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The Design and Testing of a Highly Insulating Glazing System for use with Conventional Window Systems

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Abstract

In most areas of the United States, windows are by far the poorest insulating material used in buildings. As a result, approximately 3% of the nation's energy use is used to offset heat lost through windows. Under cold conditions, conventional double glazings create uncomfortable spaces and collect condensation. However, with the recent introduction of low-emissivity (low-E) coatings and low/conductivity gas filling to respectively reduce radiative and conductive/convective heat transfer between glazing layers, some manufacturers are beginning to offer windows with R-values (resistance to heat transfer) of 4 hr-ft^2-F/Btu (0.70 m^2-C/W). This paper presents designs for and analysis and test results of an insulated glass unit with a center-of-glass R-value of 8-10; approximately twice as good as gas-filled low-E units and four times that of conventional double glazing. This high-R design starts with a conventional insulated-glass unit and adds two low-emissivity coatings, a thin glass middle glazing layer, and a Krypton or Krypton/Argon gas fill. The unit's overall width is 1" (25 mm) or less, consistent with most manufacturers' frame and sash design requirements. Using state-of-the-art low-emissivity coatings does not significantly degrade the solar heat gain potential or visible transmittance of the window. Work to date has substantiated this concept of a high-R window although specific components require further research and engineering development. Demonstration projects, in conjunction with utilities and several major window manufacturers, are planned. This high-R window design is the subject of a DOE patent application.

Introduction

Residential windows have traditionally been a building element with high heat loss rates. Approximately 3% of U.S. energy consumption, or more than 1 million barrels of oil per day is used to offset the heat lost through poorly insulating windows. With the energy crisis of the mid 1970's, double glazing or insulated glass replaced single glazing as the standard residential glazing system throughout most of the United States. Standard insulated glass has a resistance to heat transfer (R-value) approximately double that of single glazing (2 hr-ft^2-F/Btu or 0.35 m^2-C/W vs 1 Btu/hr-ft^2-F or 0.17 m^2-C/W).

Today, new technologies are upgrading the performance of a standard insulated glass unit to have an R-value of 4. These technologies are low-emissivity (low-E) coatings which reduce radiative heat transfer between glazing layers and low-conductivity gas-fills (gasses with thermal conductivities lower than air placed in the sealed space between the glazing layers) which reduce conductive/convective heat transfer.

This paper summarizes our research towards developing an insulated glass unit design with R-values significantly higher than today's best low-E argon-filled units. These high-R (R 6-10) designs are based on the novel combination of two low-E coatings, Krypton gas-filling, and a non-structural center glazing layer. Our objectives were to show that a window with R6-R10 center-of-glass (i.e., excluding window frame and edge) performance could be built to be compatible with commercially available materials and technologies; to verify predicted thermal performance values with lab and field testing; to improve on existing production technologies for greater efficiency and lower cost; to ascertain the structural integrity of such windows; to develop first-generation prototypes; and to evaluate cost-effectiveness. Current work is aimed at completing research on component parts, refining the prototype design, exploring ways to reduce frame and edge heat transfer, and demonstrating the effectiveness of these windows in test houses.

Interest in high-R windows is expected to grow as consumers and regulatory agencies become aware of their benefits. These include greater energy savings, design freedom to use more and larger windows on off-south orientations, greater occupant comfort, and less condensation. Simulation studies have shown that even north-facing R6-R10 windows with shading coefficients greater than 0.5 (i.e,. at least half the solar heat gain of clear 1/8" (3mm) glass) will outperform an insulated wall in a typical residence in a northern climate. Designers have always understood that south facing windows could become energy producers. With high-R window technology, east/west-facing windows and even north-facing windows will become net producers of energy to the house over the course of a heating season. This effect is seen in figures 1a-1c [1]. Finally, higher interior surface temperatures mean more comfortable spaces and less condensation; the interior surface temperature of an R8 window under standard ASHRAE Winter Design Conditions (0 F (-18 C) with a 15 mph (6.7 m/s) outdoors; nighttime; 70 F (20 C) inside) will be 62 F (17C), compared to 55 (13C) for a low-E argon filled double glazed unit, and 44 F (7C) for conventional double glazing.

LBL High-R Window Design

In the last decade, several designs for highly insulating windows have been developed. The air space in a double-glazed window with a low-E coating can be completely evacuated [2] or filled with a microporous, low-density insulating material, aerogel [3]. Each of these approaches are the subject of current research but are not yet proven solutions and cannot be considered commercially feasible in the short term.

The design discussed here makes use of commercially available low-E coatings, gases, and glazing materials to build a lightweight high-R glazing assembly with an overall thickness of less than one inch (25 mm) and an insulating value of R6 to R10 (1.1-1.7 m^2-C/W) or heat loss rates of U=0.16-0.10 Btu/hr-ft^2-F (0.90-0.55 W/m^2-C). Such an insulated glass unit could be used in standard frame and sash designs and would not require extensive retooling by window manufacturers. High-R windows require two gaps (i.e. three layers) and the successful reduction of both radiative and conductive/convective heat transfer. Reducing one form of heat transfer between glazing layers and not the other will create a thermal short circuit. To suppress radiation across both gaps, this design requires one low-E coating per gap. These coatings should have emissivities under 0.10 and ideally as low as 0.05 and can be on the #2 and #5, the #3 and #4, the #2 and #4, or the #3 and #5 surfaces. (Glazing surfaces are measured from the outside in.) An alternative would be to use coated glass with higher emissivities on all four gap-facing surfaces. To reduce conduction/convection within a narrow gap (gap width) requires a gas-fill with a very low-conductivity. If the gas's kinematic viscosity is too low, convective heat transfer will degrade performance. Figure 2 shows the conductivity (λ) and viscosity (υ) of gasses suitable for use in sealed insulated glass units. Krypton or krypton mixtures provide the best practical compromise between performance and cost. Figure 3 shows the nonlinear conductivity and viscosity of Kr/Air, Kr/Ar and Kr/Ar/Air mixtures changing by 10% volume every step [4].

Lines of constant U-value for LBL high-R windows with any gas fill are given as a function of λ and υ for 1/4" (6 mm) and 3/8" (9mm) gap widths in figures 4 and 5. These were determined by using a modified version of the LBL window heat transfer program, WINDOW 2.0 [5,6]. WINDOW's center of glass calculational procedure has been validated with hot plate measurements for both conventional windows [7] and high-R designs [8]. Note that for the 1/4" (6 mm) gap width, only kinematic viscosities under approximately 0.4×10^{-4} ft^2/s (0.4×10^{-5} m^2/s) influence U-value. On the other hand for 3/8" (9mm) gap widths, kinematic viscosities must be greater than 0.7×10^{-4} ft^2/s (0.7×10^{-5} m^2/s) and the dependence on thermal conductivity is not as great. While not shown, the differences between using coatings with different emissivities is simply a relative shift of the lines of constant U-value. For example, if the coating emissivities in figures 4 and 5 were 0.10 instead of 0.05, the lines of equal U-value would each move over approximately one graduation.

By overlaying the gas and gas mixture graphs (figures 2 and 3) on the U-value vs. conductivity/viscosity plots (figures 4 and 5) the combined effects of two nonlinear phenomena can be investigated. Adding a small fraction of Argon to Krypton does not significantly change the conductivity or the performance of 3/8" (9mm) gaps. Although not shown, adding a small fraction of Krypton to Argon drops the conductivity noticeably. Mixing Kr with CO_2 is not much different from mixing it with argon except that υ is higher with Argon. SF_6 mixtures, while producing reasonable conductivities, have viscosities that are too low.

The three specific designs described in Table 1, based on Krypton and Krypton/Argon mixtures, emerged as the best gasses for use in our high-R window. We use coatings with emissivities of 0.05 because the best commercially available low-E coatings are reported as having emissivities of 0.05-0.06.

In order to keep the system light-weight, nonstructural thin glass is used as the center glazing layer. Unlike conventional designs, this inner layer need not be intimately involved in the structural sealed glass joint and need not seal the two gaps from one another; small spaces of less than 1/16" (1.5mm) do not significantly increase convection and may simplify the process of assembly and gas filling. This center glazing layer, as shown in figure 6, need only be attached to the main spacer by several clips. Fewer glass/sealant joints reduce gas lost by diffusion through the sealant. The use of a double-coated center glass that sits in the air gap but is not sealed to the spacer eliminates the need for edge deletion of the low-emissivity coatings (where the coating is removed from the glass edge to improve glass to metal adhesion). Edge stripping can produce microscopic scratches that increase the possibility of glass breakage. This high-R design is the subject of a DOE patent application [9].

Table 1: LBL High-R Window Designs

Design	Gap Width in.	(mm)	Gas Fill[1]	U-value[2] Btu/hr-ft^2-F	(W/m^2-C)	SC[3]	T_v[3]
A	0.25	(6)	98%Kr/2%Air	0.13	(0.74)	0.59-0.73	0.62-0.71
B	0.375	(9)	98%Kr/2%Air	0.11	(0.63)	0.59-0.73	0.62-0.71
C	0.375	(9)	70%Kr/30%Ar	0.12	(0.68)	0.59-0.73	0.62-0.71

Field Thermal Measurements

Calculation procedures and laboratory measurements are helpful in understanding glazing heat transfer processes, in serving as references, and in developing window designs. However windows should be tested under realistic environmental conditions to validate overall performance and to determine areas of future research. LBL's Mobile Window Thermal Test Facility (MoWiTT) has the capability of accurately measuring heat flows through windows exposed to outdoor conditions [10,11]. The MoWitt consists of two room-size test chambers and a monitoring room. Our MoWiTT field tests of an LBL high-R window under winter conditions in Reno, Nevada validated predicted center of glass performance values. The sample tested was similar to design A in Table 1 except that the low-E coatings had emissivities of 0.10 and the gas/fill was approximately 90%Kr/10%Air.

