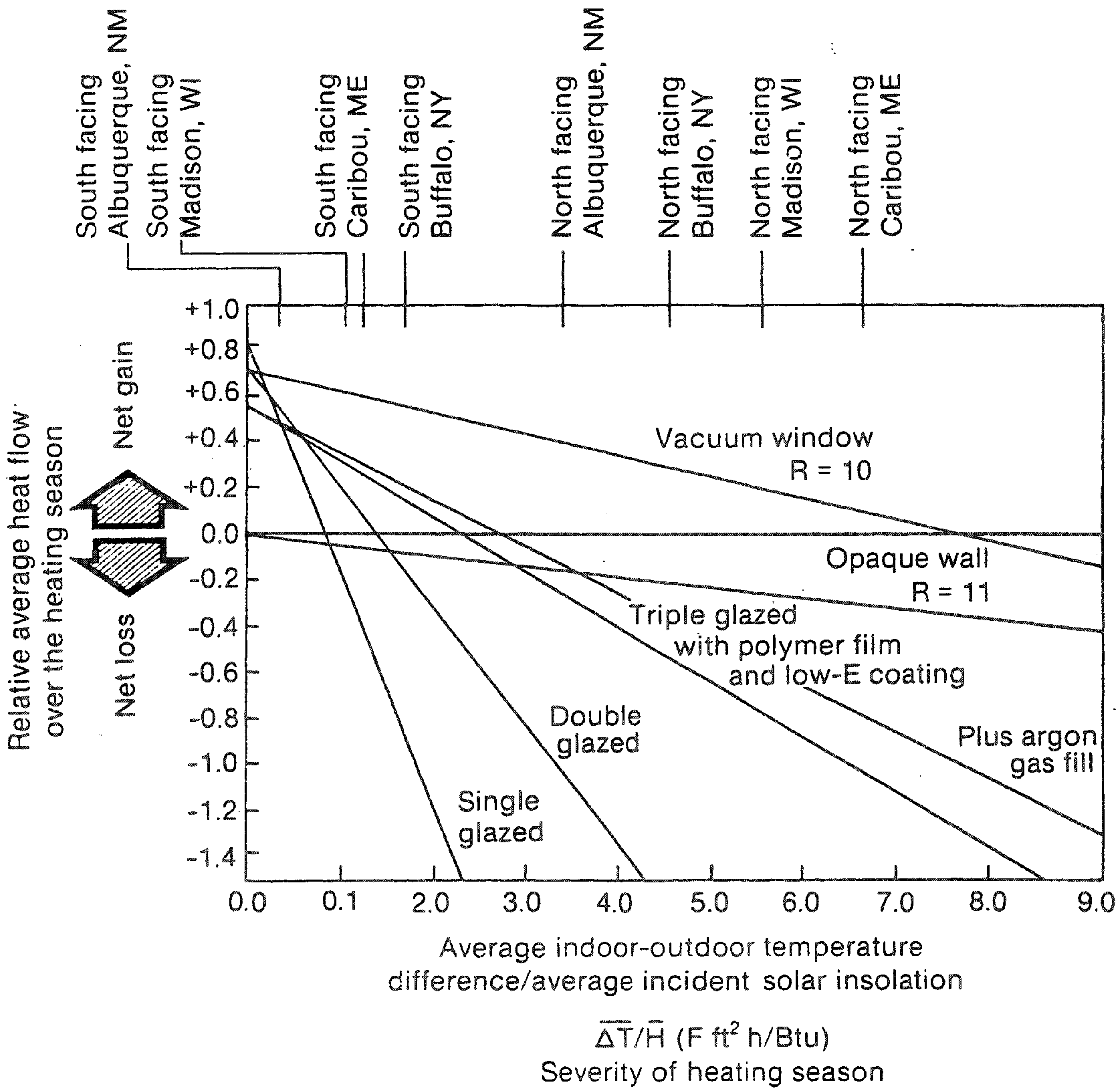

Figure 1. The net thermal efficiency of a window expressed as a function of climate parameters. A positive efficiency indicates a net useful heat gain over the heating season. Negative efficiencies imply net heat loss. Climate is expressed as the ratio of seasonally averaged indoor-outdoor temperature difference to incident solar flux (Neeper, et al., 1984).

