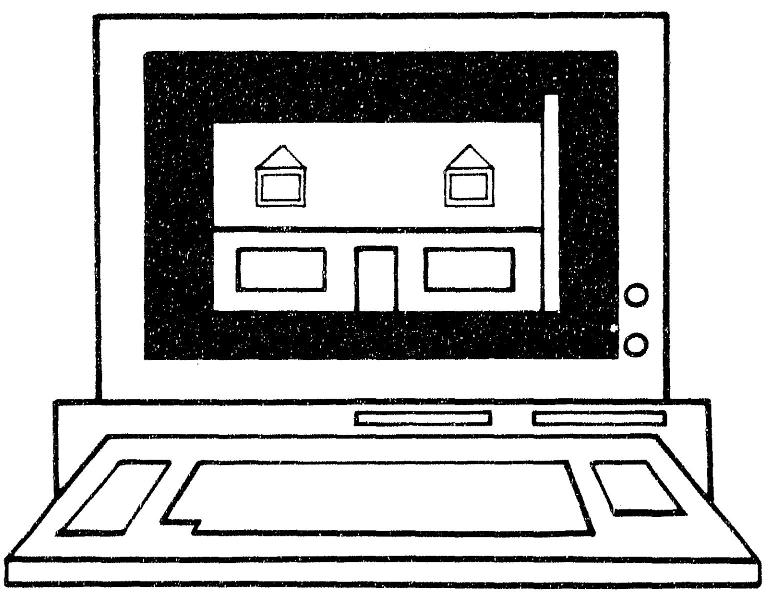
High-R Window Technology Development

Phase II Final Report



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High R Window Technology Development - Phase II

Final Report

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This report is divided into two separate sections. The first section summarizes research activities aimed at developing superwindow prototypes for three BPA monitored (RCDP Cycle II) homes. The second section summarizes the results of the monitoring effort during the 1989-1990 heating season on these three homes.

Section I:

A Superwindow Field Demonstration Program in Northwest Montana.

A Superwindow Field Demonstration Program in Northwest Montana

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 1/8 in. [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 conductive heat transfer. Krypton's low thermal conductivity permits an effective design with gap widths between 1/4 in. and 3/8 in. 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.

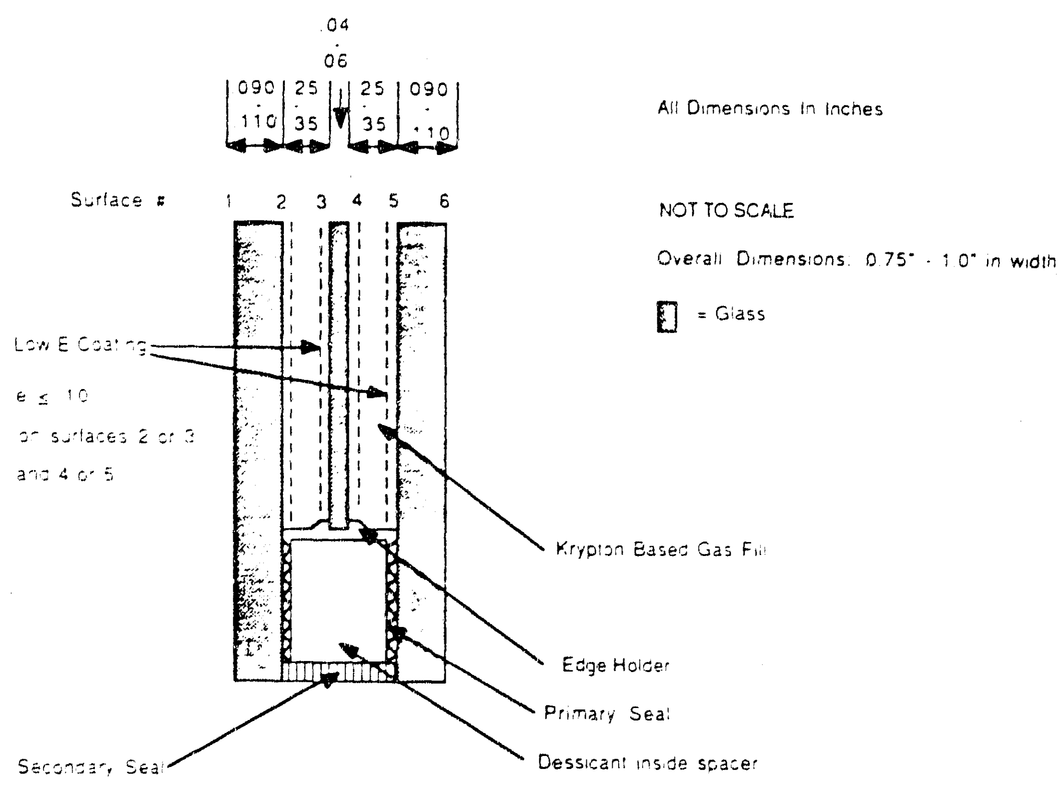

Figure 1. Cross section of LBL Superwindow.

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.

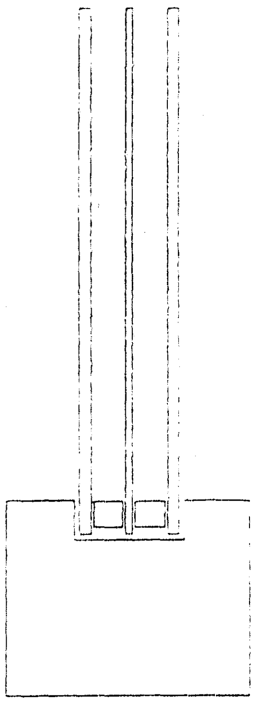

Figure 2a. Superwindow cross section with conventional edge design. Metal spacers separate three glazing layers in a wood sash. Interior gaps utilize low-E coatings.

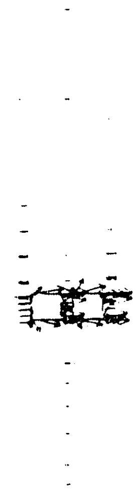

Figure 2b. Vector plot of two-dimensional heat transfer through the window cross section shown in Figure 2a. The warm interior is on the left, the cold exterior on the right. The size of the vectors denotes the magnitude of heat transfer, the arrow the direction. Small vectors may appear as dots.

Table 1. Center-of-Glass and Edge-of-Glass U-Values for a Low-E Double-Glazed Window and a Superwindow U-Value 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.

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 1/2 in. 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 (3/8 in. 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.

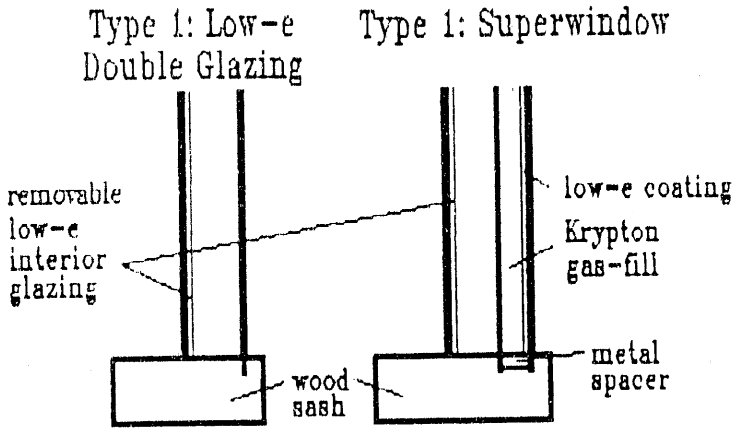

Figure 3a. Type 1 control and superwindow cross sections.

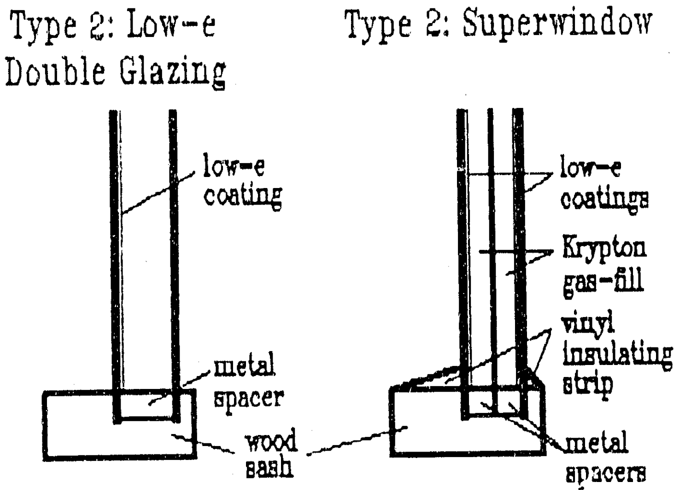

Figure 3b. Type 2 control and superwindow cross sections.

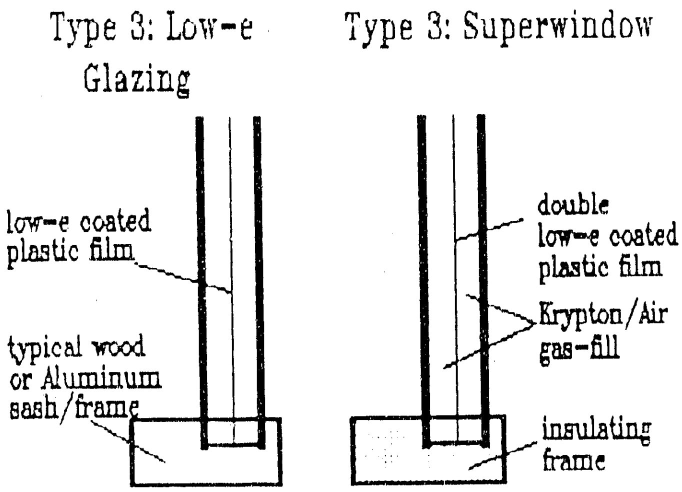

Figure 3c. Type 3 control and superwindow cross sections.

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.

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

	U-Values in Btu/h-ft²-°F (W/m²-°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	–	0.22 ± 0.04	–	0.23 ± 0.03
	–	(1.60 ± 0.21)	–	(1.26 ± 0.20)	–	(1.28 ± 0.18)

1) Type 3 Window used for WINDOW 3.1/ANSYS calculations and MoWiTT tests uses a wood frame that extends 0.5 in. over the spacer's sightline.
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.

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.

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Section II:

Monitored Thermal Performance Results of Superwindows in Three Montana Residences

Monitored Thermal Performance Results of Superwindows in Three Montana Residences

Abstract

Simulation studies have shown that highly insulating windows with moderate solar transmittances (R values greater than 6 hr-ft^2-F/Btu and shading coefficients greater than 0.5) can outperform insulated walls on any orientation, even in a northern U.S. climate. Such superwindows achieve this feat by admitting more useful solar heat gains during the heating season than energy lost through conduction, convection and infrared radiation. To test this conclusion, three new homes in northern Montana were equipped with prototype superwindows designed and manufactured in conjunction with three national window manufacturers. The thermal performance of these windows was monitored over the 1989-1990 heating season. Results indicate that the glazed areas of superwindows can in fact outperform insulated walls on obstructed off-south orientations; however further improvements in the thermal performance of window edges and frames are necessary if the entire window is to outperform an insulated wall.

Introduction

Of all residential building envelope elements, windows have typically had the highest heat loss rates. The rapid commercialization of low-emissivity coatings and low-conductivity gas-filling has begun to upgrade window performance in moderate and cold climates. Windows with R-values better than those of the best double-glazed low-emissivity, gas-filled window can provide added energy benefits in heating dominated climates. Simulation studies (Sullivan and Selkowitz, 1985) have shown that even north-facing windows with R-values greater than 6 hr-ft^2-F/Btu and shading coefficients greater than 0.5 (i.e. at least half the solar heat gain of clear single glazing) will provide more useful solar heat gain than conductive losses in a typical residence in a northern climate. Such "superwindows" thereby outperform the best insulated walls. Other advantages of superwindows include significantly higher winter interior glazing surface temperatures which result 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 R6- R10 superwindows using three glazing layers, two low-emissivity coatings, and a low-conductivity gas-fill. Previous studies have detailed the design configurations for such superwindows (Arasteh, Selkowitz, and Hartmann 1985) and have proven, through laboratory measurements, that the measured center-of-glass performance for such windows matches predictions (Arasteh, Selkowitz, and Wolfe, 1989).