The calculated center-of-glass U-value of this system (using WINDOW 2.0) is 0.13 Btu/hr-ft^2-F (0.74 W/m^2-C). Because this is an extremely low center-of-glass U-value and because this sample was built with metal spacers (which create a thermal bridge or short circuit through the glass edge), the overall U-value was expected to be much higher. Two series of tests were therefore run: (1) the frameless insulated glass unit alone, and (2) the same unit with 2 in. (50 mm) thick styrofoam insulation covering the area within 2.75 in. (70 mm) of the glazing's edge. This second case was intended to factor out the edge effect and produce a U-value more representative of the center-of-glass U-value calculated by WINDOW 2.0 and desired in a final product.

Measured nighttime U-values for the case with no edge insulation are seen in figure 7 and the measured and calculated sample heat flow in figure 8. The measured overall U-value of 0.24 ± 0.01 Btu/hr-ft^2-F (1.38 ± 0.08 W/m^2-C) is considerably higher than the calculated center-of-glass U-value of 0.13 Btu/hr-ft^2-F (0.74 W/m^2-C). This effect is also seen in figure 8, which shows the difference between the nighttime calculated heat

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[1] These designs assume the use of new gas-filling techniques discussed later in this paper.

[2] U-values were all calculated at ASHRAE Winter Design Conditions (nighttime, 70 F or 21 C inside, 0 F or -18 C outside) and are all center-of-glass U-values.

[3] This range of SC's and T_v's is based on the use of different center glazing materials and coating technologies and placement.

flow (based on the calculated center-of-glass U-value) and measured heat flows.

Testing the unit with edge insulation succeeded in greatly reducing the edge effect: the measured data is more indicative of center-of-glass performance. Figure 9 shows effective U-values as a function of time; the average value is 0.16 ± 0.04 Btu/hr-ft^2-F (0.91 ± 0.21 W/m^2-C). Figure 10 shows that the measured sample heat flow data closely fits the calculated data. Because inside/outside temperature differences during these tests were very small, resulting sample heat flows were hard to measure accurately. This is reflected in the higher standard deviations in the U-value for the case with edge insulation. The differences between this and the case without edge insulation show the importance of reducing edge heat transfer in high-R windows. This area of research is being actively pursued within the window industry and at LBL.

The sample heat flows and U-values presented here include the effects of infiltration, estimated at 2-6 Btu/hr (0.5 - 2.0 Watts). Where there are large sample heat flows (i.e., with more conventional glazings) and larger temperature differences ($>$ 30-40 F or 15-20 C), these effects are minimal. However, in these two cases, especially for cases with edge insulation, where the sample heat flow varied between 15-50 Btu/hr (5-15 Watts) and the temperature difference was less that 25 F (14 C), correcting for infiltration will make a noticeable impact on the measured U-value (reducing the case with edge insulation by approximately 0.02 Btu/hr-ft^2-F (0.1 W/m^2-C)) to 0.14 ±0.04 Btu/hr-ft^2-F (0.79 ± 0.21 W/m^2) or very close to the calculated center-of-glass U-value of 0.13 Btu/hr-ft^2-F (0.74 W/m^2-C). Differences noted are attributed to uncertainties in gas retention and filling test units as well as in measuring very low heat flows.

We see a reasonable correlation between the calculated and experimental daytime sample heat flows in figures 8 and 10. Measured daytime sample heat flows include the effects of solar radiation which dominate over heat flows driven by temperature difference. The correlation between calculated and measured data indicates that our calculated shading coefficient of approximately 0.60 for this prototype is reasonable.

Gas Filling and Sealant Integrity

Though gas-filled IG units have been sold in Europe, they are just beginning to reach the U.S. market. The obstacles to U.S. mass production have been the need to scale-up European filling techniques to larger U.S. IG plants and the lack of data on sealant durability. Since gas-filling is a primary component of this window design, we have studied gas-filling technology and how it might be refined for high-R window designs, and have analyzed several studies on sealant durability.

Gas-Filling Techniques

The procedure for filling insulated glazing systems with low-conductivity gases is generally to first drill two holes through the aluminum spacers separating the glass layers, one at the top and one at the bottom of the unit and then inject gas into the bottom slowly enough to prevent turbulence, pushing air out the top. When a sensor reads a residual amount of oxygen, the filling process is shut off and the holes plugged. Argon is generally used because it is relatively cheap and spillage costs have not been an issue. Fills of up to 90% are the best most believe can be achieved with such a process within a reasonable time period. Spillage is estimated to be on the order of 100% of the volume of the IG unit.

Using more expensive and better-performing Krypton as a gas fill requires a new look at the fill process as spillage and percentage fill become more critical issues. A new process still under development at LBL uses a vacuum chamber with IG units also placed inside the chamber. After the chamber and IG units are evacuated, they are back-filled separately (IG units with gas, chamber with air). At all times, the IG units and chamber are maintained at the same pressure (within certain tolerances) to avoid damage to the IG units. Figure 11 shows the procedure in more detail. The access holes can be sealed mechanically at the end of the process or the IG units can be filled to slightly above atmospheric pressure to ensure that no air enters the units when the access holes are sealed. Gas losses are expected to be insignificant. Such a process would be used for designs A and B and is the subject of a U.S. DOE patent disclosure.

Where a Krypton-Argon mix is desired in the window (design C), another filling technique is suggested. The window is flushed with a cheap gas such as argon using conventional techniques. Then, assuming the window requires only a moderate fraction of Krypton (on the order of 50-70%), the Krypton could be injected into the gas space. If the fraction is small enough and the filling speed slow enough, little Krypton will escape before the IG unit is sealed.

Sealants

Several studies, summarized in Table 2, show leakage rates after 20 years for different sealant systems subjected to DIN 52293 or similar tests. No U.S. standards on the durability of gas-filled units presently exist and thus this West German standard has become a de-facto U.S. standard. Although data is sparse, it appears that conventional dual-seal sealants (polysulfide, polyurethane) are acceptable. Several single-seal (i.e. the secondary seal in Figure 6 only) materials may even be acceptable; but here the case for quality control is even more important than with dual-seal glazings. Significantly lower gas leakage rates are seen for SF_6 and Ar/SF_6 mixtures than for Ar because of SF_6's larger molecular size. The difference in measured permeabilities of these sealants of up to a factor of 10 reflects this. Though we do not have similar data for Krypton, based on its molecular size, we expect that the permeability of various sealants to Krypton will be less than Argon but greater than SF_6. One subject for future research is the differential permeabilities of gasses. If permeability rates are significantly different to gasses inside the unit than for gasses outside the unit, over time, the pressure inside the unit may deviate from atmospheric. Most of the data gathered is based on 1/2 in. gaps. Gas leakage will of course vary with gap width and unit dimensions. The permeability of nonmetallic spacers (i.e., fiberglass, butyl) is also a question.

Structural Analysis

In the design of any IG unit, the structural stresses resulting from temperature-driven differences in internal and atmospheric gas pressures can be significant. Thus, with any new IG design, it is important that structural issues be addressed. A 70 F (39 C) difference between filling and use temperatures will result in a pressure differential of two psi or three hundred psf (14,000 N/m^2). For comparison, wind loads are typically 30-40 psf (1500-2000N/m^2). Luckily, glass can flex and bend slightly, expanding or contracting the sealed gas volume, thereby relieving much (but not all) of the pressure loading.

Table 2
Percent Gas Loss After 20 Years

	Ar/SF_6 mix [12]	Ar^* [13]	Ar^* [14]	Ar^* [15]	SF_6^* [15]
Single Seal					
Polysulfide	8-10	13-15		6-13	0-1
Polyurethane	8-10	13-15	15-20	33-45	3-5
Silicone			>45		
Butyl			5-7		
Polyisobutylene			4-5		
Permapol P-2			5-10		
Permapol LPM			1-4		
Thiokol LP			3-9		
Dual Seal					
Polysulfide	5-6				
Polyurethane	2-5				
Silicone	12-15				

*data extrapolated

Greater glass stresses may require costlier glass while greater deflections may compromise thermal performance.

We consider the case of two glass panes containing a sealed gas space. The space may (as assumed in this analysis) or may not contain a third central pane which allows for pressure equalization between the gas gaps. Without pressure equalization between the two gas gaps, the center pane may experience excessive stresses. In a conventional triple-glazed unit, pressure equalization may take the form of a simple 1/8 in. (3mm) hole drilled through the edge of the center glazing layer.

Stresses and deflections depend on edge constraint conditions. As shown in figure 12, clamped edge units deflect much less than simply supported (free to rotate) edges for a given pressure, and thus create greater glass stresses. These two cases represent the idealized extreme on what is actually a design continuum. The degree of edge clamping depends on spacer, sealant elasticity, and glazing bar details. Exaggerated glazing layer profiles for a glazing layer in an internally pressurized IG unit with a simply supported edge and with a clamped edge are shown in the legend of figure 12. The flexibility of the IG unit thus determines what fraction of initiating pressure can be relieved (see figure 12).

