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PROSPECTS FOR HIGHLY INSULATING WINDOW SYSTEMS

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ABSTRACT

Windows and other fenestration systems are often considered the weakest links in energy-efficient residences. This opinion is reinforced by building standards, audit guidelines, and standard window performance evaluation techniques geared toward sizing building HVAC equipment. In this paper we show that it should be possible to design highly insulating windows ($U < 0.12$ Btu/hr-ft^2-F) with high solar transmittances ($SC > 0.6$). If we then view annual window performance from the basic perspective of control of energy flows, we conclude that it should thus be possible to develop a new generation of "super windows" that will outperform the best insulated wall or roof for any orientation even in a northern climate. We review several technical approaches that suggest how such a window system might be designed and built. These include multiglazed windows having one or more low-emittance coatings and gas-filled or evacuated cavities. Another approach uses a layer of transparent silica aerogel, a microporus material having a conductivity in air of about R7 per inch. We conclude by presenting data on annual energy performance in a cold climate for a range of "super windows".

INTRODUCTION

Windows and other glazing systems are utilized in residences to satisfy a range of psychological needs and comfort requirements. Unfortunately, existing fenestration systems are usually less energy-efficient than other exterior wall components. This is especially true for residential (as compared to commercial) buildings, in which minimal internal gains and variable occupancy patterns dictate overall wall heat transfer coefficients much lower than those assumed for conventional glazing systems. Finally, this difference in energy performance between glazing and other building components is often exaggerated by the simplistic criteria used to evaluate the thermal performance of windows. These criteria often ignore the benefits of winter solar gains and of daylight.

Window thermal performance has generally been studied with respect to determining peak thermal gains or losses and thus necessary equipment sizes. With recent interest in annual energy consumption attributable to fenestration systems, it is important to evaluate window thermal performance in terms of seasonal and annual energy flows. Annual energy flows through buildings require making tradeoffs between often opposing window thermal and/or optical properties. To account for building-level interactions (i.e., solar gains or daylight vs. thermal loads), windows must be evaluated within the context of overall building energy performance. Reducing window heat transfer while maintaining relatively high solar transmittances can produce annual net window energy flows more advantageous than those of walls or roofs.

This paper begins by reviewing means by which heat is transferred through windows and factors that contribute to each of these heat transfer paths. We then discuss several technical approaches to limit window heat transfer. We present techniques by which these approaches may be combined to form window systems that optimize energy flows. The technologies presented here are either commercially available but not widely used or are speculative and innovative concepts still under development that deserve additional research, testing, and appraisal. Architectural design issues are generally omitted from this discussion. However, the new approaches presented here look like conventional windows and work without complex additional hardware. They can be treated in the same architectural manner as current windows.

In the past, energy conservation was often (incorrectly) viewed as requiring sacrifices in occupant amenity and comfort levels and in the quality of architectural design. New technologies will help correct this perspective and will make the case that good and energy-efficient design can coexist comfortably. Where relevant, issues of safety and reliability are raised. Thermal comfort issues are not explicitly addressed; however, highly insulating windows will produce a more comfortable thermal environment than conventional windows, and this may be a major motivating influence to specify high-performance window systems. These windows will also reduce condensation, another source of problems with some window systems in some climates.

PRINCIPLES OF WINDOW HEAT TRANSFER

Window thermal transfer is a combination of three modes of heat transfer: conduction through glazing elements and air; convection through air layers on the interior and exterior window surfaces and between glazing layers; and radiative heat transfer between glazing layers or between glazing layers and interior or exterior spaces. This section briefly discusses heat transfer processes through components of conventional window systems. A more detailed analysis of heat transfer through windows is given in Refs. 1 and 2. The elements of our proposed "super windows" are designed to control these heat transfer paths.

Before we discuss thermal transfer through a window system we must define a method to calculate or measure this transfer. In this paper we use the overall window heat transfer coefficient (U-value) and window shading coefficient (SC) as standards to compare window systems. The SC of a window is defined as the ratio of the solar heat gain through a glazing system (that transmitted plus the inward-flowing fraction of the radiation absorbed by the window) to the solar gain through a single light of 1/8-in. clear float glass. It should be noted that the heat transfer characteristics of a window or window component are not intrinsic properties but instead exist only for defined environmental conditions.

For complex conventional or advanced window systems, the conductive/convective component and the radiative component of a window's U-value are each reduced through the addition of various window elements. The insulating windows proposed in this paper can maintain high SCs and thus be appropriate for use in heating-dominated climates.

