A Superwindow Field Demonstration Program in Northwest Montana

D. Arasteh
Member **ASHRAE**

S. Selkowitz
Member **ASHRAE**

ABSTRACT

Of all building envelope elements, windows always have had the highest heat loss rates. However, recent advances in window technologies such as low-emissivity (low-E) coatings and low-conductivity gas fillings have begun to change the status of windows in the building energy equation, raising the average R-value (resistance to heat flow) from 2 to 4 h-ft^2-°F/Btu. Building on this trend and using a novel combination of low-E coatings, gas-fills, and three glazing layers, the authors developed a design concept for R-6 to R-10 "super" windows. Three major window manufacturers produced prototype superwindows based on this design for testing and demonstration in three utility-sponsored and -monitored energy-conserving homes in northwestern Montana. This paper discusses the design and tested performance of these three windows and identifies areas requiring further research if these window concepts are to be successfully developed for mass markets.

INTRODUCTION

Residential windows are generally expected to have high heat loss rates. Approximately 3% of U.S. energy consumption, or the equivalent of more than 1 million barrels of oil per day, is used to offset the heat lost through poorly insulated windows. During the energy crisis of the mid-1970s, double glazing replaced single glass as the standard residential glazing system throughout most of the United States. Today, low-emissivity (low-E) coatings and low-conductivity gas fills are being added to double-glazed windows to reduce radiative and conductive heat transfer. These technologies can upgrade the performance of a double-glazed window to an R-value (resistance to heat transfer) of 4 h-ft^2-°F/Btu.

However, windows with R-values higher than 4 can provide significant advantages, especially in heating-dominated climates. Simulation studies (Sullivan and Selkowitz, 1985) have shown that even north-facing R6 to R10 windows with shading coefficients greater than 0.5 (i.e., at least half the solar heat gain of clear 1/8in. [3mm] glass) will provide more useful solar heat gain than conductive losses in a typical residence in a northern climate, thereby outperforming any insulated wall. Other advantages of high-R or superwindows are higher winter interior glass surface temperatures, resulting in more comfortable spaces and reduced occurrences of condensation, and the design freedom to use more and larger windows on all orientations.

Recent research has focused on the development of superwindows using two low-emissivity coatings and low-conductivity gas fills. One such design, employing a krypton-based gas fill and a non-structural, lightweight center glazing layer, is the subject of a patent application. Low-E coatings facing each gap reduce radiative heat transfer between each pair of glazing layers; low-conductivity gas fills can then reduce con-

Dariush Arasteh is a Staff Scientist in the Windows and Daylighting Group, and Stephen Selkowitz is Program Leader of the Windows and Lighting Program in the Applied Science Division of Lawrence Berkeley Laboratory, Berkeley, California 94720.

ductive heat transfer. Krypton's low thermal conductivity permits an effective design with gap widths between 1/4in. and 3/8in. This limits the overall width of the insulated glass (IG) unit to a size that is compatible with conventional sash and frame systems, an important consideration for window manufacturers. The theory behind this specific design and results of thermal and structural testing and analysis is described in Arasteh et al. (1989). To summarize, the work presented proved that:

- windows with center-of-glass R-values between 6 and 10 can be manufactured using the proper combination of low-emissivity coatings and low-conductivity gas-fills;

- two-dimensional thermal bridging at the window's edge, where high-R glazing units meet poorly insulating edge conditions, will decrease the window's total performance;

- such units would not be more prone to breakage than conventional units;

- existing gas-filling processes should be improved for this application (an improved gas-filling system is the subject of a current patent application);

- the potential for large quantities of cheaper krypton will depend on a secure long-term demand; and

- the use of proper sealants will create an edge essentially impervious to gas flow.

A cross section of this design is shown in Figure 1.