As a follow-up to these laboratory measurements, three different superwindow prototypes were designed and manufactured in conjunction with three major national window manufacturers (Arasteh and Selkowitz, 1989). Each manufacturer's prototype was an adaptation of the superwindow principles (three layers, one low-emissivity coating per gap, and the use of low-conductivity gas fills) to their existing glazing and sash constraints. The three designs and thermal performance data on are presented in previous studies (Arasteh and Selkowitz, 1989) and summarized in Tables 1 and 2. In order to assess the annual energy impacts of these windows, the three houses and windows were monitored over the course of the 1989-1990 heating season.

It is the intent of this and related research at the Lawrence Berkeley Laboratory to provide manufacturers and consumers with real-time performance data on superwindows (compared to currently available products) in order to promote their optimum design and use. It is not the intent of this project to compare the relative performance between different manufacturers' existing window products or prototype superwindows.

Methodology: Monitoring Strategy

Definitively measuring the in-situ performance of a new window product in an occupied residence can be close to impossible. The ideal monitoring project would involve building two identical houses on identical sites, fitting one with the windows of interest (i.e. superwindows) and the other with standard or control windows. The energy use of each house would then be monitored every hour and the difference attributed to the improved windows. Unfortunately, even among supposedly identical houses, construction details and workmanship variations as well as occupancy behavior can lead to variations in energy use on the same order of magnitude as the energy impact of the windows. Such a plan, in addition to being very costly to implement, could therefore produce erroneous results unless undertaken on a very large statistical sample.

However, instrumenting a window with a heat flux sensor and several thermistors can provide both definitive qualitative and quantitative information on window thermal performance. We took such an approach in this study, equipping the interior surfaces of one superwindow and one control window in each house with a heat flux meter at the center of the glazed area and four thermistors between the center of the glazed area and the frame. Interior room and exterior temperatures are also measured. All measurements are taken every five minutes, averaged and recorded hourly. The layout of the monitoring equipment is shown schematically in Figure 1. Under no-sun conditions, and making the assumption that the windows are in steady-state each hour (i), an hourly center-of-glass U-value (Ug_i) can be calculated from the hourly center-of-glass flux (Qg_i), the hourly room temperature (T_{ri}), and the outdoor temperature (To_i):

$$Ug_i = Qg_i/(To_i - T_{ri}) \qquad (1)$$

Because solar radiation will artificially raise the temperature readout of thermistors, we can only realistically measure nighttime center-of-glass U-values. Note that the exterior film coefficient and thus the Ug_i's are based on site wind and cloud conditions which are not available. However, this is an insignificant omission since the variability in exterior film coefficients on the U-value of a low-emissivity gas-filled window is small (approximately 0.01 Btu/hr-ft^2-F) and negligible for a superwindow (approximately 0.005 Btu/hr-ft^2-F). Note also that total window U-values (including the effects of frames and edges) cannot be measured in the field.

The other three thermistors were placed to collect useful information. Under no-sun conditions, the closer a window's interior surface temperature is to ambient, the better an insulator it is. T4, the sash temperature and T3, the sightline temperature provide information on the relative thermal performances of these two areas. For conventional windows, it is generally assumed that thermal bridging from spacers does not extend beyond 2.5" from the sightline; T2 was therefore placed 2.5" from each window's sightline to test this hypothesis on superwindows.

Of primary interest to us, however, is the annual impact of these windows on the energy consumption of each house. During the day, the black heat flux meters measure both temperature-difference driven heat losses through the center-of-glass area as well as solar heat gains through the glazing assembly. (Note, our calculations are adjusted to compensate for room-bound solar gains striking the heat flux which flow outwards.) If losses are less than solar gains, the flux will be positive; if not, the flux will be negative. Due to the cold climate in northern Montana, heating was needed at all three sites for almost all hours between the beginning of September and the end of May. Figure 2 shows the average hourly exterior temperatures at all three sites for the monitoring period. While this winter was an unusually mild winter, with only one stretch of severe cold weather in February, notice that the cold weather begins early in the fall and lasts well into the spring. Because heating was needed for this entire time period, all solar gains are useful. We can therefore define the annual energy impact (Qg) of the center-of-glass by summing the flux for each hour, i:

$$Qg = \Sigma_i Qg_i \qquad (2)$$

Unfortunately, the effects of frames and edges (spacers) cannot be ignored. Frames and edges generally have significantly higher heat loss rates than center-of-glass rates of superwindows; furthermore, frames do not transmit any useful solar gains. Thus, to determine Qt, the annual energy impact of the total window (center-of-glass and frame and edge effects), we must add in the extra heat loss due to frame and edge effects and normalize for the appropriate proportion of non-glazed area. For each hour i,

$$Qt_i = Ng * Qg_i + Ne * Qe_i + Nf * Qf_i \qquad (3)$$

where Ng, Ne, and Nf are the fractions of the total window made up by the center-of-glass, edge-of-glass and frame respectively. Qe_i and Qf_i are the heat fluxes due to edge and frame effects respectively and are based on finite-element modeling (Arasteh and Selkowitz, 1989). For the purposes of this analysis, all windows are considered to be 2' wide by 4' high. On an annual basis,

$$Qt = \Sigma_i Qt_i \qquad (4).$$

Finally, we use hourly temperature data from the four thermistors to illustrate the relative thermal performance of the different portions of the window. Since the closer the interior warm side surface temperatures of a window element is to the interior temperature, the better an insulator it is, surface temperatures can provide an indication of the relative thermal performance of different window components.

Results

We first compare the average annual center-of-glass U-values for the six windows with those predicted by WINDOW 3.1, LBL's window heat transfer analysis program (LBL, 1988). This data is summarized in Table 3. In general, the agreement is very good. The superwindows show a significant improvement over the control windows. Figure 3 presents graphs of U-value over time for the six windows. Each point represents the U-value for one nighttime hour. The fluctuations in U-value are attributed to changes in wind speed, temperatures, and measurement uncertainties.

Our only information on total window U-values for the 2'x4' window size used in this study is based on calculations (see Table 2). Previous studies (Arasteh and Selkowitz, 1989) have indicated a good agreement between laboratory and calculated total window U-values.

Next, we compare the energy fluxes through all six windows over the total heating season (September - May). For comparative purposes, we calculate heat fluxes through a conventional 2x4 stud wall insulated with R-11 fiberglass insulation and a conventional 2x6 stud wall insulated with R-19 insulation. These wall heat fluxes are based on actual hourly site temperatures. Since these are electrically heated homes, the annual energy flux is given in kWh/ft^2 of window (or wall) area. We see from Figure 4 that, at two sites, the superwindows' center-of-glass area outperform the R-19 wall. In fact, at Site 219, the superwindow is a net-gainer, providing more solar heat gain than it looses through conduction, convection, and radiation. Solar gains at Site 215 are cut-off by hills to the south-west and trees to the west of the west facing monitored windows. At site 217, the two superwindows do not perform as well as expected due to the severe blockage of solar gains by the deck overhanging the windows. Unfortunately, because of the poorer thermal performance of the frames and edges and because the frames are opaque to solar radiation, the total windows (both control and superwindows) perform significantly poorer than the center-of-glass area only. Note that in a typical residential sized window, approximately 25% of the total area is made up of frame area and another 20% is edge-of-glass area (that part of the glazed area where thermal performance is degraded by thermal short circuits through the edge and frame).

Figure 5 presents the hourly (daily average) center-of-glass heat fluxes for the six windows as a function of time. Figure 6 presents total window (center plus edge plus frame) daily average fluxes for these windows. As expected, the extreme cold weather (see Figure 5) keeps even the center-of-glass areas of the superwindows from being net-gainers on a daily basis for several months in the winter. However, as Figure 7 shows, on an hourly basis at Sites 215 and 219, there are some daytime hours during the coldest part of the winter when the control windows are net gainers and more hours when the superwindows are net gainers. Note that outdoor temperatures are between 5 and 25 F for the time period shown in Figure 7.

Finally, we turn to Figure 8 to assess the variability of superwindow interior surface temperatures. (Because Site 217 was not heated, interior air and surface temperatures fluctuated significantly; this data for this site is therefor not presented.) By normalizing all temperature differences to the center-of-glass to outdoor temperature difference, we eliminate much of the scatter in these plots. In addition, we reference all temperature differences to the best insulating element of the window. We see that in general T2 is almost as high as T1; this tells us that the

2.5" rule for edge-of-glass effects is reasonable, but not perfect for superwindows. At site 215, a vinyl insulating strip was added above the sightline to minimize edge thermal bridging. This brought sightline temperatures (T3) to approximately the same as those of the sash (T4). These vinyl insulating strips were not added to the control window which had comparatively much lower sightline temperatures. These plots, as well as infrared thermography and two-dimensional heat transfer analysis performed on the windows (Arasteh and Selkowitz, 1989), confirm that the frames and edges used with these superwindow designs are thermally inferior to the glazings.

The intent of this project was to assess the potential improvements possible by changing from conventional low-e windows to superwindows, not to determine which superwindow performed best. As Figure 4 shows, all superwindows performed significantly better than their respective control windows. Furthermore, we must note that substantial differences in site characteristics forbid the comparison of superwindows with one another, or of control windows with one another. Site 217 received virtually no solar radiation. Even though sites 215 and 219 were both west facing, site 219 was partly shaded by trees and 215 was significantly shaded by hills to the southwest and trees to the west.

Energy issues are not the only ones associated with superwindows. The warmer interior surface temperatures of superwindows result in less condensation on glazing surfaces and added comfort. Figure 9 plots the average nighttime center-of-glass temperatures for the room side of the superwindow and control windows at Site 215 and Site 219. Also shown are the temperatures at which condensation and would occur on these windows (at 50% and at 60% relative humidity). Site 217 is not presented because the space behind it was not heated.

Conclusions

The monitoring of superwindow prototypes and control low-e windows in three houses in northern Montana has provided us new information on the field performance of these windows. We can make the following conclusions:

1) Field measured center-of-glass U-values agree extremely well with those predicted by WINDOW 3.1. We can therefore continue to use WINDOW with confidence for the design and evaluation of future superwindow prototypes.

2) The glazed areas of superwindows can be net annual energy gainers, even on obstructed off-south orientations in a climate as severe as northern Montana.

3) Thermal bridging resulting from the use of conductive spacers and the added heat loss from high conductivity window frames considerably degrades the thermal performance of superwindows. Increasing the thermal performance of frames and edges is mandatory for the next generation of superwindows. This issue is the topic of current research at LBL and within the industry.

A new round of superwindows from the three manufacturers involved in this project have recently been installed at the test sites. These new prototypes include glazing and/or frame and edge improvements and will be monitored over the 1990-1991 winter. These prototypes and their monitoring are the next step in our collaborative industry/utility research effort aimed at developing total windows which will outperform highly insulated walls in cold climates.

This project has fostered much interest among the industry, design professionals, and the public in superwindows. The first commercially available superwindow, offered to the public in January 1990, is an outgrowth of this project.

Acknowledgments

The author wishes to thank Jonathan Slack of LBL for his tremendous help in analyzing the data from this project. Invaluable logistical help on the monitoring side of this project was provided by Johnny Douglass and Jim Maunder of the Washington State Energy Office; Dave Eyes, Brad Hesse, and Kurt Schultz of W.S. Flemming and Associates; and the staff of the Residential Section of the Montana Department of Natural Resources and Conservation. The comments and time provided by Steve Selkowitz, Dennis DiBartolomeo, and Joe Klems of Lawrence Berkeley Laboratory are greatly appreciated. Materials and time donated by Andersen Corporation, Cardinal IG, Owens-Corning Fiberglass, Rolscreen Company, and Southwall Technologies were essential to the completion of this project.