INSULATING WINDOW COMPONENTS

Beginning with a standard double-glazed window, we present five technical approaches to reduce specific heat transfer processes. Additional insulating air spaces can be created with more glass or plastic layers. Adding a low-emittance coating to one or more glazing surfaces reduces radiative heat losses. Gas-filled evacuated, and silica aerogel-filled, window cavities are described as other means to reduce the conductive/convective heat transfer between panes in a multiglazed window. Similar results can be achieved using conventional window systems in combination with movable nighttime insulation. However, the use of movable insulation raises architectural, technical, operational, fire-safety, and energy savings questions. These issues are presented in Ref. 1; movable insulation is not addressed further in this paper.

Triple-Pane and Beyond

Heat transfer through air-filled gap(s) is dominated, at small gap widths (<1/4 in.), by conduction through the air. [Note that the thermal conductivity of air is approximately 1/40 that of glass; maintaining pockets of air (or another gas) is one key to reducing heat transfer through windows.] As gap width increases, conduction through the air is linearly reduced in proportion to the thermal conductivity of air. However, as the gap width and/or temperature gradiant increase beyond certain points, heat transfer by convection (moving air) between the panes becomes more significant. Further increasing gap width will not lower and may even increase the gap heat transfer coefficient. In conventional multiglazed window systems, the optimum gap width is usually 1/2 to 3/4 in.

The addition of more air spaces in series will reduce heat losses, although the law of diminishing returns soon sets in. An additional layer of float glass will add about R1 to a window, reducing transmittance by 10-15%. Even if low-iron glass is used to maintain higher transmittance, the added weight of additional glass layers makes the window too heavy. One solution is to replace middle glass layers with thin plastic films (0.005 in.). However, the most common choice, polyester, has relatively high reflectance losses.

Highly transparent, antireflected polyester or other lightweight plastic films are used in some multiglazed (>2 layers) window systems as inner glazing layers. Because these films are significantly more transparent than glass (T_s=0.91 vs. 0.86), the shading coefficients of window systems incorporating them are almost as high as those of double-glazed windows.

Low-Emittance Coatings

To significantly reduce heat transfer through windows, one must substantially reduce radiative losses. Eliminating all conductive and convective losses would still limit the minimum U-value of a double-glazed window to about 0.4 Btu/hr-ft^2-F (2.3 W/m-K) [Ref. 1]. One way to reduce these losses while maintaining high solar transmission calls for using thin, transparent optical films or coatings reflective to longwave thermal radiation. These low-emittance coatings (emittances range from 0.05 to 0.4 as compared to 0.84 for uncoated clear float glass) can be applied to glass or some plastic surfaces. Some commercially available sun control products such as reflective glass and solar control films will, to some extent, reduce radiative heat loss at the expense of simultaneously reducing solar transmission. But these solar control products may be undesirable where high solar and daylight transmittance are desired.

Low-emittance coatings will function with varying degrees of effectiveness in different positions in a multiple glazed window. We number the glazing substrate surfaces consecutively from the outside surface. Thus, for example, the outward-facing surface of the inner glazing on a double-glazed unit is the number 3 surface; the room-facing surface on a triple-glazed window is number 6, etc. A low-emittance coating will reduce radiative transfer at any surface, but the net impact of this reduction on overall window U-value will vary with the relative importance of radiative heat transfer at that location. For example, on the outdoor surface (number 1), heat transfer usually is dominated by convection, so low-emittance coatings have limited usefulness. In a double-glazed window, these coatings are best used on a surface in the window air gap (number 2 or number 3). The heat transfer will be nearly identical on either surface, but shading coefficient will vary with position. In a cold climate, the coating is best placed on the number 3 surface so that absorbed energy is preferentially transferred inward. In a climate where cooling is important, the coating should be placed on the number 2 surface. In both cases, direct solar transmittance is identical but the fate of the absorbed component differs. The size of this effect will vary with the absorptance of the coating. Figure 1 shows SCs for double-glazed units having low-emittance coatings on the number 3 surface. The transmission and absorptance values given are for the glazing layer with the low-emittance coating. The outer light is assumed to be 1/8-in. clear float glass.