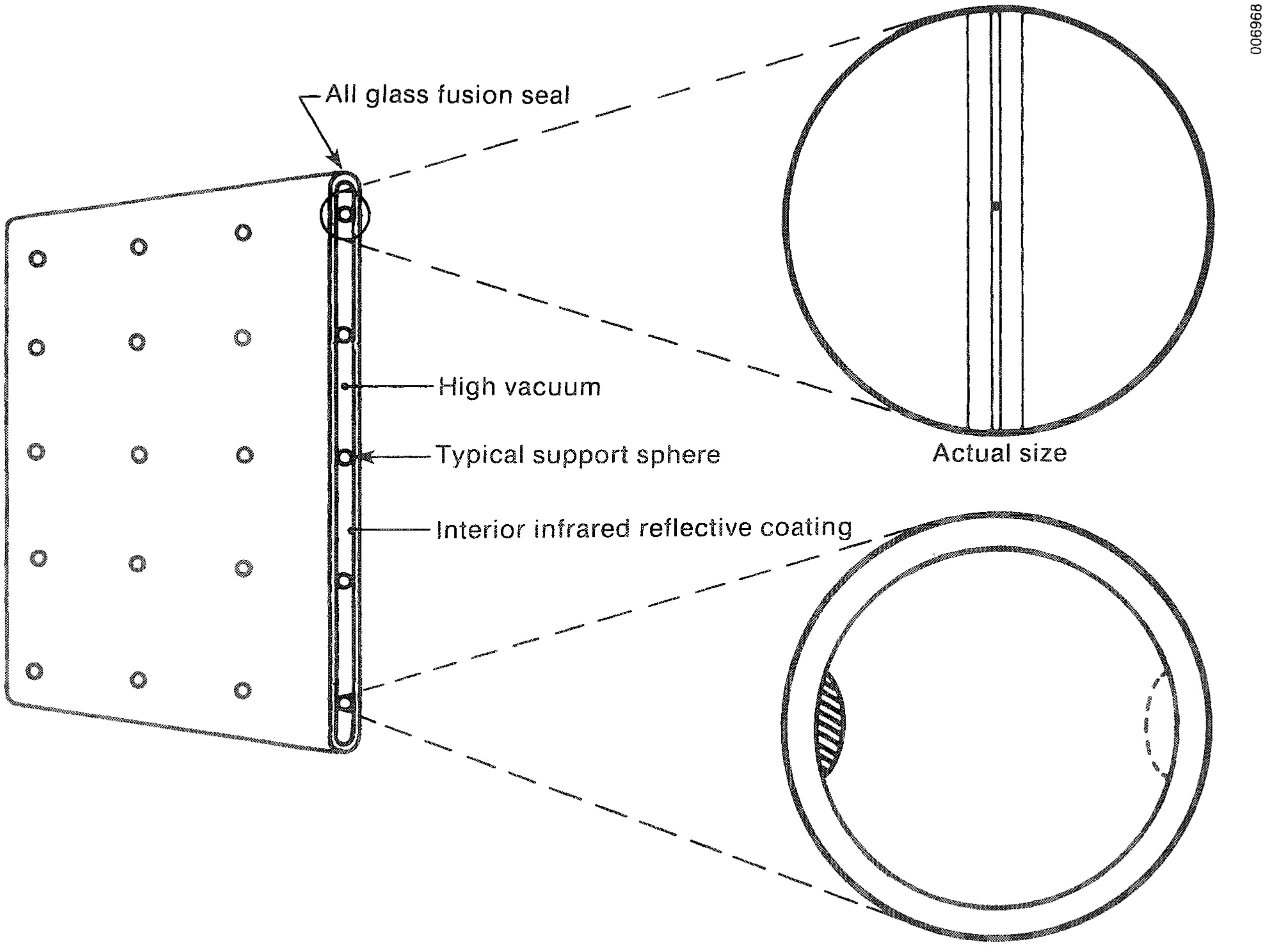

Figure 2. Schematic diagram of an edge-sealed, all-glass evacuated glazing assembly.