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Table 1: Summary of Site and Window Characteristics

	Site 215	Site 217[1]	Site 219
Location	Libby, MT	Frenchtown, MT	Kalispell, MT
Orientation	West	North	West
Site Characteristics	obstructed by hills & trees	completely obstructed by deck overhead	partially obstructed by trees
Operator Type	Casement	Casement	Casement
Frame Type	Wood, vinyl clad	Fiberglass	Wood, alum clad
Spacer Type (Control Window)	Aluminum	Aluminum	Wood
Spacer Type (Superwindow)	Aluminum; 0.5" vinyl insulating strip over sightline	Aluminum	Wood, and Aluminum
Glazing Assembly (Control Window)	Double Glazing with Low-E, Ar	Double Glazing with suspended Low-E film, air	Double Glazing with Low-E air
IG Width (Control Window)	0.75"	0.75"	1.125"
Glazing Assembly (Superwindow)	Triple Glazing with 2 Low-E, Kr	Double Glazing with suspended double coated Low-E Film, 80Kr/20air	Triple Glazing with 2 Low-E; one Kr, one air
IG Width (Superwindow)	1.0"	0.75"	1.56"

[1] Two superwindows monitored at Site 217; no control windows installed

Table 2:
Summary of Control Window and Superwindow Thermal Properties[1]

	U-values (Btu/hr-ft2-F) Center	Total[2]	Shading Coefficient (glazing only)	Visible Transmittance (glazing only)
Site 215				
Super	0.12	0.19	0.63	0.66
Control	0.25	0.32	0.76	0.77
Site 217				
Super	0.18	0.26	0.62	0.67
Control	0.31	0.35	0.68	0.71
Site 219				
Super	0.16	0.27	0.67	0.67
Control	0.35	0.40	0.86	0.77

[1]Center-of-Glass U-values, Shading Coefficients, and Visible Transmittances calculated with WINDOW 3.1. Total Window U-values based on WINDOW3.1/ANSYS calculations.

[2]Total Window U-values based on 2'x4' overall sizes.

Table 3: Summary of WINDOW 3.1 calculated and Field Measured Center-of-Glass U-values (Btu/hr-ft2-F)

	WINDOW 3.1[1]	Measured[2]
Site 215:		
Superwindow	0.12	0.13 +/- 0.01
Control	0.25	0.24 +/- 0.02
Site 217[3]		
Superwindow1	0.18	0.21 +/- 0.01
Superwindow2	0.18	0.18 +/- 0.02
Control	0.31[4]	N/A
Site 219		
Superwindow	0.16	0.17 +/- 0.03
Control	0.35	0.38 +/- 0.03

[1] ASHRAE Winter Conditions (To=0F, Ti=70F, 15mph wind, no-sun)

[2] Average of real-time (night only) conditions; September 1, 1989 through May 31, 1990

[3] Two superwindows monitored at Site 217; no control windows installed

[4] Incorrectly specified in Arasteh and Selkowitz, 1989

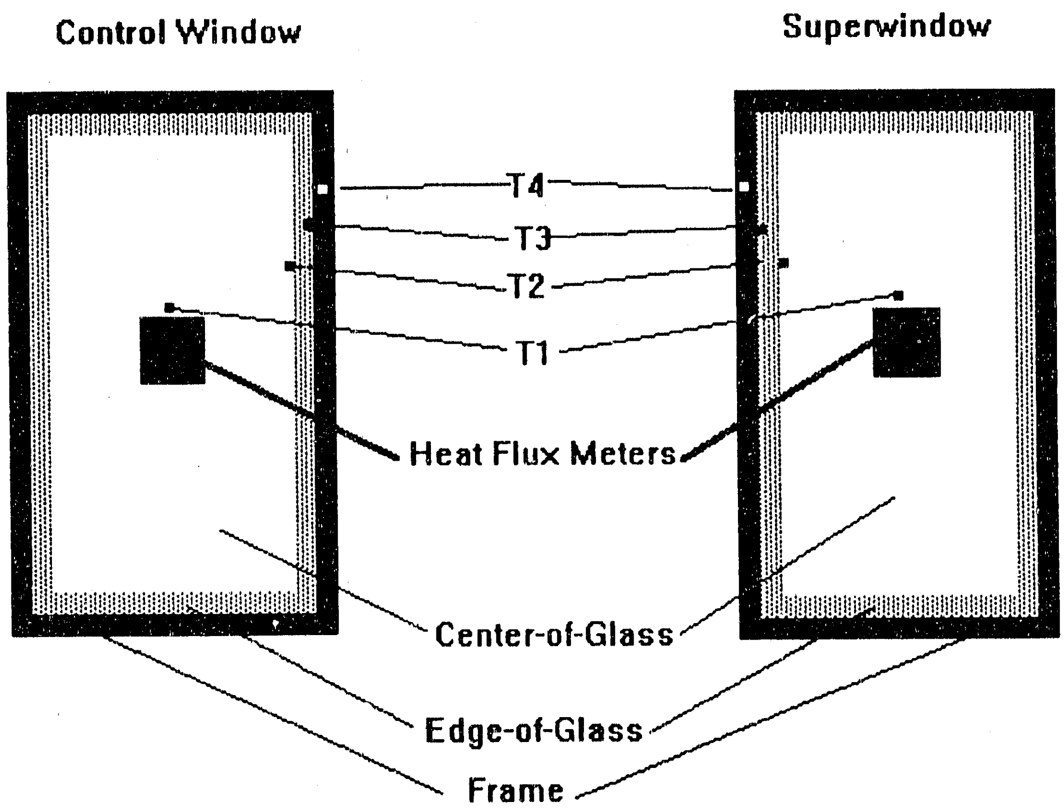

Figure 1: Side-by-side monitoring setup of control windows and superwindows and component window areas.

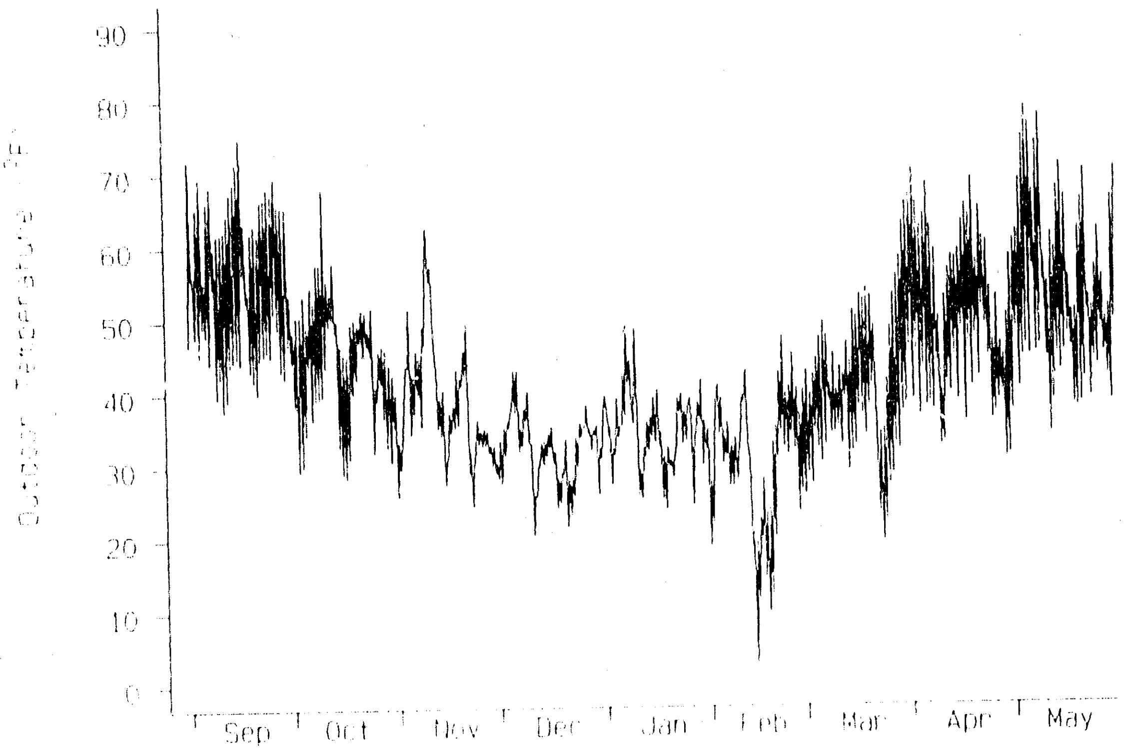

Figure 2a: Outdoor temperatures at Site 215 (Libby, MT) from September 1989 through May 1990.

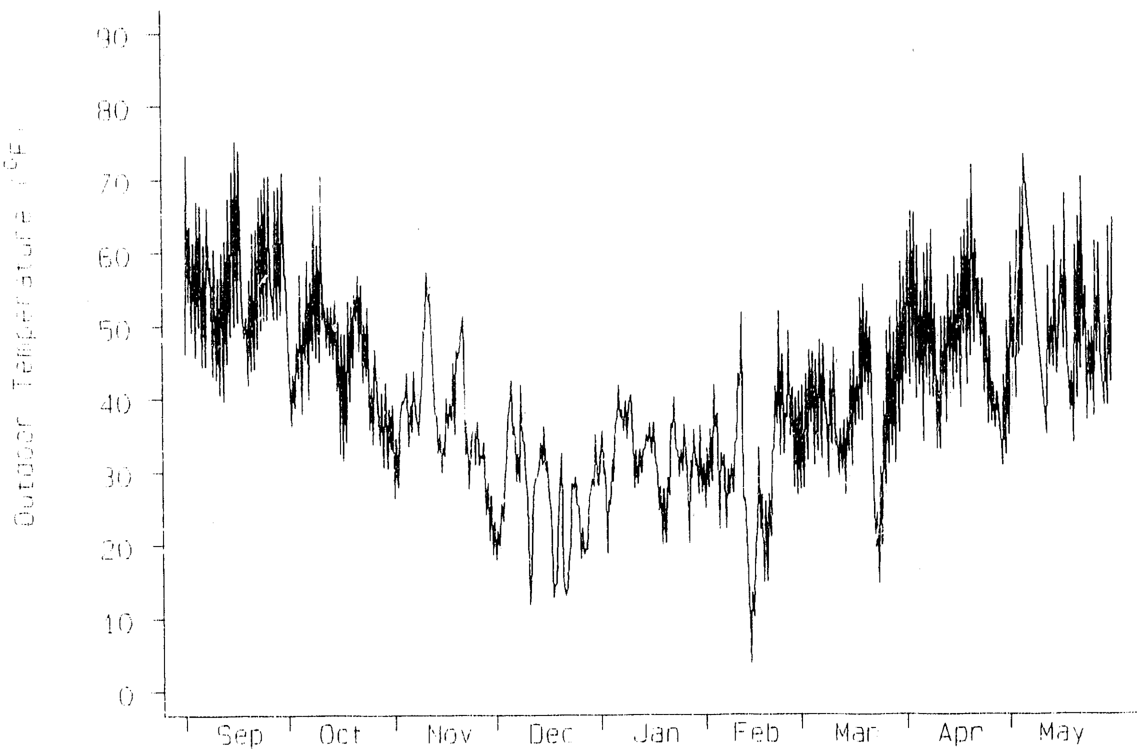

Figure 2b: Outdoor temperatures at Site 217 (Frenchtown, MT) from September 1989 through May 1990.