Coating placement is dictated by durability. The first generation of multilayer vacuum-deposited low-E coatings ("soft coats") are not highly abrasion or corrosion resistant and must be placed in a sealed double-glazed unit (as on the number 2 or 3 surfaces). However, a second generation of low-E "hard coats", applied pyrolytically in the float glass production process, are sufficiently durable to be placed on exposed interior surfaces, non-sealed double glazing, and in some cases on the number 1 surface. These coatings generally will not have emittance or transmittance properties as good as the soft coats, but expand window design possibilities, e.g., coated storm windows.

Gas-Filled Windows

By replacing the air between glazing panes with a gas that has a lower conductivity, we reduce the conductive heat transfer between glazing panes. Figure 2 [Refs. 1 and 3] presents h_g, the gap heat transfer coefficient for air and six other gases as a function of gap width for specific temperature conditions and outdoor wind speeds. For other temperature conditions, the absolute magnitude of these gap heat transfer coefficients might vary; however, the relative trends between gases will generally be similar. The relationship between h_g and gap width is a function of both thermal conductivity and kinematic viscosity. For a given gap width and temperature difference, the higher a gas's kinematic viscosity, the less convective heat transfer will occur. The ideal gas for our purposes would be one having a very low conductivity and a high viscosity. For the gases presented, over the range of realistic gap widths (1/4 to 3/4 in.), we first see a linear decrease in h_g with increasing gap width (as seen in Fig. 2 with air, argon, and CO_2) and then a leveling out (and possible rise) of h_g. As shown, the reduction of h_g is limited by radiative heat transfer; without reducing radiative heat transfer, the theoretically lowest h_g is that of an evacuated space. Generally, as indicated by Table 1 and Fig. 2, there is no ideal gas because as conductivity decreases, kinematic viscosity also generally decreases. Other options include using gas mixtures.

At a gap width of 1/4 in. , replacing air with argon, CO_2, SF_6, or either CCl_2F_2, Kr, or SO_2 reduces h_g by approximately 16, 18, 26, or 35%, respectively. While lower h_g values can be achieved with larger gap widths, the percentage reductions are generally less. The promise of gas fills is that h_g values lower than the best achievable with air at large gap widths can be realized with much smaller gap widths (1/3 the size), thereby making double- or triple-glazed windows more economical and less bulky. This improvement is achieved without any loss in solar transmittance.

Other characteristics besides heat transfer must be considered in selecting appropriate gases for window cavities. The gas must be non-toxic and environmentally sound, must not chemically attack window elements, must not diffuse through the sealant, must not be degraded by exposure to solar or ultra-violet radiation, and must not condense at low temperatures. Finally, the gas must be available at low cost. As a result of these criteria, SF_6 and argon or a mixture of these two appear to be the most commercially viable. Many European window companies manufacture gas-filled windows in significant quantities, and we expect U.S. manufacturers to offer gas-filled models in the near future. The single greatest uncertainty at present is proper specification of desiccants and sealants. However, European experience suggests that there are technically viable, cost-effective solutions.

Evacuated Glazing Spaces

The use of an evacuated space between glazing layers can reduce or eliminate conduction and convection losses between window panes. Partially evacuated air spaces are sometimes used in solar collectors to reduce thermal losses. Evacuated spaces in window systems present new technical problems including the window's ability to withstand pressure differentials, safety concerns if the window should break, sealing the evacuated space, and economical production procedures. Several current research efforts [Ref. 4] are directed at these problems.

At atmospheric pressure, convection in airspaces significantly reduces the heat transfer resistance value of air. As the airspace pressure is reduced, heat transfer by convection decreases until it is no longer a factor. At this point, and for a range of lower pressures, the heat transfer through the airspace is proportional to the conductivity of the air and the airspace thickness. Once the pressure is reduced such that the mean free path of the gas molecules is less than the airspace width (10^{-5} atm and less), the gas thermal conductivity begins to drop again. For structural reasons, air spaces generally must be smaller than 1/2 in.; we therefore require that the airspace pressure be well within this last range. Current research has focused on window systems having small interpane spacing (0.02 - 0.2 in.) at very low pressures (10^{-7} atm). At this pressure, the sealing technology becomes a critical factor and getters are required to trap gases that diffuse through the glass surfaces. The windows must also have a low-emittance coating. With an emittance of 0.05 and a hard vacuum, an evacuated window can theoretically achieve an R8 insulating value [Ref. 4].

