**Title**
An Analysis of Edge Heat Transfer in Residential Windows



**Author**
Arasteh, D

**Publication Date**
1989-10-01

# Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

## APPLIED SCIENCE DIVISION

To be presented at the ASHRAE/DOE/BTECC/CIBSE Conference on Thermal Performance of the Exterior Envelopes of Buildings IV, Orlando, FL, December 4–7, 1989, and to be published in the Proceedings

# An Analysis of Edge Heat Transfer in Residential Windows

D. Arasteh

October 1989

APPLIED SCIENCE DIVISION



**Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.**

LBL-26068
TA-269

Presented at the ASHRAE/DOE/BTECC/CIBSE Conference on Thermal Performance of the Exterior Envelopes of Buildings IV, December 4-7, 1989, in Orlando, FL, and to be published in the proceedings.

# An Analysis of Edge Heat Transfer in Residential Windows

D. Arasteh
Windows and Daylighting Group
Applied Science Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California

October 1989

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Additional support was provided by the Bonneville Power Administration under contract No. DE-AI79-86BP63401 and by a gift from the Wisconsin Power and Light Company.

# An Analysis of Edge Heat Transfer in Residential Windows

Dariush Arasteh
Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

## ABSTRACT

New window technologies are reducing heat transfer through the glazed areas of windows. Low-emissivity (low-E) coatings reduce radiative heat transfer and low-conductivity gas fills (which replace the air between glazing layers) reduce conductive heat transfer. Given these advances in insulating glass technology, researchers and manufacturers are now beginning to focus their attention on reducing heat transfer through window edges. Old edge designs are now under scrutiny and new designs are being proposed.

This paper explores window material and design parameters which influence heat transfer using two-dimensional heat-transfer modeling with an advanced finite-element computer code (ANSYS). A comprehensive set of correlations, based on ANSYS parametrics, is then developed. These correlations are compared, whenever possible, to experimental results and will be incorporated into future versions of the WINDOW program. Glazing edge designs analyzed include both double-glazed and triple-glazed options with aluminum, steel, wood, fiberglass, butyl, and insulated spacers. Single and double seal design are also analyzed.

## INTRODUCTION

In the past, windows were typically constructed of single or insulating (double) glass and wood or aluminum (with or without a thermal break) frames. Calculating heat transfer through the glass and frame areas was relatively simple. Because the U-values of these two components were not too different, an area-weighted U-value was a reasonable indicator of the window's overall thermal performance.

However, evolving window designs are reducing heat transfer through glazed areas. Low-emissivity (low-E) coatings (which reduce radiative heat transfer) and low-conductivity gas fills (which replace the air between glazing layers to reduce conductive heat transfer) are being designed into many state-of-the-art window products. A well-designed low-E, gas-filled, double-glazed window has a center-of-glass U-value of 0.25 Btu/h-ft$^2$-°F, half that of the old standard uncoated, air-filled, double-glazed window. Researchers and manufacturers are currently developing prototype glazings with even lower center-of-glass U-values. Given these advances in insulating glass technology, researchers and manufacturers are focusing their attention on reducing heat transfer through window edges. Metal spacers, the industry standard, act as thermal short circuits in a typical window design, greatly detracting from the performance of a low-E, gas-filled unit. To solve these problems, new designs and new materials are being studied.

These changes in window designs necessitate more advanced analysis tools. Window performance indices must also be determined in an accurate and consistent manner. In many cases, experimental results are not easily available, are too expensive, or are inconclusive. Computational models are an attractive alternative. One such model, WINDOW 3.1, is a public domain program that runs interactively on a personal computer (Lawrence Berkeley Laboratory 1988). WINDOW 3.1 performs a rigorous one-dimensional heat balance calculation on any user-defined glazing system (Arasteh et al. 1989). Correlations to account for edge and frame heat transfer, based on experimental work and two-dimensional heat transfer models, have been included in the program. This paper discusses design parameters that influence edge heat transfer. Existing correlations for edge-of-glass two-dimensional heat transfer are presented along with an expanded array of correlations developed using an advanced finite-element computer code (DeSalvo and Gorman 1989). Current research is aimed at updating U-values for common frame cross sections.

## BACKGROUND

In multiple-glazed windows, glazing layers are separated by spacers. Typically, these spacers are metallic, although some existing designs use a welded glass edge or, in units that are not hermetically sealed, a wood spacer. The recent introduction of higher performing insulating glass has sparked an interest in alternative spacer materials and designs. Sealants, sash, and frame surround a typical insulated glass unit (Figure 1a).

The glass-sealant-spacer-sealant-glass contact shown in Figure 1a often acts as a thermal short circuit, degrading the thermal performance of the edge-of-glass area. Figure 1b, obtained through finite-element modeling, presents the direction and magnitude of heat transfer through the window edge of Figure 1a. Note the increased edge-of-glass heat transfer within 2 to 3 in. of the spacer. Heat transfer through this wood frame is primarily one-dimensional. (Most, but not all frames exhibit primarily one-dimensional heat transfer. These trends are also reflected in Figure 1c, which shows isotherms through the same cross section under ASHRAE standard winter conditions (0°F outside, 70°F inside, 15 mph wind, nighttime). At the center-of-glass areas, the isotherms are parallel and uniform through the gap. As one gets closer to the sightline, the resistance to heat transfer (and thus the temperature difference) across the IG unit decreases. Away from the spacer, isotherms through the frame are parallel.

Heat transfer through a complete window can thus be broken down into three components - one-dimensional heat transfer through the center-of-glass area, two-dimensional heat transfer through the edge-of-glass area, and one-dimensional heat transfer through the frame. The overall heat transfer (or U-value) of the window is the area-weighted U-value of each of these three areas.

ASHRAE (1989) has adopted such a procedure for its table of published U-values in the 1989 Handbook of Fundamentals. Center-of-glass U-values were determined using the WINDOW 3.1 program. Edge-of-glass U-values were calculated from correlations to spacer type and center-of-glass U-values based on experimental work (Peterson 1987) and finite-difference modeling (Carpenter 1988). For these correlations (Figure 2), the edge-of-glass area was defined as that area within 2.5 in. of the spacer (assumed flush with the unit's sightline). This is illustrated in Figure 3. Measured frame U-values based on the frame's projected area (Bulger 1987) are given in Table 1. More recent research (Klems and Reilly, 1989) indicates that these frame U-values for aluminum frames without a thermal break may be excessively high. Current research is aimed at defining a realistic set of typical frame types and accurately determining their U-values.