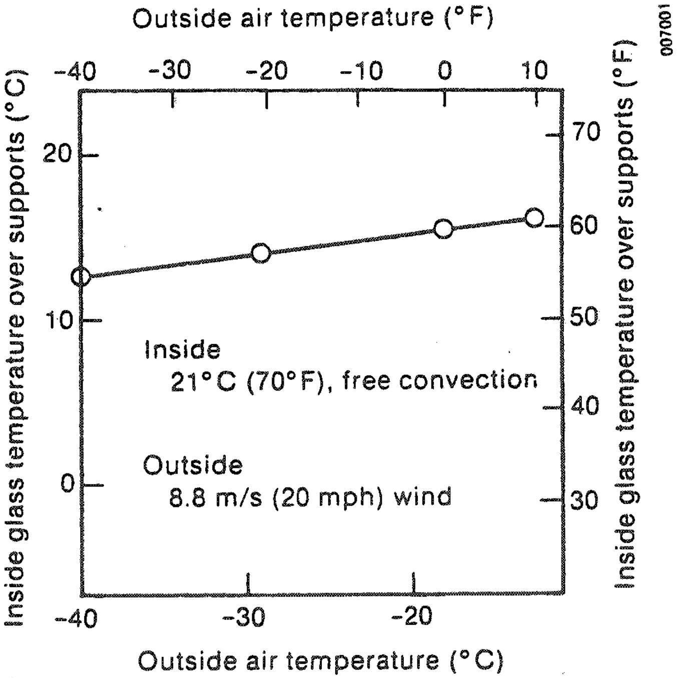

Figure 3. The effect of outside temperature on the minimum glass surface temperature on the indoor side of a vacuum window.