Aerogel Windows

A promising means of reducing window conductive/convective heat transfer in a double-glazed window is to fill the cavity with a transparent insulating material. Common insulating materials trap air in small pockets, thereby preventing convection and maintaining an overall conductance close to that of still air. Unfortunately, most insulating materials are opaque to visible light or are transparent but scatter light and distort exterior views, thus making them inappropriate for most window systems. However, silica aerogel, currently under development for use in windows, does not have these limitations. Because the silica particles are smaller than the wavelength of visible radiation, aerogel is highly transparent. Due to slight scattering effects, current aerogel samples appear slightly yellow against a bright background or show a blue haze against a dark background [Ref. 5]. Ongoing research is aimed at reducing this scattering and increasing transmittance.

With approximately 97% of the air by volume in aerogel contained in pores smaller than the mean free path of air molecules (the average distance an air molecule travels before it collides with another air molecule), the thermal conductivity of aerogel will be lower than that of air. Measurements of aerogel's thermal conductivity (1.1×10^{-2} Btu/hr-ft-F) confirm this [Ref. 5]. Replacing the air in an aerogel sample with freon further reduces the thermal conductivity to between 0.8 and 0.9×10^{-2} Btu/hr-ft-F. An even greater reduction in thermal conductivity can be achieved at low pressures where a conductivity of approximately 0.6×10^{-2} Btu/hr-ft-F is obtained at pressures under 0.1 atm [Ref. 6]. While requiring essentially the same structural strength as a window with a hard vacuum, the sealing technology for this "soft" vacuum should be simpler to achieve. Finally, because aerogel is opaque to longwave infrared radiation, net radiative losses through aerogel will be on the order of those from double-glazed windows having low-emittance coatings.

Optimum aerogel thicknesses and window configurations will depend on both window structure, aerogel production techniques, and specific site conditions. Recent research developments have produced samples using lower temperatures and pressures than previously possible, thus hastening the day when such a window insulating material might be commercially available [Refs. 5 and 7].

INSULATING WINDOW SYSTEMS

Combining two or more of the above insulating strategies can produce specific window systems having low enough U-values and high enough solar transmittances to make them net energy savers even in northern climates. We determine the U-values and shading coefficients (SC) of several window systems using a detailed thermal balance computer model [Ref. 8]. Net annual energy performance and costs can then be calculated using results from a parametric computer (DOE-2.1B) study of the energy flows in a prototypical residence.

As an example of the potential savings with window insulating options, we review analysis results for Madison WI. The number of heating degree days in Madison is greater than most U.S. climates except the northern Great Plains and parts of the Rocky Mountains. The 1512 ft^2 (143.1 m^2) one-zone, insulated slab-on-grade frame construction house is described in detail, along with the simulation procedure and results, in Ref. 9. To condense results of many simulations we examine window performance for many combinations of U-value and SC. Although we calculate summer cooling energy requirements for a heating-dominated climate, we present here only the winter heating analysis. (Note that for an annual cost analysis in situations where electricity is expensive and fuel is cheap, a small cooling load may have a greater economic impact than a large heating load.) We calculate window energy effects based on the complex, nonsteady-state time-dependent behavior of windows in residences. For clarity we present our results as the net (winter season) energy flow per square foot of window. If the net value of usable solar gain just offsets thermal losses, the net flux is zero. ("Usable" implies that the solar gain at a particular hour offsets a net building loss at that hour.) Thus windows can show net benefits (positive energy flow) or net losses. We plot lines of equal benefit and loss as a function of window parameters in Fig. 3.

We now consider several window systems using combinations of the insulating technologies previously described. These windows are evaluated at ASHRAE winter design conditions ($T_o = 0^o$ F; $T_i = 68^o$ F; wind speed = 15 mph). Their absolute performance will be different for other temperature and wind speed conditions; changing wind effects are accounted for in the DOE-2 simulations. Unless otherwise specified, all glazing material considered is 1/8 in. (3 mm) double-strength glass. The U-values and SCs are based on average or typical components. In many cases, especially where low-emittance coatings are used, the U-value and/or SC may vary noticeably from those presented. These values represent heat transfer through only the glazed portions of windows. Heat loss through sashs and frames can significantly affect net U-values, particularly when the glazing component is highly insulating. Most sash and frame elements have conductance values in the range of R1-R4.

Figure 3 shows a typical plot of U-value vs. shading coefficient for east-facing glazing in Madison. Lines of annual energy flow are superimposed on this graph for this window size, orientation, and location. Each system with a given U and SC appears as a point on the plot. Plotting single glazing and a various double- and triple-glazed systems shows that the best triple-glazed systems barely break even.