Table 1

Experimentally Measured Frame U-values

| Frame Type | Frame U-value (Btu/h-ft$^2$-°F) |
|---|---|
| Aluminum without thermal break | 1.9 |
| Aluminum with thermal break | 1.0 |
| Wood, with or without cladding | 0.4 |

## RESULTS

The ANSYS finite-element code (DeSalvo and Gorman 1989) was used to extend the data presented in Figure 2 and Table 1 to a wider range of spacer types and geometries. Spacer types examined included (abbreviations in parenthesis):

— aluminum, 0.016 in. thick, with a single seal (Al,s)
— aluminum, 0.016 in. thick, with a dual seal (Al,d)
— steel, 0.016 in. thick, with a single seal (S,s)
— steel, 0.016 in. thick, with a dual seal (S,d)
— welded glass edge in a dual glazed unit (Glass)
— butyl spacers with a 0.010 in. thick aluminum backing (Butyl)
— fiberglass spacers, 0.062 in. thick, with a dual seal (Fibergls)
— wood spacers (Wood)
— one wood and one dual-seal stainless spacer in triple units only (Wood/S,d)
— a hypothetical insulated, k=0.017 Btu/h-ft-°F, spacer (Insulated)

These spacers were chosen when this project started to represent both typical products as well as possible options for the future. Figures 4a and 4b present cross sections of windows using these spacer designs. These cross sections are intended to apply to any of the four sides of a window. This analysis was intended to be representative of heat transfer rates across all edge areas (top, bottom, both sides) of typical windows. The analysis performed does not include the effects of natural convection which would tend to increase heat transfer along the bottom of the window and decrease it along the top.

Material conductivities given in Table 2 were taken from standard references. In this study, the conductivity of the space inside the spacer was assumed to be that of the gas inside the IG unit. Note that when modeling two-dimensional heat transfer, where conductivities often differ by one or more orders of magnitude, small differences in conductivities are irrelevant. This is relevant when examining a hollow spacer filled with a gas and desiccant where the absolute conductivity of the desiccant/gas may be uncertain. For example, even with fiberglass spacers, increasing the conductivity of the material within the spacer by a factor of 5 only changes edge-of-glass U-values by 1-3%; this effect is even less with more conductive spacers.

Table 2

Approximate Material Conductivities

| Material | Conductivity (Btu/h-ft-°F) |
|---|---|
| Aluminum | 128.0 |
| Steel | 8.0 |
| Glass | 0.52 |
| Fiberglass | 0.17 |
| Sealant | 0.12 |
| Vinyl | 0.084 |
| Wood | 0.067 |
| Butyl | 0.060 |
| Insulated material | 0.017 |
| Air | 0.014 |
| Argon | 0.009 |
| Krypton | 0.005 |

A description of the double- and triple-insulated glass (IG) units examined, and their center-of-glass U-values (Btu/h-ft$^2$-°F) is given in Table 3. Note that there are two surfaces per layer and that layers and surfaces are numbered from the outside in.

Table 3

IG Units Modeled

| ID # | Layers | Low-E Coatings Surfaces | $\epsilon$ | Gap Width(s) and Fills | Center-of-Glass U-value (Btu/hr-ft$^2$°F) |
|---|---|---|---|---|---|
| 1 | 2 | | | 1/4" air | 0.59 |
| 2 | 2 | | | 1/2" air | 0.50 |
| 3 | 2 | 2 or 3 | 0.35 | 1/2" air | 0.40 |
| 4 | 2 | 2 or 3 | 0.10 | 1/2" air | 0.33 |
| 5 | 2 | 2 or 3 | 0.10 | 1/2" Ar | 0.27 |
| 6 | 3 | | | 1/4" air | 0.39 |
| 7 | 3 | | | 1/2" air | 0.32 |
| 8 | 3 | 2 or 3 & 4 or 5 | 0.10 | 1/2" Ar | 0.21 |
| 9 | 3 | 2 or 3 & 4 or 5 | 0.05 | 3/8" Kr | 0.10 |

Figures 5a and 5b give effective edge-of-glass U-values as a function of center-of-glass U-value and spacer type for double- and triple-glazed units where the top of the spacer is even with the unit's sightline. Typically, spacers are even with the sightline with the exception of the welded glass edge, which is approximately 1/2 in. below the sightline. (For this reason it is not included on this graph.)

The small deviations between the regression lines for the same spacer types of Figure 5c (which includes double- and triple-glazed units) are attributable to different edge geometries. For example, in double- and triple-glazed units with the same center-of-glass U-value, the use of a third layer of glass decreases the thermal short circuit. In double-glazed units with the same center-of-glass U-value but with different gap widths, edge-of-glass U-values will be slightly different also.

Edge geometry was the final parameter varied. By burying the spacer into the sash, the spacer's role as a thermal bridge between the two glass surfaces is reduced. Figure 6 shows edge-of-glass U-values vs. the sash height over the spacer for a low-e, argon-filled IG unit with different spacer types. Figures 7a and 7b show edge-of-glass U-values as a function of center-of-glass U-values for double- and triple-glazed units where the spacer is buried 0.5 in. into the sash. Comparing Figures 5a and 5b with 7a and 7b also shows the effects of burying the spacer deeper into the sash. Differing frame materials or the use of cladding, depending on design may affect edge-of-glass heat transfer; generally this is not the case.

Correlations for edge-of-glass heat transfer as a function of edge geometry, spacer type, and center-of-glass U-value were developed from the above data. These correlations are of the form:

$$U_e = A + B{*}U_c + C{*}U_c^2$$

where $U_e$ and $U_c$ are the edge-of-glass and center-of-glass U-values, respectively, in Btu/hr-ft$^2$°F and the regression constants A, B, and C are given in Table 4. The units of these regression coefficients A, B, and C are Btu/hr-ft$^2$°F, dimensionless, and hr-ft$^2$°F/Btu, respectively. Spacer depth refers to the distance between the top of the spacer and the units sightline.

