Improving the Thermal Performance of Vinyl-Framed Windows

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ABSTRACT

Over the last five years, vinyl-framed windows have gained an increased market share in both new and retrofit residential construction. This success has been due mainly to their low manufacturing cost and relatively good thermal performance (i.e., total window U-values with double glazing between 0.50 Btu/h·ft^2·°F [2.86 W/m^2·K] and 0.30 Btu/h·ft^2·°F [1.70 W/m^2·K]). Turning such windows into "superwindows,"—windows with a U-value of 0.20 Btu/h·ft^2·°F (1.14 W/m^2·K) or less that can act as passive solar elements even on north-facing orientations in cold climates—requires further significant decreases in heat transfer through both the glazing system and the frame/edge. Three-layer glazing systems (those with two low-emissivity coatings and a low-conductivity gas fill) offer center-of-glass U-values as low as 0.10 Btu/h·ft^2·°F (0.57 W/m^2·K); such glazings are being manufactured today and can be incorporated into existing or new vinyl frame profiles. This paper focuses on the use of a state-of-the-art infrared imaging system and a two-dimensional finite-difference model to improve the thermal performance of commercially available vinyl profiles and glazing edge systems. Such evaluative tools are extremely useful in identifying exactly which components and design features limit heat transfer and which act as thermal short circuits. Such an analysis is not possible with conventional whole-window testing in hot boxes, where testing uncertainties with superwindows are often greater than proposed improvements.

INTRODUCTION

Superwindows are very attractive from a design and energy standpoint because they can act as net energy producers for a house on all orientations of a building over the course of a heating season. Simulation studies have shown that even north-facing windows with U-values from 0.17 to 0.10 Btu/h·ft^2·°F (0.94 to 0.57 W/m^2·K) will outperform an insulated wall in a typical residence in a northern climate (Arasteh et al. 1989; Sullivan and Selkowitz 1985).

Today's vinyl-framed windows are among the most energy-efficient windows available to consumers. A typical high-performance vinyl-framed window is double glazed with one low-E coating, an argon gas fill, and an aluminum glazing spacer, with a total window U-value of about 0.40 Btu/h·ft^2·°F (2.27 W/m^2·K). However, because vinyl extrusions are very effective insulators when compared to conventional aluminum products, the energy performance of vinyl-framed windows is generally not optimized to its full potential in the window design process. Previous simulation studies have identified vinyl cross sections as likely candidates for improved products (Byars and Arasteh 1990).

Because of the high labor costs involved in replacing windows, utilities and homeowners who plan to retrofit windows should consider obtaining windows with the highest thermal performance available. To this end, a major electricity wholesaler in the Pacific Northwest is currently promoting the development and use of advanced, highly insulating vinyl-framed windows. It is planning to purchase low-U-value vinyl-framed windows for 75 new homes and 100 retrofit homes in the Northwest. To qualify for this program, the windows must be fixed or sliding vinyl-framed windows with a U-value of 0.20 Btu/h·ft^2·°F (1.14 W/m^2·K) or less.

High-performance windows, in addition to creating energy and peak demand savings, will also increase occupant comfort, allow designers the option of building homes with larger window areas, and virtually eliminate interior window condensation in all areas of the continental United States. The objective of this research, supported by this electricity wholesaler and the U.S. Department of Energy, is to provide the technical base for the development of such superwindows. To this end, infrared thermography was used in combination with two-dimensional finite-difference heat transfer modeling to improve the thermal performance of typical vinyl-framed window systems.

METHODOLOGY

A state-of-the-art infrared imaging radiometer was used in combination with two-dimensional finite-difference heat transfer modeling to identify design changes necessary for the manufacture of vinyl-framed superwindows (Arasteh et al. 1992). Hot-box testing was not used because of its expense and uncertainty in distinguishing between products with minor variations and with low U-values. U-values for all design prototypes are calculated according to the NFRC U-value simulation procedure (NFRC 1991).

The infrared imaging radiometer was used to analyze heat transfer through existing vinyl-framed windows and prototype superwindows. This process produces an image, known as a thermogram, which is a two-dimensional repre-

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sentation of the spatial surface temperature distribution on a window. These thermographic images can be used to identify the general thermal performance characteristics of a window and to pinpoint components that act as thermal bridges within the window system (Arasteh et al. 1992). The pinpointed areas of high heat transfer can then be modified to increase the overall thermal performance of the window. Figure 1 shows a cross section of a typical vinyl-framed fixed window.

Window heat transfer trends as well as total product U-values can also be studied in detail using two-dimensional heat transfer programs (LBL 1988; EE 1991). These programs model the thermal performance of the window on a component basis. The total window U-value, U_T, is the area-weighted average of the component U-values (NFRC 1991). The components are (1) center-of-glass, (2) edge-of-glass, (3) divider, (4) divider edge-of-glass, and (5) frame. These components are shown schematically in Figure 2. Component U-values are denoted U_C, U_E, U_D, U_{DE}, and U_F, respectively, and are calculated under NFRC standard winter conditions. The edge-of-glass and divider edge-of-glass regions are defined as the glazing area within 2.5 inches (63.5 mm) of the window sightline. The frame is divided into cross-sectional components corresponding to the head, sill, jamb, and meeting rail profiles as necessary.