In Figs. 4-6 generic, highly insulating window systems are plotted as a function of U-value and SC on enlarged annual energy flow diagrams. East (similar to west), south, and north orientations are analyzed. The window systems examined are:

(1) double-, triple-, and quadruple-glazings with glazing gaps ranging from 1/4 in. (6 mm) to 1/2 in. (13 mm);

These systems are shown by solid lines in Figs. 4-6. Heavy lines denote all glass glazing layers, while light lines mean that the inner layers are thin antireflective polyester films. The number of layers is shown in front of the line.

(2) double-pane windows having a low-emittance coating;

A low-emittance coating is applied to the number 3 surface (gap width of 1/2 in.). The range of emittances is varied from 0.4 (high U-value and generally high SC) to 0.05 (lower U-value and generally lower SC). These window systems are shown by a dashed line in Figs. 4-6, with the "x"'s corresponding to emittances of 0.4, 0.3, 0.2, 0.1, and 0.05.

(3) triple-pane windows having a low-emittance coating on surface 3;

The case of a emittance = 0.15 coating is shown by an "x". In this case the middle glazing layer is a thin plastic film.

(4) gas-filled windows;

U-values for the previous three window types can be lowered by using argon in 1/2-in. glazing gaps. These values are shown by solid round circles connected to their air-filled equivalents by a dotted line. Similar values can be achieved by using SF_6 or Kr with smaller gaps, while even lower U-values can be realized with these gases in larger gaps.

(5) Evacuated windows;

The theoretically predicted performance of three evacuated window systems is given in Figs. 4-6. The three points (marked by an open box) assume low-emittance coatings on the number 3 surface of 0.2 (high SC, high U), 0.1 (middle point), and 0.05 (low SC, low U). As with the case of low-emittance coatings on conventional windows, the shading coefficients given here are for average coatings. The glazing layers are separated by 1/8-in.-diameter solid glass spheres spaced every 2 inches [Ref. 4].

(6) Aerogel windows;

The thermal performance of an aerogel window is a function of the window's (1) thickness and (2) fill material and pressure. Because of the current uncertainty about some aerogel properties, the SCs and U-values of aerogel window systems in Figs. 4-6 are shown by shaded rectangular vertical boxes. We can envision two approaches. If we maintain a constant insulating value (R), replacing air with freon or a vacuum allows a thinner unit, which increases SC. Air-filled aerogel is shown by a solid rectangular box, freon-filled aerogel by a cross-hatched box, and low-pressure air-filled aerogel by a clear box. Alternatively, for a given thickness, changing the air to freon or to a soft vacuum will decrease the window's U-value while maintaining the same SC. We model an inch-thick aerogel window with these three fills. The SC stays constant while the U-value decreases, as shown by the three horizontal rectangles in Figs. 4-6.

These results assume a specific primary window area of 66 ft^2 (6.13 m^2). If the primary window-to-floor area ratio is decreased (or increased), the role of the shading coefficient in producing positive energy flows increases (or decreases). However, these results are not always linear with window size. As window size increases, benefits per unit area diminish as a greater fraction of solar gain ultimately becomes unusable. Results also vary for different building types and locations.

We do not discuss fenestration-imposed cooling loads in this paper. Where cooling loads are dominant and if the fenestration is unmanaged or poorly managed, high shading coefficients may be an overall energy liability. Different window system changes might be in order in cooling-dominated climates, including a low-emittance coating on the number 2 surface, heat-absorbing or reflective glass, and fixed or operable shading strategies.

With highly insulating windows, sash and frame conduction and infiltration can become large contributors to heat transfer. Control of air leakage is a matter of window design, window type, and manufacturers quality control. Some manufacturers routinely produce efficient windows having air leakage rates too low to measure. Window sash and frame design and thermal break construction must be controlled in order to keep these modes of heat transfer low. Typical window sash (wood or aluminum thermal breaks) has a resistance of R2 or 3, far below that of many of the window systems we discuss. In typical residential windows, sashs and frames can represent 20 to 30% of the gross opening area. Research on sash and frame effects for highly insulating window systems lags behind that of the high-resistance glazing systems, making the net thermal analysis of total window systems an essential research task.

The results presented here are largely analytical. The analytical tool used for most of these calculations compares favorably with experimental results for several simple window configurations [Ref. 8]. Experimental data on many novel window systems are not readily available and are complicated by the fact that there is no industry-wide agreement on appropriate measurement procedures. We await such data, as well as net performance data from controlled field test facilities such as the Mobile Window Thermal Test Facility at Lawrence Berkeley Laboratory [Ref. 10] to verify and extend our analytical results.