Table 4

Regression Constants for Edge/Center of-Glass U-value Correlations

| Spacer Type | Spacer Depth (in.) | Double Glazing A | Double Glazing B | Double Glazing C | Triple Glazing A | Triple Glazing B | Triple Glazing C |
|---|---|---|---|---|---|---|---|
| Al,s | 0 | 0.223 | 0.842 | -0.155 | 0.234 | 0.740 | -0.034 |
| Al,s | 0.50 | 0.084 | 1.006 | -0.196 | 0.119 | 0.825 | 0.031 |
| Al,d | 0 | 0.191 | 0.915 | -0.213 | 0.209 | 0.788 | -0.074 |
| Al,d | 0.50 | 0.078 | 0.998 | -0.175 | 0.099 | 0.878 | -0.030 |
| S,s | 0 | 0.219 | 0.694 | 0.078 | 0.212 | 0.691 | 0.106 |
| S,s | 0.50 | 0.084 | 0.949 | -0.108 | 0.102 | 0.834 | 0.050 |
| S,d | 0 | 0.192 | 0.763 | 0.014 | 0.172 | 0.748 | 0.082 |
| S,d | 0.50 | 0.071 | 0.986 | -1.410 | 0.088 | 0.865 | 0.024 |
| Glass | 0.50 | 0.078 | 0.956 | -0.089 | | | |
| Butyl | 0 | 0.138 | 0.821 | -0.002 | 0.150 | 0.784 | 0.027 |
| Butyl | 0.50 | 0.051 | 1.025 | -0.154 | 0.049 | 1.065 | -0.280 |

Table 4 (Continued)

Regression Constants for Edge/Center of-Glass U-value Correlations

| Spacer Type | Spacer Depth (in.) | Double Glazing A | Double Glazing B | Double Glazing C | Triple Glazing A | Triple Glazing B | Triple Glazing C |
|---|---|---|---|---|---|---|---|
| Fibergls | 0 | 0.167 | 0.609 | 0.245 | 0.092 | 0.831 | 0.064 |
| Fibergls | 0.50 | 0.061 | 0.944 | -0.063 | 0.045 | 0.933 | 0.000 |
| Wood | 0 | 0.120 | 0.682 | 0.243 | 0.083 | 0.825 | 0.089 |
| Wood | 0.50 | 0.034 | 0.993 | -0.077 | 0.041 | 0.929 | 0.022 |
| Wood/S,d | 0 | | | | 0.115 | 0.839 | 0.008 |
| Wood/S,d | 0.50 | | | | 0.058 | 0.901 | 0.038 |
| Insulated | 0 | 0.071 | 0.806 | 0.124 | 0.053 | 0.859 | 0.076 |
| Insulated | 0.50 | 0.015 | 1.04 | -0.109 | 0.028 | 0.931 | 0.062 |

## DISCUSSION

As seen in Figures 5 through 7, edge-of-glass U-values can be significantly higher than corresponding center-of-glass U-values. These expressions for edge-of-glass heat transfer generally agree with and expand on the experimental and analytical data used by ASHRAE (Figure 8). Furthermore, the data contained in these figures provide for a much broader analysis of possible design options.

In addition to spacer and frame type, window size will also affect overall U-values. Table 5 presents center-of-glass and complete window U-values for three window configurations of Table 3 at two window product sizes (Figure 3). The spacer type and depth are also varied. Edge-of-glass correlations presented in Figures 5 through 7 and the fixed frame U-values from Table 1 are used.

Designers and engineers typically assume center-of-glass U-values are representative of total window U-values; as Table 5 shows, this often can be misleading. From this table we see that the use and development of non-metallic spacers and alternative frame materials and designs is absolutely necessary for windows with low center-of-glass U-values to maintain low window U-values. This is particularly true with smaller windows, where a high fraction of the window is in the edge-of-glass and frame areas. Note that to reduce edge heat transfer in an insulating window, either an insulated spacer or alternative edge geometry (but not both) are essential. Because the overall window U-values in this table are based on the fixed frame U-values of Table 1, the use of insulated spacers (which will lower frame U-values) will result in slightly lower U-values than those presented in Table 5.

Burying a spacer into the frame will result in lower edge-of-glass U-values and slightly lower frame U-values. Table 5 assumes this is done while maintaining the same projected frame area. However, increasing the projected frame area to achieve this result will lead to slightly different frame and overall U-values. Depending on design conditions, burying a spacer into a frame may increase glass fracture probabilities and/or decrease the overall vision area.

Table 5

Complete Window U-values for Aluminum frames (Al); Aluminum frames with a thermal break (Al w/break) and for Wood frames for typical Residential Sized (Res) and Commercial Sized (Com) Windows

| Spacer Type | Spacer Depth | Center-of-Glass U-value | Al. Res | Al. Com | Al w/break Res | Al w/break Com | Wood Res | Wood Com |
|---|---|---|---|---|---|---|---|---|
| Double Glazing | | | | | | | | |
| Al,s | 0 | 0.50 | 0.88 | 0.73 | 0.65 | 0.59 | 0.50 | 0.50 |
| S,d | 0 | 0.50 | 0.86 | 0.72 | 0.65 | 0.59 | 0.49 | 0.49 |
| Wood | 0 | 0.50 | - | - | - | - | 0.48 | 0.49 |
| Glass | 0.5 | 0.50 | 0.85 | 0.71 | 0.63 | 0.57 | 0.47 | 0.48 |
| Al,s | 0.5 | 0.50 | 0.85 | 0.72 | 0.64 | 0.68 | 0.48 | 0.49 |
| S,d | 0.5 | 0.50 | 0.85 | 0.71 | 0.63 | 0.68 | 0.48 | 0.49 |
| Wood | 0.5 | 0.50 | - | - | - | - | 0.47 | 0.48 |
| Double Glazing, low-e, argon filled | | | | | | | | |
| Al,s | 0 | 0.27 | 0.72 | 0.54 | 0.50 | 0.41 | 0.35 | 0.32 |
| S,d | 0 | 0.27 | 0.71 | 0.53 | 0.49 | 0.40 | 0.34 | 0.31 |
| Butyl | 0 | 0.27 | 0.70 | 0.53 | 0.48 | 0.39 | 0.33 | 0.31 |
| Glass | 0.5 | 0.27 | 0.69 | 0.52 | 0.46 | 0.39 | 0.31 | 0.30 |
| Al,s | 0.5 | 0.27 | 0.69 | 0.53 | 0.47 | 0.39 | 0.31 | 0.30 |
| S,d | 0.5 | 0.27 | 0.69 | 0.52 | 0.47 | 0.39 | 0.30 | 0.30 |
| Butyl | 0.5 | 0.27 | 0.69 | 0.52 | 0.47 | 0.39 | 0.30 | 0.30 |
| Triple Glazing, two low-e (e=0.05), krypton filled | | | | | | | | |
| Al,s | 0 | 0.10 | 0.61 | 0.40 | 0.38 | 0.27 | 0.24 | 0.19 |
| S,d | 0 | 0.10 | 0.59 | 0.39 | 0.37 | 0.26 | 0.23 | 0.18 |
| Fibergls | 0 | 0.10 | 0.57 | 0.38 | 0.35 | 0.24 | 0.21 | 0.17 |
| Insulated | 0 | 0.10 | 0.56 | 0.38 | 0.34 | 0.24 | 0.20 | 0.16 |
| Al,s | 0.5 | 0.10 | 0.58 | 0.39 | 0.35 | 0.25 | 0.22 | 0.17 |
| S,d | 0.5 | 0.10 | 0.57 | 0.38 | 0.35 | 0.25 | 0.21 | 0.17 |
| Fibergls | 0.5 | 0.10 | 0.56 | 0.38 | 0.34 | 0.24 | 0.20 | 0.16 |
| Insulated | 0.5 | 0.10 | 0.56 | 0.37 | 0.33 | 0.24 | 0.20 | 0.16 |