Many of the concepts behind this specific design can be applied to commercially available windows to produce superwindows that are relatively simple modifications of existing products. The focus of our work during this phase of the project was to work with industry to manufacture, test, and monitor prototype superwindows in order to accelerate market availability. To prove to researchers, consumers, and government and utility representatives that superwindows are feasible and to demonstrate their advantages, prototypes were manufactured and installed in three energy-efficient demonstration houses built as part of the local utility's energy conservation research efforts in northwestern Montana in 1988. Monitoring equipment was installed in March 1989 to study the thermal performance of these windows through the spring of 1990. On-site infrared video thermography and lab testing added to our data base on the performance of these windows. The intent of the detailed thermal testing was not to judge one manufacturer's products against another but to verify expected superwindow performance, verify the effectiveness of new components and designs, and compare field performance with lab tests and calculated performance. This paper discusses the results of this demonstration project to date.

DESIGN ANALYSIS WITH SIMULATION PROGRAMS

Thermal testing of an initial prototype superwindow in February 1987 (Arasteh et al. 1989) confirmed our predictions of center-of-glass U-values but also pointed out how a window's overall performance can be degraded by both the significant fractional areas taken up by high-conductivity edges and frames and thermal bridging of insulating spaces by these high-conductivity elements. Finite element modeling shows the magnitude and direction of heat transfer across different regions of a typical superwindow cross-section (Figures 2a and 2b). In the glass area away from the spacer and in the frame, the vectors indicate one-dimensional heat transfer from a warm interior to a colder exterior. The size of the vectors in the frame are larger, indicating greater heat transfer. In the glass area near the spacers the vectors have a downward component, showing heat drawn from the bottom edge of the glass, down to and across the spacer to the exterior.

The model and computer code, ANSYS (DeSalvo and Gorman 1987), used to generate the results for Figure 2 were also used to study the performance of sash design and alternative materials that could reduce edge-of-glass heat transfer. While prototype insulated spacers do exist, not enough was known about their long-term structural performance and moisture and gas permeabilities at the time of construction for the prototype manufacturers to use them with confidence. A more viable alternative for this project was to recess the spacers into the sash or, conversely, to build the sash profile up around the spacer.

The importance of frame and edge effects is illustrated in Table 1, which shows center-of-glass, edge-of-glass, and total window U-values for a typical double-glazed window and a typical superwindow. Table 1 presents data for both a typical commercially available low-E window and a superwindow. While edge effects are significant for the low-E double-glazed case, they become much greater for the superwindow case. Note that edge-of-glass U-values are defined here in accordance with the methodology presented in the 1989 ASHRAE Handbook of Fundamentals (ASHRAE 1989) and are representative of the glass area within 2.5 in. of the window's sightline. The total window U-values are representative of a typical residential window measuring 4 ft by 3 ft with a center mullion (ASHRAE 1989).

Results of this finite element modeling work were presented to the manufacturers who were to build the prototype superwindows. Using this information, some of the designs of the window products selected for use were modified. These changes are described in the following section.

HIGH-R WINDOW PROTOTYPES

Three different prototypes were developed as part of this project. In each case, a manufacturer's typical low-E product was upgraded to a triple layer design incorporating two low-E coatings and a low-conductivity gas fill. Improvements were also made to the sash/frame to reduce edge-of-glass and frame heat transfer. These designs are described below:

Type 1: The typical product manufactured by this company is a non-sealed double glazed product with one glazing layer fixed in a wood (with aluminum cladding) sash and frame and an interior clip-on glazing with a pyrolitic low-E (e=0.15-0.22) coating facing the air space. Improvements to this system comprised replacing the exterior glazing layer with a low-E insulated glass unit filled with krypton/argon gas (80% to 90% Kr/20% to 10% Ar). The gap width of this unit is 5/16 in., close to the optimum width for krypton and the maximum allowable in this sash design. The interior low-e storm panel was retained; because this is a removable panel the space cannot be gas-filled. The use of a wood stop instead of a conventional metal spacer between the IG unit and the interior storm panel significantly reduced edge-of-glass heat transfer. A schematic of this design in shown in Figure 3a.

Type 2: This manufacturer's typical product, like many others, is a low-E IG unit in a wood sash/frame. Typically, the IG unit's overall width is about 0.75 in. although the sash profiles can accommodate slightly wider configurations. To improve on this design, the low-E IG unit was replaced with a triple-glazed unit 1.0 in. wide. This improved IG unit had low-e coatings on the #2 and #5 surfaces (e=0.08) and the 5/16 in.gas gaps were filled with 90% krypton/10% argon. To reduce edge-of-glass heat transfer, vinyl strips were added to the vinyl cladding, in effect submerging the metal spacers 1/2in. below the sightline. Figure 3b is a schematic of this design.