Given temperature and atmospheric pressure changes that generate an initiating pressure, the equilibrium pressure loading on a glazing layer can be determined. Stresses and deflections can then be calculated using a finite element computer code [16]. Calculated stresses may then be compared to the design stresses listed in Table 2. Inward deflections should not be so great that they threaten thermal performance.

To analyze the differences between high-R and conventional IG units, the following four configurations are considered:

Table 3:
Typical Design and Ultimate (Fracture) Stresses for Window Glass [17]

Glass Type	Design Stress Long term load psi	(MN/m^2)	Design Stress Short term load psi	(MN/m^2)	Ultimate Stress psi	(MN/m^2)
Annealed	1,900	(13.1)	2,800	(19.3)	6,000	(41.4)
Heat-Strengthened	5,900	(40.7)	7,000	(48.3)	11,000	(75.9)
Tempered	15,500	(107.0)	17,200	(118.7)	23,000	(158.7)
Failures, 60 sec load	1/1000		8/1000		500/1000	

(1) Conventional double glazed IG unit with 1/2 in. (13mm) air space;
(2) LBL high-R IG unit with two 1/4 in. (6mm) Krypton gaps and pressure equalization;
(3) LBL high-R IG unit with two 3/8 in. (9mm) Krypton gaps and pressure equalization;
(4) High-R IG unit with two 1/2 in. (13 mm) Argon gaps and pressure equalization.

Each unit measures 24 in. x 48 in. (60cm x 120 cm). A glass thickness of 0.12 in. (3mm) is specified.

The maximum stresses and deflections for these four units are summarized in Table 4. Two environmental conditions are analyzed; design installation conditions where the units were manufactured at 70 F (21 C) and installed at a similar elevation but at 0 F (-18 C) and ASHRAE standard design operating conditions (70 F or 21 C indoors, 0 F or -18 C outdoors).

Table 4:
Maximum Tensile Stresses and Deflections for Conventional and High-R IG Units
Design Installation Conditions (0 F or -18 C gas space temperature);
ASHRAE Winter Operating Conditions (0 F or -18 C outdoors; 70 F or 21 C indoors)

	Installation Conditions Stresses psi	(N/m^2)	Deflections in.	(mm)	Operating Conditions Stresses psi	(N/m^2)	Deflections in.	(mm)
(1) Double IG								
Simple	800	(5.5)	0.072	(1.8)	505	(3.5)	0.046	(1.2)
Clamped	2860	(19.7)	0.080	(2.0)	1810	(12.5)	0.051	(1.3)
(2) LBL High-R								
Simple	800	(5.5)	0.072	(1.8)	440	(3.0)	0.040	(1.0)
Clamped	2860	(19.7)	0.080	(2.0)	1580	(10.9)	0.044	(1.1)
(3) LBL High-R								
Simple	1170	(8.1)	0.106	(2.7)	660	(4.60	0.060	(1.5)
Clamped	4230	29.2)	0.118	(3.0)	2360	(16.3)	0.066	(1.5)
(4) High-R w/Ar								
Simple	1510	(10.4)	0.137	(3.5)	870	(6.0)	0.079	(2.0)
Clamped	5530	(38.2)	0.154	(3.9)	3120	(21.5)	0.087	(2.2)

The deflections given are for each pane. In case (1) there are two deflecting panes around one air gap. However, in cases (2), (3), and (4), each gas gap is bounded by one deflecting pane and the rigid center layer. Because High-R windows maintain a higher gas space temperature, pressures and resulting stresses and deflections will be less than conventional IG units with the same total gap thickness. Given that the average deflection per pane is about half the maximum, overall U-values will rise by less than 1% for cases (1) and (3) and by approximately 6% for case (2) and 4% for case (4). Wind loading is not expected to significantly change these conclusions.

Most conventional sealants are assumed to behave as simply supported edges and thus, based on Table 2, the use of standard annealed glass will be adequate for most window sizes. Note that the wider the gap widths, the greater the stresses. LBL High-R window design (2) has the equivalent thermal performance of a more conventional high-R window (4), yet the maximum stress for (2) is half that of (4). The probability of glass breakage from internal pressure changes increases with total unit thickness. Assuming measures are taken to equalize the pressure between the two gas spaces, an LBL high-R unit with 1/4 in. (6mm) gaps will have a breakage probability approximately equal to that of a conventional IG unit with a 1/2 in. (12mm) airspace.

If a rigid sealant system is used (e.g., a glass edge in double glazing), the unit's edge may behave more like a clamped edge. Because the likelihood of fracture is proportional to stresses taken to the 5th or 6th power, the breakage probability for a clamped edge is two orders of magnitude greater than the simply supported case [18]. Further modeling of sealed edges will define actual edge fixity conditions and glass stresses.

Conclusions and Future Work

The objectives of this study were to develop and test the thermal performance of a first-generation prototype high-R window and to examine issues of durability and structural integrity that relate to ultimate marketability. Work completed to date has substantiated the concept of a high-R window based on Krypton gas filling and two low-E coatings. General conclusions and current research are summarized below:

(1) An insulated-glass unit with a center-of-glass R values of 8-10 can be commercially produced using low-E coatings and Krypton based gas fills. The three options studied all incorporate two sputtered low-E coatings on the #2 or #3 and #4 or #5 surfaces with the remaining specifications as follows:

Design	Gap Width		Gas Fill	U-value		SC	T_v
	in.	(mm)		Btu/hr-ft^2-F	(W/m^2-C)		
A	0.25	(6)	98%Kr/2%Air	0.13	(0.74)	0.59-0.73	0.62-0.71
B	0.375	(9)	98%Kr/2%Air	0.11	(0.63)	0.59-0.73	0.62-0.71
C	0.375	(9)	70%Kr/30%Ar	0.12	(0.68)	0.59-0.73	0.62-0.71

(2) Current work is aimed at collaborating with several national window and insulated glass manufacturers to produce a limited number of prototypes for demonstration projects in order to stimulate interest in high-R windows and to learn more about production costs. The thermal performance of these windows will be compared with that of conventional windows and insulated walls under the same conditions.

(3) Using conventional metal spacers in a highly insulating window will significantly reduce the effective R value around the perimeter. This must be remedied by an insulating sash/frame and/or with an insulated edge design and is the subject of current research.

(4) Based on data for Argon-filled units, the gas diffusion rates for most double-sealed units are acceptable. The diffusion rates for Krypton are expected to be lower because of its larger molecular size. The differential permeability rates for gasses inside and outside the IG unit of any edge seal should be evaluated for specific edge designs.

(5) While spot prices for pure Krypton can be high, quotes for large volumes of crude Krypton are \$15-20/cf (\$0.50-0.70/liter). This translates to \$0.55-0.75/ft^2 (\$6.0-\$8.0/m^2) of typical high-R window assuming alternative low-wastage filling techniques. This cost is about 1/2 the cost of the two low-E coatings.

(6) Alternative gas-filling techniques which achieve a higher fill percentage with less spillage will be useful in the production of high-R glazings. Preliminary investigations of such a process using vacuum chambers have been undertaken. Development of this and other new filling procedures is the subject of current research.

(7) Narrow gas gap widths, with the same thermal performance as larger gap widths, will result in less stresses and deflections for the same environmental conditions. It is important that multiple gap designs allow for pressure equilibrium between the two gas spaces; this will greatly mitigate stresses on the exterior glazing and virtually eliminate pressure loading on the center layer. Conventional edge designs are usually assumed to act as simply supported edges. Under this assumption, high-R window designs will not experience excessive stresses and deflections. However, glass stresses for clamped edges will be significantly greater. High-R edge details, including determining exactly where on the continuum between simply supported and clamped edges conventional designs lie, will continue to be researched. The use of alternative spacers and edge designs will also be explored.