## CONCLUSIONS

With the manufacture of insulating glass units with lower U-values, it is important that the relationship between overall window U-values and commonly calculated center-of-glass U-values be well understood. Such an understanding will lead to meaningful comparisons between different window products and a realistic assessment of the need to develop new frame and edge materials. Finite-element modeling performed as part of this study verified the approach recently proposed by ASHRAE of calculating overall window U-values as the area-weighted average of the three components of the window, the center-of-glass, the edge-of-glass (that area within 2.5 in. of the sightline), and the frame area.

Rigorous center-of-glass U-value calculation procedures exist; correlations presented in this paper expand on previous data and provide for an accurate assessment of edge-of-glass heat transfer by relating edge-of-glass U-values to center-of-glass U-values and spacer materials. Experimental frame U-values for a few generic frame types are presented. Developing a more extensive catalogue of frame U-values is the next step in calculating accurate window system U-values. The correlations and values presented here agree well with the limited experimental data available; however more extensive component and total window heat transfer measurements are necessary to validate this study. With the use of less conductive spacer and frame materials, convective effects at the top and bottom of an insulated glass unit and along the interior frame/sash-IG unit interface may become more important. These topics are the subjects of current research.

## REFERENCES

Lawrence Berkeley Laboratory, 1988. Windows and Daylighting Group. WINDOW 3.1 users and reference guide. Berkeley, CA.

Arasteh, D., Reilly, S., and Rubin, M., 1989. "A versatile procedure for calculating heat transfer through windows." ASHRAE Transactions, Vol. 95, Part 2.

ASHRAE, 1989. ASHRAE Handbook of Fundamentals. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Bulger, M. 1987. Letter to ASHRAE TC4.5 subcommittee on window U-values, November 24.

Carpenter, S. 1988. Letter to ASHRAE TC4.5 subcommittee on window U-values, January 26.

DeSalvo, G.J., and Gorman, R.W. 1989. ANSYS engineering analysis system user's manual, version 4.4. Houston, PA: Swanson Analysis Systems.

Klems, J.H., and Reilly, S. 1989. "Window Nighttime U-values: A Comparison between Computer Calculations and MoWiTT Measurements-DRAFT." Windows and Daylighting Group, Lawrence Berkeley Laboratory, Berkeley, CA.

Peterson, C.O., Jr., 1987. "How is low-E performance criteria determined?" Glass Digest, January 15.

## ACKNOWLEDGEMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Additional support was provided by the Bonneville Power Administration under contract No. DE-AI79-86BP63401 and by a gift from the Wisconsin Power and Light Company. This work would not have been possible without the efforts of John Wolfe whose aid in ANSYS modeling was invaluable. The author wishes to thank Bill Edwards of the Mechanical Engineering Department at Lawrence Berkeley Laboratory for his continual assistance throughout this project.

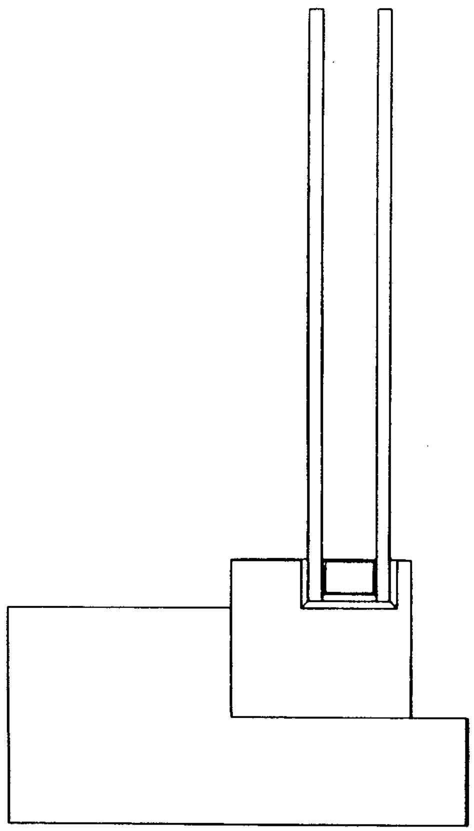


Figure 1a. Cross section of window edge and frame. Shown are two glazing layers separated by a desiccant filled metal spacer sealed inside a wood sash which rests on a wood frame.

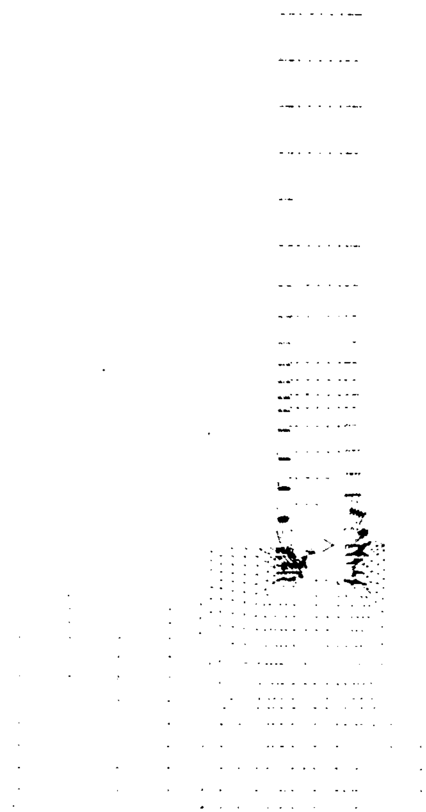
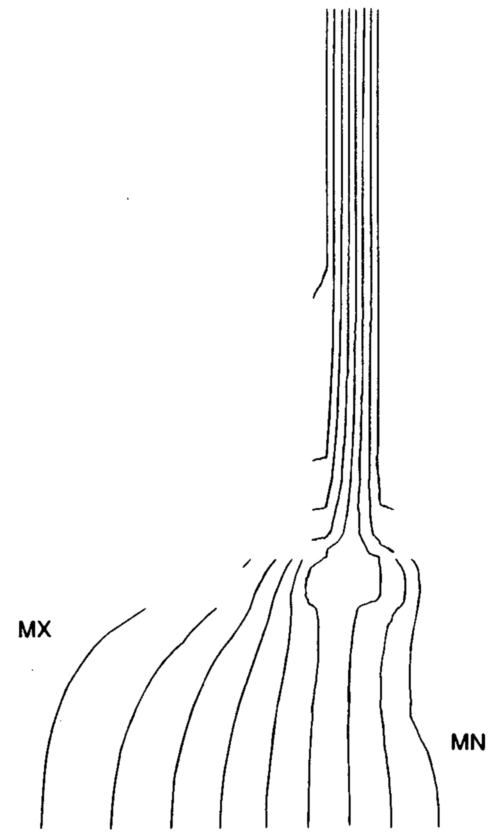