Type 3: The typical product manufactured by this company and its associates is a double-glazed window with a thin, low-E coated plastic film stretched between the glazing layers. Because this design already has two gaps, usually near the optimum width (3/8in. in this case), all that was needed was the addition of a second low-e surface and krypton-based gas fill. (The gas-filling technique used here results in an 80% krypton/20% air gas-fill.) The second low-e coating was created by coating the second surface of the plastic film; the same effect could be achieved by utilizing one light of low-E glass. Typically, IG units manufactured by this process are used in all frame types. For this project, however, an insulating frame manufactured from a fiberglass shell and filled with loose fiberglass insulation was used. The conductivity of this frame system is lower than that of a wood frame. Although this techniques was not used in these windows, the IG units can be imbedded in the sash to reduce edge-of-glass heat transfer. Figure 3c is a schematic of this design.

RCDP FUTURE HOMES DEMONSTRATION PROJECT

Bonneville Power Administration (BPA), the Pacific Northwest's electrical utility company has, in recent years, actively encouraged construction of energy-efficient electrically heated homes. BPA's Residential Construction Demonstration Project (RCDP), begun in 1986, has supported the construction and monitoring of approximately 400 model homes built to the Model Conservation Standards (MCS) of the Northwest Power Planning Council. These standards incorporate state-of-the-art energy-conserving technologies and construction practices. In 1987, BPA added a "Future Houses" demonstration program to the RCDP program to develop and test innovative- energy-efficient features. In 1988 and 1989, five of these future houses were built and equipped with monitoring systems and three were selected to incorporate the superwindows developed as part of this project.

While the direct impact of these 400 homes and 50+ superwindows on the Northwest's energy usage is small, these programs are effective in heightening public awareness of the energy savings and more comfortable living spaces that are possible, in evaluating the effectiveness of new technologies and techniques, and in teaching home-builders and their crews energy-conserving construction practices.

RESULTS OF WINDOW TESTING

As part of this project, the performance of the prototype superwindows was evaluated using all available analysis tools, laboratory testing procedures, and field testing procedures. Calculational procedures and laboratory tests are helpful in understanding glazing heat transfer processes, in serving as references, and in developing new products but windows should also be tested under realistic environmental conditions to validate overall performance and to pinpoint areas of needed research.

The original superwindow design that was modified by the three manufacturers was developed using the WINDOW 3.1 program (Lawrence Berkeley Laboratory 1988; Arasteh et al. 1987). Finite element modeling using the ANSYS program allowed the authors to more accurately understand two-dimensional heat transfer effects in these window designs and to predict total window U-values. Table 2 reports WINDOW 3.1/ANSYS results for the three window types under standard ASHRAE winter conditions of 70 °F indoors; nighttime, 0 °F outdoors, and a 15 mph wind (ASHRAE 1989).

These windows were also tested in LBL's Mobile Window Thermal Test (MoWiTT) Facility in order to measure actual field performance. This facility can accurately measure heat flows through windows exposed to outdoor conditions (Klems 1985; Klems and Keller 1986). This facility consists of two room-size chambers and a control room. Field tests for these three superwindows under winter conditions in Reno, NV are also reported in Table 2. Each window was tested for approximately one week. Nighttime U-values were corrected for ASHRAE standard winter conditions and for possible infiltration into the facility's chambers and are reported in Table 2. Heat fluxes measured are a function of both the conductance (U-value) of the sample and the temperature difference across the sample. Because the conductivities of these superwindows are quite low and because temperature differences are dependent on weather conditions, sample heat flows sometimes dropped into the 10 to 15 W range under milder winter conditions. (This was especially true during tests of types 1 and 2.) As a result, the experimental error for the U-values is about ± 20% (Klems, to be published). Nevertheless, there is general agreement between measured performance and calculated results.