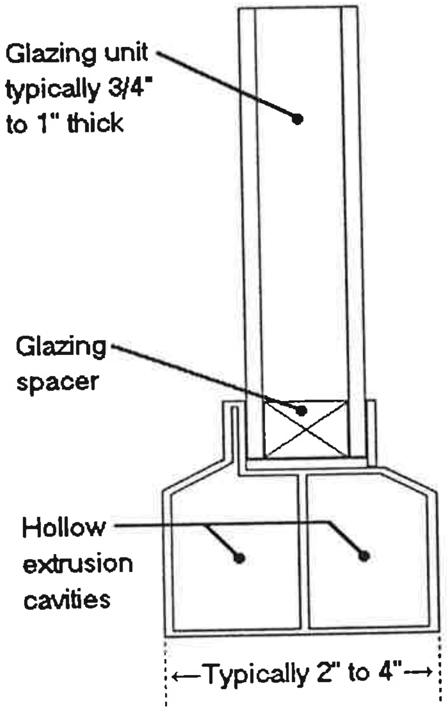

Figure 1 *Cross section of a typical vinyl-framed fixed window. The frame has hollow extrusion cavities separated by a vinyl webbing to provide structural support. Vinyl frames are typically 2 to 4 inches (50 to 100 mm) thick at the base. The glazing system is typically air- or argon-filled, with one low-E coating and a total width of 3/4 to one inch (19 to 25 mm). Non-thermally-broken aluminum glazing spacers are typically used in this type of window.*

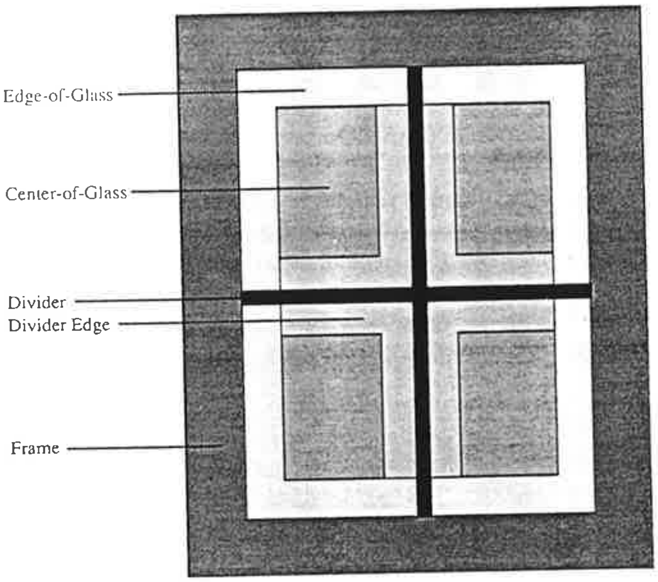

Figure 2 *Window components in elevation. Two-dimensional finite-difference heat transfer programs are used to calculate U-values for each of the window components. The frame may be modeled as a series of subcomponents, including the head, sill, jamb, and meeting rail profiles as necessary. The total window U-value,* U_T, *is an area-weighted average of the component U-values.*

RESULTS

To produce a superwindow, each of the component parts of the window system must be optimized. This section presents results of the authors' research efforts, identifying steps that will improve the thermal performance of each of the main components of a window system.

Glazing System Improvements

As the glazing system accounts for 70% to 90% of the area of a typical vinyl-framed window, it is imperative that heat transfer through this area be reduced significantly. Advanced high-performance glazing technologies exist and have been proved effective over the past several years (Arasteh et al. 1989; Arasteh and Selkowitz 1989). In order to achieve the required center-of-glass performance, glazing systems suitable for use with superwindows must be of a three-layer design with two glazing cavity gaps. Each of the two gaps must

- have a low-E coating on one of the glazing surfaces facing the gap,

- be filled with a low-conductivity gas,
- be the proper gap width for the gas used, and
- have coating emissivities of less than 0.2 and ideally less than 0.1.

Argon, the most commonly used gas in gas-filled windows, can be used very effectively in superwindow designs. Each argon-filled gap must be between 7/16 in. (11.1 mm) and ½ in. (12.7 mm) wide; this will result in insulating glass units as thick as 1⅜ in. (34.9 mm). Insulating glass units this wide or even wider can be used with minor design changes to vinyl-frame profiles. To avoid redesigning the frame and sash to accommodate wider insulating glazing units, krypton- or krypton/argon-filled gaps, as little as 5/16 in. (7.9 mm) thick each, can be used to achieve the same (or even slightly higher) performance than with argon alone. Table 1 presents glazing configurations for achieving low center-of-glass U-values.

Other glazing system options, such as four-layer low-E air- or gas-filled designs, can be equally or more effective. For the remainder of this paper, which focuses on frame and edge effects, we will assume the use of a high-performance, triple-pane glazing unit with two 5/16-in. (7.9-mm) krypton-filled gaps, two low-E coatings of E = 0.08, and a center-of-glass U-value of 0.116 Btu/h·ft^2·°F (0.660 W/m^2·K).

Frame Improvements

More than just superglazings are required to make a superwindow. The good thermal performance of vinyl-framed windows is due to the relatively low thermal conductivity of vinyl and the fact that vinyl frames are hollow, thereby using trapped air to insulate. In order to improve the performance over that of current vinyl extrusions, one must minimize the aggregate effect of conductive, convective, and radiative heat transfer. Conductive heat transfer through a frame profile is a function of the path length and cross-sectional area in the direction of heat transfer and of the material conductivity of the frame components. Maximum conductive path length, minimum cross-sectional area, and the use of materials with low thermal conductivity will result in the lowest U-values. The conductive path length may be increased by going to wider frame profiles. The thickness of the extrusion walls and inner webbings, which are parallel to the direction of heat transfer, should be reduced to minimize the cross-sectional area of heat flow while still maintaining structural integrity.

While vinyl has an inherently low thermal conductivity, the presence of metal reinforcements within the frame can significantly degrade the thermal performance of the vinyl profile. The high thermal conductivity of metal structural members can create a thermal short circuit between the warm and cold sides of the frame, effectively shortening the path length of heat transfer. The effects of short path length and/or metal reinforcements are especially pronounced in meeting rails of sliders and single- or double-hung windows. Two-dimensional heat transfer modeling has shown that the meeting rails typically have the lowest thermal performance of any of the frame profiles in a window. Metal reinforcements should be avoided if at all possible, and conductive path lengths, especially at the weather seal, should be maximized. Often the controlling resistance to heat transfer across the meeting rail is just the thickness of the weatherstrip, so it is critical that this area be analyzed when designing frame profiles. Figure 3 shows a heat flow plot for the meeting rail profile of an aluminum-reinforced vinyl-framed window calculated using a two-dimensional finite-element program (EE 1991). Each line superimposed on the profile indicates a unit increment of heat flow. The closer the lines, the greater the heat flow through the