CONCLUSIONS

This paper reviews the primary heat transfer pathways in windows. We discuss using low-emittance coatings to reduce radiative heat transfer as well as using aerogel, low-conductivity gases, and evacuated spaces to reduce conductive/convective losses. A window system must minimize all these heat loss mechanisms to produce annual net energy benefits.

It is well known that conventional south-facing windows, in energy-efficient residences, can provide net energy benefits. For the east/west case, several window systems currently available or using currently available technologies can produce a positive net winter energy flow. These include gas-filled triple- and gas filled double-glazed units having low-emittance coatings. These coatings are making rapid inroads into the product lines of major window manufacturers.

Using aerogel or evacuated windows can provide much greater energy savings for south, east, and west windows and can also turn north windows into energy producers. While these window systems offer significant energy-producing potentials, their commercial introduction awaits the successful conclusion of current research efforts. While many advanced systems will see first use in new construction, some will also be used for retrofit and renovation, so that these technologies will ultimately become commonplace, particularly in cold climates.

We remind the reader that results presented here are based primarily on analysis and simulation, rather than field measurements, and that the performance values selected are representative of a wide range, rather than being definitive values offered by all manufacturers. Since commercial offerings are in a state of flux, readers are advised to consult manufacturers for specific product data.

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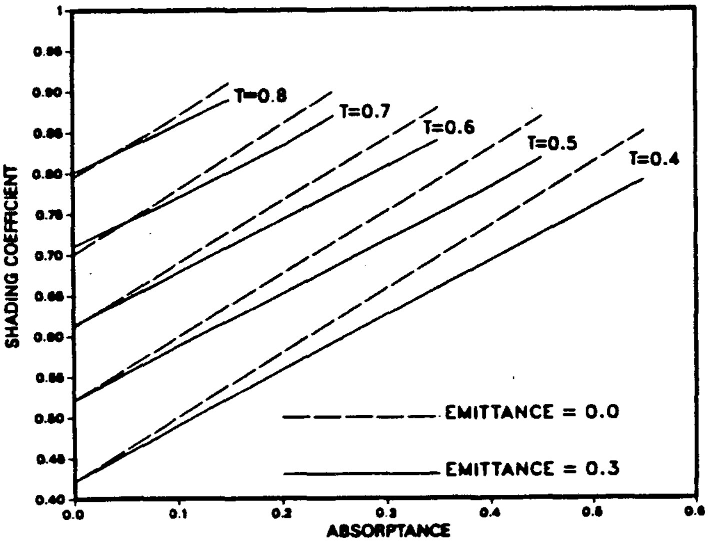

Figure 1. SC of a double-glazed window as a function of transmittance absorptance, and emittance (of the inner-coated light). The low-E coating is on the No. 3 surfaces and the gap width is 1/2 in. Environmental conditions are standard ASHRAE winter conditions (T_{in} = 70°F, T_o = 0°F, wind speed = 15 mph). For E = 0, U = 0.28 Btu/hr-ft^2-F; for E= 0.3, U = 0.39 Btu/hr-ft^2-F.

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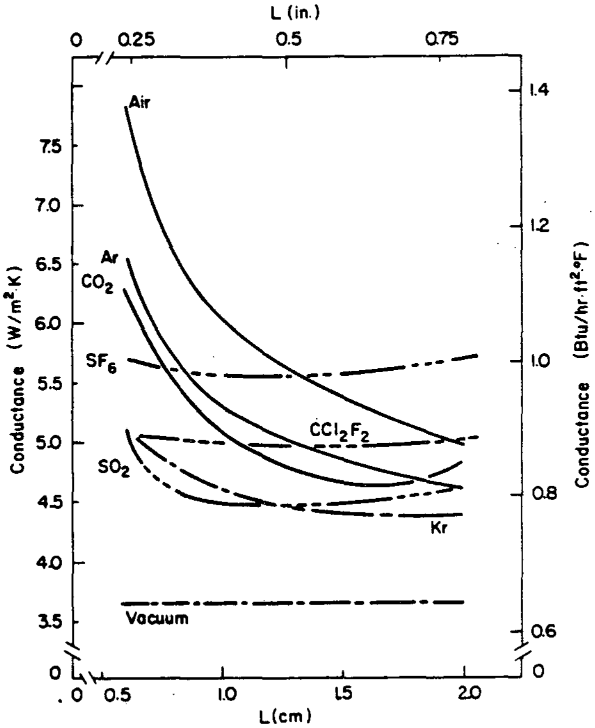

Figure 2. Total gas space conductance vs. gap width for double glazing, where the mean pane temperature is 50°F and the pane temperature difference is 18°F ± 1°F.