Laboratory testing is commonly used for regulatory agency certification of windows and by manufacturers to test design modifications. Table 2 reports some superwindow laboratory performance data.

For Type 1, the lab tested overall window U-value of 0.27 is slightly higher than the calculated value and within the range of MoWitt measured field performance. Operators at this laboratory reported that their tested U-values are usually slightly higher than similar values from other laboratories. The Type 2 window was tested at three different laboratories with different results, all within the range of calculated and MoWitt tests. Finally, while there were no lab tests made on the Type 3 window, calculated and MoWiTT field measurements agree well.

During the spring of 1989, when construction of some of the RCDP homes was completed and the homes were occupied, an infrared video imaging system was used to study the actual performance of these windows. This system produced images showing interior and exterior wall/window surface temperatures. These images were post-processed to produce useful data. For example, average center-of-glass area temperatures, as shown in Table 3, show good agreement with WINDOW 3.1 predicted temperatures under the same environmental conditions. The proper calculation of surface temperatures indicates proper heat transfer calculation rates. Furthermore, window surface temperatures are directly related to occupant comfort. Under cold winter conditions, superwindows will have significantly higher interior surface temperatures and produce less draught than conventional windows. Occupants of both of these houses, who had spent one winter with both the low-E control windows and superwindows, emphasized that they felt much more comfortable next to the superwindows.

Temperature sensors and heat flux meters were installed on both control windows and superwindows in the three RCDP homes in March and April of 1989. These data will be collected and stored every hour for one year. An analysis of these data in 1990 will give us further insight into these windows' performance.

FUTURE DIRECTIONS AND CONCLUSIONS

The commercialization and widespread use of superwindows represents an opportunity to reduce U.S. oil consumption by almost one million barrels of oil per day (American Council for an Energy-Efficient Economy, 1986). With this energy savings comes an architectural freedom to use larger window areas on any orientation of a building. Superwindows will almost always be free of condensation and frost and much more comfortable for the occupant. Our research efforts to date in this field have included:

- developing a prototype design for a superwindow utilizing commercially available components,
- verifying our initial performance calculations with laboratory and field measurements,
- identifying manufacturing issues and working with industry to solve these engineering problems, and
- involving major window manufacturers in the production of prototype high-R windows for use in utility demonstration projects. Manufacturers which supplied prototypes are now continuing work in this field to determine whether they will offer such products to the consumer.

Further efforts by researchers, industry, utilities, and representatives of window users are necessary before large-scale commercialization of superwindows can be successful.

To achieve R6 to R10 for the complete window, edge and frame heat loss around today's superwindows must be reduced. The use of alternative frame and edge materials as well as alternative energy-conscious designs using both conventional and new materials is an area of current research.

While different methods of testing window performance (calculations, laboratory tests, field tests, and infrared thermography) all show that superwindows perform significantly better than conventional double-glazed low-E windows, determination of a window's absolute performance depends on the testing procedure and individual test set-up. This issue is exacerbated in the case of superwindows since heat flows measured through them are significantly less than conventional window products, making the differences between designs and R-values that much more difficult to determine.

Because of the current supply and demand for krypton, supplies for large-scale window use at reasonable prices are limited. Projects such as this one, which demonstrate the effectiveness of krypton-filled units, are intended to help connect window manufacturers with specialty gas companies in order to solve this problem.

Windows have long been neglected by much of the building industry and the public as having the potential to be better insulators. Current building codes and many design tools intended to help architects, engineers, builders, and homeowners decide on the proper window type are often out of date and do not reflect the potential of today's state-of-the-art products, let alone tomorrow's superwindows. Utilities and public agencies must therefore sponsor professional education programs and support development of accurate information for updating building codes.

REFERENCES

Amercian Council for An Energy-Efficient Economy. 1986. "Federal R&D on energy efficiency: A $50 billion contribution to the U.S. economy." Washington, D.C.

Arasteh, D.; Selkowitz, S.; and Wolfe, J. 1989. "The design and testing of a highly insulating glazing system for use with conventional window systems." *Journal of Solar Energy Engineering, Transactions of the ASME,* Vol 111. February.