TABLE 1
Low U-Value Glazing System Requirements

U_C Btu/h·ft^2·°F (W/m^2·K)	Glazing option
0.167 (0.949)	triple-glazed, two low-E coats of E = 0.20, argon filled 15/32" (11.9 mm) gaps
0.143 (0.813)	triple-glazed, two low-E coats of E = 0.10, argon filled 7/16" (11.1 mm) gaps
0.125 (0.709)	triple-glazed, two low-E coats of E = 0.05, argon filled 15/32" (11.9 mm) gaps
0.116 (0.660)	triple-glazed, two low-E coats of E = 0.08, krypton filled 5/16" (7.9 mm) gaps
0.111 (0.633)	triple-glazed, two low-E coats of E = 0.05, 75 % krypton, 25% argon filled 7/16" (11.1 mm) gaps
0.100 (0.568)	quadruple-glazed, two low-E suspended films of E = 0.08, krypton filled 5/16" (7.9 mm) gaps

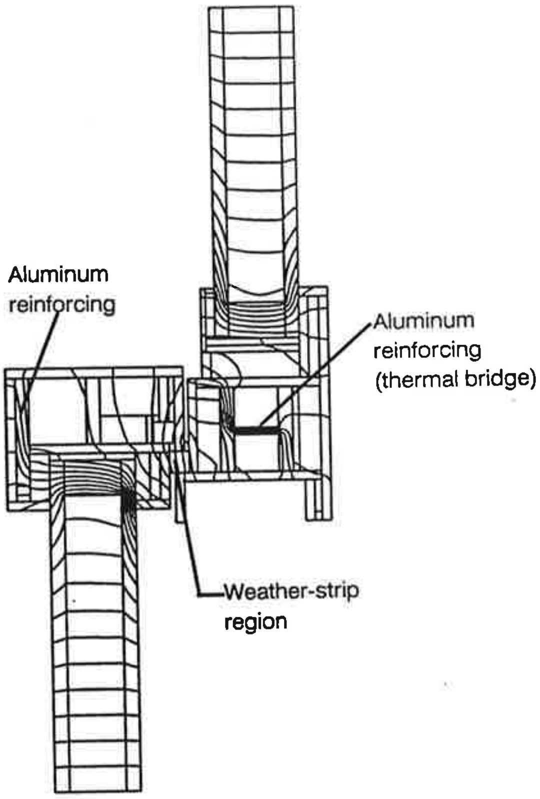

Figure 3 *Heat flow plot for the meeting rail of an aluminum-reinforced vinyl-framed window as modeled under NFRC winter conditions using a two-dimensional finite-difference program (EE 1991). The total heat flow through the profile is 22.88 Btu/h·ft (22.00 W/m), and the heat flow through adjacent flow lines (superimposed on the profile) is 0.46 Btu/h·ft (0.44 W/m). The glazing spacers and aluminum reinforcements (vertical bar on far left of profile and H-shaped member on right side of profile) are regions of high heat flow.* U_E = *0.430 Btu/h·ft²·°F (2.44 W/m²·K) and* U_F = *0.990 Btu/h·ft²·°F (5.62 W/m²·K).*

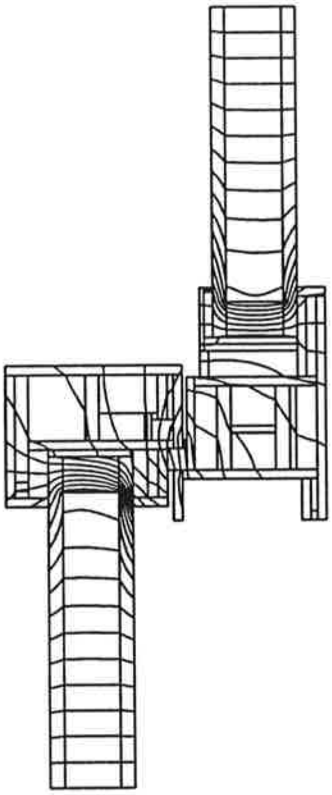

Figure 4 *Heat flow plot for the meeting rail of a vinyl-framed window as modeled under NFRC winter conditions using a two-dimensional finite-difference program (EE 1991). The heat flow through the reinforcement area (Figure 3) has been significantly decreased by replacing the aluminum reinforcements with vinyl. The total heat flow through the profile is 21.63 Btu/h·ft (20.79 W/m), and the heat flow through adjacent flow lines is 0.46 Btu/h·ft (0.44 W/m). The short path length through the meeting rail weatherstrip contributes to relatively high heat flow through that region.* U_E *= 0.422 Btu/h·ft²·°F (2.40 W/m²·K) and* U_F *= 0.875 Btu/h·ft²·°F (4.97 W/m²·K).*

region. Figure 4 shows the same profile, but with the aluminum reinforcements replaced by vinyl. Total heat flow in Figure 4 is less, but high heat flow through the weather-stripped area is still a problem.

Heat transfer across air cavities within the profile is dependent on convective and radiative mechanisms. While convective loops may set up in a small cavity, such as those seen when looking at a cross-sectional schematic of the profile, evidence of convection in the third dimension, along the length of the extrusion cavity, has been detected using infrared thermographic imaging. A commercially available fixed vinyl-framed window with exterior dimensions of 16 inches wide by 24 inches high was subject to a 65°F (18°C) temperature differential between the exterior and interior sides. The interior (warm side) surface temperatures were then measured with an infrared imaging radiometer. The thermographic image (Figure 5) revealed a temperature gradient between the top and bottom of the frame, with the bottom of the frame being cooler than the top by 6.0°F ±0.2°F (3.3°C ±0.1°C). The test was performed using a glazing system with a center-of-glass U-value of 0.125 Btu/h·ft²·°F (0.71 W/m²·K). As this glazing had a very uniform edge temperature profile, the frame temperature gradient is due to convective heat transfer inside the hollow cavities of the vinyl extrusion. In order to reduce the convective heat transfer, the size of the air cavities must be reduced and/or the cavities must be eliminated in a way that does not increase the solid conduction through the frame. Three methods of reducing this convective heat transfer were analyzed.