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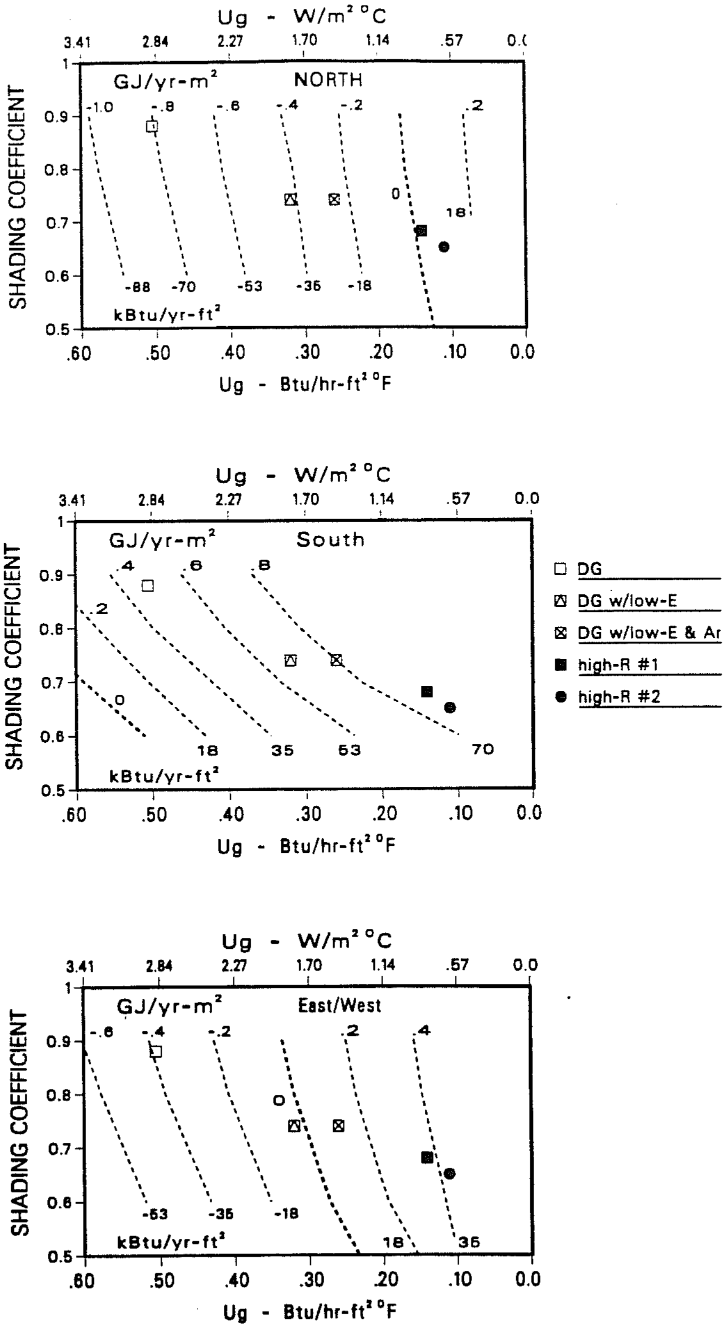

Figures 1a,1b,1c: Net annual useful energy flux in kBtu/yr-ft^2 (and GJ/yr-m^2) of window area through 66 ft^2 (6.1 m^2) of north, south, and east/west -facing glazing systems in a prototypical house in Madison, WI expressed as a function of window U-value and Shading Coefficient. Glazing systems studied include standard double glazing, low-e coated double glazing, low-e coated double glazing with an argon fill, an LBL high-R window with 1/4" (6 mm) Kr filled gaps and emissivities of 0.10, and an LBL high-R window with 3/8" (9 mm) Kr filled gaps and emissivities of 0.05. Shading Coefficient is defined as the ratio of the solar heat gain at a near normal angle of incidence through a specific glazing system to the solar heat gain through double strength glass.

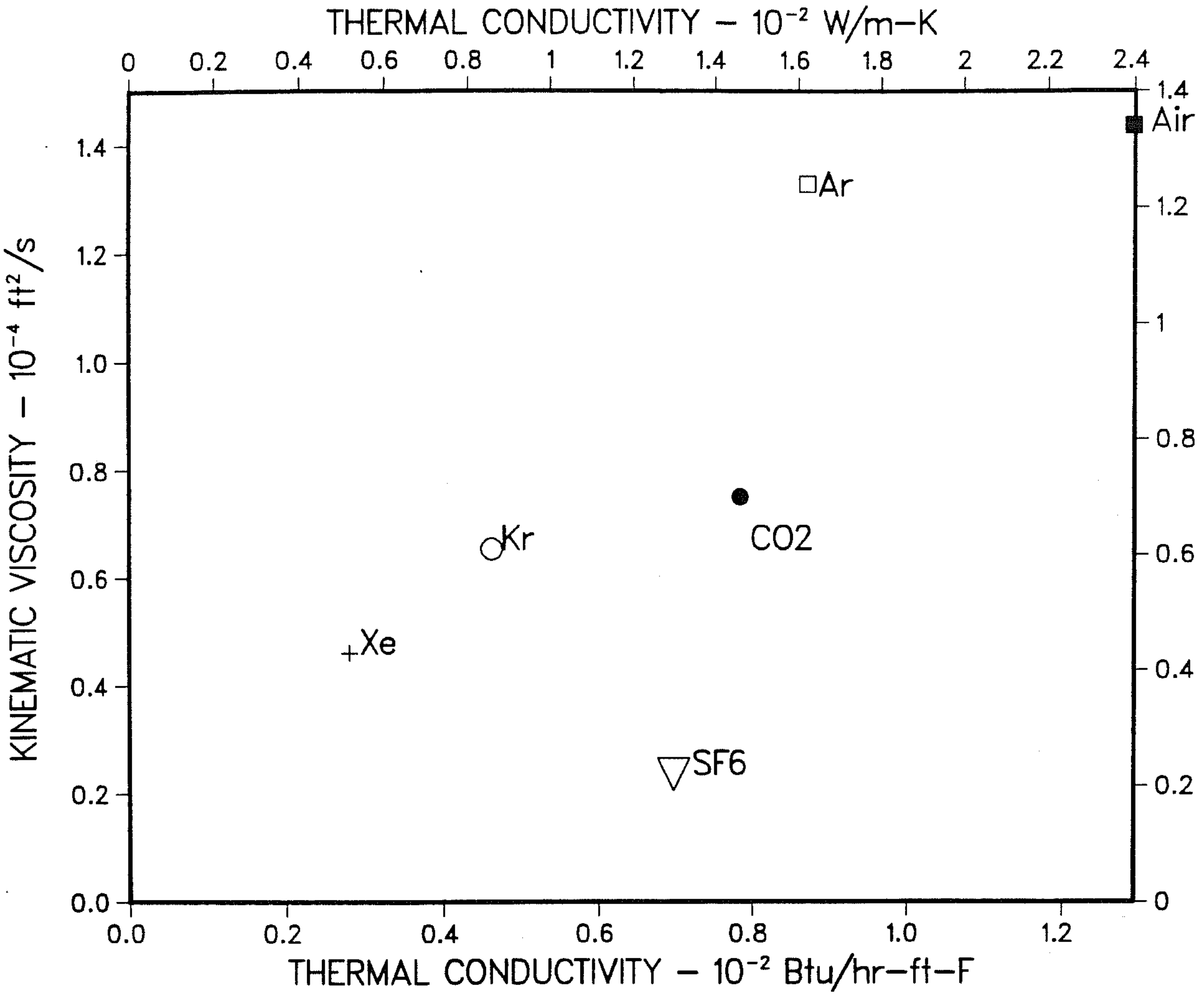

Figure 2: Thermal conductivity and kinematic viscosity of gasses suitable for use in gas-filled windows.

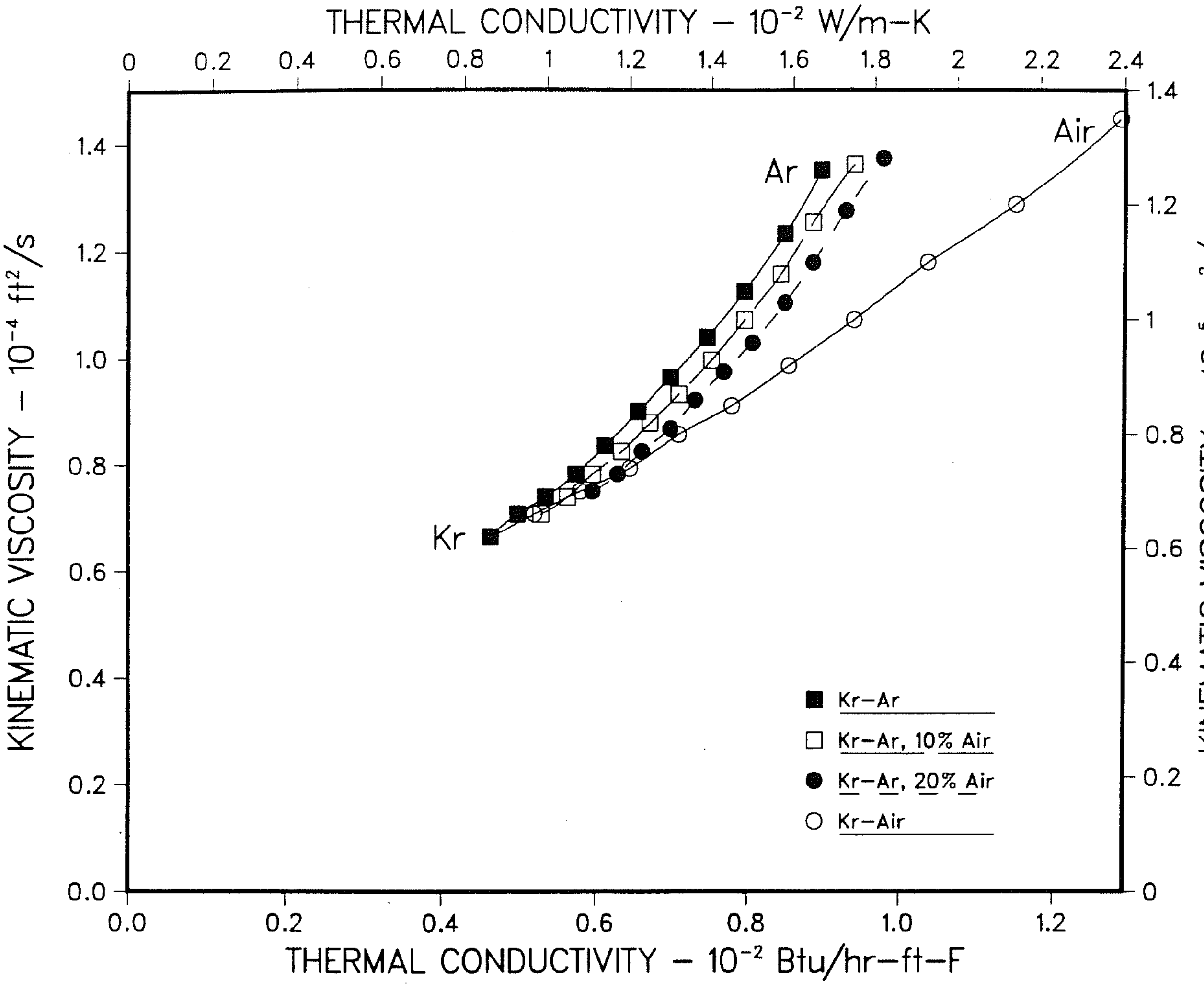

Figure 3: Thermal conductivity and kinematic viscosity of Krypton/Air mixtures and of Krypton/Argon mixtures with 0, 10, and 20% air.