Figure 1b. Vector plot of two-dimensional heat transfer through the window cross section of Figure 1a. The warm interior is assumed on the left, the cold exterior on the right. The size of the vector denotes the magnitude of heat transfer; the arrow denotes the direction. Note that all glass two-dimensional heat transfer occurs within the bottom 2.5 in. of the glass panes modeled. Small vectors may appear as dots.




XBL 901-6201

Figure 1c. Isotherms through the (low-E, gas-filled) window cross section of Figure 1a under ASHRAE standard winter conditions (0 °F outside, 70 °F inside, nighttime; 15 mph wind speed). Contours begin at 7 °F and proceed in 7 °F increments to 63 °F.

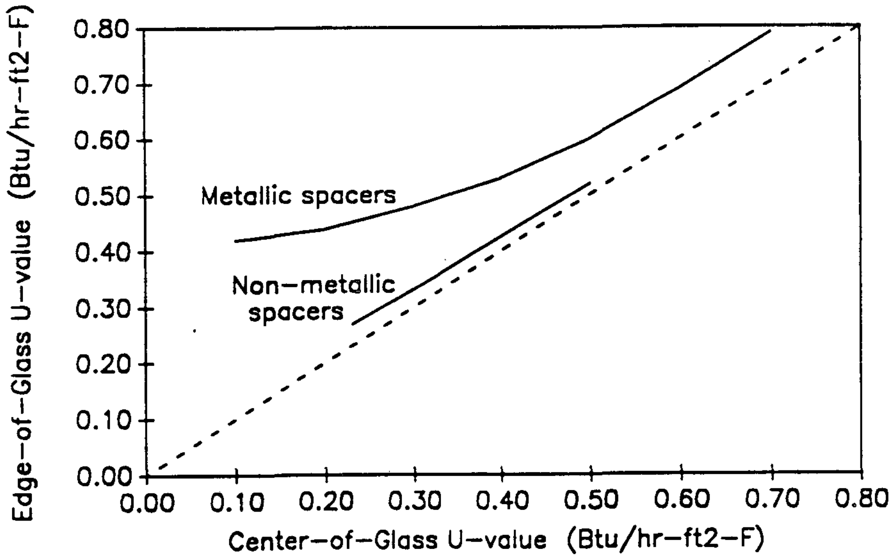



Figure 2. Edge-of-glass U-values as a function of center-of-glass U-values for metallic and non-metallic (i.e. glass, wood, fiberglas) spacers, as adopted by ASHRAE for the 1989 Handbook of Fundamentals.

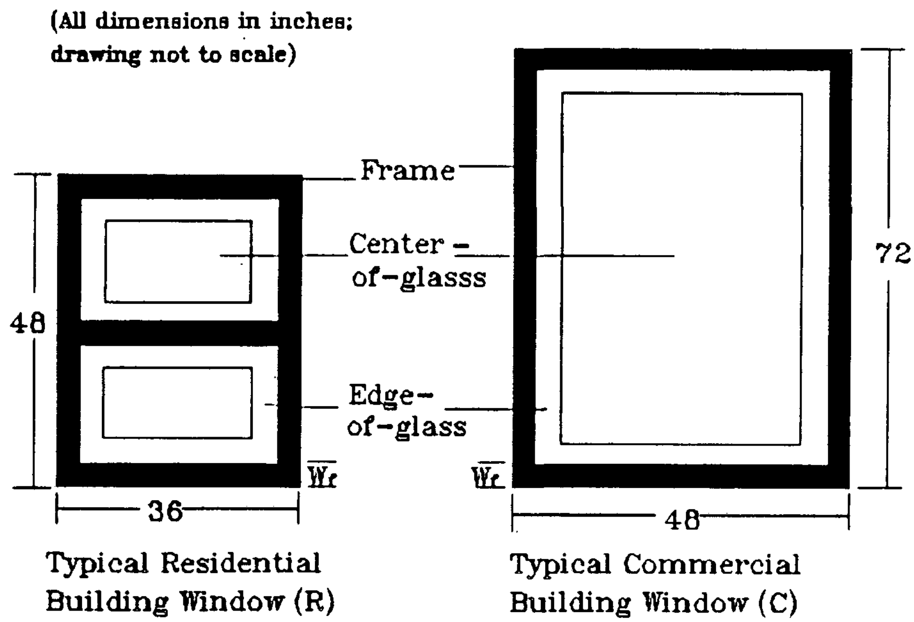



Figure 3. Two typical product sizes (R=residential, C=commercial) as adopted by ASHRAE for the 1989 Handbook of Fundamentals. The projected width of frame ($W_f$) varies with window type (operable aluminum - 2.25"; operable wood or PVC - 2.75"; nonoperable - 1.50").

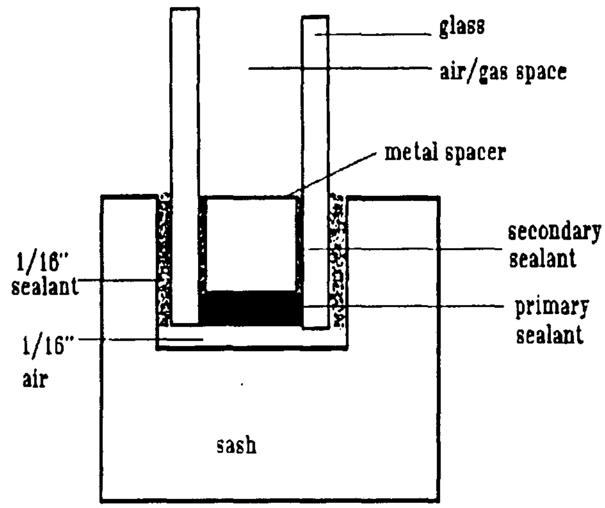



Figure 4a. Cross section of metal (1/64" thick) and fiberglass (1/16" thick) spacer systems modeled. Wood and insulated spacers are modeled by replacing the spacer and primary sealant shown in the figure with either wood or the insulating material. Butyl spacers are modeled by replacing the spacer shown with solid butyl with a metal backing.