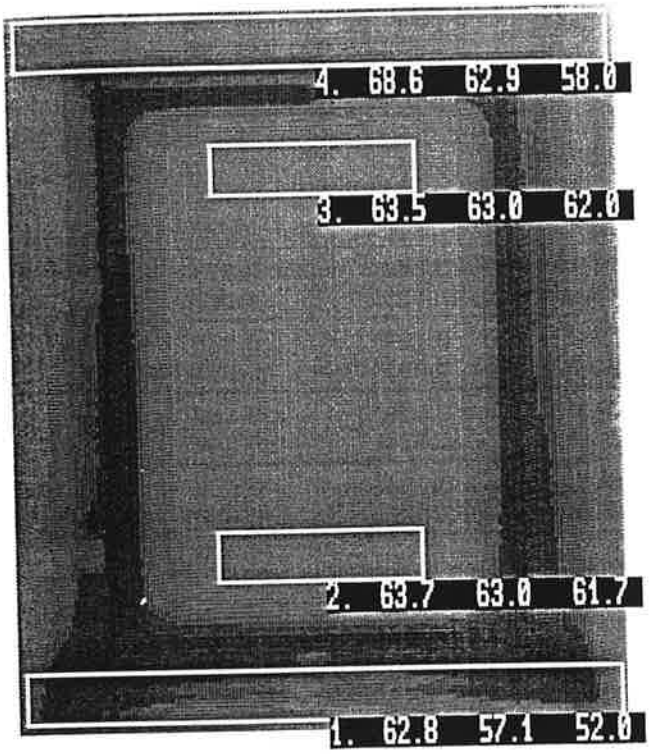

Figure 5 *Thermographic image of the warm side of a standard vinyl-framed fixed window with an R-8 h·ft^2·°F/Btu (R-1.41 m^2·K/W) center-of-glass glazing. The window was subjected to a temperature differential of 65°F (36°C) and a cold-side wind speed estimated at 7 mph parallel to the glazing surface. The maximum, average, and minimum temperatures are given in degrees Fahrenheit for four rectangularly bounded regions. Convective airflow within the hollow extrusion cavities creates a temperature gradient between the top (region #4, average temperature 62.9°F [17.2°C]) and bottom (region #1, average temperature 57.1°F [13.9°C]) of the frame, while the temperature of the insulating glazing unit (regions #2 and 3) is fairly uniform.*

1. The size of the air cavities can be reduced by adding thin vinyl webbings within the extrusion cavities in addition to the structural webbings already present. This can be done as part of the extrusion process. Computer modeling using a two-dimensional heat transfer program (EE 1991) was performed for four possible webbing configurations of a fixed-window vinyl profile. The window was modeled with the high-performance triple-pane glazing unit and an insulating spacer. Webbings parallel to the direction of heat flow reduced the frame U-value by 14%, as did webbings configured in a cross-hatch pattern. Webbings perpendicular to the direction of heat flow reduced the frame U-value by 31%. The effect on the edge-of-glass region is much less, as shown in Table 2.
2. Large air cavities within the frame profile were broken up by inserting a convection-suppressing baffle into the hollow extrusion cavities subsequent to the extrusion process. A vinyl-framed fixed window and a vinyl-framed casement window were fitted with baffles made of crumpled aluminized-polyester sheeting and subjected to a temperature differential. The aluminized coating provides a low-emissivity surface and serves to reduce the radiative heat transfer across the extrusion cavities, while the presence of the crumpled sheeting suppresses the convective heat transfer. The surface temperatures of the warm side of the frames were measured with an infrared imaging radiometer and compared to the surface temperatures of the unmodified frames. The casement window was subject to a 38°F (21°C) temperature differential, and the frame surface temperature was increased 2°F to 4°F (1°C to 2°C) by the addition of the baffle. The fixed window, which had the same profile as modeled in the vinyl webbing study (no. 1 above), was subjected to a 65°F (36°C) temperature differential, and the frame surface temperature of the warm side was increased by 5°F (3°C) with the addition of the baffle. While infrared thermography cannot yet be used to calculate accurate U-values from measured surface temperatures, the increased surface temperatures with the addition of the baffle do indicate a significant performance increase over that of the standard hollow extrusion profiles. Figure 6 gives the warm-side surface temperature profiles for the standard and modified casement windows, and Figure 7 gives the warm-side surface temperature profiles for the standard and modified fixed windows.
3. Convective and radiative heat transfer across hollow extrusion cavities can be reduced by filling the extrusion cavities with a polyurethane or other foam fill. A polyurethane-foam-filled vinyl-framed fixed window, as in method 1 above, was subjected to a 65°F (36°C) temperature differential, and the warm-side surface temperature profile of the frame was measured with an infrared imaging radiometer. The foam-filled frame surface temperatures were 5°F to 6°F (3°C) higher than the standard frame and 1°F (0.5°C) higher than the low-E baffle configuration, indicating a much better thermal performance than that of the standard frame and slightly better than the low-E baffle-filled profile. Computer modeling also indicates that foam filling a vinyl profile will significantly reduce the frame U-value. The warm-side surface temperatures predicted by the model were validated with data from the infrared thermographic tests performed on the foam-filled window. Comparison of the data is shown in Figure 8.