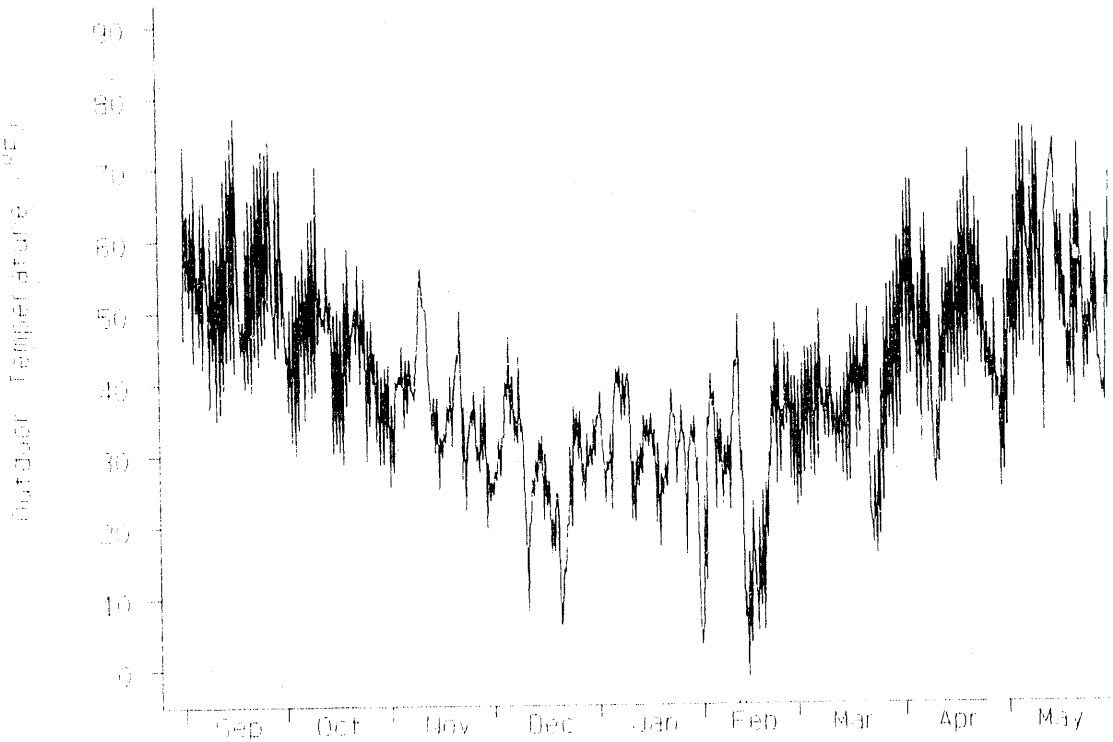

Figure 2c: Outdoor temperatures at Site 219 (Kalispell, MT) from September 1989 through May 1990.

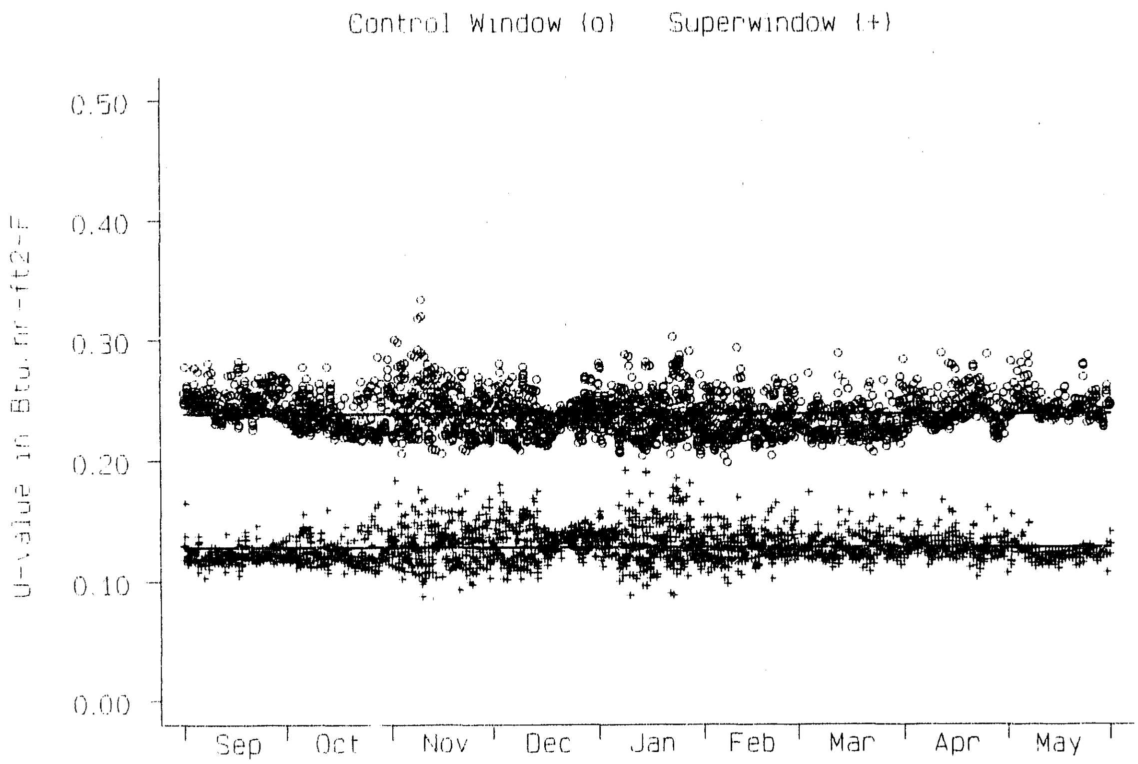

Figure 3a: Nighttime hourly center-of-glass U-values for the control window and superwindow at Site 215 (Libby, MT).

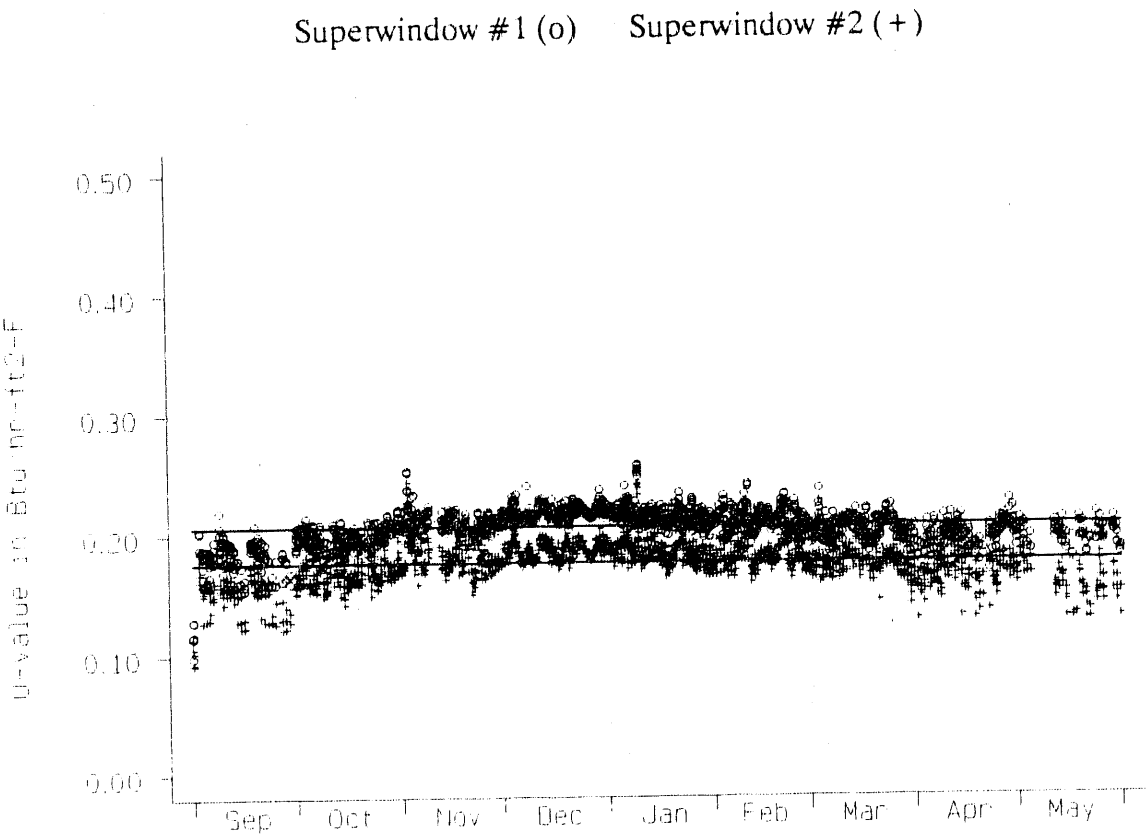

Figure 3b: Nighttime hourly center-of-glass U-values for the superwindows at Site 217 (Frenchtown, MT).

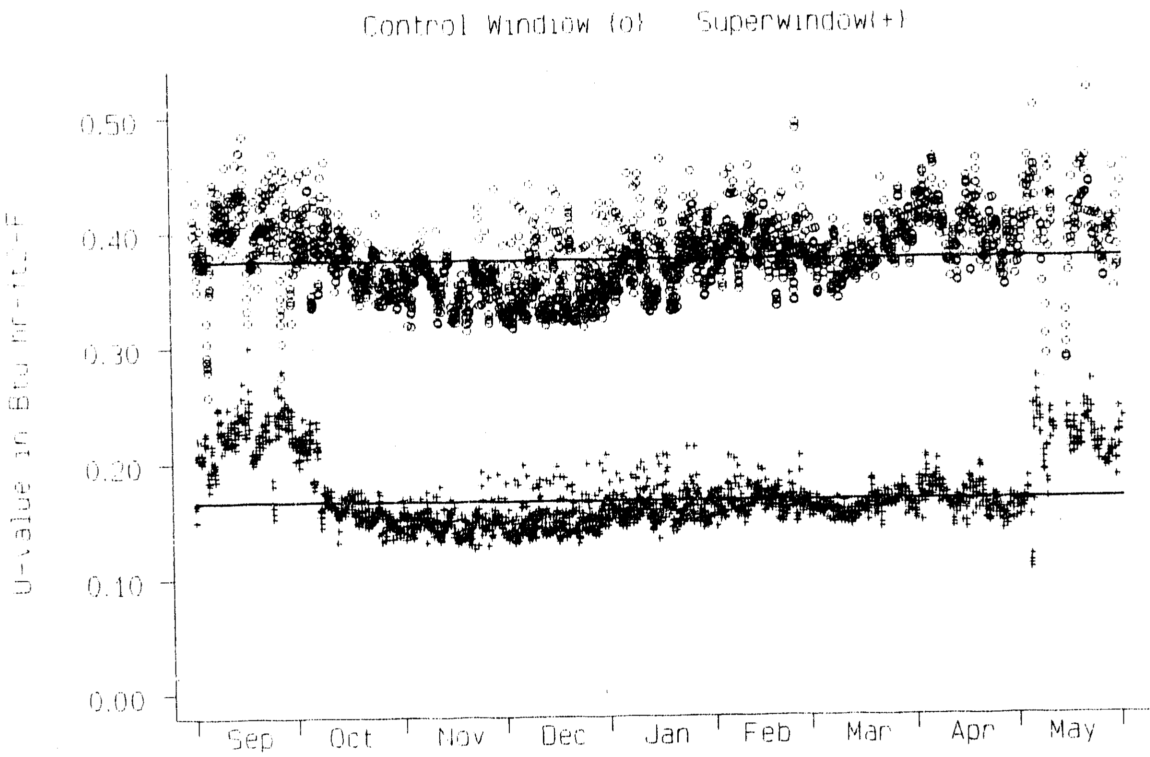

Figure 3c: Nighttime hourly center-of-glass U-values for the control windows and superwindow at Site 219 (Kalispell, MT).