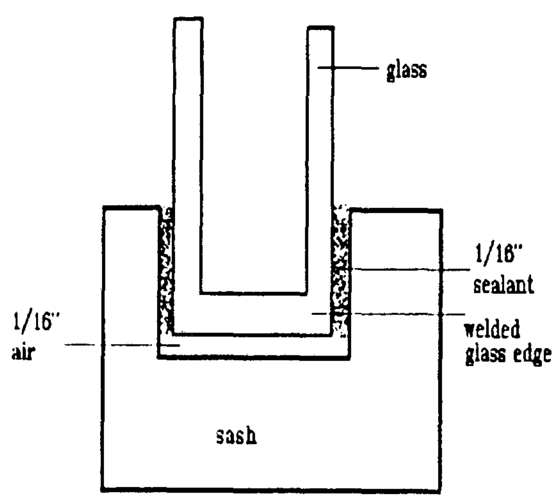



Figure 4b. Cross section of welded glass edge modeled

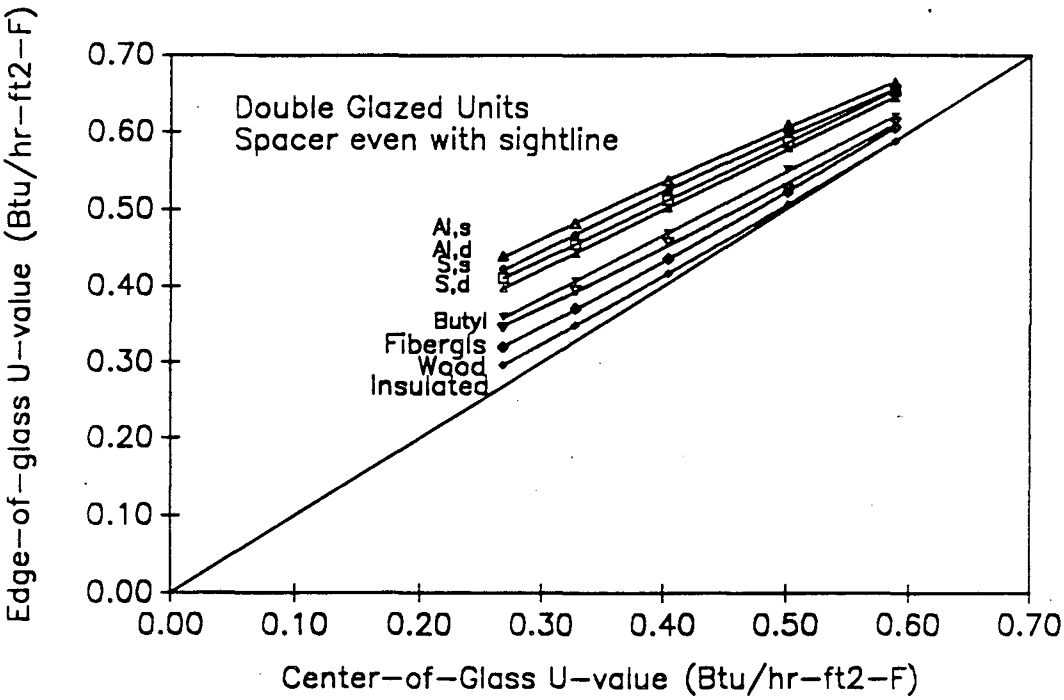



Figure 5a. Edge-of-glass U-values as a function of center-of-glass U-values and spacer type for double-glazed units where the spacer is even with the sightline

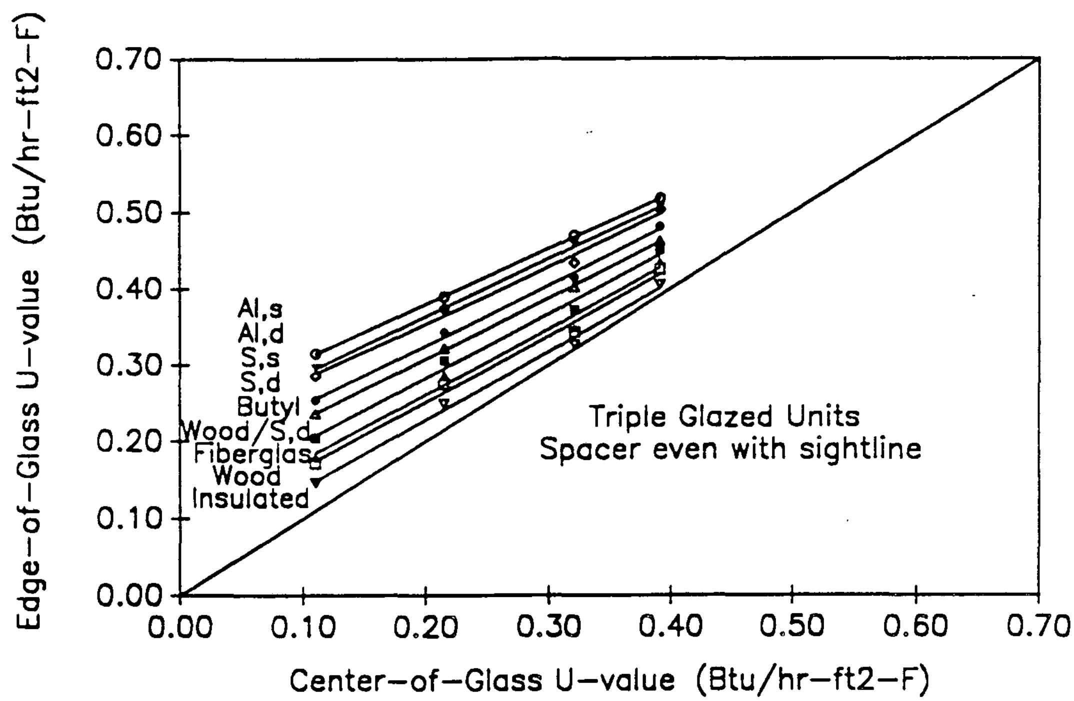



Figure 5b. Edge-of-glass U-values as a function of center-of-glass U-values and spacer type for triple-glazed units where the spacer is even with the sightline