   While foam filling is desirable from an energy efficiency standpoint, there are limitations imposed by both the extrusion process and the frame manufacturing process. Extrusion manufacturers recycle their vinyl scrap and buy back clean vinyl scrap from the window manufacturer. The use of polyurethane for the foam

TABLE 2
Addition of Thin Webbings to a Standard Fixed-Window Vinyl Frame with an Insulating Spacer*

	U-Values Btu/h·ft²·°F (W/m²·K)			
	U_C	U_F	U_E	U_T
No additional webbings	0.116 (0.659)	0.310 (1.761)	0.198 (1.125)	0.179 (1.017)
Parallel to heat flow	0.116 (0.659)	0.265 (1.505)	0.192 (1.091)	0.168 (0.954)
Cross-hatched	0.116 (0.659)	0.266 (1.511)	0.189 (1.074)	0.167 (0.949)
Perpendicular to heat flow	0.116 (0.659)	0.213 (1.210)	0.190 (1.079)	0.156 (0.886)

* U-value calculations based on NFRC AA size 24" x 48" (0.61 m x 1.22 m), frame cross section 4" wide at base with 2.5" projected area and a high-performance triple-glazing with an insulating spacer. (NFRC 1991)

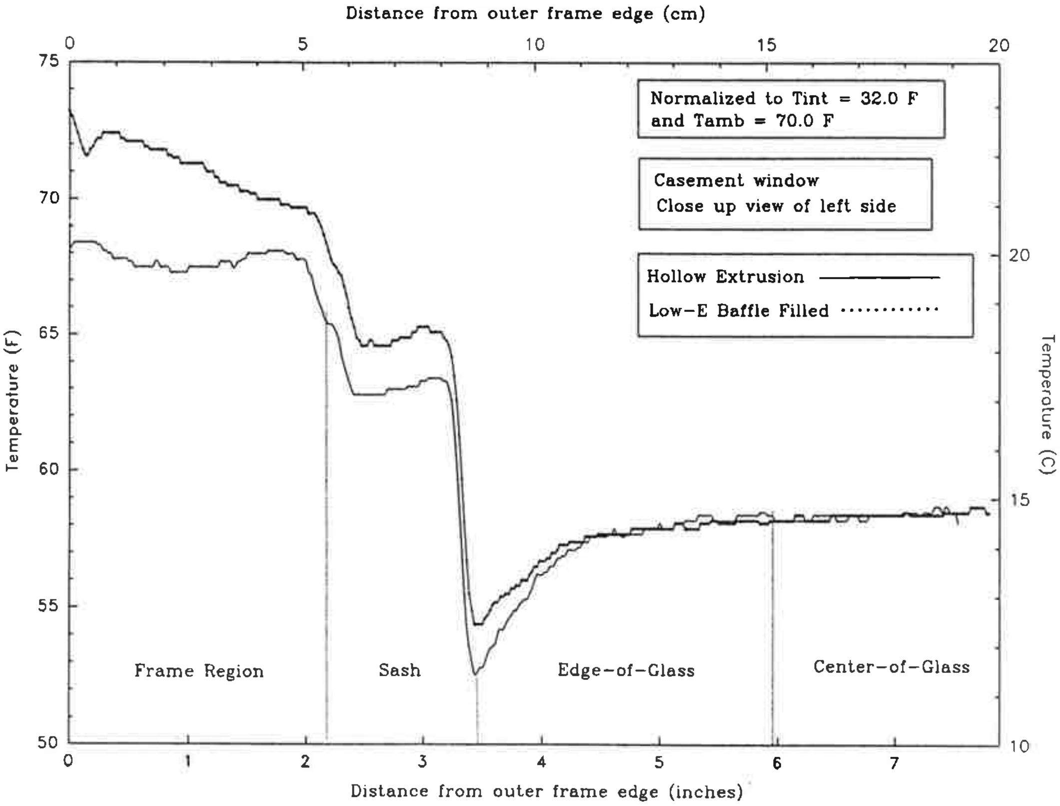

Figure 6 *Comparison of warm-side surface temperature data from infrared images of the left side of a standard vinyl-framed casement window and a vinyl-framed casement window with a low-E baffle. Both windows were fitted with clear, air-filled, double-glazed IG units with aluminum glazing spacers. The windows were subject to a temperature differential of 38°F (21°C) and a cold-side wind speed estimated at 7 mph parallel to the glazing surface. The higher surface temperatures of the frame filled with a low-E baffle indicate better thermal performance than that of the standard frame. Low surface temperatures at the sash/edge-of-glass interface indicate thermal bridging due to the aluminum glazing spacers.*