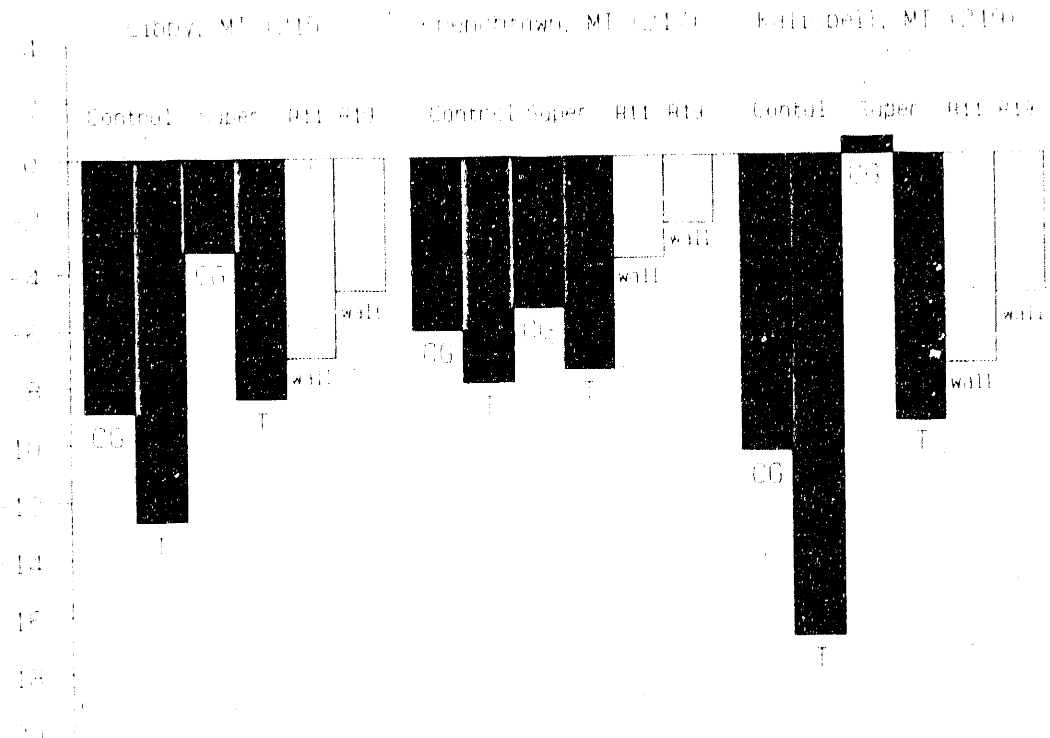

Figure 4: Yearly heating season energy flux for the center-of-glass areas of the control windows and superwindows, for the total area (center, edge, and frame) of the control windows and the superwindows, and for R11 and R19 walls. Center-of-glass heat fluxes are measured; other fluxes are based on calculations and real time data.

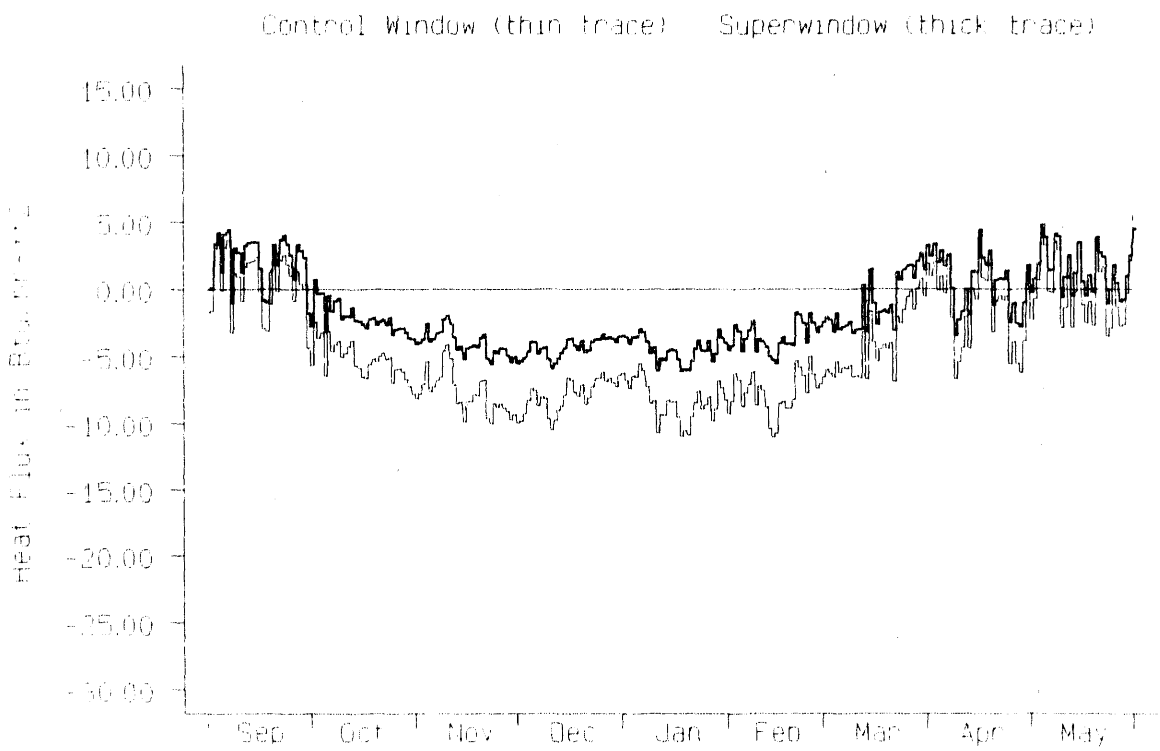

Figure 5a: Hourly (daily average) center-of-glass heat fluxes for the control window and superwindow at Site 215 (Libby, MT).

Superwindow #1 (o)   Superwindow #2 (+)

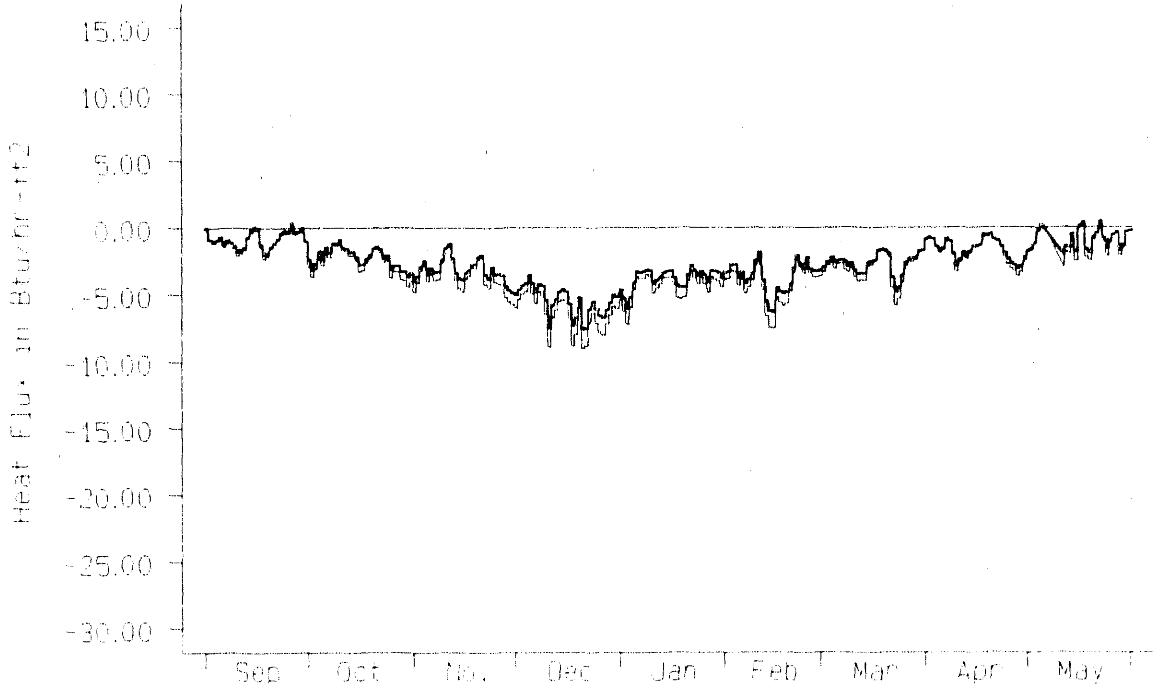

Figure 5b: Hourly (daily average) center-of-glass heat fluxes for the superwindows at Site 217 (Frenchtown, MT).

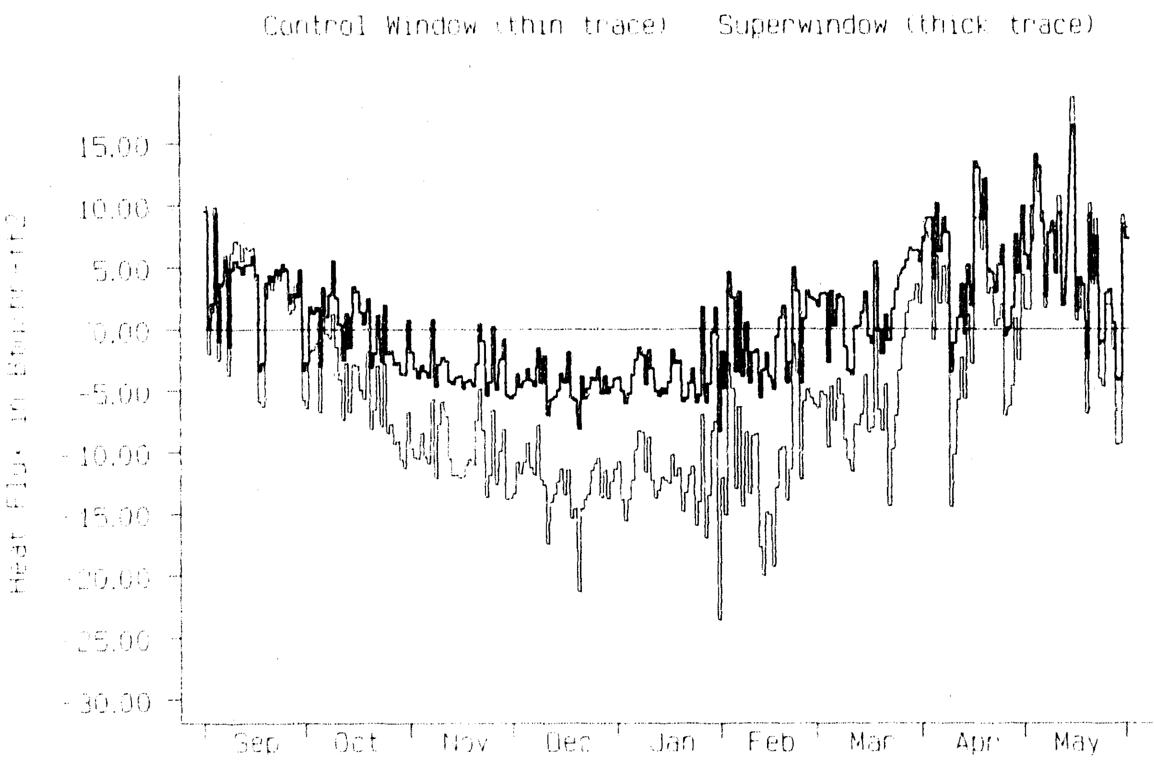

Figure 5c: Hourly (daily average) center-of-glass heat fluxes for the control window and superwindow at Site 219 (Kalispell, MT).

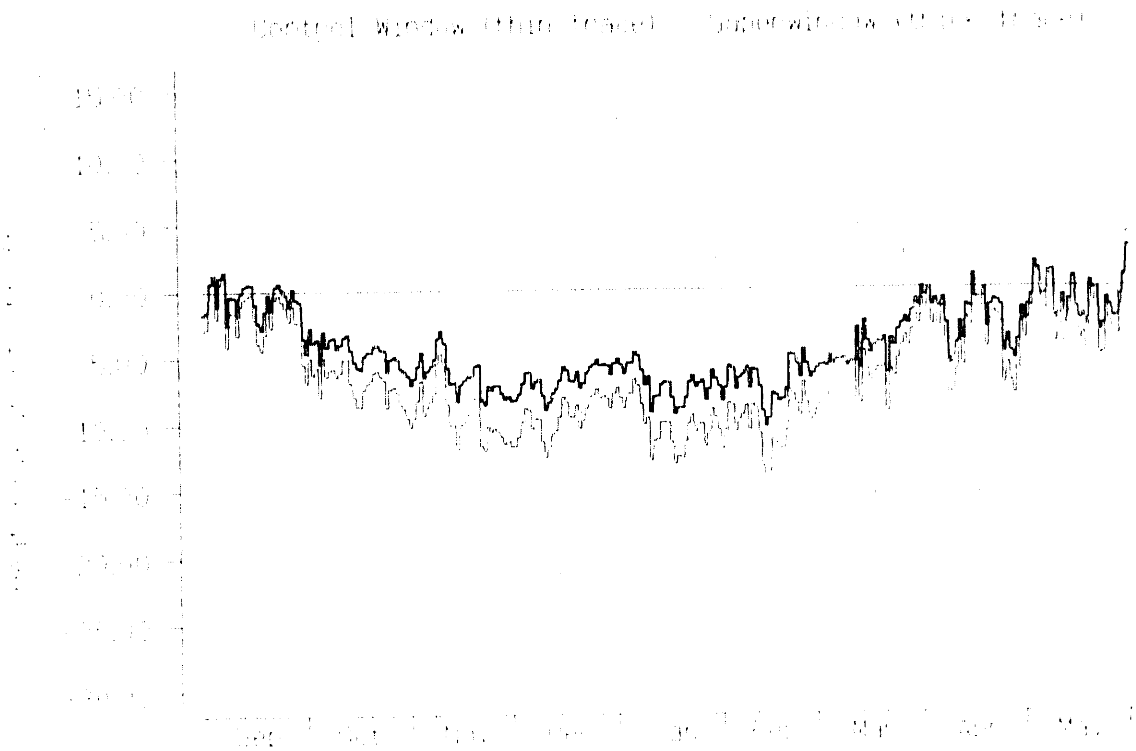

Figure 6a: Daily total window (center, edge, and frame) heat fluxes for the control window and superwindow at Site 215 (Libby, MT).