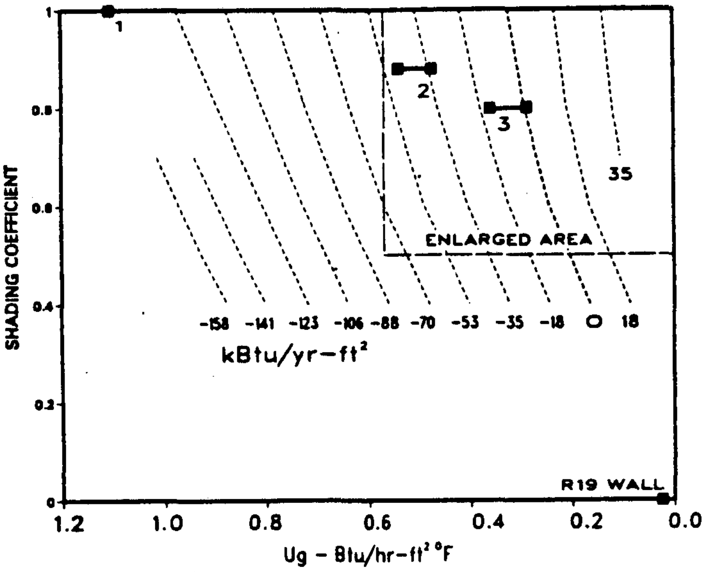

Figure 3. Net annual useful energy flux (kBtu/yr-ft² of window area) through 66 ft² of east-facing single-, double-, and triple-glazed windows expressed as a function of window U-value and for a prototypical house in Madison WI. The heat flux of an R19 wall is shown as a reference.

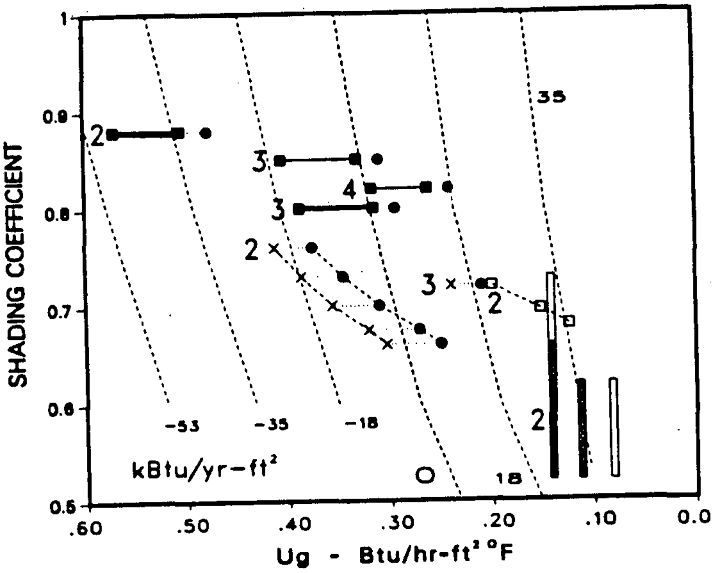

Figure 4. Net annual useful energy flux (kBtu/yr-ft² of window area) through 66 ft² of east-facing double-, triple-, and high-insulating window systems expressed as a function of window U-value and for a prototypical house in Madison WI.

1	SINGLE GLAZING
2	DOUBLE GLAZING
3	TRIPLE GLAZING
4	QUADRUPLE GLAZING
■—■	GAP WIDTHS RANGE FROM 1/4-1/2 INCH; ALL GLAZING LAYERS ARE GLASS
●—■	GAP WIDTHS RANGE FROM 1/4-1/2 INCH; MIDDLE GLAZING LAYERS ARE PLASTIC
X	LOW-EMITTANCE COATING, GAP WIDTH 1/2 INCH
·····	LOW-EMITTANCE COATING VARIES
□	EVACUATED SPACE (1/8 INCH)
●	GAS-FILLED VERSION OF WINDOW SYSTEM CONNECTED BY DOTTED LINE
▯	AEROGEL AIR WINDOW AT LOW PRESSURE
▨	AEROGEL FREON WINDOW AT ATMOSPHERIC PRESSURE
▮	AEROGEL AIR WINDOW AT ATMOSPHERIC PRESSURE