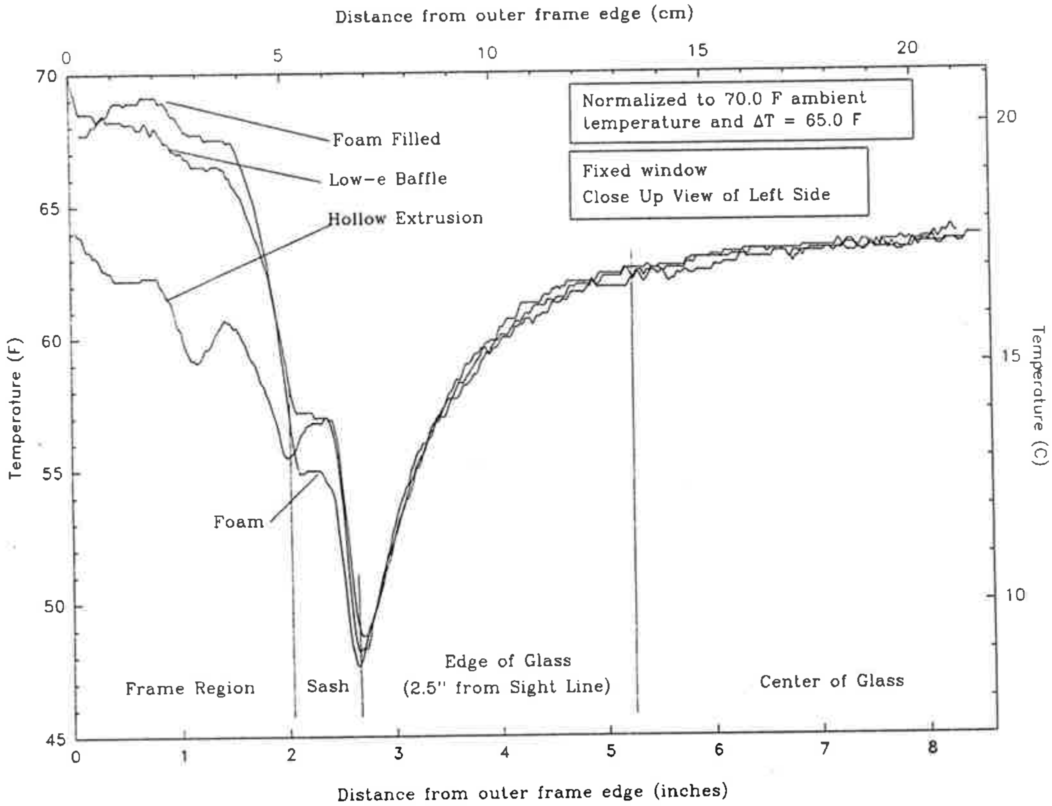

Figure 7 *Comparison of warm-side surface temperature data from infrared images of the left side of a vinyl-framed fixed window for three different frame fills. All three windows were fitted with an R-8 h·ft^2·°F/Btu (R-1.41 m^2·K/W) center-of-glass IG with a thermally broken spacer. The windows were subject to a temperature differential of 65°F (36°C) and a cold-side wind speed estimated at 7 mph parallel to the glazing surface. Surface temperature profiles are plotted for the standard hollow extrusion, the frame with a low-E baffle, and the foam-filled frame. The higher surface temperatures of the foam-filled frame and the frame with a low-E baffle indicate better thermal performance than that of the standard frame. Low surface temperatures at the sash/edge-of-glass interface indicate significant thermal bridging due to the thermally broken glazing spacers.*

filling of lineals will result in contaminated vinyl scrap, which currently cannot be recycled. The material cost, disposal cost, and landfill penalty for nonrecycled scrap provide a substantial disincentive to foam filling. The second problem is that screw holes and weep holes are currently punched into the lineals using a mechanical punch that is inserted into the hollow lineal cavity. If the lineals are foam filled before cutting to size, the foam will interfere with the punching operation. One might try to avoid this by scraping out some of the foam, but any additional step in manufacturing adds time and expense. Lastly, foam filling may interfere with the weep holes in the frame. Advanced foam-filling methods, such as the use of coextruded PVC foams, may solve the recyclability problem and also give better thermal performance. These methods are currently the subject of investigation in the window industry.

Spacer Improvements

Heat flow through a window is at a maximum along the path of least thermal resistance, sometimes called the controlling resistance. As thermally improved vinyl frames and advanced glazings are used, the glazing spacer often becomes the controlling resistance to heat flow. Aluminum spacers are the weakest link in an advanced glazing system and significantly degrade the overall thermal performance of the window. The effect of metal spacers is clearly seen with the use of infrared imaging. Infrared thermography and computer simulation have also shown that even thermally broken spacers are the weak link in advanced window systems. This effect is seen in Figure 7, where low warm-side surface temperatures in the spacer region indicate a high rate of heat flow through the insulating spacer relative to the frame and center-of-glass regions.

Current aluminum spacers that are not thermally broken have an R-value on the order of 0.01 h·ft^2·°F/Btu (0.002 m^2·K/W), and computer modeling indicates that even the best thermally broken spacers on the market today have an R-value of approximately 1.0 h·ft^2·°F/Btu (0.18 m^2·K/W) or less. Computer simulations indicate that the inclusion of an improved thermally broken spacer in a high-performance window system will provide a significant decrease in total window U-values. Replacing a conventional thermally broken spacer with a hypothetical R-2 spacer in a triple-

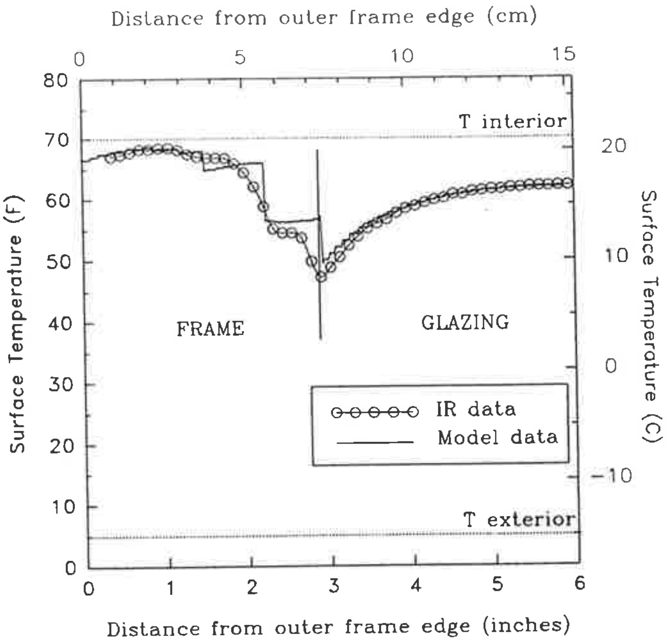

Figure 8 *Warm-side surface temperatures for the left side of the frame and edge of a foam-filled, vinyl-framed fixed window as computed using a two-dimensional finite-difference program and as measured using infrared thermographic imaging. The window was subject to a temperature differential of 65°F (36°C), and the cold-side wind speed is estimated at 7 mph parallel to the glazing surface. The only significant difference between the computed and measured temperatures is seen at the frame/glass interface and is most likely due to the use of convective film coefficients in the model, which do not accurately represent edge conditions (Arasteh et al. 1992).*

glazed, fixed vinyl-framed superwindow will lower the total window U-value by 6%. Table 3 gives a matrix of simulated total window U-values as a function of spacer type for a standard fixed vinyl frame, a foam-filled fixed vinyl frame, and a vinyl-framed horizontal slider with aluminum reinforcements in the meeting rail. We find that, in all cases, going to a spacer with an R-value of 1.0 to 2.0 h·ft^2·°F/Btu (0.18 to 0.35 m^2·K/W) will provide a significant improvement in total window U-values. This result is shown graphically in Figure 9. Replacing a standard aluminum spacer with a thermally improved spacer will change the warm-side surface temperature distribution of a window, as shown in Figure 10.

Frame/Glazing Interface

The glazing spacer creates a thermal bridge between the inner and outer glazing, thus the interface of the frame and glazing tends to be a region of high heat flow. This effect was initially identified using infrared thermography and later confirmed with two-dimensional heat transfer modeling. A foam-filled, vinyl-framed fixed window with a high-performance triple-pane glazing and an insulating spacer was both simulated and tested using the infrared imaging system. The computer simulation indicates that two methods of reducing this heat flow are the inclusion of a thermal break at the frame/glazing interface and recessing the glazing spacer below the sightline of the window. The findings are as follows.