Superwindow #1 (o)   Superwindow #2 (+)

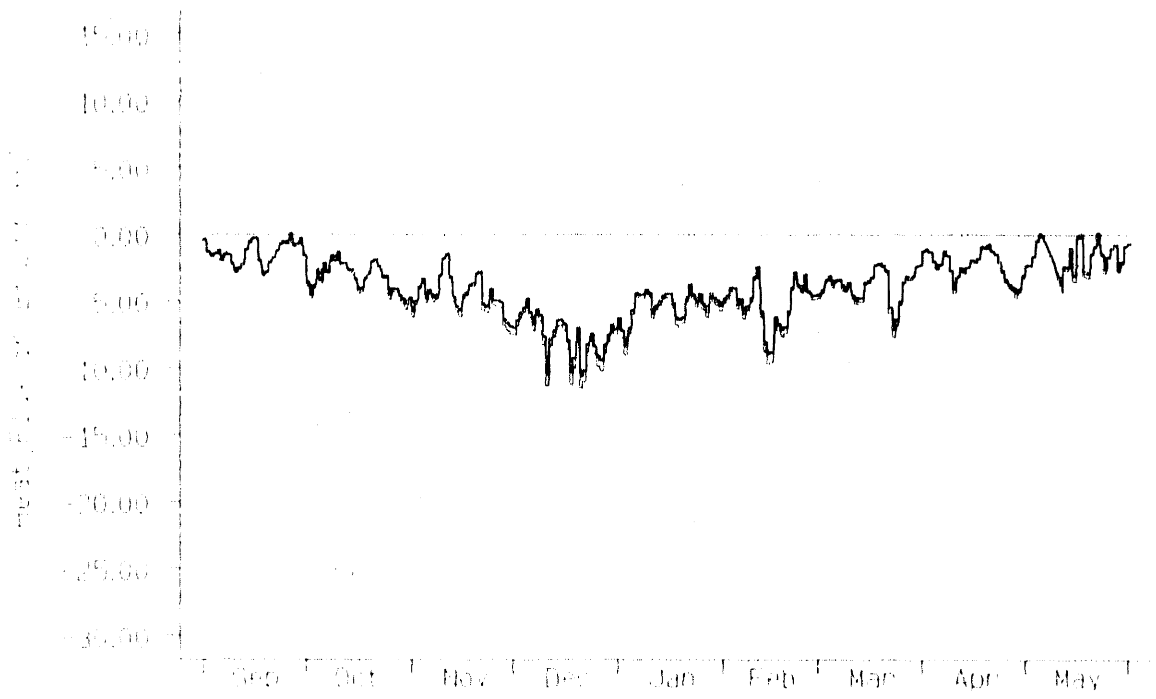

Figure 6b: Daily total window (center, edge, and frame) heat fluxes for the superwindows at Site 217 (Frenchtown, MT).

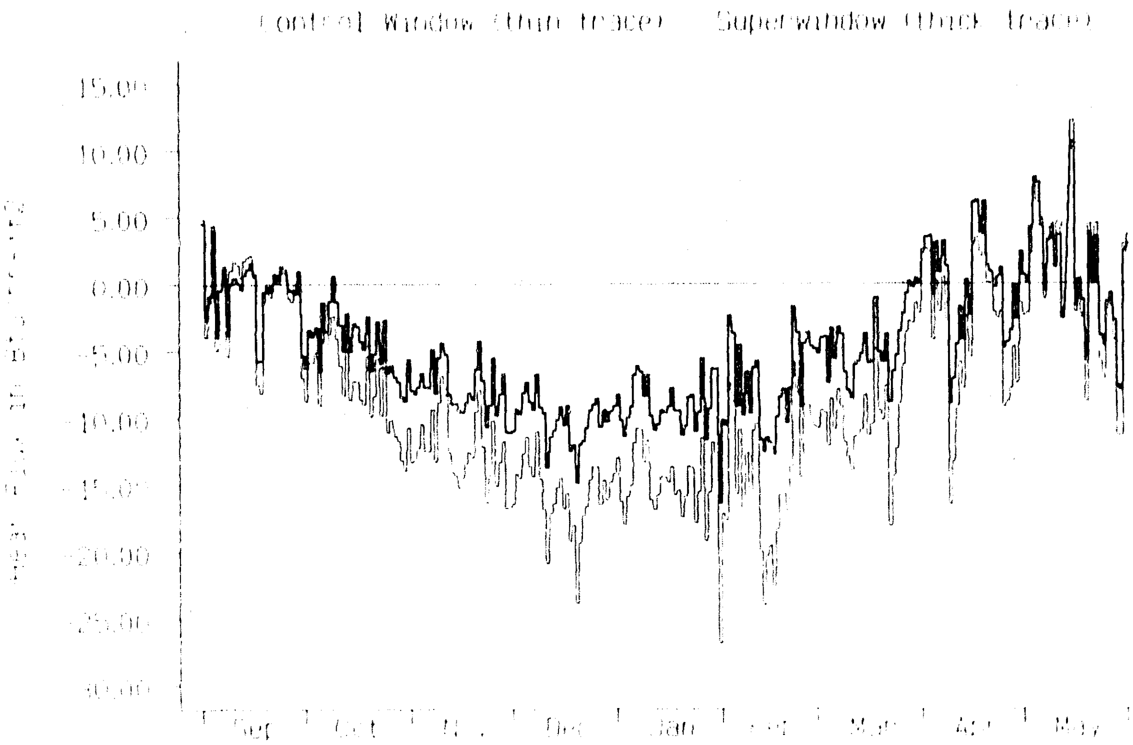

Figure 6c: Daily total window (center, edge, and frame) heat fluxes for the control window and superwindow at Site 219 (Kalispell, MT).

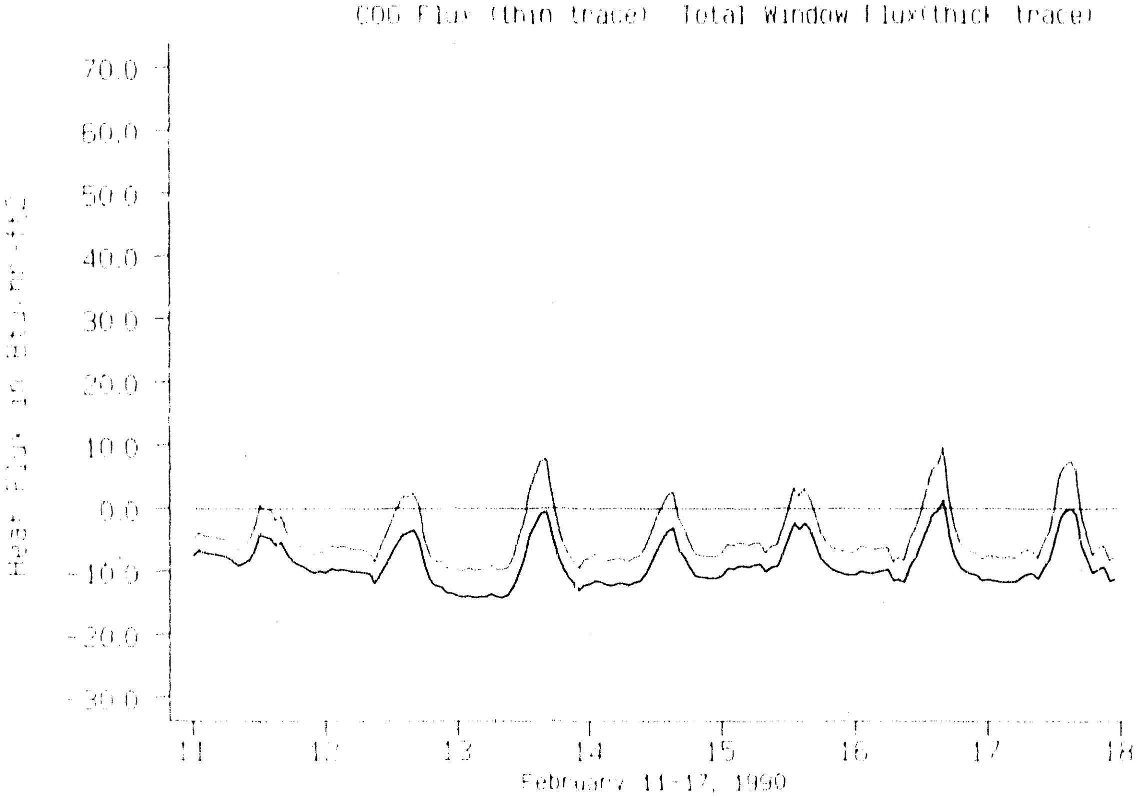

Figure 7a: Hourly center-of-glass and total (center, edge, and frame) heat fluxes for the superwindow at Site 215 (Libby, MT) between February 11 and 19, 1990.

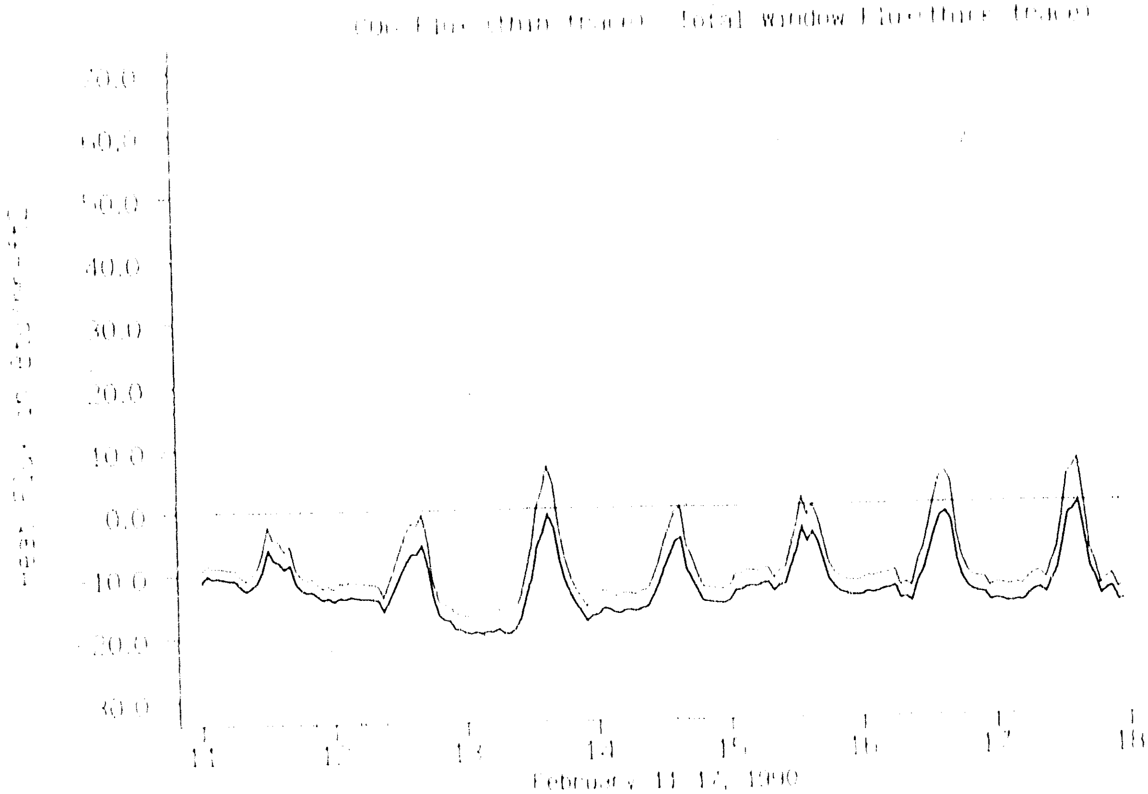

Figure 7b: Hourly center-of-glass and total (center, edge, and frame) heat fluxes for the control window at Site 215 (Libby, MT) between February 11 and 19, 1990.