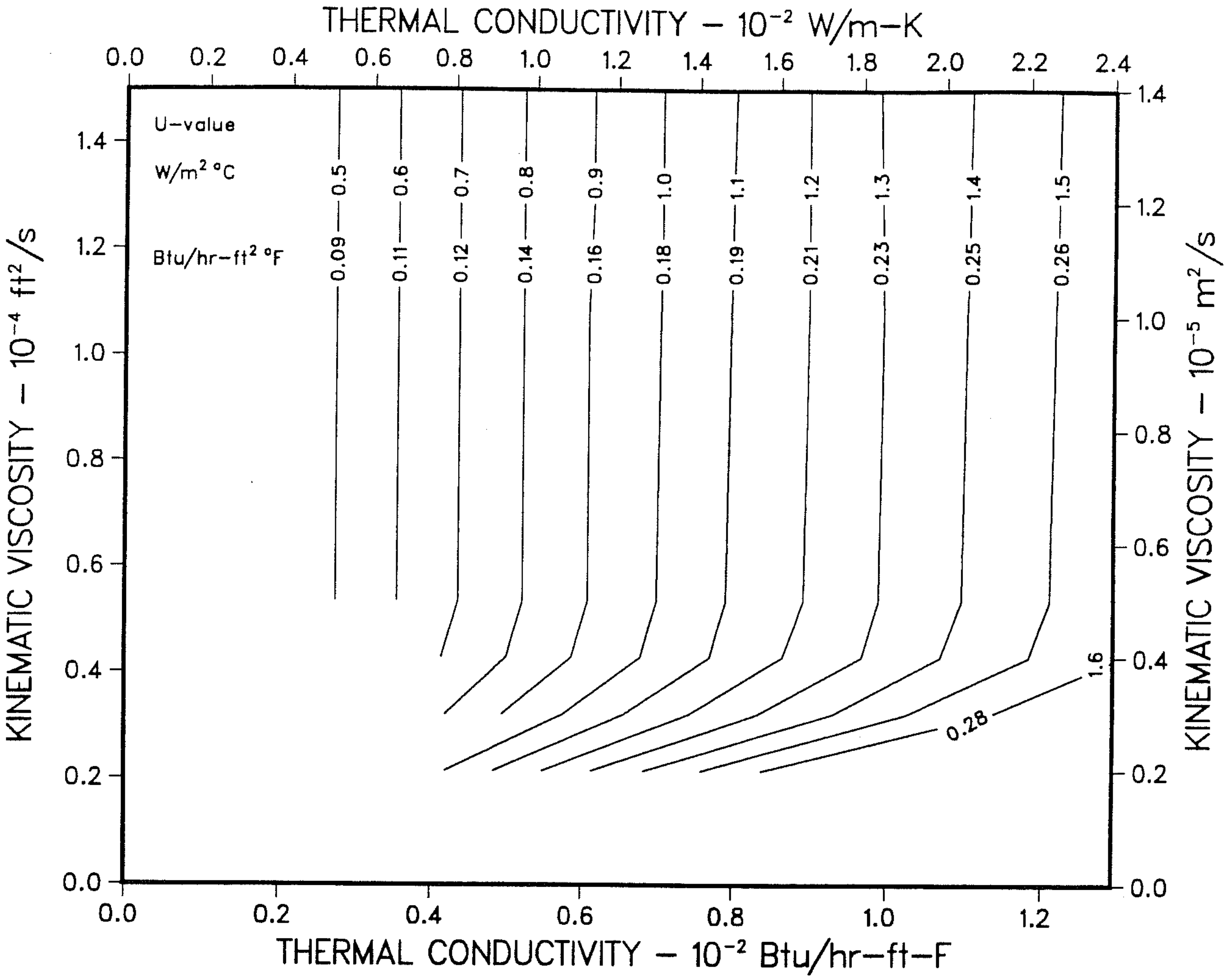

Figure 4: Lines of constant U-values as a function of gas conductivity and kinematic viscosity (absolute viscosity/density) for a triple glazed configuration with emissivities of 0.05 on surfaces 2 or 3 and 4 or 5 and gap widths of 1/4 in. (6mm).

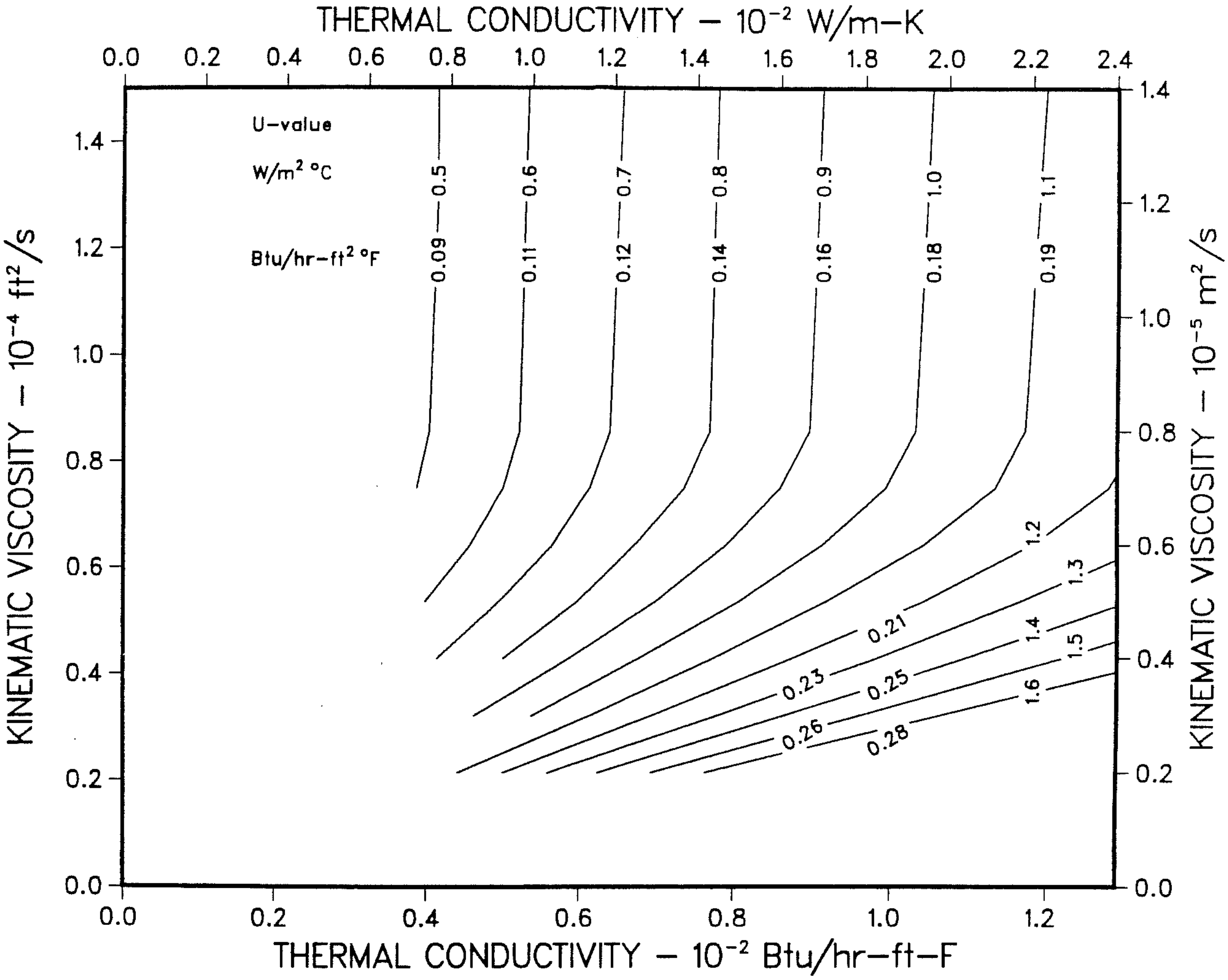

Figure 5: Lines of constant U-values as a function of gas conductivity and kinematic viscosity (absolute viscosity/density) for a triple glazed configuration with emissivities of 0.05 on surfaces 2 or 3 and 4 or 5 and gap widths of 3/8" (9mm).