Arasteh, D. 1989. "An analysis of frame and edge heat transfer in residential windows." Submitted to the *Thermal Performance of the Exterior Envelopes of Buildings IV.*

Arasteh, D.; Hartmann, J.; and Rubin, M. 1987. "Experimental verification of a model of heat transfer through windows." *ASHRAE Transactions,* Vol. 93, Part. 1, pp. 1425-1431.

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

DeSalvo, G. J., and Gorman, R. W. 1987. ANSYS engineering analysis system user's manual, version 4.3. Houston, PA: Swanson Analysis Systems.

Klems, J. H. 1985. "Toward accurate prediction of comparative fenestration performance," Lawrence Berkeley Laboratory Report 19550. April.

Klems, J. H., and Keller, H. 1986. "Thermal performance measurements of sealed insulating glass units with low-E coatings using the MoWiTT field test facility." *ASHRAE Transactions,* Vol. 93, Part 1.

Klems, J. H., to be published. "Winter Performance of North-Facing Superwindows." Lawrence Berkeley Laboratory, Berkeley, CA.

Lawrence Berkeley Laboratory, 1988. "WINDOW 3.1: A PC program for analyzing window thermal performance. LBL-25686, October.

Sullivan, R., and Selkowitz, S. 1985. "Window performance analysis in a single-family residence," in: *Proceedings of the ASHRAE/DOE/BTECC Thermal Performance of the Exterior Envelopes of Buildings III Conference,* December, pp. 858-871.

ACKNOWLEDGMENTS

The authors wish to thank Guy Kelley, Dennis DiBartolomeo, Joe Klems, John Wolfe, and Bill Edwards at LBL; Joe Flores of the Bonneville Power Administration; Johnny Douglas and Mike Lubliner of the Washington State Energy Office; Jim Maunder of the State of Montana Division of Natural Resources and Conservation; Dave Eyes and Brad Hesse of W.S. Flemming & Associates; Steve Logan, John Mohar, and Brendt Nelson for their contributions to this project. The materials and time donated by Air Products, Andersen Corporation, Cardinal IG, Interpane Coatings, Owens-Corning Fiberglas, Rolscreen Company, Southwall Corporation, and the Semling-Menke Company were essential to the completion of this project.

This work was supported by the Residential Technology Section of the Bonneville Power Administration of the U.S. Department of Energy under Contract No. DE-AI79-86BP63401; 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-ACO3-76SF00098; and by a gift from the Wisconsin Power and Light Company, Madison, WI.

Table 1: Center-of-Glass and Edge-of-Glass U-values
for a Low-E Double-Glazed Window and a Superwindow
U-values in Btu/h-ft^2-°F (W/m^2-°C)

	Al Spacer[1]			
	even with sightline	1/2" (12.7 mm) below sightline	even with sightline	1/2" (12.7 mm) below sightline
Low-E Double Glazing				
- center-of-glass	0.33 (1.87)	0.33 (1.87)	0.33 (1.87)	0.33 (1.97)
- edge-of-glass	0.47 (2.67)	0.38 (2.16)	0.35 (1.99)	0.34 (1.93)
- total window[2]	0.39 (2.21)	0.36 (2.04)	0.36 (2.04)	0.35 (1.99)
Superwindow				
- center-of-glass	0.10 (0.59)	0.10 (0.59)	0.10 (0.59)	0.10 (0.59)
- edge-of-glass	0.30 (1.68)	0.20 (1.11)	0.15 (0.83)	0.13 (0.74)
- total window[2]	0.21 (1.19)	0.19 (1.08)	0.17 (0.97)	0.17 (0.97)

[1] Aluminum spacer, dual sealant.
[2] ASHRAE typical Residential Window, 3 ft x 4 ft with center mullion. Wood frame with a U-value of 0.4 Btu/h-ft^2-F (2.27 W/m^2-C) for double-glazed low-E windows and 0.3 Btu/h-ft^2-F (1.70 W/m^2-C) for the superwindows.