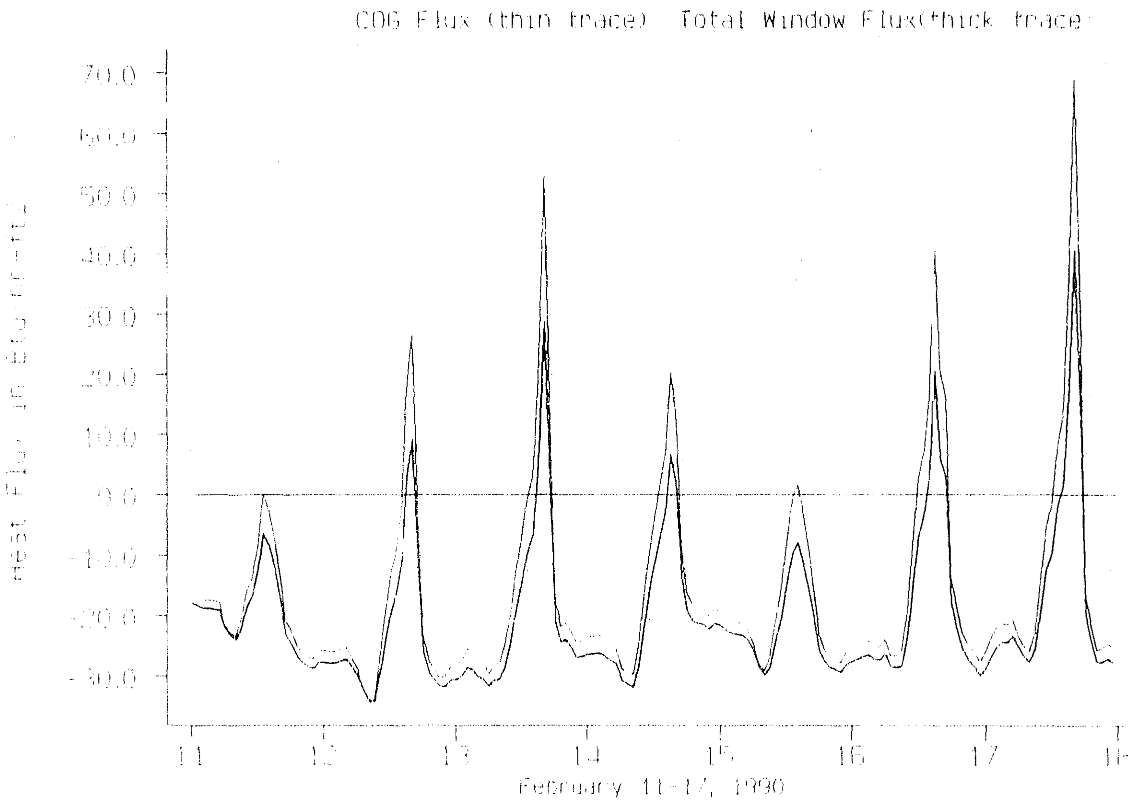

Figure 7c: Hourly center-of-glass and total (center, edge, and frame) heat fluxes for the control window at Site 219 (Kalispell, MT) between February 11 and 19, 1990.

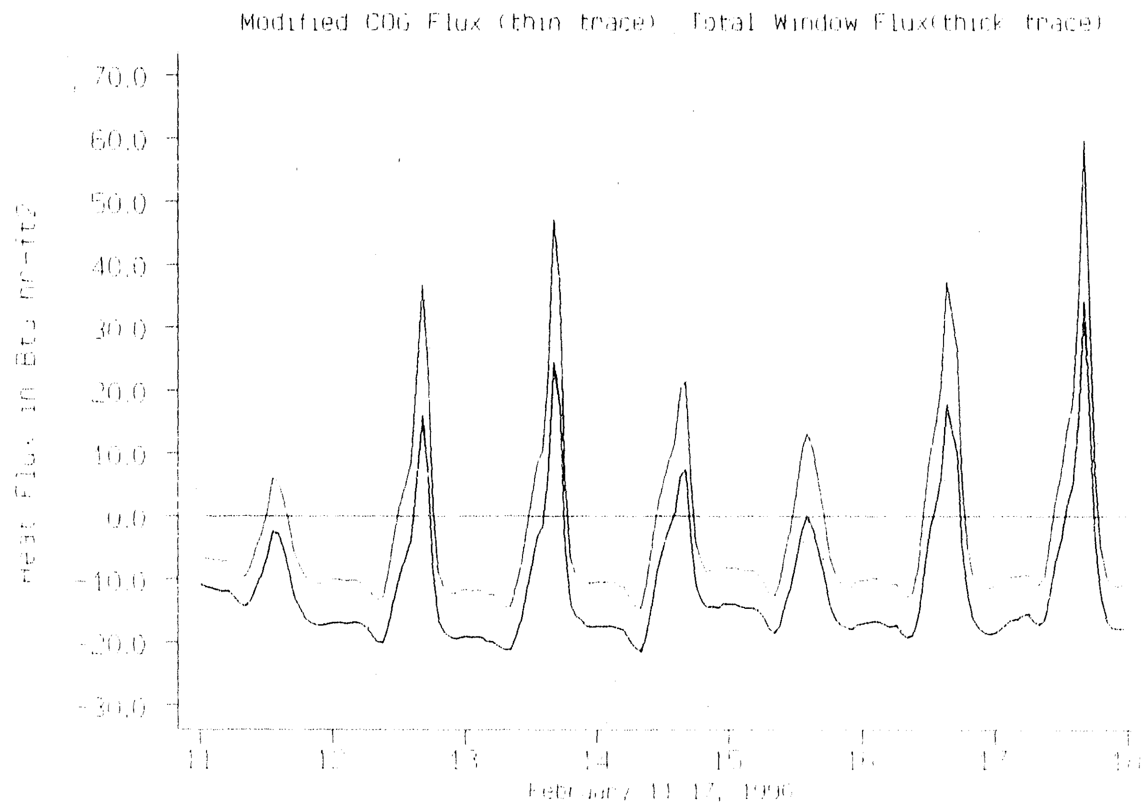

Figure 7d: Hourly center-of-glass and total (center, edge, and frame) heat fluxes for the superwindow at Site 219 (Kalispell, MT) between February 11 and 19, 1990.

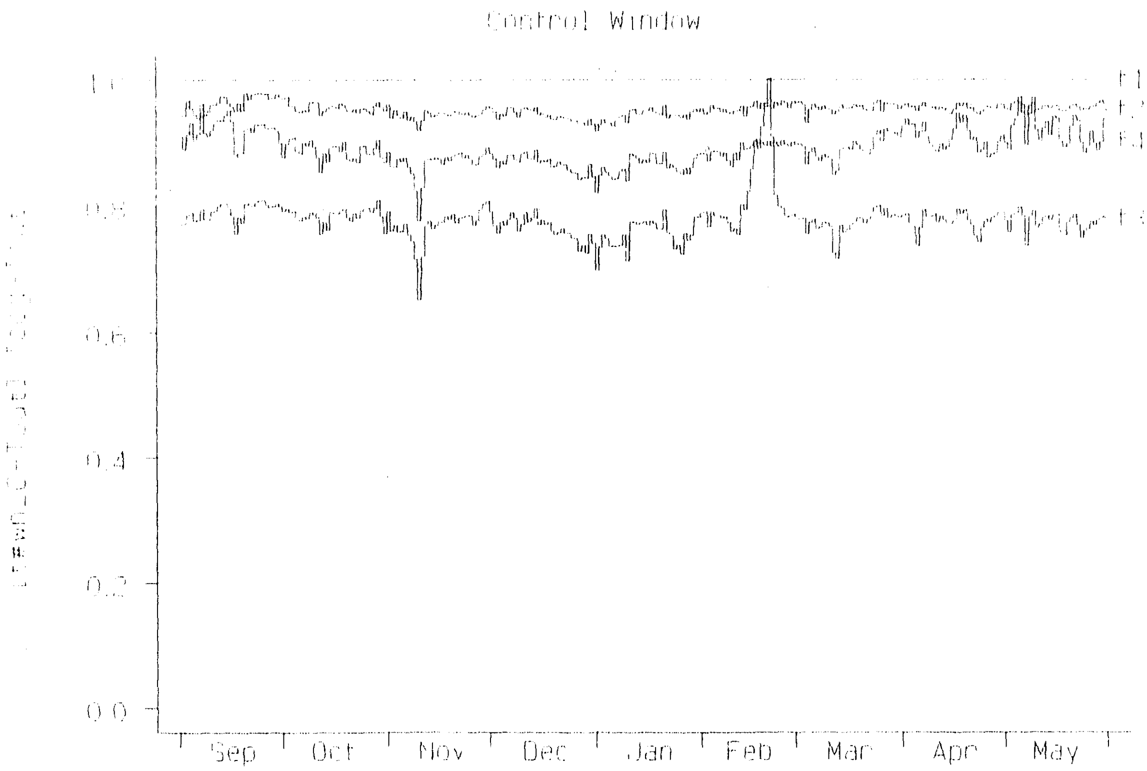

Figure 8a: Normalized nighttime warm side surface temperatures for the control window at Site 215 (Libby, MT).

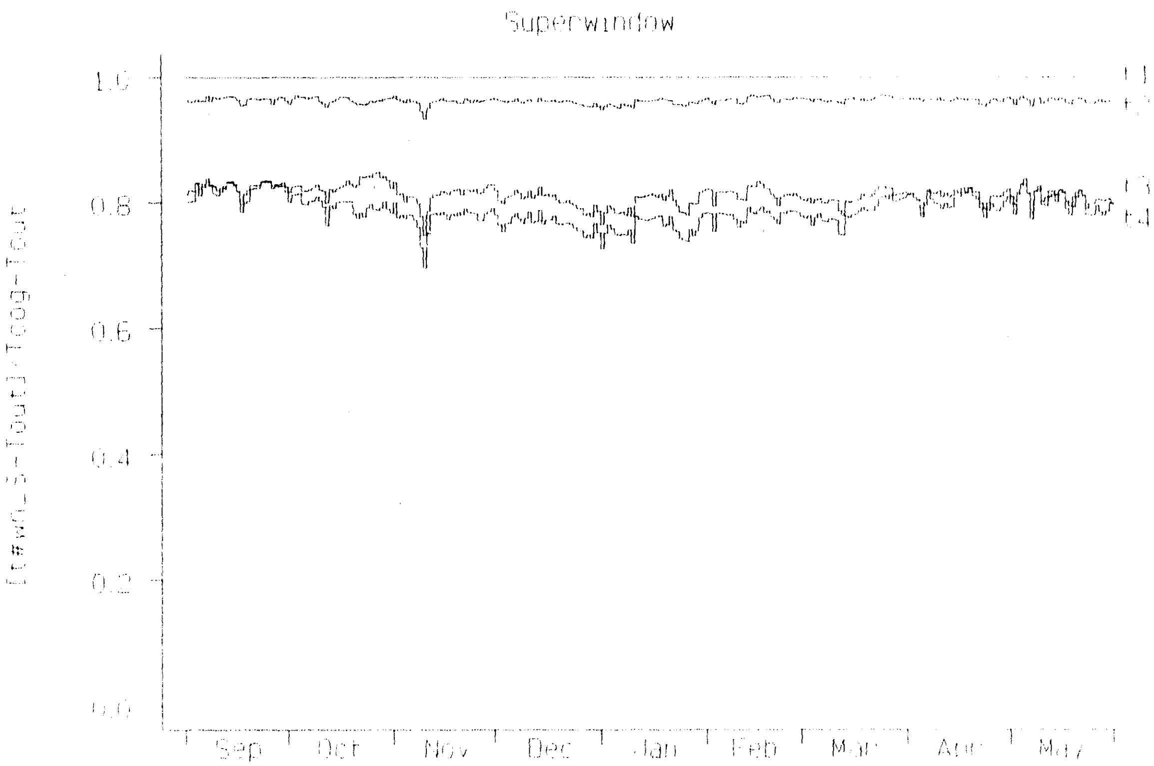

Figure 8b: Normalized nighttime warm side surface temperatures for the superwindow at Site 215 (Libby, MT).