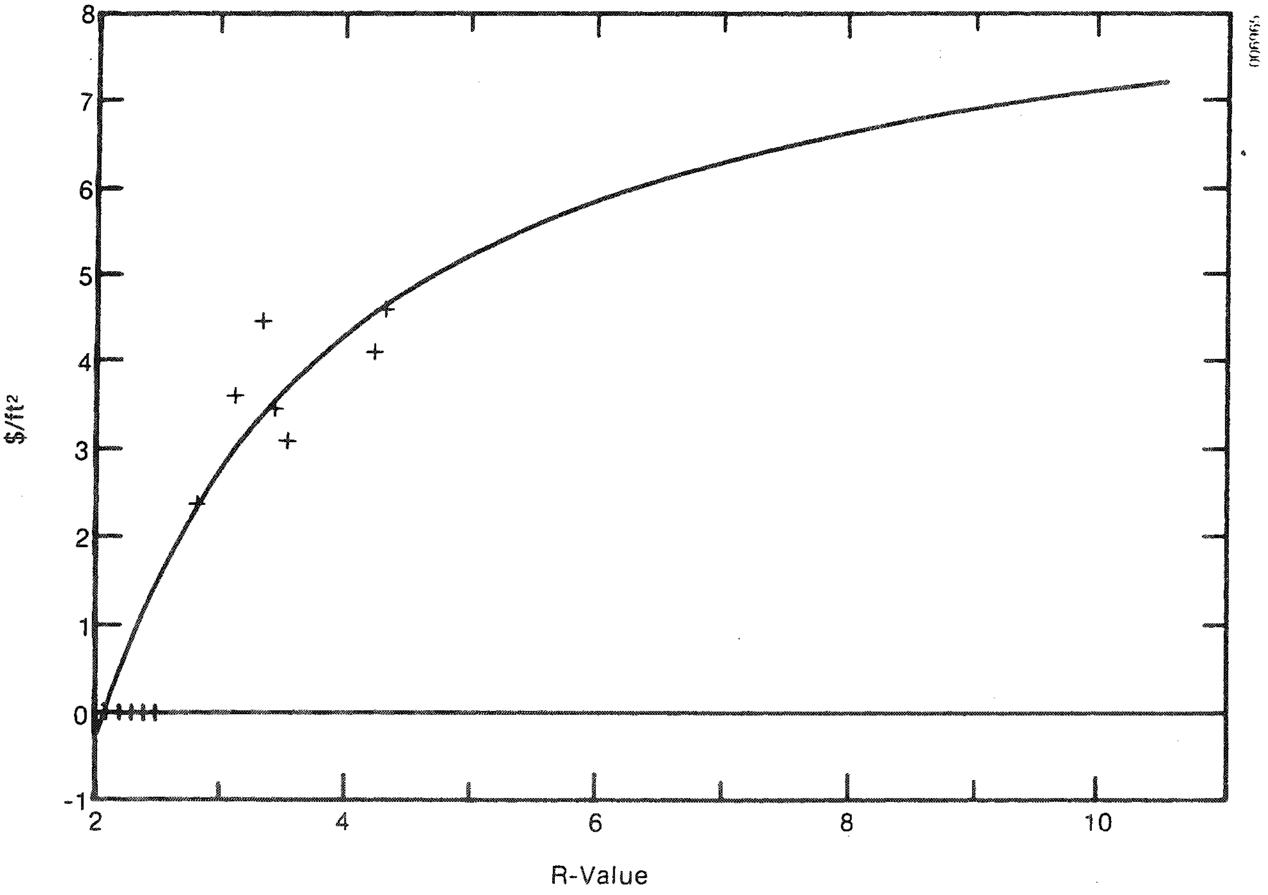

Figure 4. Added dollar value of R using double glazing as a base [$/ft^2 over cost of double-pane (glass only)].

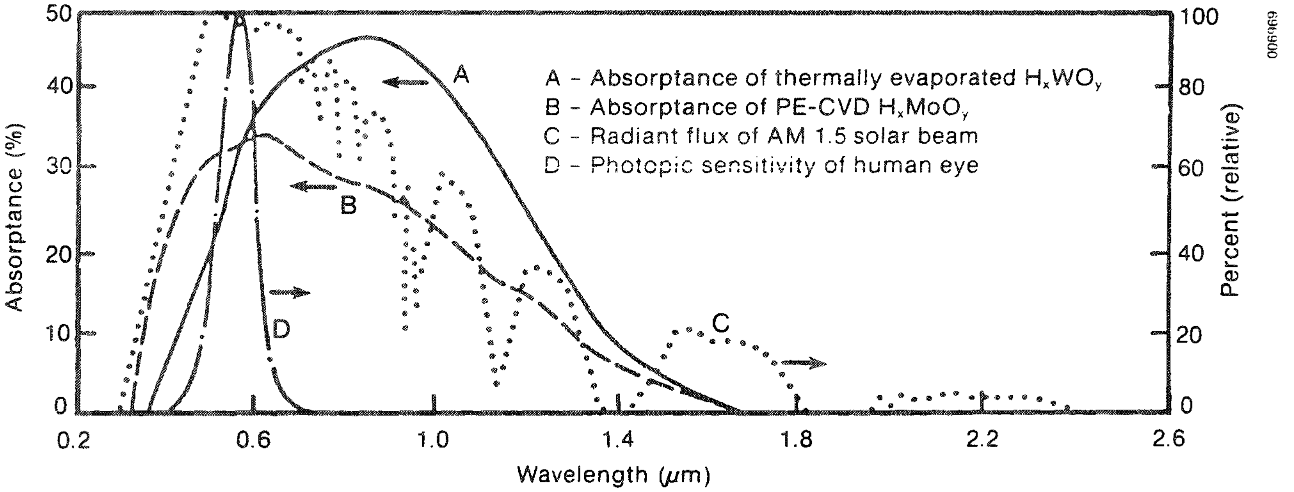

Figure 5. Comparison of optic sensitivity with tungsten and molybdenum electrochromic transmittance. A and B are read in absorbtance (%), C and D in percent (relative).