Table 2: Calculated and Measured Superwindow Center-of-Glass (COG)
and Total Window (Total) U-values

	U-values in Btu/h-ft^2-°F (W/m^2-C)					
	Type 1		Type 2		Type 3[1]	
	COG	Total	COG	Total	COG	Total
WINDOW 3.1/ ANSYS[2]	0.17 (0.97	0.26 (1.47)	0.12 (0.68)	0.17 (0.97)	0.15 (0.85)	0.22 (1.25)
Laboratory						
Lab 1 (AAMA)		0.27 (1.51)				
Lab 2 (AAMA)				0.15 (0.85)		
Lab 3 (AAMA)				0.22 (1.25)		
Lab 4 (ASTM)				0.18 (1.02)		
MoWiTT[2]	- -	0.25 ± 0.04 (1.60 ± 0.21)	- -	0.22 ± 0.04 (1.26 ± 0.20)	- -	0.23 ± 0.03 (1.28 ± 0.18)

[1] Type 3 Window used for WINDOW 3.1/ANSYS calculations and MoWiTT tests uses a wood frame that extends 0.5in over the spacer's sight-line.
[2] Window sizes are 3 ft x 4 ft with wood frames of varying dimensions.

Table 3: Measured (infrared video camera) vs. WINDOW 3.1 (W3) Center-of-Glass Surface Temperatures for Superwindows and Control (Low-E Double-Glazed) Windows

	Temperatures[1] in °F (°C)						
	T_i	T_{g-i}		T_{g-o}		T_o	Comments
	IR	IR	W3	IR	W3	IR	
Double Glazing - Type 1	68.7 (20.5)	63.5 (17.5)	64.4 (18.0)	37.0 (2.8)	36.7 (2.6)	35.6 (2.0)	10-15 mph wind (5-7 m/s wind)
Superwindow - Type 1	68.7 (20.5)	59.5 (15.3)	60.4 (15.8)	38.3 (3.5)	37.6 (3.1)	35.6 (2.0)	10-15 mph wind (5-7 m/s wind)
Double Glazing - Type 2	72.3 (22.4)	68.9 (20.5)	68.9 (20.5)	37.9 (3.3)	37.6 (3.1)	35.6 (2.0)	no wind (no wind)
Superwindow - Type 2	72.3 (22.4)	65.1 (18.4)	64.6 (18.1)	40.1 (4.5)	- (-)	35.6 (2.0)	no wind (no wind)

[1] T_i - interior air temperature; T_{g-i} - interior glass surface temperature; T_{g-o} - outdoor glass surface temperature; T_o - exterior air temperature