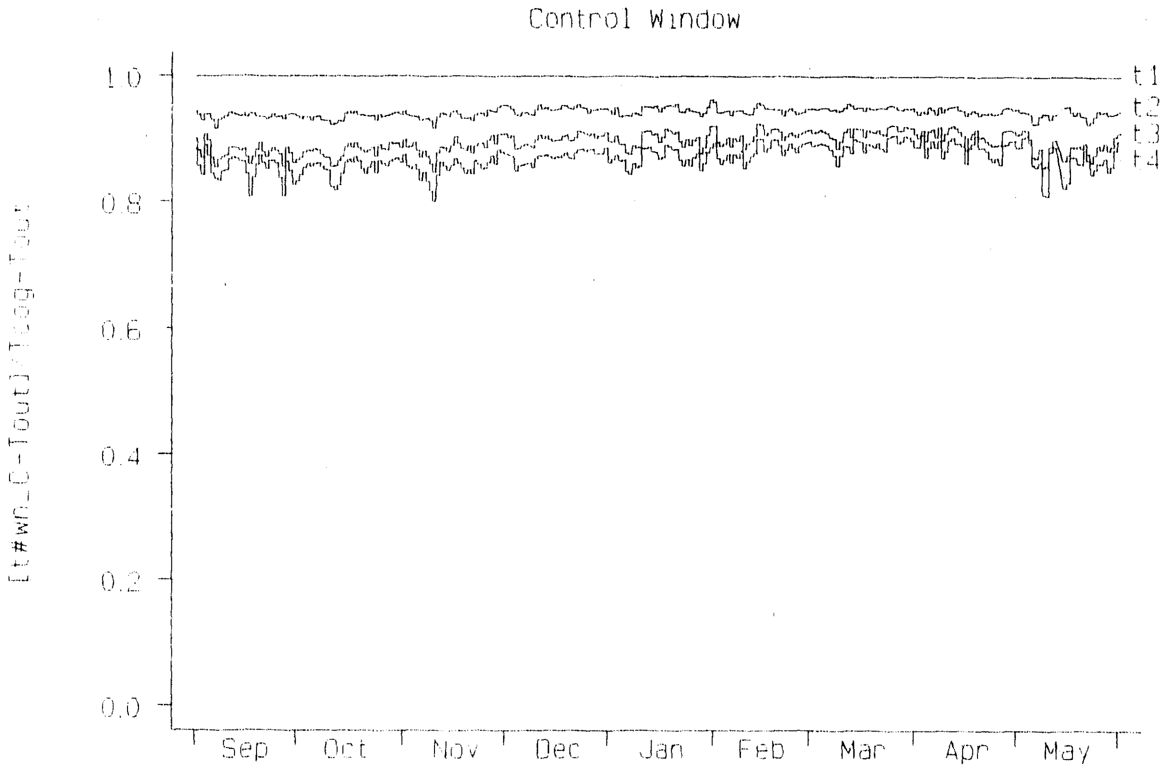

Figure 8c: Normalized nighttime warm side surface temperatures for the control window at Site 219 (Kalispell, MT).

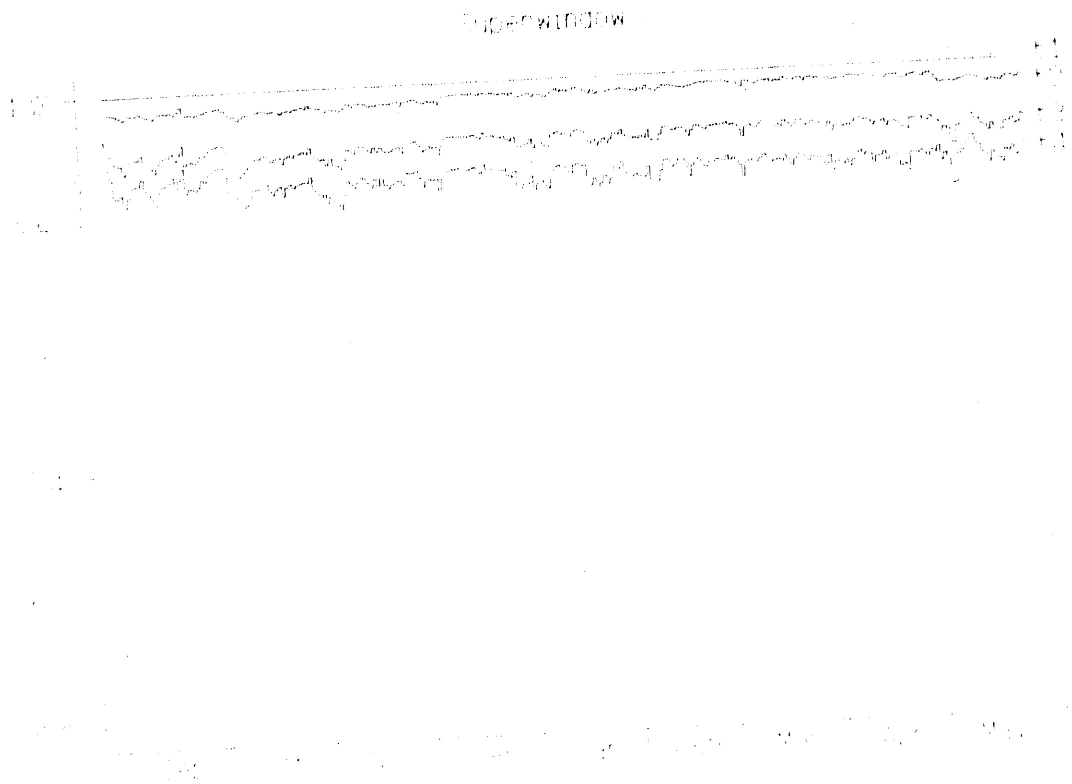

Figure 8d: Normalized nighttime warm side surface temperatures for the superwindow at Site 219 (Kalispell, MT).

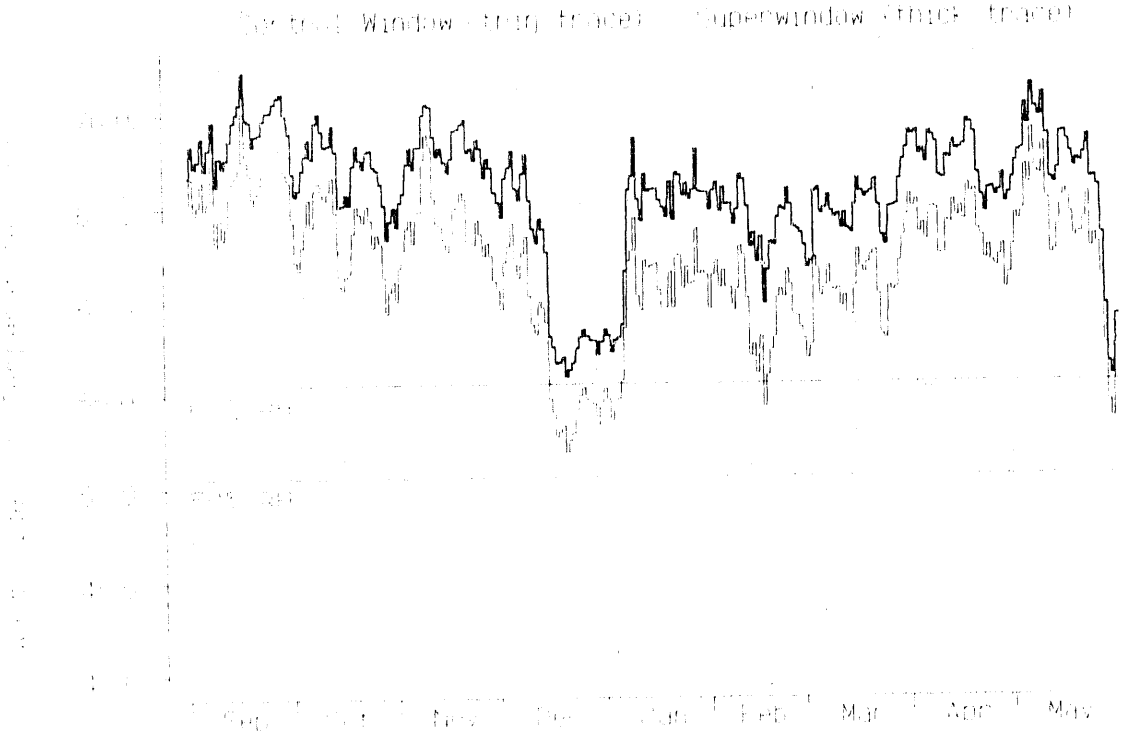

Figure 9a: Average nighttime center-of-glass temperatures for the control windows and the superwindows at Site 215 (Libby, MT). Also shown are the temperatures at which condensation will occur for 50% RH and 60% RH.

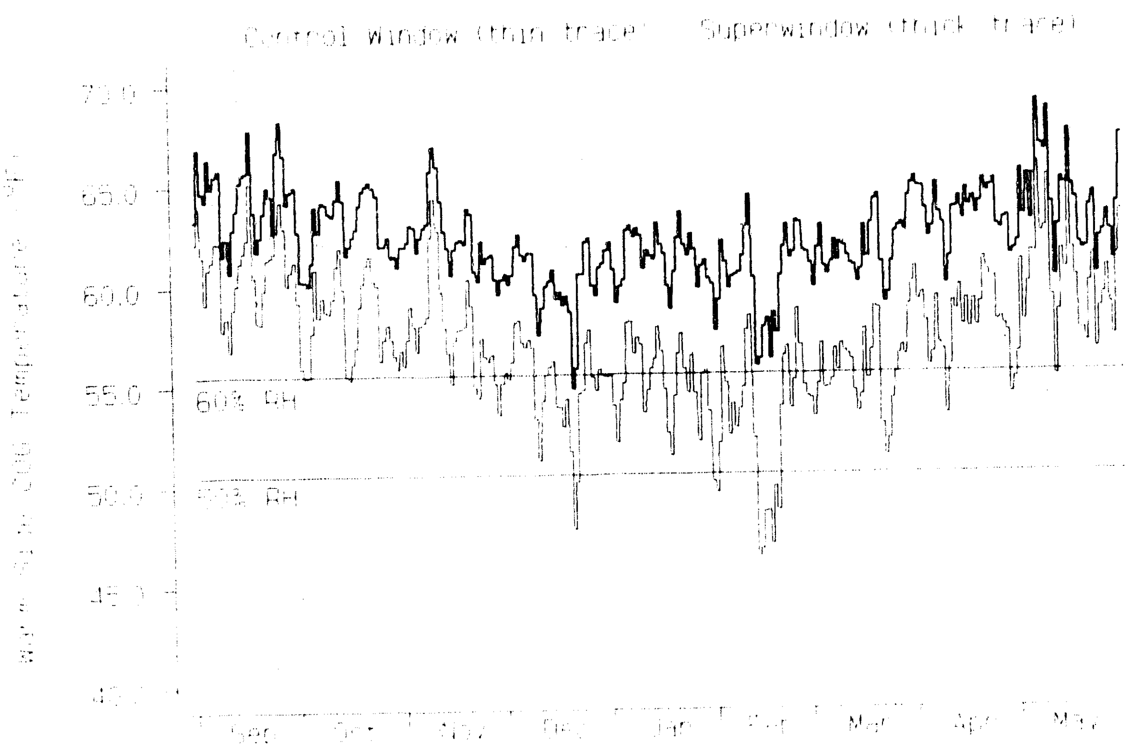

Figure 9b: Average nighttime center-of-glass temperatures for the control windows and the superwindows at Site 219 (Kalispell, MT). Also shown are the temperatures at which condensation will occur for 50% RH and 60% RH.

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