1. A low-thermal-conductivity foam strip can be used in place of conventional glazing tape in order to create a thermal break between the frame and the glazing. Computer modeling indicates that this modification will improve the overall performance of a typical superwindow by about 5% where metal glazing spacers are used but will not significantly increase the performance where insulating spacers are used. Infrared testing of a prototype window system confirms that this modification will produce a small effect when the low-thermal-conductivity foam strip is added on the warm side of the glazing but will have no effect when used on the cold side of the glazing. To date, laboratory tests have not quantitatively determined the effect of this type of modification.
2. While a thermal break between the frame and glazing will reduce the heat transfer between those two components, the path of least resistance to heat flow may be through the glass itself. The high thermal conductivity of glass provides a direct link between the glazing spacer and the exterior or interior conditions. To reduce this link, the glazing spacer can be recessed into the frame with respect to the sightline of the window. For a recess depth of one-half inch (12.7 mm), computer simulation indicates a greater than 10% overall U-value decrease when using metal glazing spacers and a 3% to 5% overall U-value decrease when using insulating glazing spacers in a fixed vinyl-framed superwindow. Modeling results are summarized in Table 4.

CONCLUSIONS

Vinyl-framed superwindows can be a significant component in improving the thermal performance of both new and retrofit residential building envelopes. Rapid growth in the vinyl-frame superwindow market is expected, and utility incentive programs will play a strong role in pushing these technologies onto the market. Infrared imaging and computer simulation offer powerful and cost-effective tools for the design of these advanced fenestration products. This study identifies design changes necessary to turn typical double-glazed vinyl windows into superwindows. While this study has focused on fixed window configurations, the trends of U-value changes with design and material modifications are valid for nonfixed windows.

TABLE 3
Total Window U-Values vs. Spacer Type*

U_{total} Btu/h·ft^2·°F (W/m^2 C)

	horizontal slider	hollow fixed frame	foam-filled** fixed frame
Aluminum spacer	0.232 (1.317)	0.245 (1.391)	0.210 (1.192)
R1 spacer	0.195 (1.107)	0.188 (1.067)	0.151 (0.857)
R2 spacer	0.185 (1.050)	0.177 (1.005)	0.137 (0.778)
R3 spacer	0.180 (1.022)	0.169 (0.960)	0.132 (0.749)
R5 spacer	0.177 (1.005)	0.166 (0.943)	0.126 (0.715)
R7 spacer	0.175 (0.994)	0.164 (0.931)	0.126 (0.715)

* U-value calculations based on NFRC AA size, frame cross section 4" wide at base with 2.5" projected area and a high-performance triple-glazing.

** Increase overall U-value by 4% when using vinyl webbing rather than the foam-fill or aluminized polyester fill options.

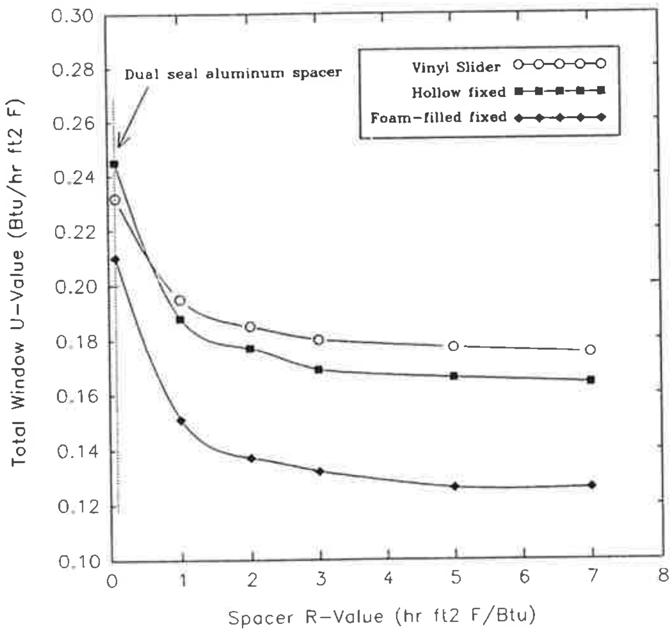

Figure 9 *Graph of modeled total window U-values versus a range of glazing spacer R-values. Thermal performance is calculated for a 2-ft-by-4-ft fixed vinyl-framed window for both hollow and foam-filled extrusion cavities. Thermal performance is also calculated for a 3-ft-by-5-ft vinyl-framed horizontal sliding window with aluminum meeting rail reinforcements. The modeled sizes were chosen such that the glazing edge to total window area ratios are the same. Significant performance gains are obtained by replacing a conventional dual-seal aluminum spacer with an insulating (R-1) spacer or a hypothetical R-2 spacer.*