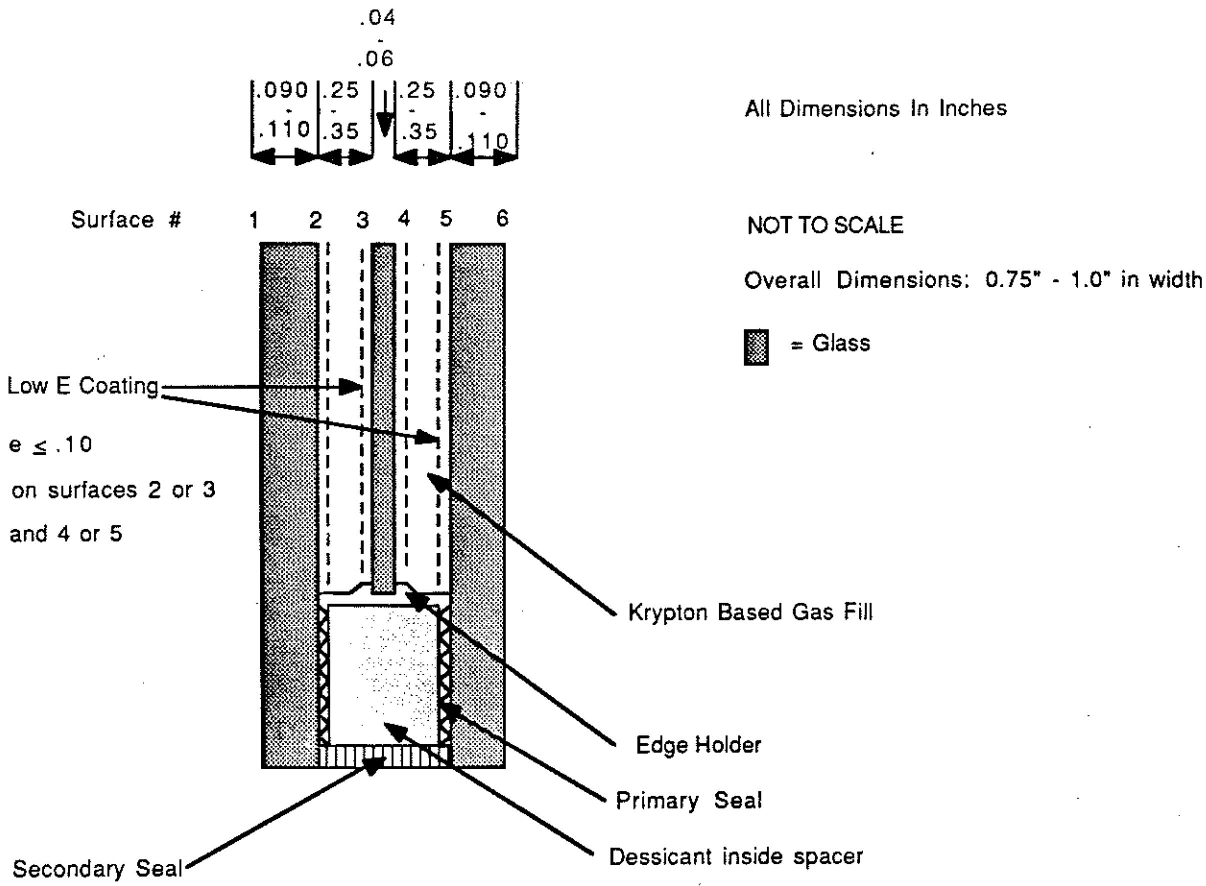

Figure 1. *Cross Section of LBL Superwindow*

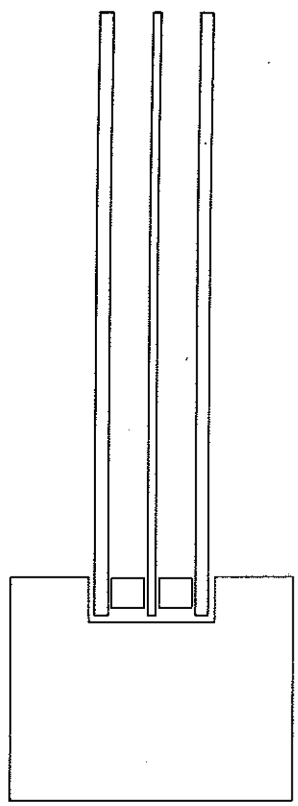

Figure 2a. *Superwindow cross-section with conventional edge design. Metal spacers separate three glazing layers in a wood sash. Interior gaps utilize low-e coatings.*

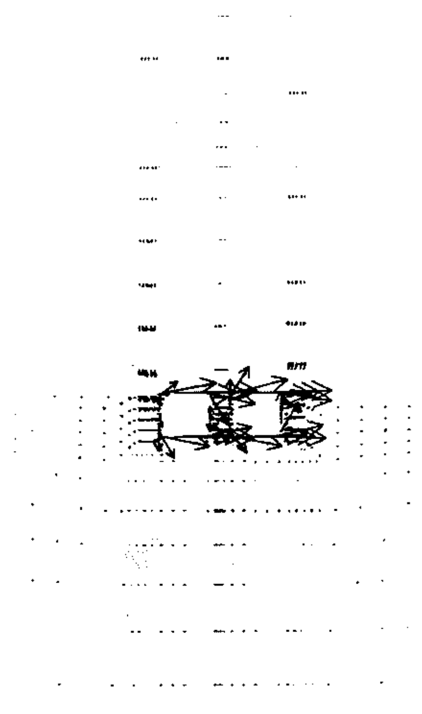

Figure 2b. *Vector plot of 2-dimensional heat transfer through the window cross section shown in Fig. 2a. The warm interior is on the left, the cold exterior on the right. The size of the vectors denotes the magnitude of heat transfer, the arrow the direction. Small vectors may appear as dots.*