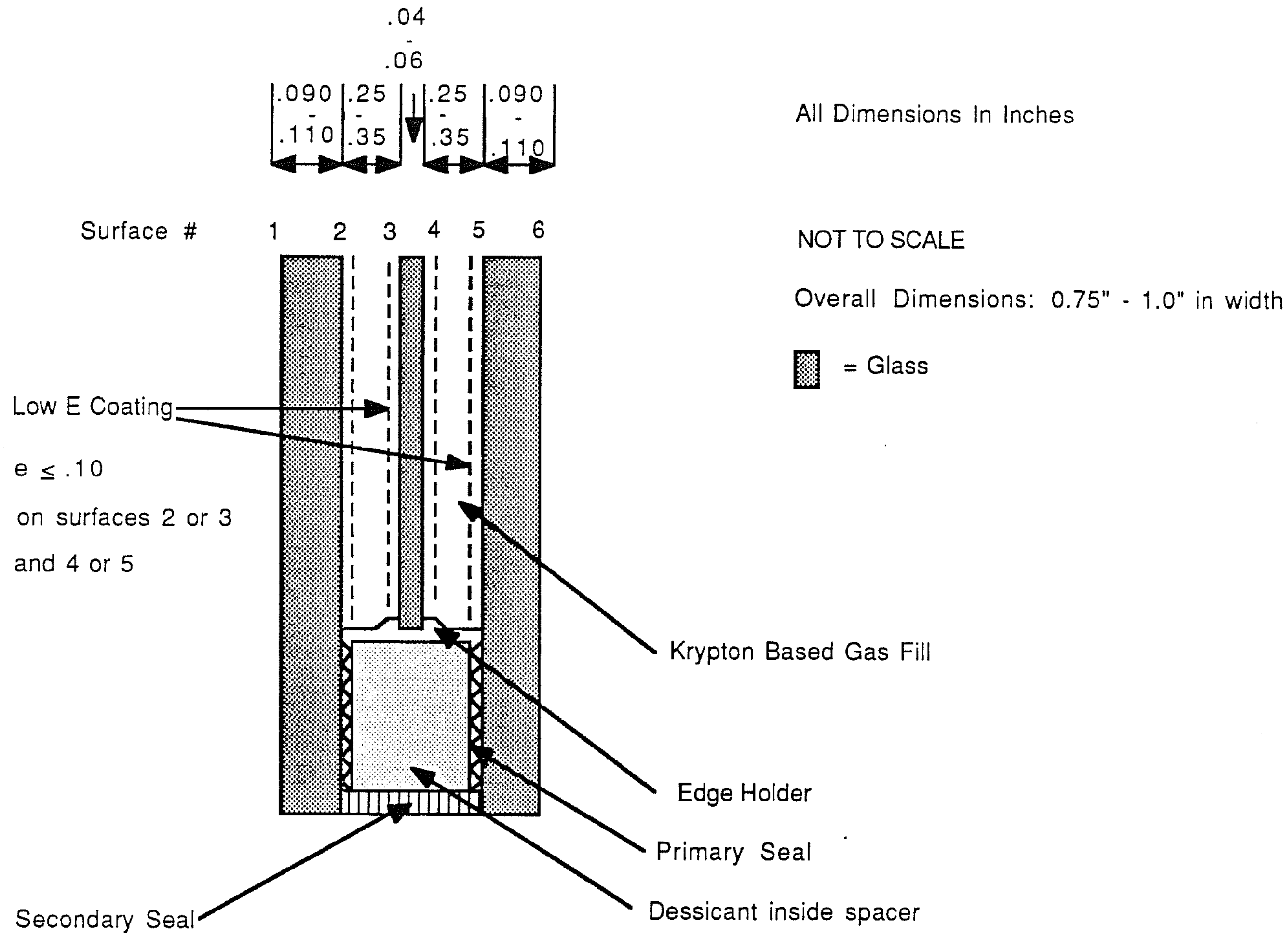

Figure 6: Cross Section of LBL High-R Window.

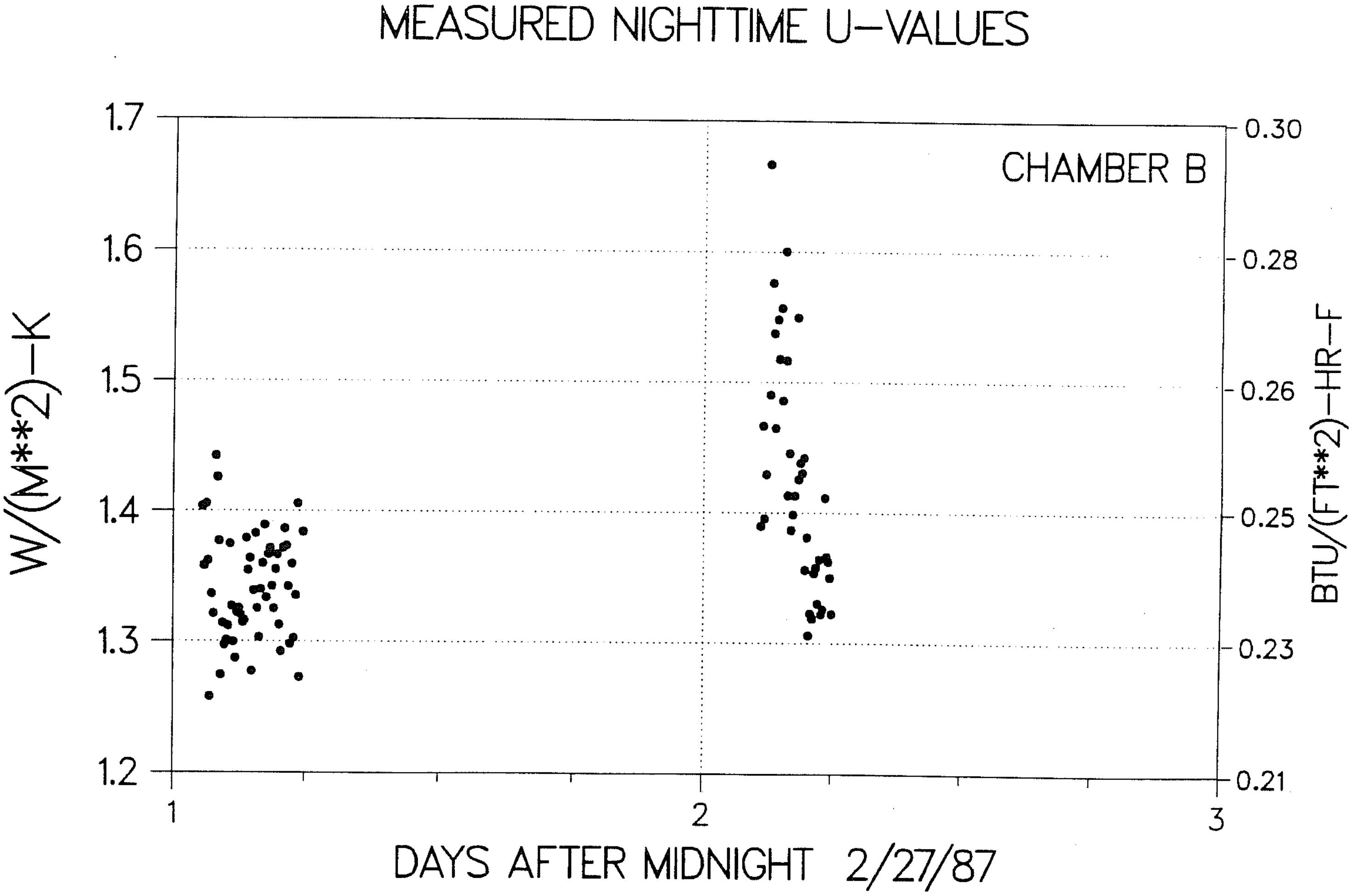

Figure 7: Measured nighttime overall U-values for the sample LBL High-R Window (no edge insulation). Points represent data taken every minutes from midnight to sunrise.