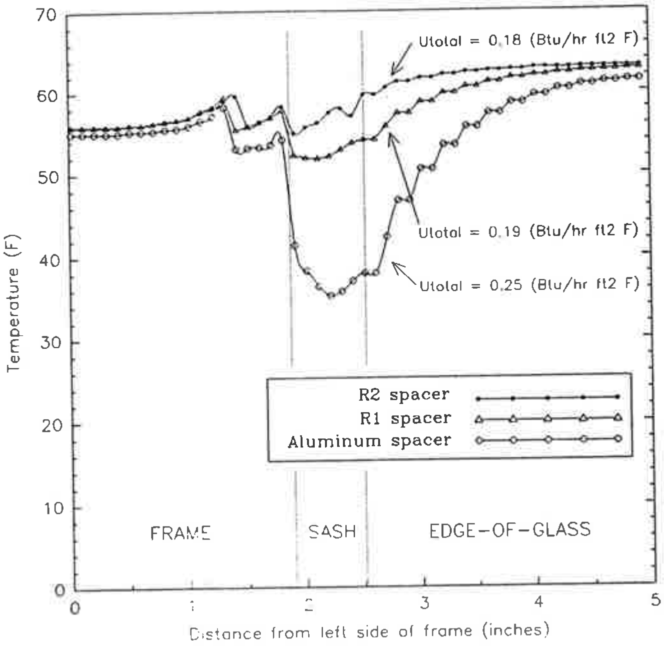

Figure 10 *Simulated warm-side surface temperature profiles for a hollow vinyl-framed fixed window subject to NFRC winter conditions. Profiles are shown for the frame and the 2.5-in. edge-of-glass region. The window was modeled with a dual-seal aluminum spacer, an R-1 spacer, and an R-2 spacer. In all cases, a high-performance triple glazing with a center-of-glass U-value of 0.116 Btu/h·ft^2·°F (0.660 W/m^2·K) was used. The aluminum spacer gives the lowest surface temperatures, indicating poor thermal performance. The R-2 spacer brings the edge temperature closest to that of the frame, giving a 38% decrease in total heat flow through the window.*

TABLE 4
Modified Frame/Glazing Interface for Fixed-Window Vinyl Profiles*

Metal spacer

	U_C Btu/h·ft^2·°F (W/m^2·K)	U_F Btu/h·ft^2·°F (W/m^2·K)	U_E Btu/h·ft^2·°F (W/m^2·K)	U_T Btu/h·ft^2·°F (W/m^2·K)
Foam-filled frame	0.116 (0.659)	0.300 (1.703)	0.275 (1.561)	0.208 (1.181)
Foam-filled with insulating trim strip	0.116 (0.659)	0.280 (1.590)	0.259 (1.471)	0.199 (1.130)
Foam-filled with recessed glazing	0.116 (0.659)	0.304 (1.726)	0.181 (1.028)	0.186 (1.056)

Insulating spacer

	U_C Btu/h·ft^2·°F (W/m^2·K)	U_F Btu/h·ft^2·°F (W/m^2·K)	U_E Btu/h·ft^2·°F (W/m^2·K)	U_T Btu/h·ft^2·°F (W/m^2·K)
Foam-filled frame	0.116 (0.659)	0.194 (1.10)	0.176 (1.00)	0.153 (0.869)
Foam-filled with insulating trim strip	0.116 (0.659)	0.187 (1.06)	0.173 (0.983)	0.151 (0.857)
Foam-filled with recessed glazing	0.116 (0.659)	0.199 (1.13)	0.143 (0.812)	0.147 (0.835)

* U-value calculations based on NFRC AA size 24" x 48" (0.61 m x 1.22 m), frame cross section 4" wide at base with 2.5" projected area and a high-performance triple-glazing.

In general, one must work harder to achieve lower U-values in nonfixed windows due to solid conduction through more complex frames and meeting rails, but it can be done. The recommended design changes are summarized in Figure 11 and include the following:

1. The window must be fitted with a high-performance glazing unit. Low center-of-glass U-values are achieved with a three-glazing-layer design with two glazing cavity gaps. Each of the two gaps must have a low-E coating on one of the glazing surfaces facing each gap. The gap must be filled with a low-conductivity gas, such as argon or krypton, and be the proper gap width for the gas used. The low-E coatings should have emissivities of less than 0.2 and ideally less than 0.1.
2. The high-performance glazing unit should be constructed with a thermally broken insulating spacer.
3. The window frame should be constructed of a low-thermal-conductivity material, such as vinyl. Frame cross sections should be as wide as possible to maximize the path length for conductive heat transfer. Convective and radiative heat transfer within large air cavities of a frame profile can be significantly reduced by filling the cavity with an expanded foam fill, a low-emissivity baffle, or by placing additional thin vinyl webbings in the cavity perpendicular to the direction of heat transfer. Metal reinforcements within the frame should be avoided. Conductive path lengths at meeting rail weatherstrips should be maximized.
4. Heat transfer at the frame/glazing interface can be reduced by recessing the glazing into the frame profile and by using an insulating glazing tape between the warm-side glazing surface and the frame.

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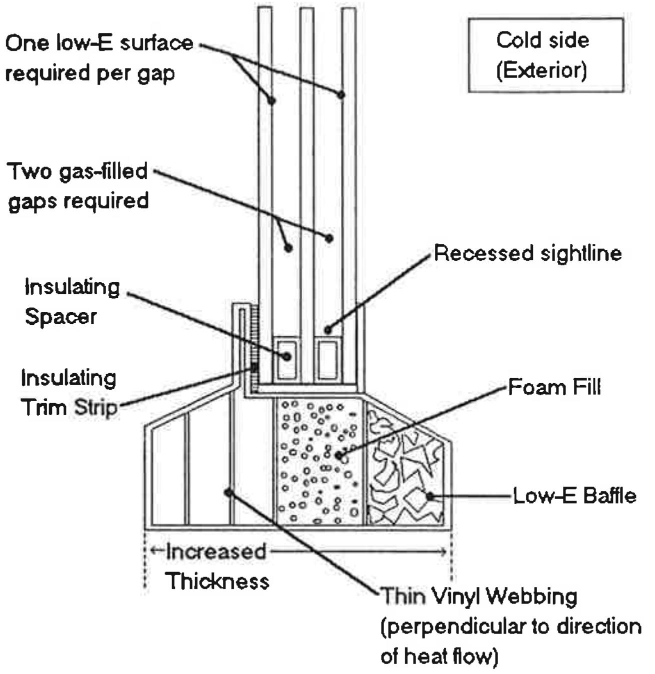

Figure 11 *Schematic diagram of a hypothetical vinyl-framed superwindow. A triple-glazed IG unit filled with low-thermal-conductivity gas with one low-E coating per gap and an insulating spacer is mounted in a wide-profile vinyl frame. The low-E coatings should have an emissivity of 0.1 or less for maximum thermal performance. The frame extrusion cavities are filled with an expanded foam or low-E baffle or have additional thin vinyl webbings installed to reduce convective heat transfer. The glazing unit is mounted with a recessed sightline and low-thermal-conductivity glazing tape in order to minimize frame and edge-of-glass heat transfer.*

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