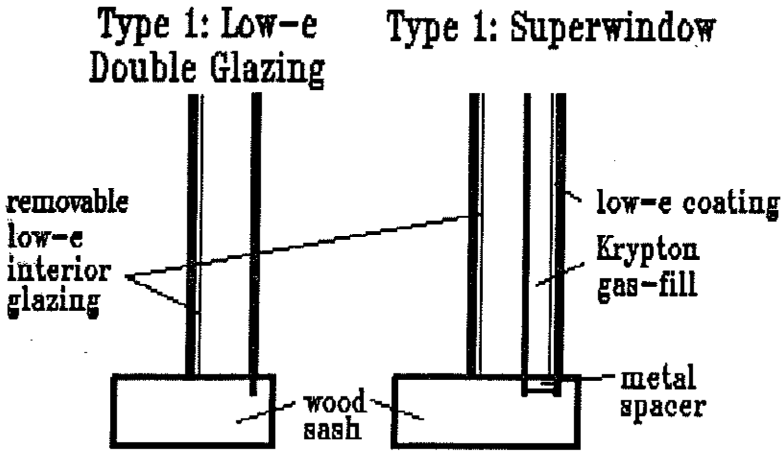

Figure 3a. Type 1 control and super-window cross sections

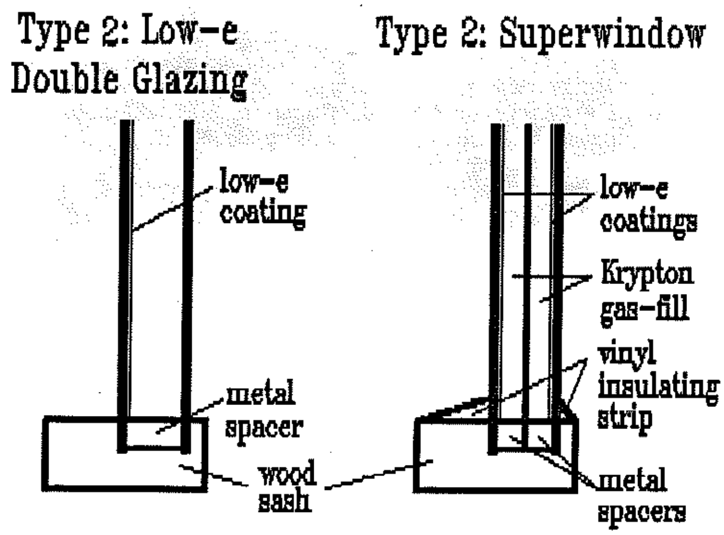

Figure 3b. Type 2 control and super-window cross sections

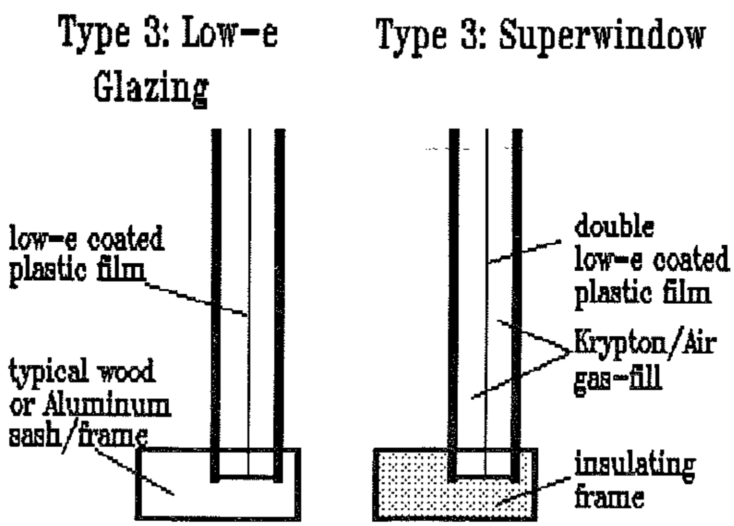

Figure 3c. Type 3 control and super-window cross sections