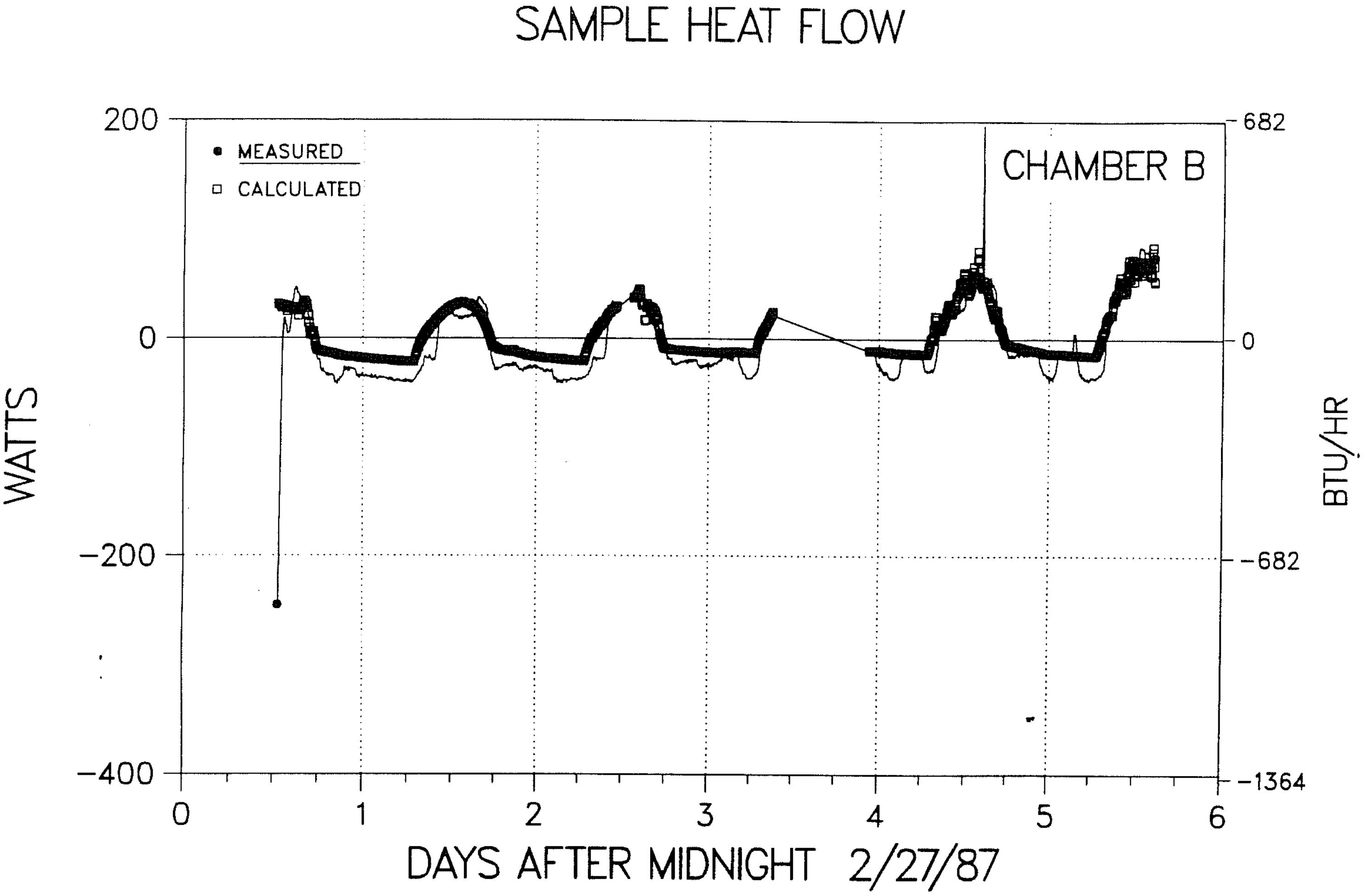

Figure 8: Measured vs. Calculated Sample Heat Flow for a sample LBL High-R Window (no edge insulation). Calculated points were taken every five minutes and appear as the heavy line in the figure.

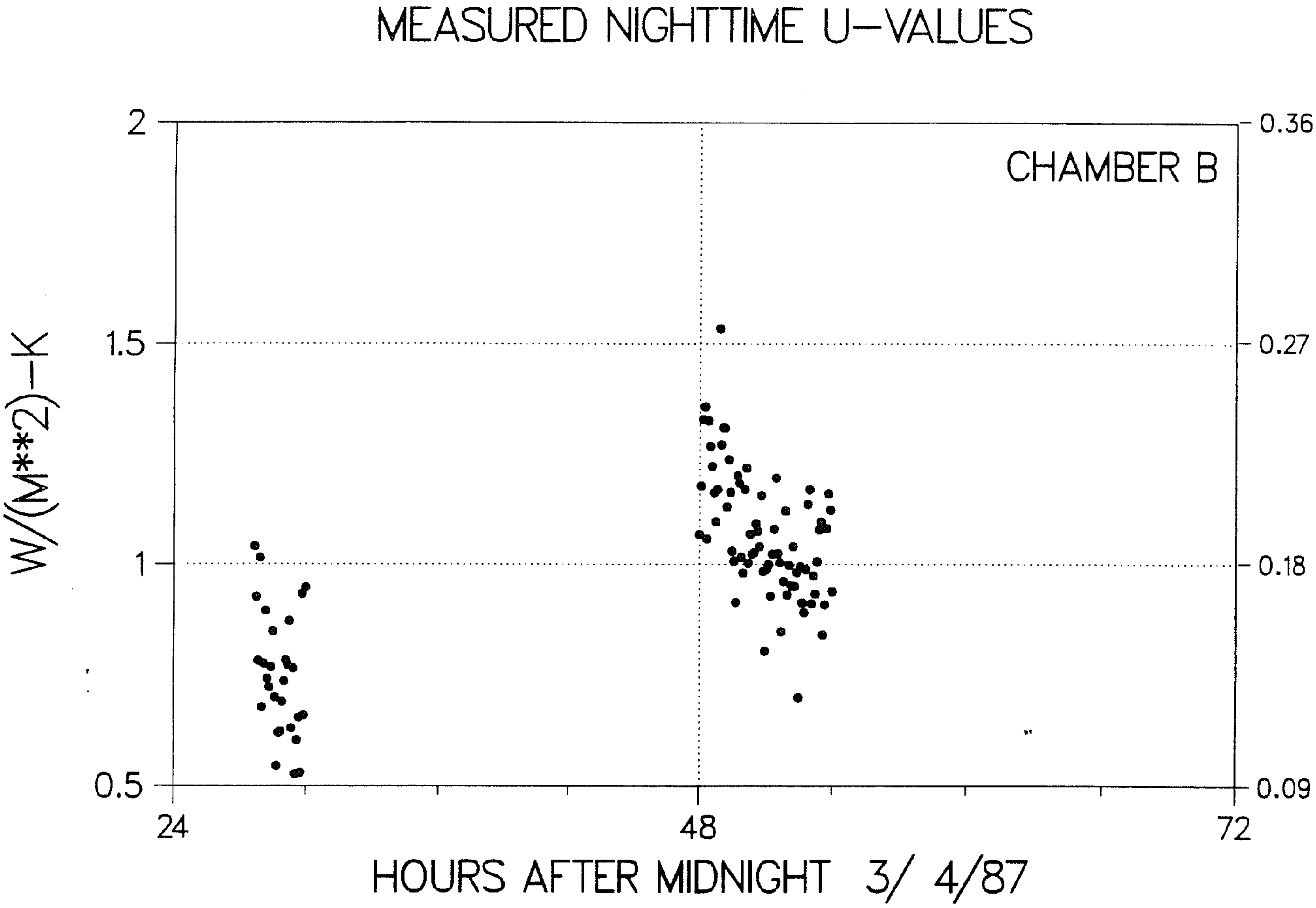

Figure 9: Measured nighttime overall U-values for a sample LBL High-R Window. Edges masked with styrofoam and edge effect factored out. Points represent data taken every minutes from midnight to sunrise.

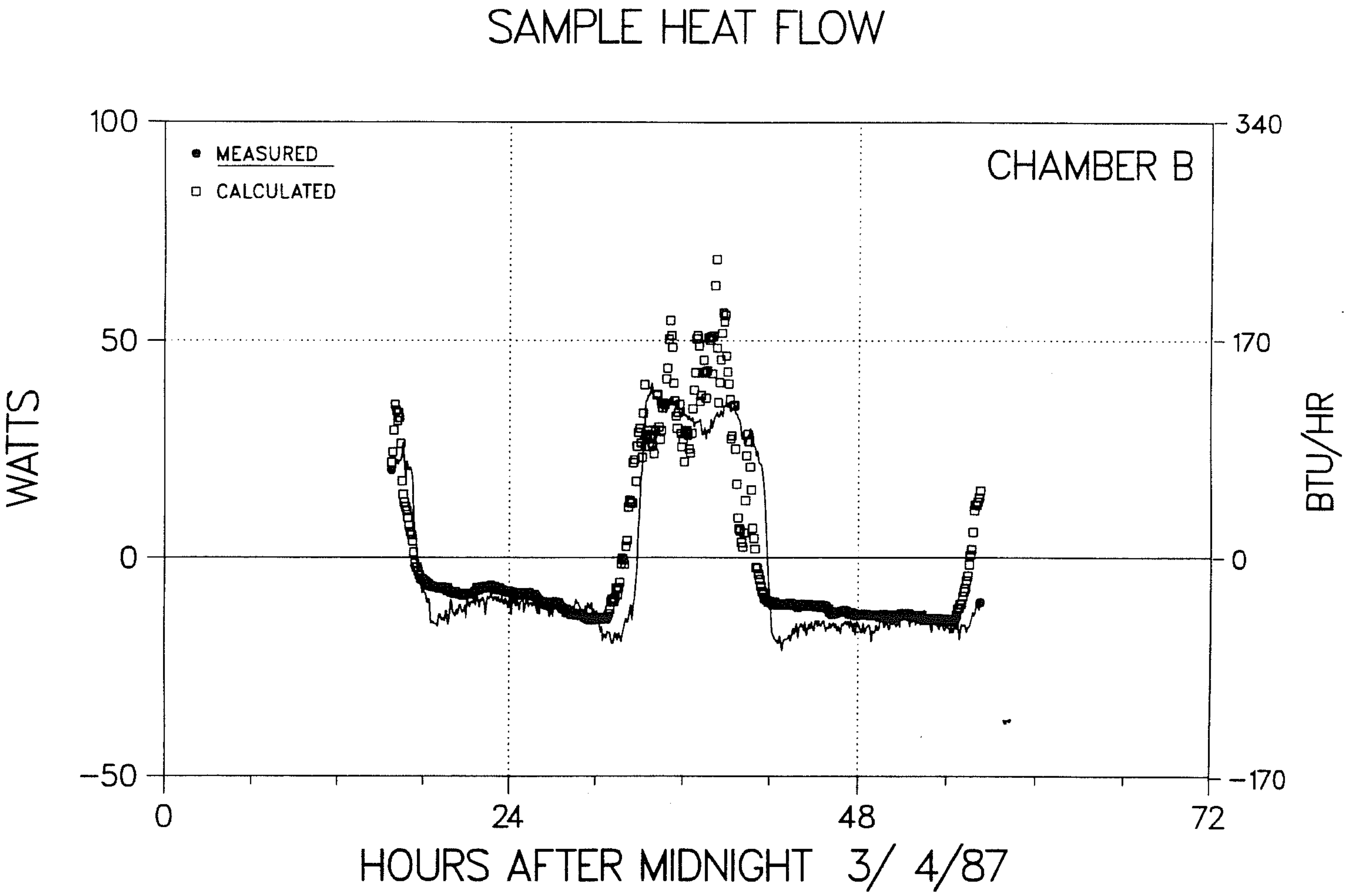

Figure 10: Measured vs. Calculated Sample Heat Flow for a sample LBL High-R Window. Edges masked with styrofoam and edge effect factored out.