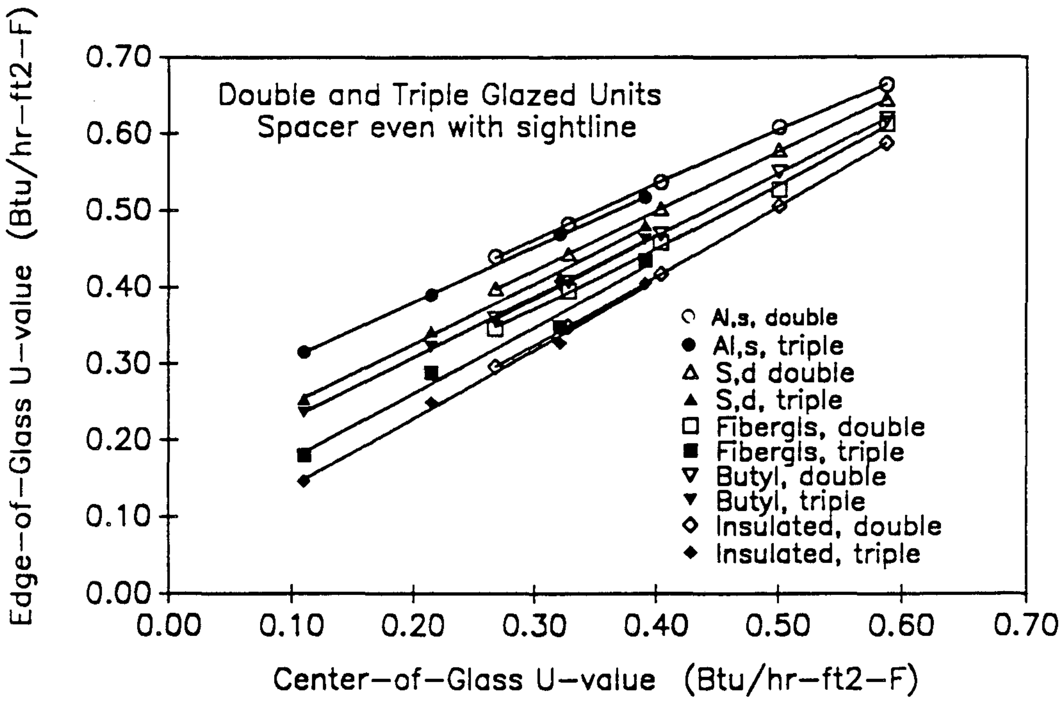



Figure 5c. Edge-of-glass U-values as a function of center-of-glass U-values and spacer type for double- and triple- glazed units where the spacer is even with the sightline

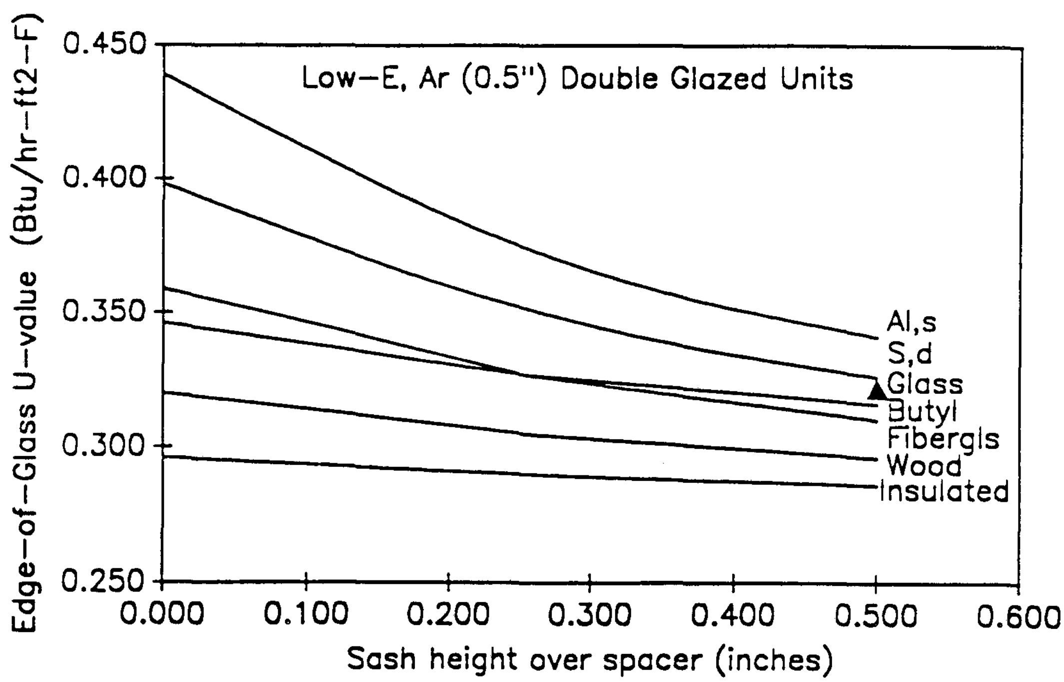



Figure 6. Edge-of-glass U-values as a function of center-of-glass U-values for a low-E, argon-filled IG unit as a function of sash height over the spacer and spacer type; only one point is given for the welded glass edge design because this is the typical design used and feasible