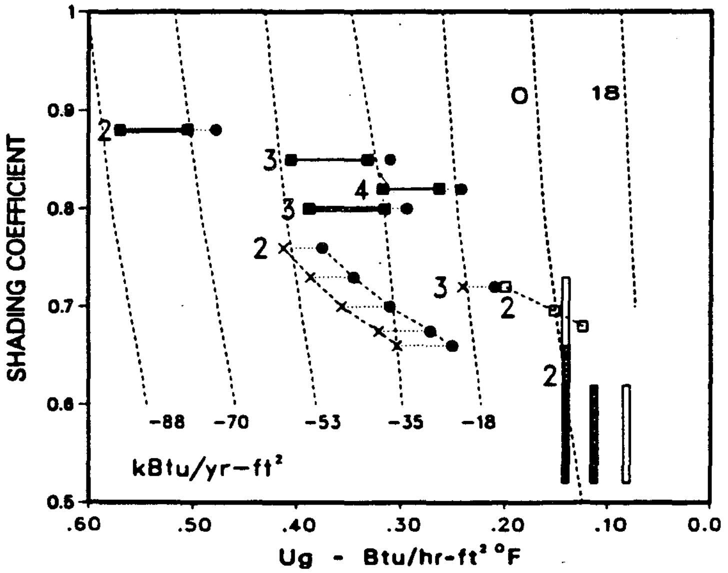

Figure 5. Net annual useful energy flux (kBtu/yr-ft² of window area) through 66 ft² of north-facing double-, triple-, and high-insulating window systems expressed as a function of window U-value and for a prototypical house in Madison WI.

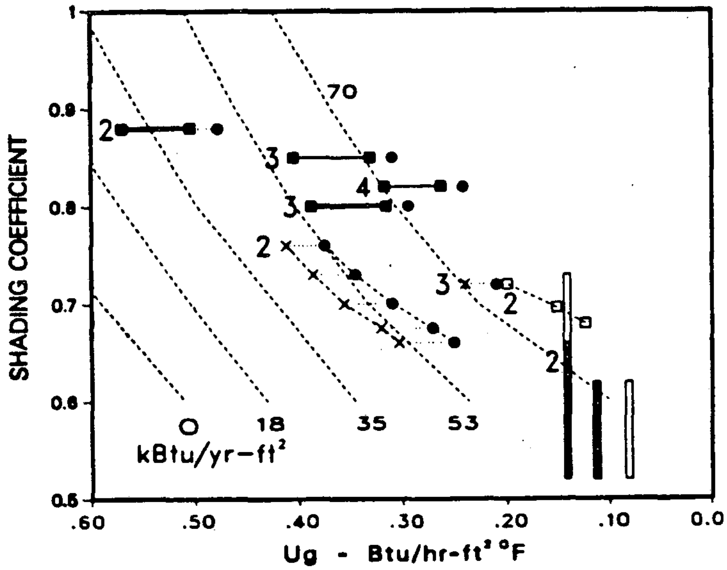

Figure 6. Net annual useful energy flux (kBtu/yr-ft² of window area) through 66 ft² of south-facing double-, triple-, and high-insulating window systems expressed as a function of window U-value and for a prototypical house in Madison WI.

1	SINGLE GLAZING
2	DOUBLE GLAZING
3	TRIPLE GLAZING
4	QUADRUPLE GLAZING
■—■	GAP WIDTHS RANGE FROM 1/4-1/2 INCH; ALL GLAZING LAYERS ARE GLASS
■—■	GAP WIDTHS RANGE FROM 1/4-1/2 INCH; MIDDLE GLAZING LAYERS ARE PLASTIC
X	LOW-EMITTANCE COATING, GAP WIDTH 1/2 INCH
·····	LOW-EMITTANCE COATING VARIES
□	EVACUATED SPACE (1/8 INCH)
●	GAS-FILLED VERSION OF WINDOW SYSTEM CONNECTED BY DOTTED LINE
▯	AEROGEL AIR WINDOW AT LOW PRESSURE
▨	AEROGEL FREON WINDOW AT ATOMSPHERIC PRESSURE
▮	AEROGEL AIR WINDOW AT ATMOSPHERIC PRESSURE