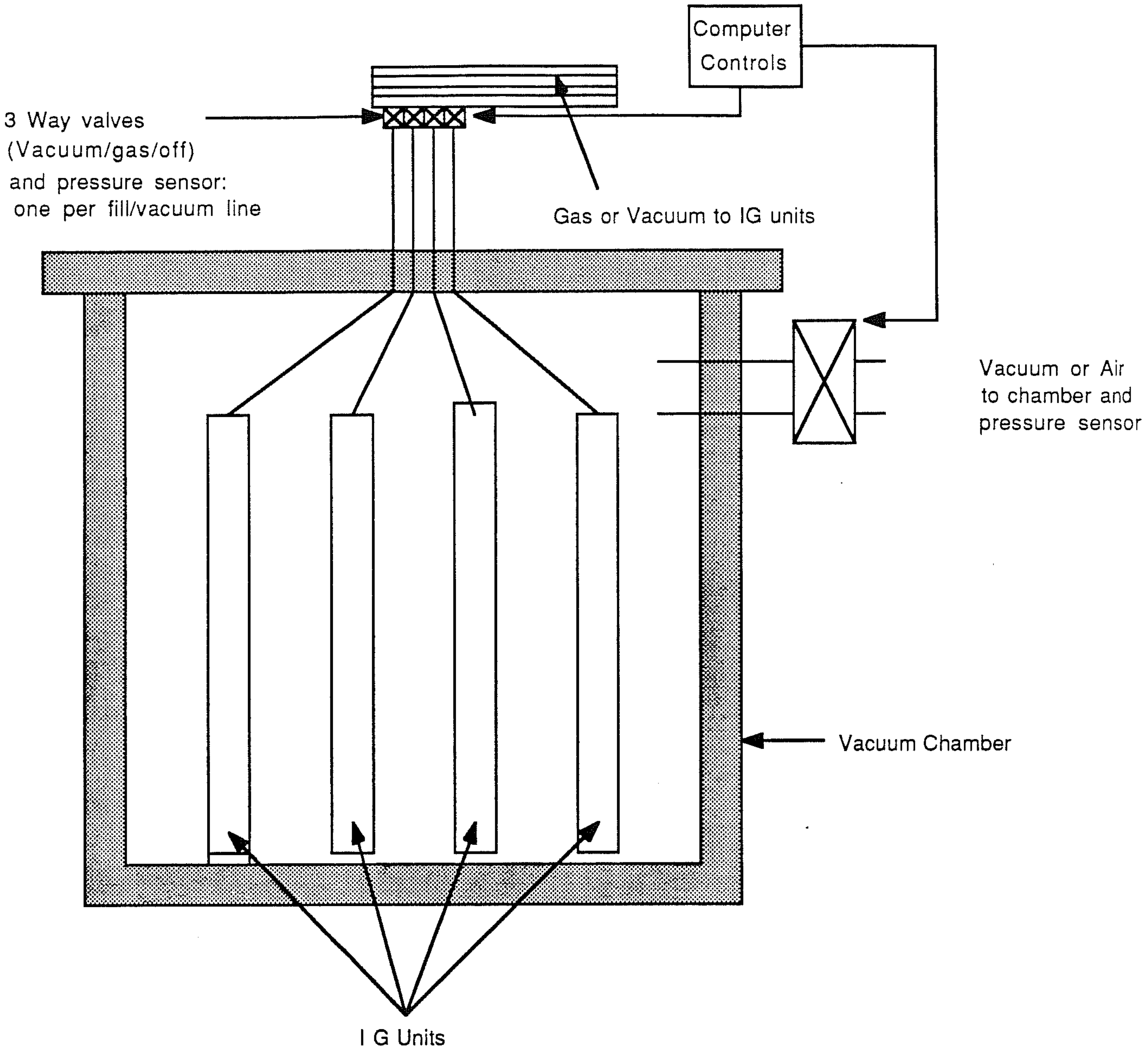

Figure 11: Schematic of LBL Vacuum Chamber Window Gas-Filling Appartus.

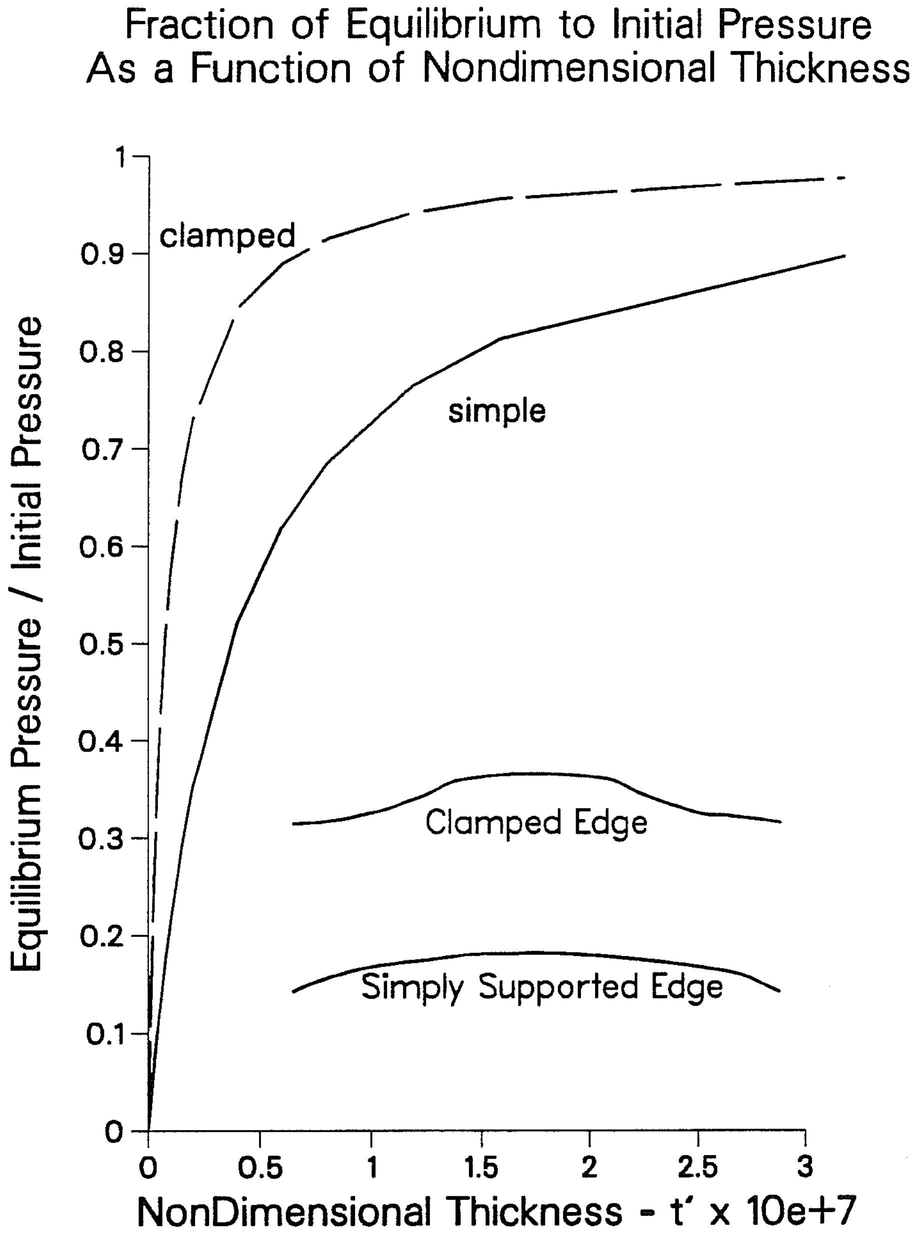

Figure 12: Equilibrium (actual) to initial (zero displacement) pressure ratio for clamped and simple supported edges as a function of non-dimensional thickness, $t' = gh^3/(ab)^2$ where g=gas gap thickness, h=glass thickness, a=pane width. Based on aspect ratio of a/b=2. Profiles for an IG unit with a clamped edge and for one with a simply supported edge are given in the legend.