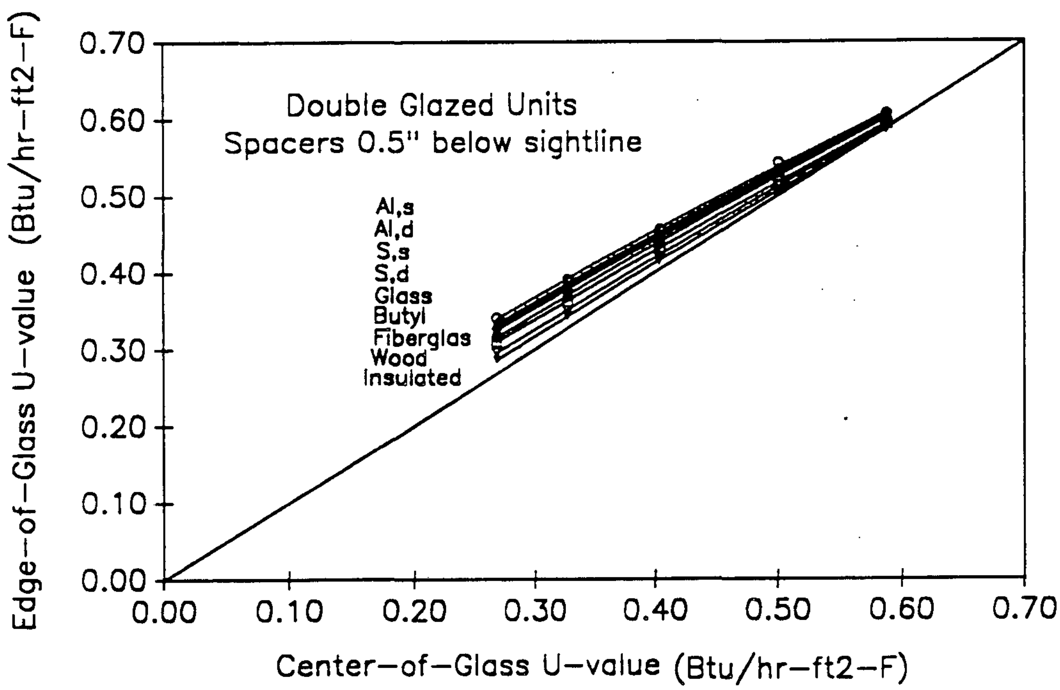



Figure 7a. Edge-of-glass U-values as a function of center-of-glass U-values and spacer type for double-glazed units where the spacer is 0.5 in. below the sightline

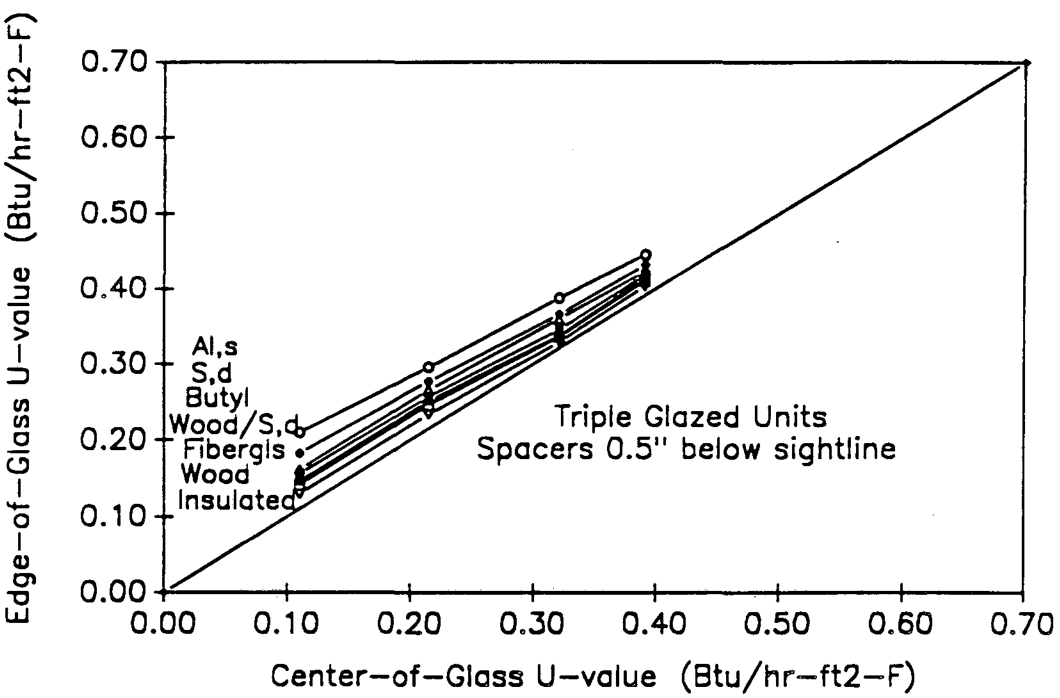



Figure 7b. Edge-of-glass U-values as a function of center-of-glass U-values and spacer type for triple-glazed units where the spacer is 0.5 in. below the sightline

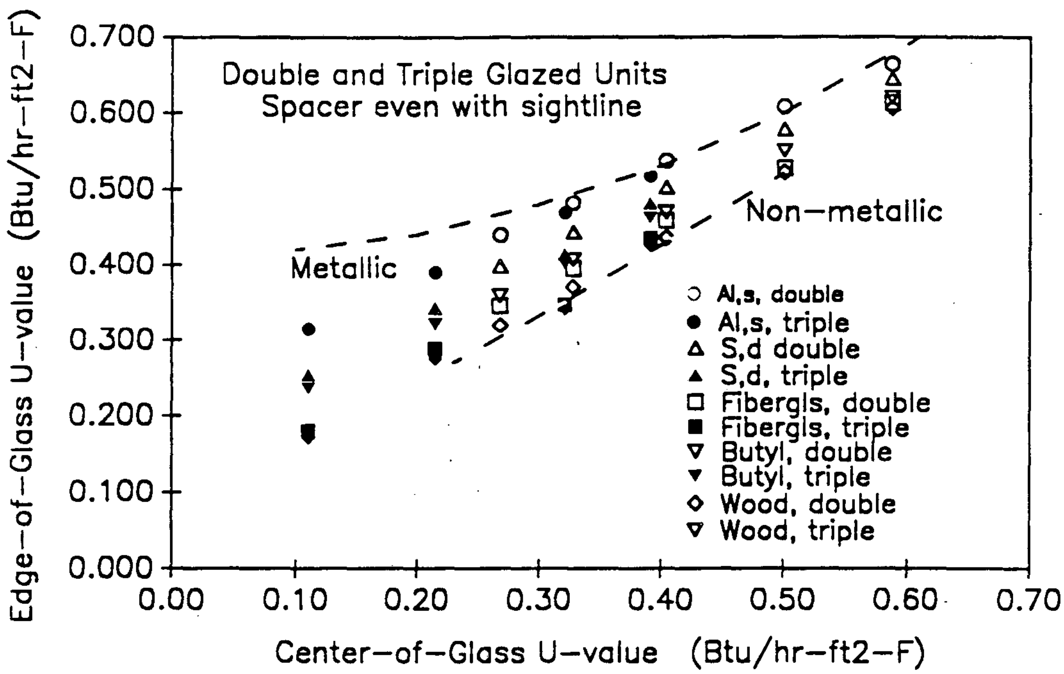



Figure 8. Edge-of-glass U-values as a function of center-of-glass U-values for double- and triple-glazed units. Data adopted by ASHRAE for metallic and non-metallic spacers (dashed lines) are shown compared to data from this study for specific spacer types

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720